NEUROMUSCULAR TRAINING AND ADAPTATIONS IN YOUTH ATHLETES

EDITED BY: Urs Granacher, Christian Puta, Holger Horst Werner Gabriel, David G. Behm and Adamantios Arampatzis

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NEUROMUSCULAR TRAINING AND ADAPTATIONS IN YOUTH ATHLETES

Topic Editors:
Urs Granacher, University of Potsdam, Germany
Christian Puta, Friedrich-Schiller-University Jena, Germany
Holger Horst Werner Gabriel, Friedrich-Schiller-University Jena, Germany
David G. Behm, Memorial University of Newfoundland, Canada
Adamantios Arampatzis, Humboldt-Universität zu Berlin, Germany



Young athlete performing neuromuscular training.
Image: University of Potsdam, with permission to use the image of the young adult.

The Frontiers Research Topic entitled "Neuromuscular Training and Adaptations in Youth Athletes" contains one editorial and 22 articles in the form of original work, narrative and systematic reviews and meta-analyses. From a performance and health-related standpoint, neuromuscular training stimulates young athletes' physical development and it builds a strong foundation for later success as an elite athlete.

The 22 articles provide current scientific knowledge on the effectiveness of neuromuscular training in young athletes.

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EDITORIAL
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Editorial: Neuromuscular Training and Adaptations in Youth Athletes

Urs Granacher[1]*, *Christian Puta*[2], *Holger H. W. Gabriel*[2], *David G. Behm*[3] and *Adamantios Arampatzis*[4]

[1] Research Focus Cognition Sciences, Division of Training and Movement Sciences, University of Potsdam, Potsdam, Germany, [2] Department of Sports Medicine and Health Promotion, Friedrich-Schiller-University Jena, Jena, Germany, [3] School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NL, Canada, [4] Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany

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Editorial on the Research Topic

Neuromuscular Training and Adaptations in Youth Athletes

Myer et al. (2011b) defined neuromuscular training (NT) as a training program that incorporates general (e.g., fundamental movements) and specific (e.g., sport-specific movements) strength and conditioning activities, such as resistance, dynamic stability, balance, core strength, plyometric, and agility exercises with the goal to enhance health- and skill-related physical fitness components and to prevent injuries. According to this definition, agility, balance, plyometric, power, stability, and strength training are subsets of NT.

Over the past decades, the number of scientific publications on NT in non-athletic youth grew exponentially and provided convincing evidence to overcome long-term held myths on detrimental effects of particularly strength training in youth (e.g., damage to growth plates, high injury risk) (**Figure 1**). Today, the positive effects of NT in general and strength training in particular are well-documented. Findings from original work, systematic reviews and meta-analyses proved the effectiveness of NT on muscular fitness, motor skills, sports performance, resistance to injuries, metabolic and mental health in non-athletic youth (Behringer et al., 2011; Myer et al., 2011a; Faigenbaum et al., 2013; Granacher et al., 2016). Less is known on the effectiveness of NT in young athletes. Moreover, findings from NT studies in non-athletic youth cannot directly be translated to young athletes because physiology and proficiency in motor performance differ markedly between non-athletic and athletic populations. Despite the limited knowledge, several national and international scientific organizations recommended to implement NT in young athletes' regular training routines to (i) stimulate their physical and athletic development, (ii) tolerate the demands of long-term training and competition, and (iii) induce long-term health promoting effects that are robust over time and track into adulthood (Behm et al., 2008; Faigenbaum et al., 2016; Lloyd et al., 2016). Therefore, more research is needed on NT-related effects and physiological adaptations in young athletes.

In 2007, the German Federal Institute of Sport Science (BISp) recognized the discrepancy between these practically relevant but not always scientifically substantiated recommendations (Horn et al., 2012) and launched a new research program with funding opportunities on strength training in young athletes. Consequently, several researchers across Germany intensified their efforts and furthered our knowledge in the field (Behringer et al., 2010, 2011, 2013). As part of the BISp research program, the so-called KINGS-study was established in 2014 which is a 4-year interdisciplinary and multi-centered research project that aims at examining performance-enhancing and health-promoting effects of strength training in young athletes according to sex, maturational status, and sport discipline (https://www.uni-potsdam.de/kraftprojekt/english.php).

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Université de Lausanne, Switzerland

***Correspondence:**
Urs Granacher
urs.granacher@uni-potsdam.de

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Of note, KINGS is an acronym and it stands for the German phrase "**K**RAFTTRAINING **I**M **N**ACHWUCHSLEISTUN**GSS**PORT" (engl. Strength Training in Young Athletes). A first achievement of this research consortium was the development and subsequent validation of a conceptual model on the implementation of strength training during the different stages of long-term athlete development (LTAD) (Granacher et al., 2016). Many researchers from the KINGS research consortium acted as authors and editors of this Frontiers Research Topic. We purposely selected the title NT and not just strength training to broaden the scope of the articles that are eligible to be included in this Research Topic. Accordingly, the aims of our Research Topic entitled "Neuromuscular Training and Adaptations in Youth Athletes" were to provide in-depth knowledge in the form of original work, review articles, and meta-analyses on the effects of NT on muscular fitness, athletic performance, and injury prevention in young athletes during the different stages of LTAD.

Overall, 22 articles from 110 authors from Australia, Europe, North and South America were published in this Research Topic. **Table 1** outlines a summary of the included articles according to article type, contents, and authors.

With regards to number of total views (August, 2018), the top 3 papers of this Research Topic were Behm et al., Steib et al., and Granacher and Borde.

In the form of a systematic review and meta-analysis, Behm et al. examined the effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth. Based on the statistically aggregated findings of 107 studies, moderate effects of power (effect size [ES] = 0.69) and strength training (ES = 0.53) on jump measures. In terms of sprint performances, both power (ES = 0.38) and strength training (ES = 0.48) produced small effects. Finally, power training showed trivial effects on lower body strength (ES = 0.16), while strength training caused large effects (ES = 1.14). More specifically, children and untrained individuals achieved larger ES compared with adolescents and trained individuals. Based on their findings, Behm et al. concluded that strength training should be applied before power training to induce an adequate foundation of strength for subsequent power training activities.

Using a systematic review and meta-analysis, Steib et al. studied the dose-response relationship of NT for injury prevention in youth young athletes. The authors identified 16 trials that examined the effects of NT on lower extremity injuries, including any form of muscular, ligamentous or bony injuries (traumatic or overuse). The authors reported an overall risk reduction of 42% with NT. Training frequencies of 2–3 sessions per week revealed the largest risk reduction, and a weekly training duration of more than 30 min tended to be more effective compared to lower training duration. Finally, interventions lasting more than 6 months were not superior compared with shorter programs.

In an original research article, Granacher and Borde examined the effects of a 1-year sport-specific training and/or physical education on physical fitness, body composition, cognitive and academic performances in young athletes and their non-athletic peers. For this purpose, 45 prepubertal fourth graders from an elite sport class or age-matched peers from a regular class. Young athletes participated in sports that afforded an early start into LTAD (e.g., swimming, gymnastics). Over the 1-year intervention period, the authors observed an average weekly training volume of 620 min for the athletes and 155 min for their non-athletic peers. Sport-specific training did not have a negative impact on growth rates. Better performances were found in physical fitness and physical education grades in favor of the participants from the elite sports class. Similar performances were observed after the intervention for measures of cognition and academics. The authors concluded that sport-specific training in combination with physical education promotes young athletes' physical fitness development during LTAD and does not impede their cognitive and academic performances (Granacher and Borde).

In addition to the above mentioned most frequently viewed papers, another 3 articles from this Frontiers Research topic had a similar scope and focused on muscle and tendon adaptations in young athletes. Mersmann et al. provided a narrative review of current evidence and concepts on the prevention of tendinopathies in young athletes. According to these authors, adolescent athletes are particularly vulnerable to imbalanced development of muscle strength and tendon mechanical properties. This was confirmed in another cross-sectional study of the same research group (Mersmann et al.) in which they provided evidence of imbalanced musculotendinous adaptations in adolescent volleyball athletes compared with age-matched non-athletic peers. These imbalances appear to be a precursor of tendinopathies. There is evidence that these non-uniform musculotendinous adaptations are related to high prevalence rates of tendon overload injuries during maturation (Simpson et al., 2016). Increased levels of circulating sex steroid hormones with growth and maturation could be a critical factor that even augment imbalanced development of muscle strength and tendon mechanical properties (Murray and Clayton, 2013). For instance Cassel et al. showed greater thickness in Achilles and Patellar tendons in adolescent boys compared with girls. Besides growth and sex-related circulating hormones, mechanical loading represents another critical factor that influences the development of muscle and tendon adaptations. In fact, muscle and tendon differ with regards to the time course of adaptation to mechanical loading as well as the responsiveness to certain types of mechanical stimulation. Therefore, it seems that there are tissue-specific (muscle vs. tendon) dose-response relationships that either promote or prevent non-uniform musculotendinous development. For instance plyometric training is characterized by short and intensive bouts of eccentric followed by concentric muscle actions. This stimulus primarily induces neuromuscular but not tendinous adaptations. Consequently, the application of high plyometric training volumes during adolescence may promote the development of musculotendinous imbalances by increasing the risk of sustaining tendon injuries. In their narrative review article, Mersmann et al. provided an evidence-based concept for a specific loading program with the goal to prevent

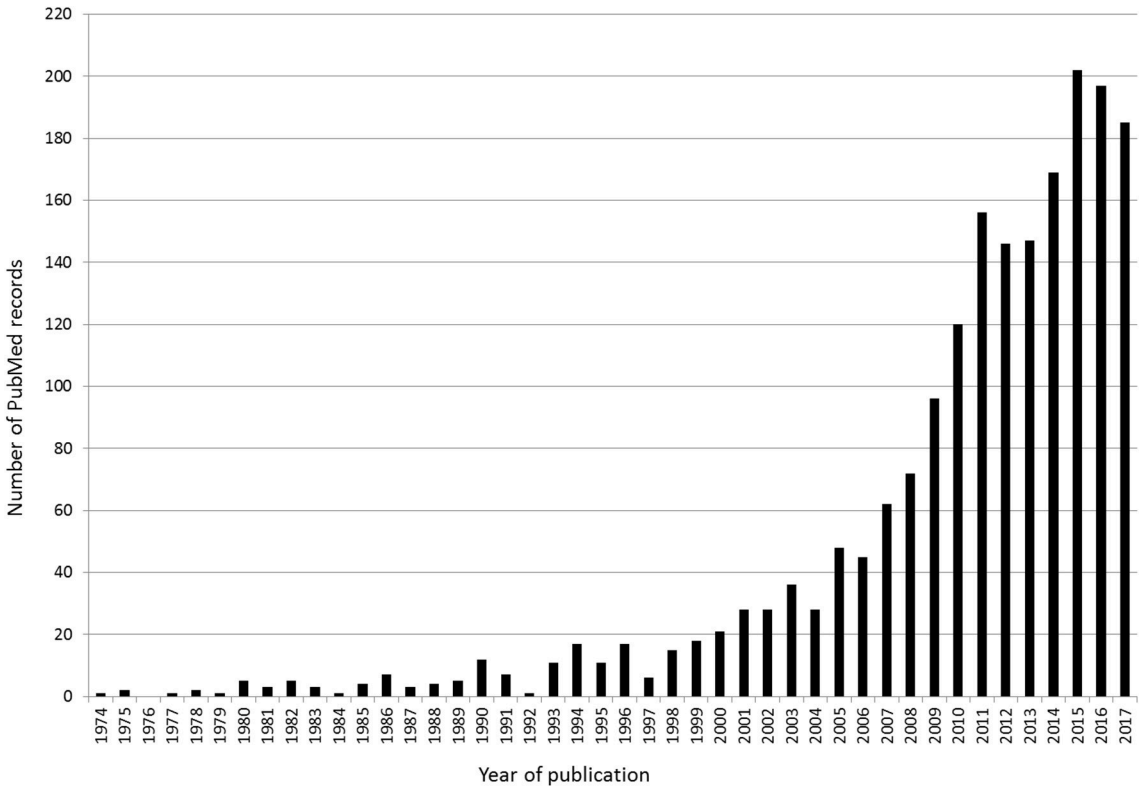


FIGURE 1 | This figure illustrates the results of a systematic search in PubMed according to the following Boolean search syntax: *(("neuromuscular training" OR "strength training" OR "resistance training" OR "plyometric training" OR "power training" OR "stability training" OR "balance training" OR "agility training") AND (child* OR adolescent* OR youth*))*. The following filters were activated: humans; preschool child: 2–5 years; child: 6–12 years; adolescent: 13–18 years. Overall, the search retrieved $N = 1{,}999$ items.

tendon injuries through increased tendon stiffness. This program includes five sets of four repetitions with an intensity of 85–90% of the maximal isometric voluntary contraction and a 3 s movement/contraction duration that provides high magnitude tendon strain (Mersmann et al.).

A rather new and therefore neglected topic in the field of LTAD is how factors like training volume and intensity, performance fatigability, stress and pressure due to school (grades) and competition (success) affect young athletes' mental health. Therefore, Weber et al. studied symptoms of anxiety and depression in young athletes according to age and sex. Overall, 326 young athletes from different sports were enrolled and classified into the age groups late childhood (12–14 years) and late adolescence (15–18 years). Anxiety and depression scores were assessed using the Hospital Anxiety and Depression Scale (HAD Scale). Overall, 7.1% (subclinical scale) and 3.1% (clinical scale) of the young athletes were classified as possible and probable cases suffering from anxiety. In addition, 9.5% (subclinical scale) and 3.7% (clinical scale) of the examined athletes were classified as possible and probable cases for depression. Late childhood athletes showed a slightly lower mean anxiety score compared with late adolescent athletes. No significant age effects were observed for the depression score. Moreover, no sex-related effects were found for anxiety and depression, although female adolescent athletes scored slightly higher in both HAD subscales. The authors concluded that sports medical and sports psychiatric interventional approaches are needed to prevent anxiety and depression in young athletes by teaching coping strategies (Weber et al.).

The 22 articles in this Research Topic furthered our knowledge in the field of NT and adaptations in young athletes. However, there are still voids in the literature. For instance, while Gäbler et al. examined the general effectiveness of concurrent strength and endurance training on physical fitness and athletic performance in youth in the form of a systematic review and meta-analysis, more original research is needed in regards of sequencing effects of strength and endurance training in young athletes. Further, most studies conducted in young athletes focussed on performance-related outcomes following a specific intervention program. The underlying neuromuscular, musculotendinous, and skeletal adaptations are largely unresolved. However, information on physiological mechanisms are crucial to understand maturation and sex-specific dose-response relations. Finally, an important issue not only in elite but also in young athletes is return-to-play (Canty and Nilan, 2015). What are adequate test batteries that can be applied in the

TABLE 1 | This table contains a summary of the 22 articles published in this research topic entitled "Neuromuscular Training and Adaptations in Youth Athletes" according to article type, contents, and authors.

Article type	**Authors**
11 longitudinal studies	Cassel et al.; Granacher and Borde; Hopper et al.; Kobal et al.; Lesinski et al.; Blume et al.; Müller et al.; Prommer et al.; Puta et al.; Ramirez-Campillo et al.; Weber et al.
4 cross-sectional studies	Mersmann et al.; Mueller et al.; Wiewelhove et al.; Prieske et al.
4 systematic reviews and meta-analyses	Behm et al.; Faude et al.; Steib et al.; Gäbler et al.
3 narrative reviews	Mersmann et al.; Bencke et al.; Zemkova et al.
Contents	**Authors**
10 articles included child and adolescent athletes	Behm et al; Faude et al.; Mersmann et al.; Müller et al.; Steib et al.; Wiewelhove et al.; Bencke et al.; Gäbler et al.; Weber et al.; Zemkova et al.
10 articles included adolescent athletes	Cassel et al.; Hopper et al.; Kobal et al.; Lesinski et al.; Mersmann et al.; Mueller et al.; Blume et al.; Prieske et al.; Puta et al.; Ramirez-Campillo et al.
2 articles included child athletes	Granacher and Borde; Prommer et al.
15 articles included boys and girls	Behm et al.; Cassel et al.; Faude et al. ; Granacher and Borde; Mersmann et al.; Mersmann et al.; Mueller et al.; Müller et al.; Steib et al; Blume et al.; Gäbler et al.; Prommer et al.; Puta et al.; Weber et al.; Zemkova et al.
4 articles included girls	Hopper et al.; Lesinski et al.; Bencke et al.; Prieske et al.
3 articles included boys	Kobal et al.; Wiewelhove et al.; Ramirez-Campillo et al.
11 articles focused on performance-enhancing topics	Behm et al.; Granacher and Borde; Kobal et al.; Lesinski et al.; Müller et al.; Wiewelhove et al.; Gäbler et al.; Prieske et al.; Prommer et al.; Ramirez-Campillo et al.; Zemkova et al.
12 articles focused on health-promoting topics	Cassel et al.; Faude et al.; Hopper et al.; Mersmann et al.; Mersmann et al.; Mueller et al.; Müller et al.; Steib et al.; Bencke et al.; Blume et al.; Puta et al.; Weber et al.
11 articles included physical fitness measures as performance-related outcomes	Behm et al.; Granacher and Borde; Kobal et al.; Lesinski et al.; Müller et al.; Wiewelhove et al.; Gäbler et al.; Prieske et al.; Prommer et al.; Ramirez-Campillo et al.; Zemkova et al.
4 articles included measures of sport-specific or athletic performance	Faude et al.; Müller et al; Gäbler et al.; Zemkova et al.
1 article included measures on cognitive/academic performances	Granacher and Borde
4 articles included lower extremity injury risk factors and rates as health-related outcomes	Hopper et al.; Müller et al.; Steib et al.; Bencke et al.
3 articles focused on tendon overload risk factors and injury rates	Cassel et al.; Mersmann et al.; Mersmann et al.
1 article included sports-related risk factors	Hopper et al.
2 articles included immune status and immunological stress responses	Blume et al.; Puta et al.
1 article focused on low back pain risk factors	Mueller et al.
1 article focused on measures of mental health	Weber et al.
4 articles focused on neuromuscular training	Faude et al.; Hopper et al.; Steib et al.; Zemkova et al.
3 articles focused on strength training	Behm et al.; Puta et al.; Ramirez-Campillo et al.
1 article focused on power training	Behm et al.
2 articles focused on plyometric training	Kobal et al.; Ramirez-Campillo et al.
1 article focused on combined strength and endurance training (concurrent training)	Gäbler et al.
1 article focused on endurance training	Prommer et al.
4 articles focused on sport-specific training	Granacher and Borde; Lesinski et al.; Mersmann et al.; Müller et al.

laboratory but also in the field during the different stages of rehabilitation to provide information on young athletes' state of recovery? This information is needed to individualize rehabilitation programs and to determine readiness for return-to-play.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis

David G. Behm[1], James D. Young[1], Joseph H. D. Whitten[1], Jonathan C. Reid[1], Patrick J. Quigley[1], Jonathan Low[1], Yimeng Li[1], Camila D. Lima[1], Daniel D. Hodgson[1], Anis Chaouachi[2,3], Olaf Prieske[4] and Urs Granacher[4]*

[1] School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NL, Canada, [2] Tunisian Research Laboratory "Sport Performance Optimisation", National Center of Medicine and Science in Sports, Tunis, Tunisia, [3] Sports Performance Research Institute New Zealand, Auckland University of Technology, Auckland, New Zealand, [4] Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany

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***Correspondence:**
David G. Behm
dbehm@mun.ca

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Numerous national associations and multiple reviews have documented the safety and efficacy of strength training for children and adolescents. The literature highlights the significant training-induced increases in strength associated with youth strength training. However, the effectiveness of youth strength training programs to improve power measures is not as clear. This discrepancy may be related to training and testing specificity. Most prior youth strength training programs emphasized lower intensity resistance with relatively slow movements. Since power activities typically involve higher intensity, explosive-like contractions with higher angular velocities (e.g., plyometrics), there is a conflict between the training medium and testing measures. This meta-analysis compared strength (e.g., training with resistance or body mass) and power training programs (e.g., plyometric training) on proxies of muscle strength, power, and speed. A systematic literature search using a Boolean Search Strategy was conducted in the electronic databases PubMed, SPORT Discus, Web of Science, and Google Scholar and revealed 652 hits. After perusal of title, abstract, and full text, 107 studies were eligible for inclusion in this systematic review and meta-analysis. The meta-analysis showed small to moderate magnitude changes for training specificity with jump measures. In other words, power training was more effective than strength training for improving youth jump height. For sprint measures, strength training was more effective than power training with youth. Furthermore, strength training exhibited consistently large magnitude changes to lower body strength measures, which contrasted with the generally trivial, small and moderate magnitude training improvements of power training upon lower body strength, sprint and jump measures, respectively. Maturity related inadequacies in eccentric strength and balance might influence the lack of training specificity with the unilateral landings and propulsions associated with sprinting. Based on this meta-analysis, strength training should be incorporated prior to power training in order to establish an adequate foundation of strength for power training activities.

Keywords: children, boys, girls, plyometric training, resistance training

INTRODUCTION

In contrast to the prior myths of health concerns regarding resistance training (RT) for children (Rians et al., 1987; Blimkie, 1992, 1993; Faigenbaum and Kang, 2005), the contemporary research emphasizes the beneficial effect of youth RT for health, strength, and athletic performance (Sale, 1989; Webb, 1990; Faigenbaum et al., 1996, 2009; Falk and Tenenbaum, 1996; Payne et al., 1997; Golan et al., 1998; Hass et al., 2001; McNeely and Armstrong, 2002; Falk and Eliakim, 2003; American College of Sports Medicine, 2006; Faigenbaum, 2006; Malina, 2006; Behm et al., 2008; Granacher et al., 2016). With a properly implemented youth RT program, muscular strength and endurance can increase significantly beyond normal growth and maturation (Pfeiffer and Francis, 1986; Weltman et al., 1986; Sailors and Berg, 1987; Blimkie, 1989; Ramsay et al., 1990; Faigenbaum et al., 1996, 1999, 2001, 2002). Falk and Tenenbaum (1996) conducted a meta-analysis and reported RT-induced strength increases of 13–30% in pre-adolescent children following RT programs of 8–20 weeks. The Canadian Society for Exercise Physiology (CSEP) position stand (Behm et al., 2008) indicated that the literature provided a clear positive effect for improving muscle strength. In contrast, there were far fewer RT studies that measured power capacities, which only provided small effects for adolescents and unclear effects of RT on improving power for children (Weltman et al., 1986; Faigenbaum et al., 1993, 2002, 2007b, 1996; Lillegard et al., 1997; Christou et al., 2006; Granacher et al., 2016).

The small or unclear effects of traditional strength/RT on measures of power in children in the Behm et al. (2008) review could be attributed to the few studies published up to that year that monitored proxies of power. The recent Granacher et al. (2016) review cited only three studies with girls as participants compared to 27 studies with boys but still reported small to barely moderate effects of RT on muscular power. Other factors contributing to smaller effects of traditional strength/RT on measures of power in children could be the lack of training mode specificity (Sale and MacDougall, 1981; Behm and Sale, 1993; Behm, 1995) or perhaps maturation-related physiological limitations upon power training adaptations in children. The typical strength RT protocol for children involves training 2–3 times per week (Malina, 2006), with moderate loads (e.g., 50–60% of 1RM) and higher repetitions (e.g., 15–20 reps) (Faigenbaum et al., 1996, 2009; Lillegard et al., 1997; Christou et al., 2006; Faigenbaum, 2006; Benson et al., 2007; Behm et al., 2008). According to the concept of training specificity, an effective transfer of training adaptations occurs when the training matches the task (e.g., testing, competition) (Sale and MacDougall, 1981; Behm and Sale, 1993; Behm, 1995). Since high power outputs involve explosive contractions with forces exerted at higher velocities, RT programs using low to moderate loads at slower velocities would not match power characteristics. However, recently there are a number of publications that have implemented power training programs (e.g., plyometric training) for children that would adhere to the training specificity principle. Plyometric exercises involve jumping, hopping, and bounding exercises and throws that are performed quickly and explosively (Behm, 1993; Behm et al., 2008; Cappa and Behm, 2011, 2013). With plyometric training adaptations, the neuromuscular system is conditioned to react more rapidly to the stretch-shortening cycle (SSC). Plyometric training can be safe and may improve a child's ability to increase movement speed and power production provided that appropriate training and guidelines are followed (Brown et al., 1986; Diallo et al., 2001; Matavulj et al., 2001; Lephart et al., 2005; Marginson et al., 2005; Kotzamanidis, 2006; Behm et al., 2008). Johnson et al. (2011) published a meta-analysis that only included seven studies that they judged to be of low quality. They suggested that plyometric training had a large positive effect on running, jumping, kicking distance, balance, and agility with children. Hence, further analysis is needed with a greater number of power training studies involving children and/or adolescents.

While many power activities involve shorter duration, higher intensity, explosive type contractions (anaerobic emphasis), children are reported to possess reduced anaerobic capacities (Behm et al., 2008; Murphy et al., 2014) with a lower reliance on glycolysis (Ratel et al., 2006, 2015), and lower power outputs (Falk and Dotan, 2006) compared to adults. In the recently published scoping review (Granacher et al., 2016), Granacher and colleagues were able to show small effect sizes following RT on measures of power in child athletes and moderate effect sizes in adolescent athletes. However, these authors looked at general RT effects only and did not differentiate between strength and power training programs. Moreover, only studies conducted with youth athletes were analyzed.

Thus, it was the objective of this systematic review and meta-analysis to investigate whether there are different effects following strength vs. power training on measures of muscle strength, power, and speed in trained and untrained children and adolescents. It is hypothesized that in accordance with the concept of training specificity, power training programs will provide more substantial improvements in power and speed measures than traditional strength programs with youth. Furthermore, since trained individuals would have a greater foundation of strength, we expected greater power training related effects in trained compared to untrained youth.

METHODS

Search Strategy and Inclusion/Exclusion Criteria

This review included randomized controlled trials and controlled trials that implemented either traditional strength/resistance training or power training in youth. A literature search was performed by four co-authors separately and independently using PubMed, SPORT Discus, Web of Science, and Google Scholar databases. The topic was systematically searched using a Boolean search strategy with the operators AND, OR, NOT and a combination of the following keywords: ("strength training" OR "resistance training" OR "weight training" OR "power training" OR "plyometric training" OR "complex training" OR "compound training" OR "weight-bearing exercise") AND (child OR children OR adolescent OR adolescents OR youth OR puberty OR prepuberal* OR kids OR kid OR teen* OR girl* OR boy OR boys)

NOT (patient OR patients OR adults OR adult OR man OR men OR woman OR women). All references from the selected articles were also crosschecked manually by the authors to identify relevant studies that might have been missed in the systematic search and to eliminate duplicates.

Inclusion Criteria (Study Selection)

Studies investigating traditional strength/resistance training or power training in youth were included in the review if they fulfilled the following selection criteria: the study (1) was a randomized controlled trial or a controlled trial; (2) measured pre- and post-training strength [e.g., maximal loads (i.e., 1 repetition maximum: 1RM) or forces with squats, leg extension or flexion, isokinetic maximal measures], power-related [e.g., countermovement jump (CMJ), horizontal or standing long jump (SLJ)] or speed-related (e.g., 10-m sprint time) dependent variables; (3) training duration was greater than 4 weeks; (4) used healthy, untrained (i.e., physical education classes and/or no specific sport) or trained (i.e., youth athletes from different sports) youth participants under the age of 18 years; (5) was written in English and published prior to January 2017; and (6) was published in a peer-reviewed journal (abstracts and unpublished studies were excluded). Studies were excluded if precise means and standard deviations, or effect sizes were not available or if the training study combined both strength and power exercises. Our initial search resulted in 652 applicable studies (see flow chart: **Figure 1**).

Statistical Analyses

For statistical analyses, within-subject standardized mean differences of the each intervention group were calculated [SMD = (mean post-value intervention group—mean pre-value intervention group)/pooled standard deviation]. Subsequently, SMDs were adjusted for the respective sample size by using the term (1-(3/(4N-9))) (Hedges, 1985). Meta-analytic comparisons were computed using Review Manager software V.5.3.4 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2008). Included studies were weighted according to the magnitude of the respective standard error using a random-effects model. A random effect model was used because the relative weight assigned to each of the studies has less impact on computed combined effect size. In other words, in the fixed effect model, one or two studies with relatively high weight can shift the combined effect size and associated confidence intervals in one particular direction, whereas in a random effect model this issue is moderated.

Further, we used Review Manager for subgroup analyses: computing a weight for each subgroup (e.g., trained vs. untrained), aggregating SMD values of specific subgroups, and comparing subgroup effect sizes with respect to differences in intervention effects across subgroups. To improve readability, we reported positive SMDs if superiority of post values compared with pre-values was found. Heterogeneity was assessed using I^2 and χ^2 statistics. SMDs were calculated to evaluate the magnitude of the difference between traditional resistance and plyometric training according to the criterion of 0.80 large; 0.50 medium and 0.20 small (Cohen, 1988).

RESULTS

Training Program Prescriptions

The descriptive statistics for the strength and power training program prescriptions are illustrated in **Table 1**. There were 28.5% more strength training studies within the literature review likely due to the fact that power training experiments for children began more recently (power: 1999 vs. strength: 1986 with one pediatric strength study published in 1958). Strength training studies on average had younger participants (∼12 vs. 13 years), 45.2% longer duration training programs (∼8 vs. 12 weeks) and implemented approximately 1 less exercise per training session. There were substantially more untrained or physical education student participants in the strength studies (i.e., strength studies with physical education and untrained: 31 vs. power studies with physical education and untrained: 6 with soccer athletes used most often (strength: 9 studies and power: 20 studies). Details of all studies in the review are depicted in **Tables 2A,B**.

Muscle Power (Jump) Measures

Table 3 shows that power (plyometric) training studies provided higher magnitude changes in jump performance than strength training studies. In terms of general descriptors, power training studies exceeded strength training studies with trained (moderate vs. small), untrained (large vs. moderate)(**Figures 2**, **4**) and adolescent (moderate vs. small) populations (**Figures 3**, **5**). For the overall or general results (**Figures 2**, **4**) as well as with children (**Figures 3**, **5**), the descriptive classifications were the same (moderate magnitude improvements), although the precise SMDs values were higher with power training. When comparing specific populations (power and strength training combined), untrained individuals (moderate to large magnitude) experienced greater jump height gains than trained participants (small to moderate). Similarly, with training groups combined, children experienced larger jump height gains than adolescents, although the descriptive classification only differed with strength training (moderate vs. small), but not power training.

Sprint Speed Measures

In contrast to power (jump) results, strength training studies tended to provide better sprint time results than power training (**Table 2**). However, it was only in the children and adolescent strength vs. power training comparison where the descriptive classifications for strength training exceeded power training with moderate vs. small and small vs. trivial classifications, respectively (**Figures 7**, **9**). In contrast, power training (only 3 measures) provided a greater magnitude change than strength training (30 measures) with untrained populations demonstrating a large vs. moderate improvement in sprint time (**Figures 6**, **8**). Again, similar to power (jump) measures, untrained and child populations had greater magnitudes and descriptors than trained and adolescents respectively for both strength and power training.

Muscle Strength Measures

There were very few power training studies that measured lower body strength with no studies that utilized children or differentiated between trained and untrained individuals

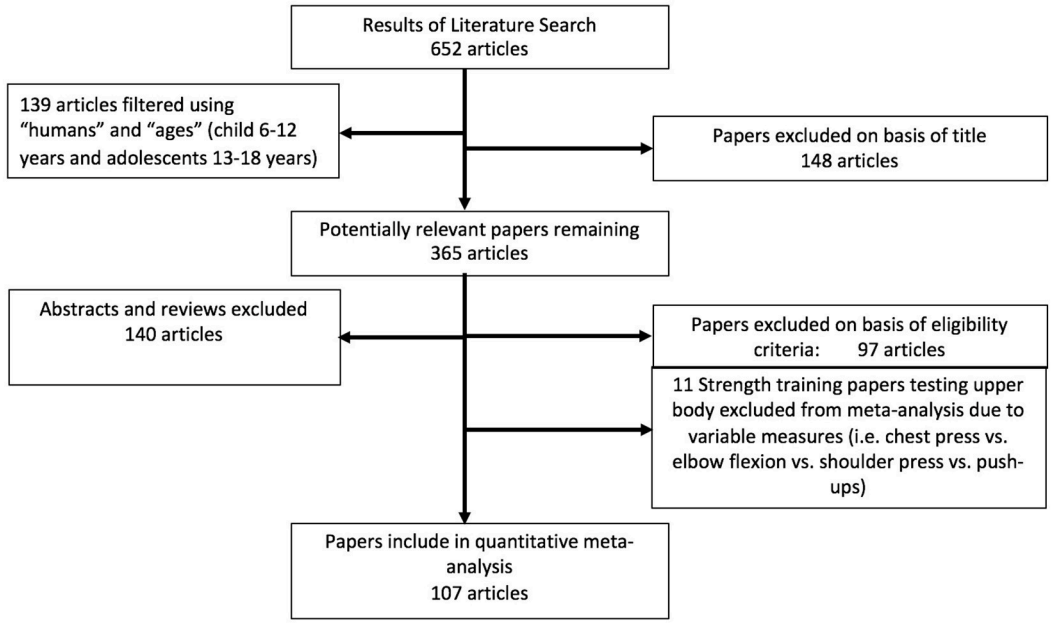


FIGURE 1 | Flow chart illustrating the different phases of the search and study selection.

TABLE 1 | Training participants and program characteristics.

No. of Studies	No. of studies with all male subjects	No. of studies with all female subjects	No. of studies with male and female subjects	Age (years)	Training frequency (sessions per week)	Training Weeks	Sets	No. of Exerc.	Reps
Strength 63 (1958, and 1986–2016)	32	1	30	12.37 ± 0.73	2.2 ± 0.52	12.45 ± 14.04	2.76 ± 1.16	6.15 ± 2.94	9.83 ± 4.08
Power 52 (1999–2016)	38	11	3	13.5 ± 0.86	2.27 ± 0.58	8.57 ± 4.34	2.15 ± 1.81	7.69 ± 4.94	9.94 ± 7.91

reps, repetitions; Exerc, exercises. Values provided in first four columns are sums, whereas the last six columns are means and standard deviations.
Number of studies: *Strength participants: Physical Education: 15 studies, Untrained: 16 studies.*
Sports: Soccer: 9 studies, Rugby: 4, Gymnasts: 2, Basketball, 2, Baseball: 2, Football: 2, Swimming, Handball, American Rowing, Judo, Wrestling, and assorted other sports or trained states.
Power participants: Physical Education: 3 studies, Untrained: 3 studies.
Sports: Soccer: 20 studies, Rugby: 4, Gymnasts: 2, Basketball, 6, Swimming: 2, Volleyball: 2, Baseball, American Football, Handball, Rowing, Judo, Wrestling, Rowing, Track, Field hockey, Tennis, and assorted other sports or trained states.

(**Figure 10**). The 4 power training measures within our review used adolescents with only a trivial magnitude improvement compared to large magnitude improvements in all categories (0.88–1.35) with the 45 strength training measures (**Figures 11**, **12**).

DISCUSSION

This is the first systematic review and meta-analysis that compared the effects of strength vs. power training on measures of muscle strength, power, and speed in trained and untrained youth. The most pertinent findings of the present study were the tendencies for training specificity with power measures (power training more effective than strength training), but a lack of training specificity with sprint measures (strength training more effective than power training) with youth. Thirdly, strength training exhibited uniformly large magnitude changes to lower body strength measures, which contrasted with the generally trivial, small and moderate magnitude training improvements of power training upon lower body strength, sprint and jump power measures, respectively. Furthermore, untrained youth displayed more substantial improvements in jump and sprint measures with both power and strength training compared to trained youth.

The greater magnitude improvements in power measures with power vs. strength training corresponds with the training specificity principle (Sale and MacDougall, 1981; Behm, 1988, 1995; Behm and Sale, 1993). Training specificity dictates that training adaptations are greater when the training mode,

TABLE 2A | Strength type resistance training program descriptions.

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
Assuncao et al., 2016	U	MF	Low rep.: 13.8 ± 0.9	17	2	9	2	8	4–6	4–6 RM	Low rep.:											
			High rep.: 13.7 ± 0.7	16	2	9	2	8	12–15	12–15 RM	1 RM chest press	Effect sizes only										
											1 RM squat	Effect sizes only										
											High rep.:											
											1 RM chest press	Effect sizes only										
											1 RM squat	Effect sizes only										
Benson et al., 2007	PE	MF	12.3 ± 1.3	32	2	8	2	11	8	RPE 15–18	Bench press	29.6	8.2	41.1	9.5	38.9						
											Bench press/kg	0.5	0.1	0.7	0.2	40.0					
											Leg press	109.2	39.1	152.1	43.4	39.3					
											Leg press/kg	1.9	0.4	2.6	0.7	36.8					
Blimkie, 1989		M	10.4 ± 0.8	14	3	10	3–5	6	10–12		EF MVIC 100°	14.7	5.3	18.0	4.8	22.4						
Channell and Barfield, 2008	T	M	15.9 ± 1.2	21	3	8	3–5	2–4	3–20	60–100%	Squat	144.0	41.6	161.6	29.3	12.2	CMJ	0.6	0.7	0.6	0.4	3.4
											Power clean	72.6	17.8	84.3	15.6	16.1						
											Squat	132.6	30.9	160.9	26.0	21.3	CMJ	0.5	0.9	0.5	0.9	2.1
											Power clean	69.2	17.8	70.1	12.9	1.3						
Chelly et al., 2009	T	M	17.0 ± 0.3	11	2	8	3	1	2-4	80–90%	Squat	105.0	14.0	142.0	15.0	35.2	SJ	0.3	0.0	0.4	0.0	9.4
																	CMJ	0.3	0.0	0.4	0.0	5.9
																	5 Long jump	10.6	0.3	11.1	0.2	4.7
																	5 m Velocity m/s	3.5	0.2	3.8	0.1	7.1
																	40 m Max velocity m/s	7.8	0.5	8.8	0.4	11.9
Christou et al., 2006	T	M	13.8 ± 0.4	9	2	16	2–3	10	8–15	55–80%	Leg press	102.8	2.5	163.9	7.4	59.4	SJ	0.3	0.0	0.3	0.0	12.0
											Bench press	36.0	1.6	55.0	3.1	52.8	CMJ	0.3	0.0	0.4	0.0	20.0
																	10 m Sprint	2.2	0.1	2.1	0.0	3.2
																	30 m Sprint	5.1	0.2	4.9	0.1	2.6
Contreras et al., 2017	T T	M	15.5 ± 1.2 Hip thrust	13	2	12	1	4	6–12	6–12 RM	Front squat	77.6	12.4	83.1	13.8	7.1	CMJ Long jump	0.6 2.3	0.1 0.2	0.6 2.4	0.8 0.2	3.6 16.3

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
																	10 m Sprint	1.8	0.1	1.7	0.1	1.1
																	20 m Sprint	3.1	0.1	3.1	0.1	1.9
			15.5 ± 0.7	11							Front squat	75.0	10.5	84.6	10.0	12.9	CMJ	0.5	0.1	0.6	0.1	7.7
			Front squat														Long jump	2.3	0.2	2.3	0.3	1.8
																	10 m Sprint	1.8	0.1	1.8	0.1	0.6
																	20 m Sprint	3.2	0.1	3.1	0.2	–0.6
Coskun and Sahin, 2014	U	MF		18	2	6	2	8	10–12	10 RM	Leg press	27.1	8.6	42.7	12.6	57.6						
Dalamitros et al., 2015	T	M	14.8 ± 0.5	11	2	24		4			KE PT 60 R	196.6	61.6	209.8	45.8	6.7						
											KE PT 60 L	188.5	47.0	206.4	44.2	9.5						
											KF PT 60 R	102.8	28.7	108.5	29.0	5.5						
											KF PT 60 L	100.7	28.6	107.5	29.7	6.8						
Dorgo et al., 2009	PE	MF	16.0 ± 1.2	63	3	18	12–28		10–14		Push up	9.7	1.1	12.6	1.1	29.9						
											Pull up	7.6	0.9	12.1	0.9	59.2						
dos Santos Cunha et al., 2015	U	M	10.4 ± 0.5		3	12	3	7	6–15	60–80%	EF 1 RM kg	6.4	0.8	10.6	0.9	65.6						
											EF 1 RM kg/FFM	2.6	0.3	4.3	0.6	65.4						
											EF Isok 30	4.9	1.2	6.1	1.3	24.5						
											EF Isok 90	4.4	0.8	5.2	0.8	18.2						
											EF Isom 45	4.4	1.4	6.0	1.1	36.4						
											EF Isom 90	7.7	1.9	9.3	1.8	20.8						
											KE 1 RM kg	10.8	1.6	18.7	2.0	73.1						
											KE 1 RM kg/FFM	1.1	0.1	2.0	0.1	81.8						
											KE Isok 30	7.6	1.1	9.6	1.3	26.3						
											KE Isok 90	6.5	0.5	8.3	0.7	27.7						
											KE Isom 45	8.5	1.6	9.5	1.2	11.8						
											KE Isom 90	9.8	1.5	11.8	1.7	20.4						
											KE PT 60 R	196.6	61.6	209.8	45.8	6.7						
											KE PT 60 L	188.5	47.0	206.4	44.2	9.5						
											KF PT 60 R	102.8	28.7	108.5	29.0	5.5						
											KF PT 60 L	100.7	28.6	107.5	29.7	6.8						
											Overhead press 10 RM	7.5	2.5	14.1	3.1	87.0						
Faigenbaum et al., 1996	U	MF	10.8 ± 0.4	15	2	8	2–3	5	6	8 RM	Leg extension 6 RM	18.0	1.8	28.0	4.6	55.6	CMJ	23.5	1.4	24.9	1.5	6.0
											Chest press 6 RM	21.8	2.2	30.1	4.6	38.1						

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
Faigenbaum et al., 1999	U	MF	7.8 ± 1.4	15	2	8	1	11	6–8	Fail	Chest press	24.5	5.9	25.8	6.4	5.3						
											Leg extension	18.4	7.0	24.1	7.6	31.0						
			8.5 ± 1.6	16					13–15	Fail	Chest press	25.7	9.1	29.9	9.7	16.3						
											Leg extension	19.3	9.0	27.2	10.9	40.9						
Faigenbaum et al., 2001	U	MF	8.1 ± 1.6	44	2	8	1	1	6–8		Heavy load chest press	24.5	5.9	25.8	6.4	5.3						
									13-15		Moderate load chest press	25.7	9.1	29.9	9.7	16.3						
											Heavy med ball chest press	23.8	4.3	27.8	4.1	16.8						
											Med ball chest press	24.1	3.9	25.8	3.8	7.1						
Faigenbaum et al., 2002	U	MF	9.7 ± 1.4	20	2	8	1	12	10–15	10–15 RM	Chest press	21.7	7.0	24.2	7.7	11.5	Long jump	129.5	5.6	139.5	15.6	7.7
											Leg press	56.9	24.0	71.1	27.5	25.0	CMJ	22.8	3.9	24.9	4.5	9.2
											Grip strength	35.8	6.9	38.2	7.4	6.7						
Faigenbaum et al., 2007a	PE	MF	13.9 ± 0.4	22	2	9	3	9	7	12–15 RM	Squat 10 RM	56.9	15.0	67.6	15.4	18.8	Med ball throw	356.5	55.1	368.3	59.1	3.3
											Bench press 10 RM	41.1	9.4	47.4	10.5	15.3	CMJ	48.9	6.6	51.1	8.6	4.5
Faigenbaum et al., 2014	PE	MF	7.5 ± 0.3	21	2	8	2	5	7–10		Pull up	7.6	0.9	10.3	0.9	35.5	Long jump	111.9	11.2	116.4	11.6	4.0
											Push up	1.9		2.5		31.6						
Faigenbaum et al., 2015	PE	MF	9.5 ± 0.3	20	2	8	1	13	30–45 Sec		Push up	11.5	0.9	15.9	1.8	38.3	Long jump	121.2	5.4	130.2	6.3	7.4
Faigenbaum et al., 2007b	T	M	13.6 ± 0.7	14	2	6	3	6	10–12	12 RM							CMJ	48.2	10.7	49.6	10.1	2.9
																	Long jump	190.0	23.1	192.2	25.4	1.2
																	Ball toss	321.7	58.0	339.4	85.2	5.5
Falk and Mor, 1996		MF	6.4 ± 0.4	14	2	12	3	4	15	15 RM							Long jump	101.0	13.0	115.0	18.0	13.9
																	Ball put	233.0	28.0	244.0	43.0	4.7
Ferrete et al., 2014	T	MF	9.3 ± 0.3	11	2	26	2–4	6	6–10								CMJ	22.3	0.7	23.8	4.3	6.7
Flanagan et al., 2002	T	MF	8.8 ± 0.5	14	2	11	1–3	8	10–15								Med ball (resisted)	321.8	29.9	336.0	26.0	4.0
	T		8.6 ± 0.5	24	2	11	Var	5	Var								Long jump (resisted)	134.3	32.8	148.7	25.9	9.0
																	Med ball (BW)	234.3	34.5	267.9	39.2	12.0
																	Long jump (BW)	138.5	21.8	144.8	16.4	4.0

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
Funato et al., 1986	PE	MF	11.0 ± 0.3	20	3	12	2	1	3	100% MVIC	EF MVIC					5.7						
											EE MVIC					17.5						
Gonzalez-Badillo et al., 2015	T	M	U16: 14.9 ± 0.3	17	2	26	2–4	7	5–10 and 20 m	40-105%							CMJ (U16)	35.4	3.9	39.1	4.9	10.5
			U18: 17.8 ± 0.4	16	2	26	2–4	7	5–10 and 20 m	40–105%							CMJ (U18)	38.4	3.0	41.3	4.5	7.6
Gorostiaga et al., 1999	T	M	15.1 ± 0.7	9	2	6	4	5		40–90%	KE force	208.0	29.1	235.8	41.1	13.4	Throwing velocity	71.7	6.7	74.0	7.0	3.2
																	SJ	32.2	3.2	33.3	3.3	3.4
	T		15.1 ± 0.5								KF force	100.0	12.2	109.0	15.4	9.0	CMJ	34.1	3.1	35.2	3.6	3.2
Granacher et al., 2010	PE	MF	8.6 ± 0.5	17	2	10	3	5	10–12	70–80%	Isok KE 60	40.1	8.6	47.8	8.7	19.2	CMJ	21.5	2.6	22.2	2.7	3.3
											Isok KF 60	32.8	5.2	37.1	7.1	13.1						
											Isok KE 180	33.1	5.4	38.3	6.6	15.7						
											Isok KF 180	28.7	3.6	32.1	4.2	11.8						
Granacher et al., 2011b	PE	MF	16.7 ± 0.6	14	2	8	4	7	10	30–40%	KE MVIC	1501	404	1632	304	8.7	CMJ	27.4	4.5	29.5	4.9	7.7
										Ballistic												
Granacher et al., 2011a	PE	MF	8.6 ± 0.5	17	2	10	3	7	10–12	70–80%	Iso KE 60	40.1	8.6	47.8	8.7	19.2	CMJ	21.5	2.6	22.2	2.7	3.3
											Isok KF 60	32.8	5.2	37.1	7.1	13.1						
											Isok KE 180	33.1	5.4	38.3	6.6	15.7						
Granacher et al., 2014	T	MF	13.7 ± 0.6	13	2	6	3	3	40–50 s or 20–25		CSTS ventral TMS	65.5	37.0	74.7	39.3	14.0	CSTS long jump	187.6	47.4	189.6	39.0	1.1
			13.8 ± 0.9	14	2	6	3	3	40–50 s or 20–25		CSTS dorsal TMS	152.2	98.0	214.8	32.8	41.1						
											CSTS lateral right TMS	46.9	18.9	51.1	18.3	9.0						
											CSTS lateral left TMS	46.5	20.8	51.4	18.7	10.5	CSTU long jump	201.1	20.0	207.1	18.8	3.0
											CSTU ventral TMS	67.9	34.1	83.1	28.7	22.4						
											CSTU dorsal TMS	129.9	55.0	173.3	20.4	33.4						
											CSTU lateral right TMS	46.7	12.1	50.4	14.7	7.9						
											CSTU lateral left TMS	201.1	10.3	51.4	10.6	8.0						

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
Hammami et al., 2016b	T	M	BPT: 12.7 ± 0.3	12	3	8	2	5	8–15	Max	Isok KF 180	28.7	3.6	23.1	4.2	−19.5	BPT CMJ	25.5	4.0	29.2	2.9	14.5
			PBT: 12.5 ± 0.3	12	3	8	2	5	8–15	Max							PBT CMJ	24.7	2.4	26.8	1.8	8.5
																	BPT long jump	186.0	15.9	220.7	10.3	18.7
																	PBT long jump	177.1	11.6	206.8	13.9	16.8
																	Bench press throw	87.9	16.9	97.5	21.2	10.9
Harries et al., 2016	T	M	16.8 ± 1.0	8	2	6	1–6	10	3–10	60–90%	Squat	127.9	26.4	171.2	41.2	33.9						
											Bench press	87.9	16.9	97.5	21.2	10.9						
Hettinger, 1958	NR	MF	<2.9: 12.6 ± 3.8	9	1–2	8–23	1	2	1	Max	Lower arm flexors (boys maturity <2.9)	10.9	1.7	13.0	2.1	19.3						
			>3.0: 12.7 ± 2.3	15							Lower arm flexors (girls maturity <2.9)	9.4	1.3	10.7	1.5	13.8						
											Lower arm extensors (boys maturity <2.9)	7.7	1.0	10.8	2.4	40.3						
											Lower arm extensors (girls maturity <2.9)	6.3	1.3	8.7	1.3	38.1						
											Lower Arm Flexors (Boys Maturity >3.0)	19.0	3.9	23.6	4.8	24.2						
											Lower arm flexors (girls maturity >3.0)	16.2	3.6	17.3	3.6	6.8						
											Lower arm extensors (boys maturity >3.0)	13.1	1.3	19.0	4.7	45.0						
											Lower arm extensors (girls maturity >3.0)	10.1	2.1	12.6	2.4	24.8						
Ignjatovic et al., 2011	T	M	15.7 ± 0.8	23	2	12	3	9	8–12	8–12 RM	30% Bench press	367.2	65.4	392.4	61.3	6.9						
											40% Bench press	405.3	71.8	432.0	68.1	6.6						

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
											50% Bench press	455.9	84.5	475.0	77.1	4.2						
											60% Bench press	503.0	86.6	526.8	82.0	4.7						
Kotzamanidis et al., 2005	T	M	17.1 ± 1.1	11	2	9	4		3-8	8,6,3 RM	Half squat	140.5	15.6	154.5	15.7	10.0	Squat jump	25.7	3.1	26.2	3.5	1.9
											Step up	65.5	7.6	76.4	7.1	16.7	40 cm DJ	18.4	5.5	18.9	5.5	2.6
											Leg curl	53.6	6.7	62.3	5.6	16.1	CMJ	27.2	3.4	27.5	3.3	0.9
																	30 m Sprint	4.3	0.2	4.3	0.2	0.5
Lloyd et al., 2016	PE	M	Pre-PHV: 12.7 ± 0.3	10	2	6	3	4	10	10 RM							Pre-PHV squat jump	22.3	4.9	24.8	4.6	11.2
			Post-PHV: 16.3 ± 0.3	10													Post-PHV squat jump	32.4	5.0	34.6	5.1	6.8
																	Pre-PHV 10 m sprint	2.3	0.2	2.2	0.2	4.4
																	Post-PHV 10 m sprint	1.9	0.1	1.8	0.1	5.3
																	Pre-PHV 20 m sprint	3.4	0.3	3.4	0.3	0.0
																	Post-PHV 20 m sprint	2.8	0.2	2.7	0.2	3.6
Lubans et al., 2010	U	MF	15.0 ± 0.7	F: 37	2	8	2	10	8–12	RPE 15–18	Girls (bench press) FW	49.9	13.0	62.0	11.9	24.2						
				E: 41	2	8	2	10	8–12	RPE 15–18	Girls (incline leg press) FW	173.6	47.2	234.3	50.5	35.0						
											Girls (bench press) ET	50.5	15.2	56.5	14.5	11.9						
											Girls (incline leg press) ET	181.4	53.3	283.6	64.3	56.3						
											Boys (bench press) FW	31.2	6.2	36.4	6.7	16.7						
											Boys (incline leg press) FW	144.8	34.2	191.0	51.3	31.9						
											Boys (bench press) ET	31.7	7.2	35.9	7.1	13.2						
											Boys (incline leg press) ET	156.2	20.0	186.2	30.1	19.2						
Moore et al., 2013	T	M	16.0 ± 2.0	14	3	20	3		20	Low	Posterior shoulder endurance test	30.0	14.0	88.0	36.0	193.3						
Moraes et al., 2013	U	M	15.5 ± 0.9	14	3	12	3	9	10–12	10–12 RM	Bench press	40.6	6.1	48.3	7.2	19.0	Long jump	137.1	22.6	139.8	21.5	2.0
											Leg press	231.4	39.3	435.7	37.0	88.3	CMJ	29.4	6.0	30.8	6.0	4.8

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
Muehlbauer et al., 2012	PE	M	16.8 ± 0.8	6	2	8	4–6	7	10	30–40%	Boys leg press MVIC	1786	319	1912	280	7.0	Boys CMJ	31.1	2.2	33.3	2.9	7.1
		F	16.6 ± 0.5	8							Girls leg press MVIC	1287	329	1639	325	27.3	Girls CMJ	24.6	3.7	26.7	4.1	8.5
Negra et al., 2016	T	M	12.8 ± 0.2	13	2	12	4	1	8–12	40–60%	Squat	102.0	25.2	127.8	15.2	25.3	Long jump	1.7	0.2	1.9	0.2	15.5
																	CMJ	24.1	4.6	29.8	3.4	23.5
Ozmun et al., 1994	U	MF	10.5 ± 0.6	8	3	8	3	1	7–10	10 RM	Isok EF					27.8						
											Isot EF					22.6						
Piazza et al., 2014	T	M	12.0 ± 1.8	19	2	6	3	12	12	12 RM							Squat jump	427.1	35.3	440.1	28.0	3.0
																	CMJ	449.7	34.5	481.3	30.8	7.0
Pikosky et al., 2002			11.0		2	6	1	9	15	15 RM	Chest press	22.7	1.5	25.1	1.7	10.6						
											KE	18.6	2.4	31.1	3.2	67.2					
Pesta et al., 2014	U	M	15.3 ± 1.0	13	3	10	2	3	12		KE MVIC	1245	226	1329	225	6.8	Squat jump	31.5	3.6	35.9	5.9	14.0
																	CMJ	33.5	4.4	37.8	5.8	12.8
Prieske et al., 2016	T	M	16.6 ± 1.1	20	2–3	9	2–3	5	15–20		Trunk flexors MVIC	657	92	681	89	3.7	CMJ	36.0	3.4	35.5	3.2	–1.4
(Stable)											Trunk extensors MVIC	603	98	644	93	6.8	20 m Sprint	3.0	0.1	3.0	0.1	0.3
Prieske et al., 2016	T	M	16.6 ± 1.0	19	2–3	9	2–3	5	15–20		Trunk flexors MVIC	624	99	617	97	–1.1	CMJ	34.0	3.4	34.3	2.7	0.9
(Unstable)											Trunk extensors MVIC	591	67	614	115	3.8	20 m Sprint	3.0	0.1	3.0	0.1	0.7
Ramsay et al., 1990	U	M	9–11	13	3	20	3–5	6	Failure	70–85%	Bench press					34.6						
											Leg press					22.1						
											Isok PT EF					25.8						
											Isok PT KE					21.3						
Rhea et al., 2008			17.4 ± 2.1	32	1–3.	12	4	5	5–10	75–85%							CMJ (W)	928.3	229.1	1145.4	285.9	23.4
Riviere et al., 2017	T	M	17.8 ± 0.9	Traditional: 8	2	6	3–6	6	2–4	70–90%	Bench press	105.6	23.3	110.6	24.7	4.7						
				Variable: 8							Bench press	95.6	9.6	100.6	10.9	5.2						
Rodriguez-Rosell et al., 2016			12.6 ± 0.5	15	2	6	2–3	4	4–8	45–60%	Squat (U 13)	38.6	17.9	57.2	15.9	48.2	10 m Sprint (U13)	1.9	0.6	1.8	0.7	3.2
			14.6 ± 0.5	14							Squat (U 15)	64.0	14.5	81.7	16.6	27.7	20 m Sprint (U13)	3.4	0.1	3.3	0.1	2.7
																	CMJ (U13)	26.6	4.3	29.8	3.9	12.0
																	10 m Sprint (U15)	1.8	0.6	1.8	0.6	1.7

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
																	20 m Sprint (U15)	3.1	0.1	3.1	0.1	1.3
																	CMJ (U15)	32.4	5.2	35.7	6.1	10.2
Sadres et al., 2001		MF	9.2 ± 0.3	27	2	84	1–4	3–6	5–30	30–70%	KE	18.0	5.0	31.3	7.0	73.9						
											KF	9.0	4.0	16.8	4.5	86.7						
Sander et al., 2013	T	M	13.1	18	2	104	5	5	4–10	4–10 RM	Back squat	25.0	9.6	90.0	13.5	260.0						
											Front squat	21.4	8.5	81.4	14.4	280.4						
Santos and Janeira, 2012	T	M	14.5 ± 0.6	15	3	10	2–3	6	10–12	10 RM							Med ball throw 3 kg	3.4	0.4	3.7	0.4	7.6
																	Squat jump	24.8	3.3	27.9	4.0	12.5
																	CMJ	33.3	4.3	36.7	4.2	10.2
																	Depth jump	34.8	4.1	38.1	4.3	9.5
Sarabia et al., 2015	T	M	15.0 ± 1.0	11	2	11	3–6	2			Half Squat	627.9	183	685.1	182	9.1	CMJ	31.2	3.6	32.5	2.3	4.1
											Bench press	328.0	42	341.1	49	4.0	Squat jump	28.5	3.6	31.2	2.3	9.6
																	Med ball throw	9.4	1.0	10.6	1.0	13.1
Sewall and Micheli, 1986	NR	MF	10–11	10	3	9	3	3	10	50–100%	Isom KE	19.8		24.1		21.7						
											Isom KF					12.6						
											Isom SE	16.3		21.2		30.1						
											Isom SF	5.8		7.7		32.8						
Siegel et al., 1989	U	MF	8.4 ± 0.5	50	3	12	Var	Var	Var	Var	Boys ($N = 26$)											
											Cable flexion	11.4	2.3	11.3	2.3	–0.9						
											Cable extension	12.7	2.5	12.6	2.5	–0.8						
											Handgrip right	13.4	3.1	14.9	3.3	11.2						
											Handgrip left	12.8	3.2	14.0	3.2	9.4						
											Chin up	2.4	2.5	3.8	3.6	58.3						
											Girls ($N = 24$)											
											Cable flexion	11.2	1.7	11.8	1.9	5.4						
											Cable extension	10.1	2.3	9.3	2.0	–7.9						
											Handgrip right	10.5	2.0	11.9	2.7	13.3						
											Handgrip left	9.9	2.1	11.3	2.6	14.1						
											Chin up	1.2	1.6	1.8	1.9	50.0						
Steele et al., 2017	U	MF	14.0 ± 1.0	17	2	9	2	8	4–6	4–6 RM	Bench press	31.4	7.0	36.0	2.8	14.6						
	U	MF	14.0 ± 1.0	16	2	9	2	8	12–15	12–15 RM	Bench press	30.9	7.0	35.3	2.8	14.2						
Teng et al., 2008			14.0 ± 1.0	12	2	12	3		10		Isok KF	54.0	18.0	57.0	16.0	5.6						
											Isok KE	106.0	20.0	118.0	26.0	11.3						

(Continued)

TABLE 2A | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	%Δ	Power	Pre	*SD*	Post	*SD*	%Δ
Tran et al., 2015	T	MF	14.0 ± 1.1	10	2	7	3	6	5–12		Isom mid thigh pull					12.7	CMJ					5.7
Tsolakis et al., 2004	U	M	11.8 ± 0.8	9	3	8	3	6	10	10 RM	Isom EF	85.1	8.3	100.2	8.4	17.7						
											Isot EF	3.2	1.6	4.0	1.5	24.2						
Velez et al., 2010	PE	MF	16.1 ± 0.2	13	3	12	2–3	12	10–15		10 RM bench press	42.0	19.2	49.5	19.8	17.9						
											10 RM seated row	61.5	21.9	71.0	24.7	15.4						
											10 RM shoulder press	38.0	21.3	49.3	4.7	29.7						
											10 RM squat	105.0	33.5	152.1	52.8	44.9						
Weakley et al., 2017	T	M	16.9 ± 0.4	35	1	12		5			Squat	77.4	32.6	96.0	18.6	24.0	10 m Sprint	1.9	0.1	1.9	0.1	–0.5
											Bench press	68.5	12.8	75.2	10.6	9.8	40 m Sprint	5.8	0.2	5.8	0.2	0.7
																	CMJ	33.8	5.2	36.2	5.6	0.7
Weltman et al., 1986	T	M	8.2 ± 1.3	16	3	14		10	30 sec		KF 30°·s	19.5	5.4	24.1	7.5	23.6	Long jump	124.8	14.3	128.6	19.2	3.0
											KF 90°·s	16.2	3.8	19.6	6.3	21.0	CMJ	21.1	4.8	23.3	3.4	10.4
											KE 30°·s	26.9	10.3	33.5	12.2	24.5						
											KE 90°·s	23.6	9.1	28.0	13.1	18.6						
											EF 30°·s	11.3	3.7	14.6	5.5	29.2						
											EF 90°·s	10.1	4.0	13.8	5.7	36.6						
											EE 30°·s	11.5	3.3	15.2	3.6	32.1						
											EE 90°·s	11.2	3.2	13.3	3.3	18.5						
Wong et al., 2010		M	13.5 ± 0.7	28	2	12	3	7–10	5–15								CMJ	55.5	6.6	58.8	7.3	5.9
																	10 m Sprint	2.1	0.2	2.0	0.1	4.8
																	30 m Sprint	4.9	0.3	4.7	0.3	2.2

%Δ, Percent change from pre-test to post-test; BPT, balance training before plyometric training; BW, bodyweight; cm, centimeter; CMJ, counter movement jump; CSTS, core strength training on stable surface; CSTU, core strength training on unstable surface; EE, elbow extension; EF, elbow flexor; ET, elastic tubing; Ex, exercises; FFM, fat free mass; Freq, frequency; FW, free weight; Int, intensity; Isok, isokinetic; Isom, isometric; Isot, isotonic; KE, knee extension; KF, knee flexion; kg, kilogram; m, meter; Med, Medicine; Mod, moderate; MVIC, maximal voluntary isometric contraction; N, number of participants; PBT, plyometric training before balance training; PE, physical education students; PHV, peak height velocity; Post, post-test; Power, power measures; Pre, pre-test; PT, peak torque; Reps, repetitions; RM, repetition maximum; RPE, rating of perceived exertion; s, second; SD, standard deviation; Strength, strength measures; T, trained youth; TMS, trunk muscle strength; Tr, training status; U, untrained youth; Var, varied; Wks, weeks.

*Additional Citations for **Table 2A** are found in the text reference list (Hettinger, 1958; Funato et al., 1986; Sewall and Micheli, 1986; Weltman et al., 1986; Blimkie, 1989; Ozmun et al., 1994; DeRenne et al., 1996; Gorostiaga et al., 1999; Sadres et al., 2001; Flanagan et al., 2002; Pikosky et al., 2002; Tsolakis et al., 2004; Drinkwater et al., 2005; Benson et al., 2007; Faigenbaum et al., 2007a, 2014, 2015; Channell and Barfield, 2008; Rhea et al., 2008; Teng et al., 2008; Chelly et al., 2009; Dorgo et al., 2009; Lubans et al., 2010; Velez et al., 2010; Wong et al., 2010; Ebada, 2011; Granacher et al., 2011a,b, 2014, 2015; Ignjatovic et al., 2011; Muehlbauer et al., 2012; Santos and Janeira, 2012; Moore et al., 2013; Moraes et al., 2013; Sander et al., 2013; Coskun and Sahin, 2014; Ferrete et al., 2014; Pesta et al., 2014; Piazza et al., 2014; Dalamitros et al., 2015; Gonzalez-Badillo et al., 2015; dos Santos Cunha et al., 2015; Sarabia et al., 2015; Tran et al., 2015; Eather et al., 2016; Harries et al., 2016; Lloyd et al., 2016; Negra et al., 2016; Prieske et al., 2016; Rodriguez-Rosell et al., 2016; Contreras et al., 2017; Steele et al., 2017; Weakley et al., 2017).*

TABLE 2B | Power (plyometric) resistance training program descriptions.

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
Alves et al., 2016	U	MF	10.9 ± 0.5	45	2	8	2–3	6	4–8								1 kg Ball throw	3.6	0.6	3.8	0.6	5.6
																	3 kg Ball throw	2.2	0.4	2.4	0.4	9.1
																	Single leg jump	1.3	0.2	1.4	0.2	7.7
																	CMJ	0.2	0.0	0.2	0.0	0.0
Arabatzi, 2016	U	MF	9.3 ± 0.6	12	3	4	10	3	8–12								CMJ	18.8	0.5	21.0	0.5	11.7
																	Drop Jump	20.7	0.4	22.7	0.5	9.9
Attene et al., 2015	T	F	14.9 ± 0.9	18	2	6	2	5	6								CMJ	26.9	3.6	30.0	3.7	11.3
																	Squat jump	22.7	3.2	26.2	3.6	15.4
Borges et al., 2016	T	M															5 m Sprint	1.0	0.6	1.1	0.7	3.9
																	30 m Sprint	4.2	0.9	4.3	0.2	0.7
Buchheit et al., 2010	T	M	14.5 ± 0.5	8	1	10	4–6	4–6									10 m	1.9	0.1	1.9	0.1	0.5
																	30 m	4.7	0.3	4.6	0.2	1.9
																	CMJ	35.4	7.8	40.6	8.8	14.7
Chaabene and Negra, 2017	T	M	LPT: 12.7 ± 0.2	13	2	8	5–6		10–15								LPT: 5 m sprint	1.19	0.04	1.1	0.06	–7.5
			HPT: 12.7 ± 0.3	12	2	8	9–13		12–15								HPT: 5 m sprint	1.2	0.1	1.16	0.09	–3.3
																	LPT: 30 m sprint	4.98	0.12	4.84	0.17	–2.8
																	HPT: 30 m sprint	5.17	0.34	5.03	0.34	–2.7
Chelly et al., 2015	T	M	11.9 ± 1.0	14	4	10	3–10	6	3–10								Squat jump	0.2	2.8	0.2	0.0	14.3
																	CMJ	0.2	0.0	0.3	0.0	8.7
																	Drop jump	0.2	0.0	0.3	0.0	13.6
Cossor et al., 1999	T	M	11.7 ± 1.2	19	3	20	2	15	10–15													
																	Vertical jump	199.7	65.8	212.5	59.1	6.4
de Hoyo et al., 2016	T	M	SQ: 18 ± 1.0	9	2	8	1–3	8	2–3								CMJ	35.5	4.3	37.9	3.6	6.8
			RS: 17 ± 1.0														20 m Sprint	3.0	0.1	3.0	0.1	0.3
			PL: 18 ± 1.0														50 m Sprint	6.6	0.2	6.5	0.3	1.4
Diallo et al., 2001		M	12.3 ± 0.4	10	3	10		3														
																	CMJ	29.2	3.9	32.6	3.4	11.6
																	Squat jump	27.3	4.0	29.3	3.3	7.3
																	Running velocities 20 m (m/sec)	5.6	0.1	5.7	0.2	2.7
Faigenbaum et al., 2007b	T	M	13.4 ± 0.9	13	2	6	1–2	10–12	6–10								VJ	43.1	8.4	46.5	9.2	7.9
																	Long jump	181.1	25.9	191.9	28.5	6.0
																	9.1 m sprint	2.2	0.1	2.2	0.2	0.0
																	Ball toss	319.2	96.9	358.4	85.2	12.3

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
Faigenbaum et al., 2009	PE	MF	9.0 ± 0.9	40	2	9	1	12–14	6		Curl up	29. 1	10.7	31	9.9	6.5	Long jump	132.0	27.5	139.9	27.0	6.0
							1		8		Push up	4.6	5.6	8.7	9.5	89.1						
							1		10													
Fernandez-Fernandez et al., 2016	T	M	12.5 ± 0.3	30	5	8	2–4	6–8	10–15								CMJ	30.1	4.3	32.0	4.1	6.3
																	5 m Sprint	1.2	0.1	1.1	0.1	5.1
																	20 m Sprint	3.5	0.2	3.4	0.2	3.7
																	Long jump	184.0	11.7	200.0	17.3	8.7
																	Medicine ball throw	626.0	91.6	680.0	114	8.6
Granacher et al., 2015	T	M	15.0 ± 1.0	12	2	8	3–5	16	5–8								CMJ IPT	44.1	4.4	46.1	3.8	4.5
																	CMJ SPT	41.1	4.2	46.4	4.9	12.9
																	Drop jump IPT	28.9	3.9	31.2	3.2	7.9
																	Drop jump SPT	27.2	4.2	30.2	2.5	11.1
																	10 m Sprint IPT	1.9	0.1	1.9	0.1	157.0
																	10 m Sprint SPT	1.9	0.1	1.9	0.1	2.1
																	30 m Sprint IPT	4.4	0.2	4.4	0.2	–0.7
																	30 m Sprint SPT	4.5	0.2	4.5	0.3	1.1
Hall et al., 2016	T	F	12.5 ± 1.7	10	2	6	1∼4	20	1–6								CMJ	43.5	6.1	45.3	5.8	4.1
Hammami et al., 2016b	T	M	BPT: 12.7 ± 0.3	12	2	8	1∼3	10	8–15								CMJ BPT	25.5	4.0	29.2	2.9	14.5
			PBT: 12.5 ± 0.3														CMJ PBT	24.7	2.4	26.8	1.8	8.5
																	Long jump BPT	186.0	15.9	220.7	10.3	18.7
																	Long jump PBT	177.1	11.6	206.8	13.9	16.8
																	10-m Sprint BPT	2.1	0.1	2.0	0.1	4.7
																	10 m Sprint PBT	2.1	0.1	1.9	0.2	9.5
																	30-m Sprint BPT	5.1	0.2	5.0	0.3	2.0
																	30 m Sprint PBT	5.1	0.2	5.0	0.2	2.0
Hammami et al., 2016a	T	M	15.7 ± 0.2	15	2	8	4–10	4	7–10		Dom leg PT (N–m)	41	7	46	7	12.2	5 m Sprint	1.1	0.1	1.0	0.1	7.3
Hewett et al., 1996	T	F	15.0 ± 0.6	11	3	6		16			NonDom leg PT (N–m)	37	7	46	8	24.3						
Kotzamanidis et al., 2005	T	M	17.0 ± 1.1	12	2	9	4		3–8	8,6,3 RM	Half squat	140.4	15.5	154.5	15.7	10.0	Squat jump	25.7	3.1	26.2	3.5	1.9
											Step up	65.5	7.6	76.4	7.1	16.7	DJ40	18.4	5.5	18.9	5.5	2.6

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
											Leg Curl	53.6	6.7	62.3	5.6	16.1	CMJ	27.2	3.4	27.5	3.3	0.9
																	30-m running speed	4.3	0.2	4.3	0.2	0.5
Kotzamanidis, 2006	U	M	11.1 ± 0.5	15	2	10	3										10 m speed (s)	2.3	0.2	2.2	0.1	2.2
																	30 m speed (s)	5.7	0.1	5.6	0.0	3.3
																	Vertical jump	23.0	4.5	31.0	4.1	34.7
King and Cipriani, 2010	T	M	FP: 15.1 ± 0.9	10	2	6	3	6	3–10								Vertical jump FP	68.1		67.3		–1.1
			SP: 15.2 ± 1.1	10													Vertical Jump SP	67.2		63.6		–5.3
Lephart et al., 2005	T	F	14.5 ± 1.3	14	3	8		11	10		Quads PT 60°/s (%BW)	211.8	45.2	227.6	23.9	7.5						
											Hams PT 60°/s (%BW)	106.3	32.6	112.7	14.4	6.0						
											Quads PT 180°/s (%BW)	128.5	22.9	147.2	18.1	14.6						
											Hams PT 180°/s (%BW)	88.4	23.7	83.6	16.3	–5.4						
											Hip abd isom PT (%BW)	169.4	34.1	165.5	35.6	–2.3						
Lloyd et al., 2012	GE9	M	9.4 ± 0.5	20	2	4	2–4	5	3–10								Hopping reactive index					
	GE 12		12.3 ± 0.3	22													GE9	0.90	0.25	0.90	0.24	0.0
	GE 15		15.3 ± 0.3	20													GE12	0.91	0.24	1.01	0.26	11.0
																	GE15	1.46	0.28	1.52	0.26	4.1
Lloyd et al., 2016	PE	M	12.7 ± 0.3	10	2	6	2	4	3–10								10 m sprint pre-PHV	2.3	0.2	2.2	0.2	4.3
			16.4 ± 0.2	10													20 m sprint pre-PHV	3.4	0.2	3.3	0.2	2.9
																	Squat jump pre-PHV	24.6	4.9	28.3	4.6	15.0
																	10 m sprint post-PHV	1.9	0.1	1.0	0.1	47.4
																	20 m sprint post-PHV	2.7	0.3	2.6	0.3	3.7
																	Squat jump post-PHV	32.3	6.4	32.7	6.3	1.2

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
Marques et al., 2013	T	M	13.4 ± 1.4	26	2	6	2–6	8	8–30								CMJ					7.7
																	30 m Sprint					1.7
Martel et al., 2005	T	F	15.0 ± 1.0	10	2	6	1	7	2–5		Isok PT Quad 60°	108	29	120	25		CMJ	33.4	4.7	37.1	4.5	11.0
											PT Hamstrings 60°	69	13	79	12							
											PT Quad 180°	61	17	69	21							
											PT Hamstrings 180°	48	13	56	10							
Marta et al., 2014		M	10.8 ± 0.4	76	2	8	2–6	8	3–30								1 kg Ball throw T1	333.5		355.7		6.7
																	3 kg Ball throw T1	213.3		233.2		9.3
																	Standing long Jump T1	126.8		133.8		5.6
																	CMJ T1	21.4		22.6		5.5
																	20 m Sprint T1	4.3		4.2		2.5
																	1 kg Ball throw T2	370.2		387.5		4.7
																	3 kg Ball throw T2	240.7		256.3		6.5
																	Standing long Jump T2	121.4		127.0		4.6
																	CMJ T2	20.9		22.0		5.1
																	20 m Sprint T2	4.4		4.4		1.8
Matavulj et al., 2001	T	M	15–16		3	6	3	1	10													
	DJ 50 cm			11							DJ 50 cm					0.3	DJ 50 cm					4.8
	DJ 100 cm			11							DJ 100 cm					0.03	DJ 100 cm					5.6
McCormick et al., 2016	T	F																				
	FP		16.3 ± 0.7	7	2	6	4	9	6								CMJ FP	48.3	5.4	50.1	5.3	3.8
	SP		15.7 ± 0.7	7													CMJ SP	47.7	7.1	52.6	9.4	10.3
																	Standing long Jump FP	176.9	18.5	187.1	14.2	6.0
																	Standing long Jump SP	177.9	30.1	191.9	29.1	7.9

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
Meylan and Malatesta, 2009	T	M	13.3 ± 0.6	14	2	8	2–4	4	6–12	1–5							SJ	30.1	4.1	30.5	3.2	0.6
																	CMJ	34.6	4.4	37.2	4.5	7.9
																	10 m Sprint	1.96	0.07	1.92	0.1	2.1
Michailidis et al., 2013	T	M	10.7 ± 0.7	24	2	12	2–4	4	5–10		10 RM Squat						30 m Sprint					–3.0
																	CMJ					27.6
																	SJ					23.3
																	DJ					15.9
Moran et al., 2016	T	M	12.6 ± 0.7	9	2		1	3	5–10								CMJ Pre-PHV	28.0	4.0	28.1	4.0	0.4
			14.3 ± 0.6	8													CMJ Mid-PHV	32.5	6.0	32.8	3.7	0.9
																	10 m Sprint Pre-PHV	2.3	0.1	2.3	0.1	0.4
																	10 m Spring mid-PHV	2.2	0.2	2.1	0.1	2.3
																	30 m Sprint pre-PHV	5.5	0.3	5.4	0.3	0.5
																	30 m Sprint mid-PHV	5.0	0.3	4.9	0.3	0.4
Noyes et al., 2012	T	F	14–17	57	3	6	1	17	5								VJ	26.2	12.3	28.5	12.0	8.8
																	18 m Sprint	3.5	0.3	3.5	0.4	0.3
Noyes et al., 2013	T	F	15.0 ± 1.0	62	3	6	1	17	5								37 m Sprint	6.1	0.4	6.0	0.4	2.0
																	VJ 2 Step	40.7	8.9	42.1	8.3	3.4
																	CMJ	32.9	6.7	32.6	25.8	–0.9
Noyes et al., 2012	T	F	14.5 ± 1.0	34	3	6	1	17	5–25		Sit-up (reps)	37.7	5.3	40.5	5.9	7.4	CMJ	40.1	7.1	41.5	4.5	3.5
Pereira et al., 2015	T	M	14.0	10	2	8	2	5	8–20								CMJ	26.9	4.5	32.3	9.0	20.1
																	Medicine ball throw	7.5	15.2	7.9	14.3	5.2
Piazza et al., 2014	T	F	11.9 ± 1.0	18	2	6	1	10	3													
																	SJ	410.4	41.6	421.5	28.4	2.7
																	CMJ	457.2	30.6	485.0	33.8	6.1
Potdevin et al., 2011	T	M	14.3 ± 0.2	12	2	6	2–10	13	4–12								CMJ	28.9	4.8	32.5	4.2	12.2
																	SJ	26.2	3.8	31.1	4.9	18.9
Ramirez-Campillo et al., 2013	T	M	13.2 ± 1.8	38	2	7	2	3	10								CMJ	27.0	5.8			4.3
																	20 m Sprint	4.3	0.6			0.4
Ramirez-Campillo et al., 2014	T	M	13.2 ± 1.8	38	2	7	2	7	10	High							CMJ	26.7	4.7			2.2
																	20 m Sprint	4.39	0.48			3.7

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
Ramirez-Campillo et al., 2015a	T	M	11.6 ± 2.7	12	2	6	2	6	5–10								30 m sprint	6.0	0.6			6.5
																	CMJ	30.5	9.3			15.4
																	Horizontal jump	153.0	4.1			14.6
Ramirez-Campillo et al., 2015b		M	NPPT: 13.0 ± 2.1	8	2	6	2	2	5								Vert CMJ w/arms					
			PPT: 12.8 ± 2.8	8			2		5–10								NPPT	28.5	10.4			10.9
																	PPT	27.9	8.7			16.6
																	Horz CMJ w/arms					
																	NPPT	163.0	42.6			4.6
																	PPT	160.0	27.9			7.9
																	Right leg horiz CMJ w/arms					
																	NPPT	138.0	35.3			2.8
																	PPT	138.0	27.7			13.5
																	Left leg horiz CMJ w/arms					
																	NPPT	136.0	42.9			14.1
																	PPT	134.0	27.0			21.2
																	Maximal kicking velocity					
																	NPPT	68.3	15.4			5.7
																	PPT	67.1	16.3			10.1
																	10 m sprint time					
																	NPPT	2.6	0.4			0.9
																	PPT	2.7	0.3			1.6
Ramírez-Campillo et al., 2015c	T	M	BG: 11.0 ± 2.0	12	2	6	2–3	6	5–10								CMJ:					
			UG: 11.6 ± 1.7	16													BG	31.1	2.0			18.7
			BUG: 11.6 ± 2.7	12													UG	29.5	4.3			7.9
																	BUG	30.5	9.3			15.4
																	Horizontal CMJ					
																	BG	166	33			17.4
																	UG	153	22			8.9
																	BUG	153	41			14.6

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
																	Maximal kicking velocity					
																	BG	59.2	18.4			8.4
																	UG	59.9	10.8			14.0
																	BUG	61.8	19.6			12.0
																	30 m Sprint					
																	BG	5.7	0.5			–3.2
																	UG	6.1	0.4			–6.2
																	BUG	6.0	0.6			–6.5
Rosas et al., 2016	T	M	12.3 ± 2.3	21	2	6		6	4–8								CMJ	31.7	9.0			4.3
																	Horizontal jump	159.0	35.7			6.1
Santos and Janeira, 2012	T	M	15.0 ± 0.5	14	2	10	2–4	6	6–15								Squat jump	25.2	3.5	29.2	4.1	15.8
																	CMJ	30.3	4.3	34.5	5.0	13.8
																	Medicine ball throw	3.4	0.4	3.9	0.4	14.9
Santos et al., 2012	U	M	13.3 ± 1.0	30	2	8	1–5	7–8	3–8								GR Group					
																	CMJ	0.3	0.1	0.3	0.1	4.4
																	Long jump	1.5	0.3	1.6	0.3	4.7
																	1 kg Medicine ball throw	7.5	1.7	8.2	1.6	8.7
																	3 kg Medicine ball throw	4.7	1.0	5.1	1.1	9.9
																	20 m	4.5	0.5	4.1	0.4	10.8
																	GCOM group					
																	CMJ	29.8	0.1	31.6	0.1	6.0
																	Long jump	1.7	0.3	1.7	0.3	4.2
																	1 kg Medicine ball throw	7.3	1.6	7.6	1.7	4.5
																	3 kg Medicine ball throw	4.6	1.1	5.1	1.2	11.1
																	20 m	4.4	0.6	3.8	0.3	13.0
Skurvydas et al., 2010		M	10.3 ± 0.3	13	2	8	1	1	30		MVIC	79.4	22.1	86.6	23.1	9.1	CMJ	24.1	3.8	32.8	5.1	36.1
Skurvydas and Brazaitis, 2010		M	10.2 ± 0.3	13	2	8	1	1	30								Girls	21.8	3.3	29.9	3.8	37.7

(Continued)

TABLE 2B | Continued

Article	Tr	Sex	Age	*N*	Freq	Wks	Sets	Ex	Reps	Int	Strength	Pre	*SD*	Post	*SD*	% Δ	Power	Pre	*SD*	Post	*SD*	% Δ
Sohnlein et al., 2014	T	M	13.0 ± 0.9	12	2	16	2–5	9	6–16	Max							10 m Sprint	1.8	0.1	1.8	0.1	2.2
																	30 m Sprint	4.4	0.2	4.3	0.1	2.5
																	5 m Sprint	1.1	0.0	1.0	0.0	3.8
																	20 m Sprint	3.2	0.1	3.1	0.1	3.2
Szymanski et al., 2007	T	M	15.4 ± 1.1	25	3	12	2	7	6–10		Dom TRS					17.1	Standing long jump	2.3	0.2	2.5	0.1	7.3
											NonDom TRS					18.3	Medicine ball hitter's throw					10.6
											Parallel squat (kg)	106.3	23.4	145	27.7	26.7						
											Bench press (kg)	71.7	15.9	86.1	15.2	16.7						
Thomas et al., 2009	T	M	17.3 ± 0.4	12	2	6				Chu's							5 m Sprint					
																	DJ trained	1.0	0.1	1.1	0.1	1.9
																	CMJ trained	1.1	0.1	1.1	0.1	0.9
																	10 m Sprint					
																	DJ trained	1.8	0.1	1.8	0.2	1.1
																	CMJ trained	1.8	0.1	1.8	0.2	0.0
																	20 m Sprint					
																	DJ trained	3.1	0.1	3.1	0.2	1.0
																	CMJ trained	3.2	0.1	3.2	0.3	0.6
Witzke and Snow, 2000	PE	F	14.6 ± 0.5	25	3	12	2–3	Str:7	8–12	5–15% BW	Leg strength	96	19.9	107.7	17.3	16.7	Leg power	392.0	82.0	445.0	91.0	13.5
						24	2–3	Plyo: 5–20	2–20	mod-high												

%Δ, percent change from pre-test to post-test; BPT, balance training before plyometric training; BW, bodyweight; cm, centimeter; CMJ, counter movement jump; DJ, drop jump; Dom, dominant; Ex, exercises; FP, frontal plane; Freq, frequency; GCOM, combined resistance training and endurance; GR, resistance training alone; Int, intensity; IPT, plyometric training on unstable surface; Isok, isokinetic; Isom, isometric; kg, kilogram; m, meter; Mod, moderate; MVIC, maximal voluntary isometric contraction; N, number of participants; Nm, newton meter; NonDom, non-dominant; NPPT, no plyometric training; PBT, plyometric training before balance training; PE, physical education students; Pre, pre-test; PHV, peak height velocity; PL, plyometric; Post, post-test; Power, power measures; PPT, plyometric training; Reps, repetitions; RS, resisted sprinting; s, second; SD, standard deviation; SJ, squat jump; SP, sagittal plane; SPT, plyometric training on stable surface; SQ, squat; ST, Strength; Strength, strength measures; T, trained youth; Tr, training status; TRS, torso rotational strength; U, untrained youth; Wks, weeks.

*Additional Citations for **Tables 2A,B** are found in the text reference list (Hewett et al., 1996; Cossor et al., 1999; Witzke and Snow, 2000; Diallo et al., 2001; Matavulj et al., 2001; Martel et al., 2005; Szymanski et al., 2007; Meylan and Malatesta, 2009; Thomas et al., 2009; Buchheit et al., 2010; King and Cipriani, 2010; Skurvydas and Brazaitis, 2010; Skurvydas et al., 2010; Potdevin et al., 2011; Santos and Janeira, 2011; Lloyd et al., 2012; Noyes et al., 2012, 2013; Santos et al., 2012; Marques et al., 2013; Michailidis et al., 2013; Ramirez-Campillo et al., 2013, 2015a,b; Marta et al., 2014; Piazza et al., 2014; Sohnlein et al., 2014; Attene et al., 2015; Chelly et al., 2015; Pereira et al., 2015; Alves et al., 2016; Arabatzi, 2016; Borges et al., 2016; de Hoyo et al., 2016; Fernandez-Fernandez et al., 2016; Hall et al., 2016; McCormick et al., 2016; Moran et al., 2016; Rosas et al., 2016).*

TABLE 3 | Summary of meta-analysis results.

	General	Trained vs.	Untrained	Children vs.	Adolescents
Power training effects on jump measures	0.69 Moderate	0.67 Moderate	**0.80 Large**	***0.74 Moderate***	*0.57 Moderate*
Strength training effects on jump measures	0.53 Moderate	0.48 Small	**0.61 Moderate**	***0.68 Moderate***	*0.42 Small*
Power training effects on sprint measures	0.38 Small	0.32 Small	**1.19* Large**	***0.47 Small***	*0.13 Trivial*
Strength training effects on sprint measures	0.48 Small	0.45 Small	**0.57* Moderate**	***0.73 Moderate***	*0.36 Small*
Power training effects on lower body strength measures	0.16** Trivial	Not reported	Not reported	Not reported	*0.16** Trivial*
Strength training effects on lower body strength measures	1.14 Large	1.23 Large	**1.08 Large**	***1.39 Large***	*0.88 Large*

Shaded row values illustrate higher magnitude changes compared to the corresponding measure. Bolded values illustrate higher magnitude changes for untrained vs. trained participants. Bolded and underlined values indicate higher magnitude changes for children vs. adolescents.
**3 studies met inclusion criteria; **4 studies met the inclusion criteria.*

velocities, contraction types and other training characteristics most closely match the subsequent activity, sport or tests. The higher speed and power movements associated with power training would be expected to provide more optimal training adaptations for explosive type jump measures. Power training (e.g., plyometrics) can improve youth's ability to increase movement speed and power production (Behm et al., 2008). Chaouachi et al. (2014) reported similar findings when they compared training programs that involved two types of power training (Olympic weight lifting and plyometric) and traditional RT. In accordance with the present review and the concept of training specificity, both plyometric and Olympic weight lifting in the Chaouachi study provided greater magnitude improvements in CMJ than traditional RT.

It should be noted though, that while the numerical SMD values for power training exceeded strength training for power measures, the descriptor categorization overall was the same: moderate for both power and strength training. Thus, while it is conceded that power training demonstrates a numerical advantage over strength training for power measures (e.g., jump performance), the relative extent or degree of superiority was not overwhelming. The relative magnitude of improvement with power training (moderate to large: 0.6–0.8) for power measures (e.g., jumps) did not match the training specific extent or consistency of improvements associated with strength training on lower body strength (uniformly large: 0.88–1.35). Hence, the training specific response of strength training (strength training effects on strength measures) was consistently more substantial than the power training specific response (power training effects on jump power measures). Furthermore, power training specificity did not extend to another power and speed related measure: sprint speed.

Strength training magnitudes of change exceeded power training for sprint measures (exception of untrained participants). These findings contradict the long-held concept of training specificity (Sale and MacDougall, 1981; Behm, 1988, 1995; Behm and Sale, 1993). Slower, more deliberate movements of traditional RT would not be expected to provide optimal training adaptations for sprint measures that involve higher speed, stretch-shortening cycle (SSC) type activities. Again, similar findings were reported by Chaouachi et al. (2014) who found that traditional RT provided superior training adaptations compared to both Olympic weight lifting and plyometric training for 5 and 20 meter sprints. However, Radnor et al. (2017) reported contradictory results to the present meta-analysis with plyometric training and combined strength and plyometric training providing more positive responders than strength training alone for sprint velocity. The Radnor study incorporated school aged boys (not specifically trained) whereas the present review included both highly trained athletes and untrained youth. Similar to Radnor and colleagues, untrained youth in this meta-analysis participating in power training had greater magnitude improvements in sprint measures than trained athletes or the mean results of both populations.

One of the main factors contributing to optimal sprint performance is the capacity to generate a high rate of muscular force (Aagaard et al., 2002; Cronin and Sleivert, 2005; Cormie et al., 2007). Sprint actions employ stretch-shortening cycle (SSC) actions that involve the sequential combination of eccentric and concentric muscle contractions (Komi, 1986). SSC based actions tend to promote greater concentric force outputs when there is a rapid and efficient storage and transfer of elastic energy from the eccentric to the concentric phases (Cavagna et al., 1968; Bosco et al., 1982a,b; Cormie et al., 2010). Elastic and contractile (e.g., increased time for muscle activation, pre-load effect, muscle-tendon interaction, stretch reflexes) components affect maximal power output (Cavagna et al., 1968; Ettema et al., 1990; Lichtwark and Wilson, 2005; Avela et al., 2006). These mechanical and reflexive contributions occur over a short duration and thus the transition from eccentric to concentric phases must be brief (McCarthy et al., 2012). Reaction forces from sprints and hurdle jumps can generate reaction forces of ∼4–6 times the individual's body mass (Mero et al., 1992; Cappa and Behm, 2011). Since the predominant jump measures were from bilateral CMJ and squat jumps, the ground reaction forces upon each limb would have been substantially lower (typically ½) than with high speed sprinting (with unilateral landings) (Dintiman and Ward, 2003; Cappa and Behm, 2011). The training specific related power (jump height) improvements seen with power training in this review would not necessitate similar eccentric strength capacities compared to the reaction forces experienced with sprinting. An individual who lacks sufficient eccentric strength must accommodate the eccentric forces by

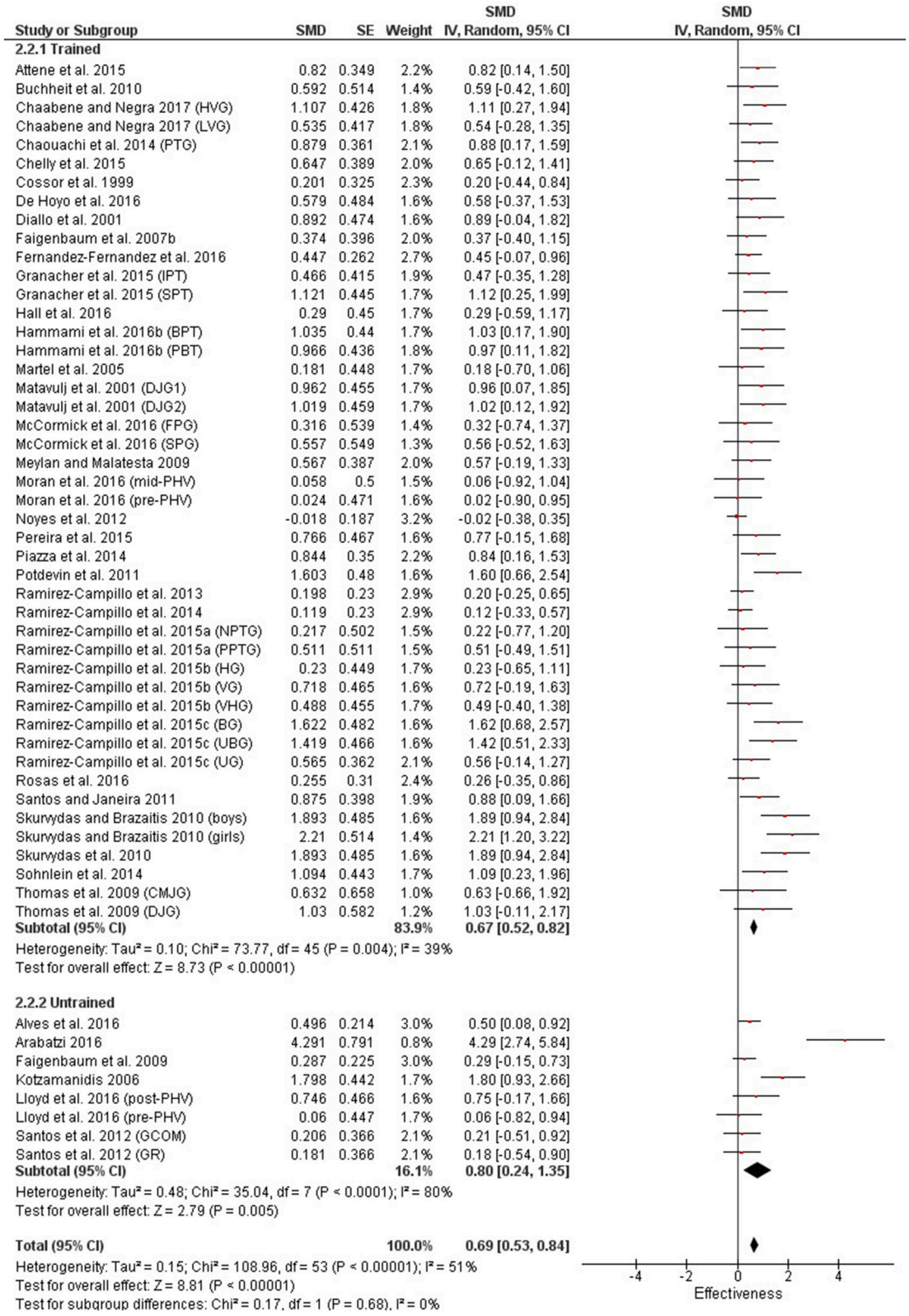


FIGURE 2 | Power training effects on jump measures for trained and untrained subjects. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

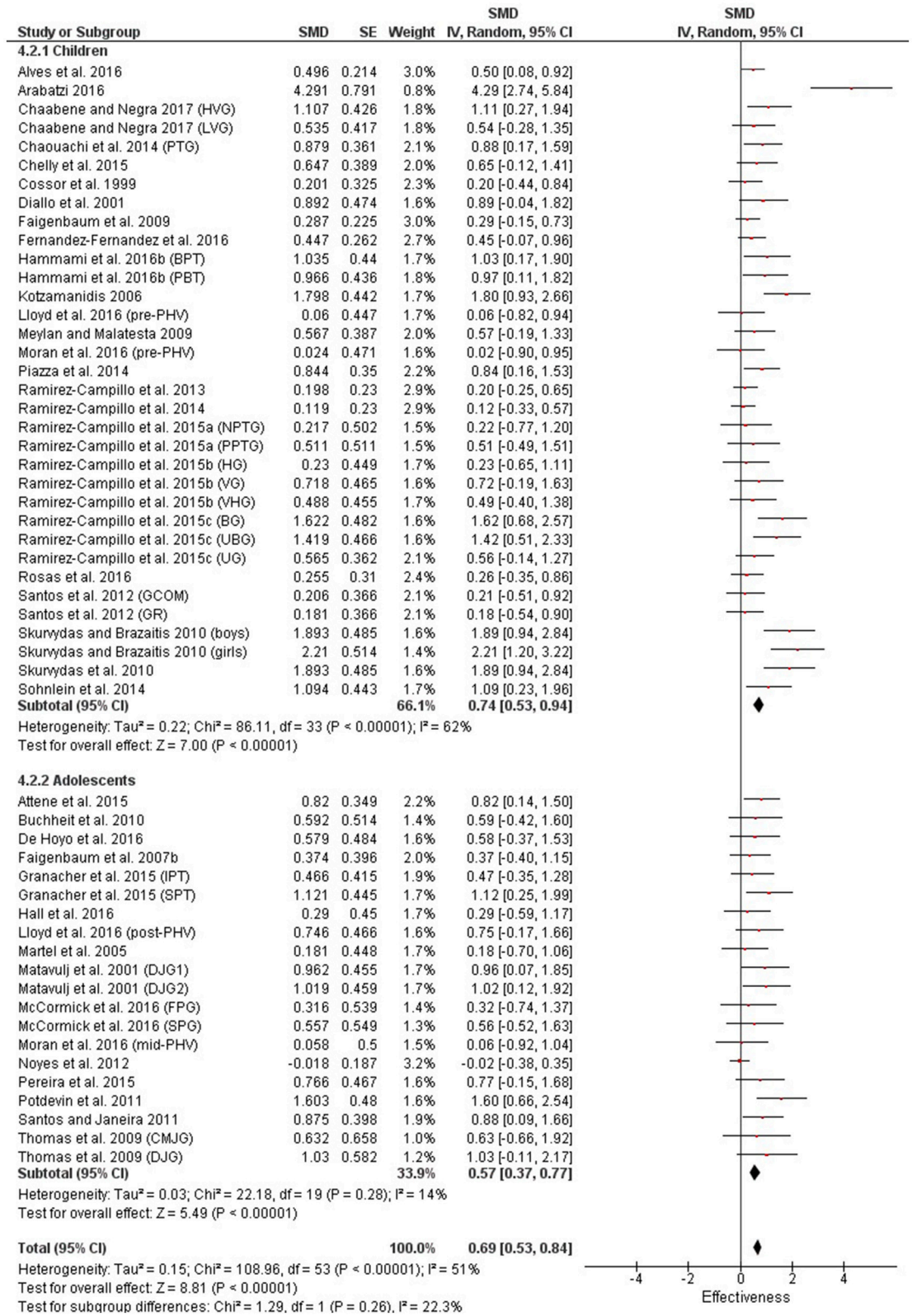


FIGURE 3 | Power training effects on jump measures for children and adolescents. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

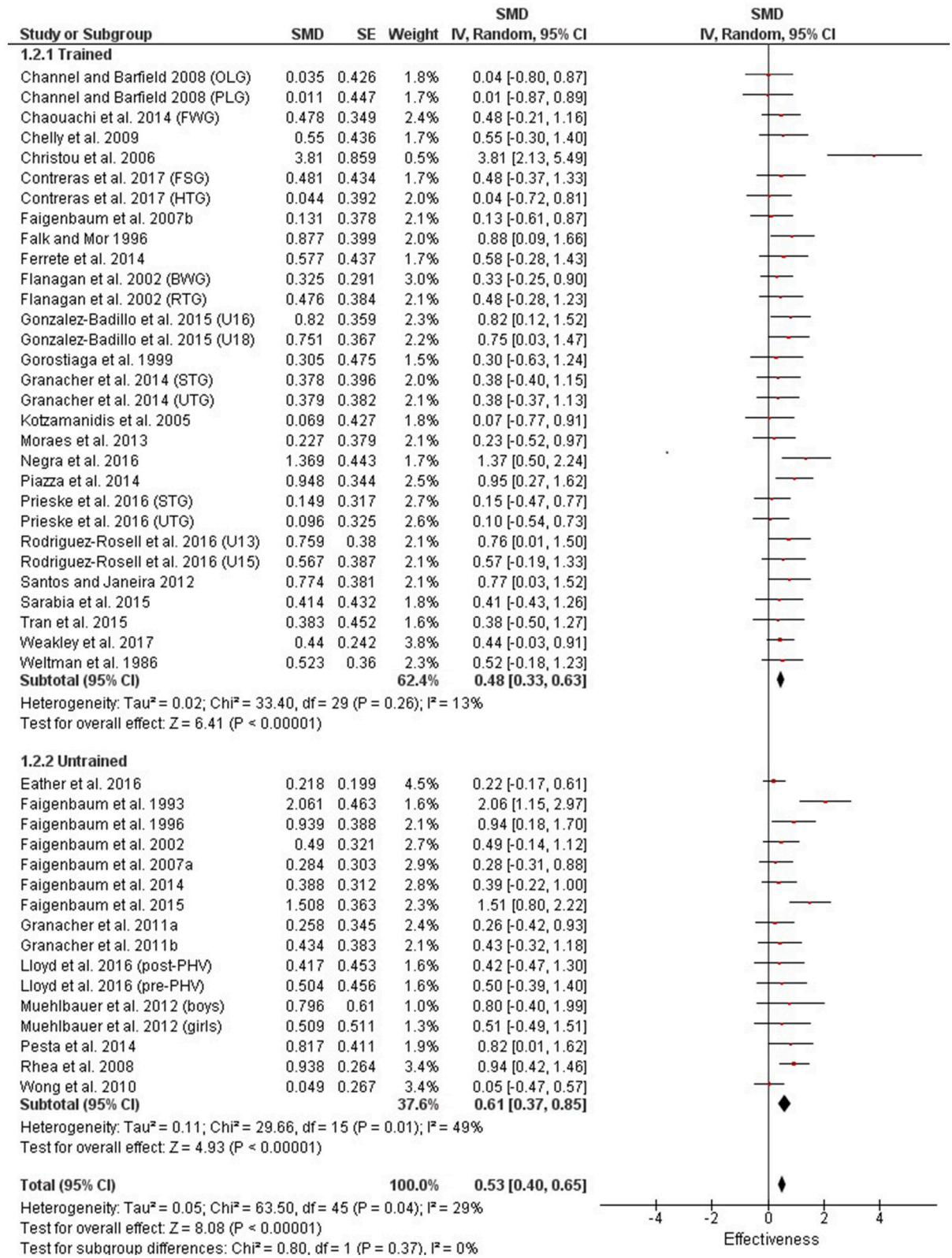


FIGURE 4 | Strength training effects on jump measures for trained and untrained subjects. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

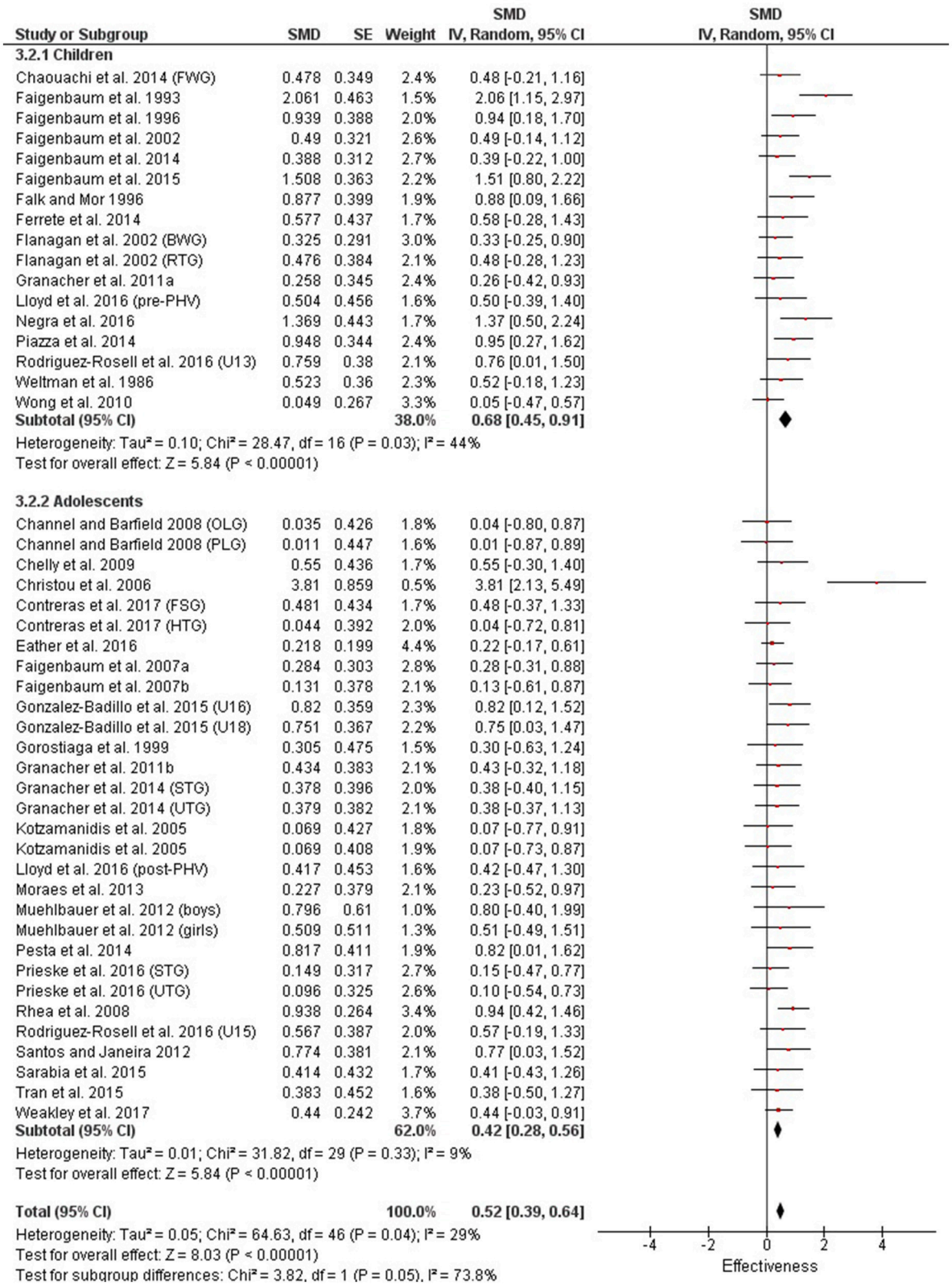


FIGURE 5 | Strength training effects on jump measures for children and adolescents. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

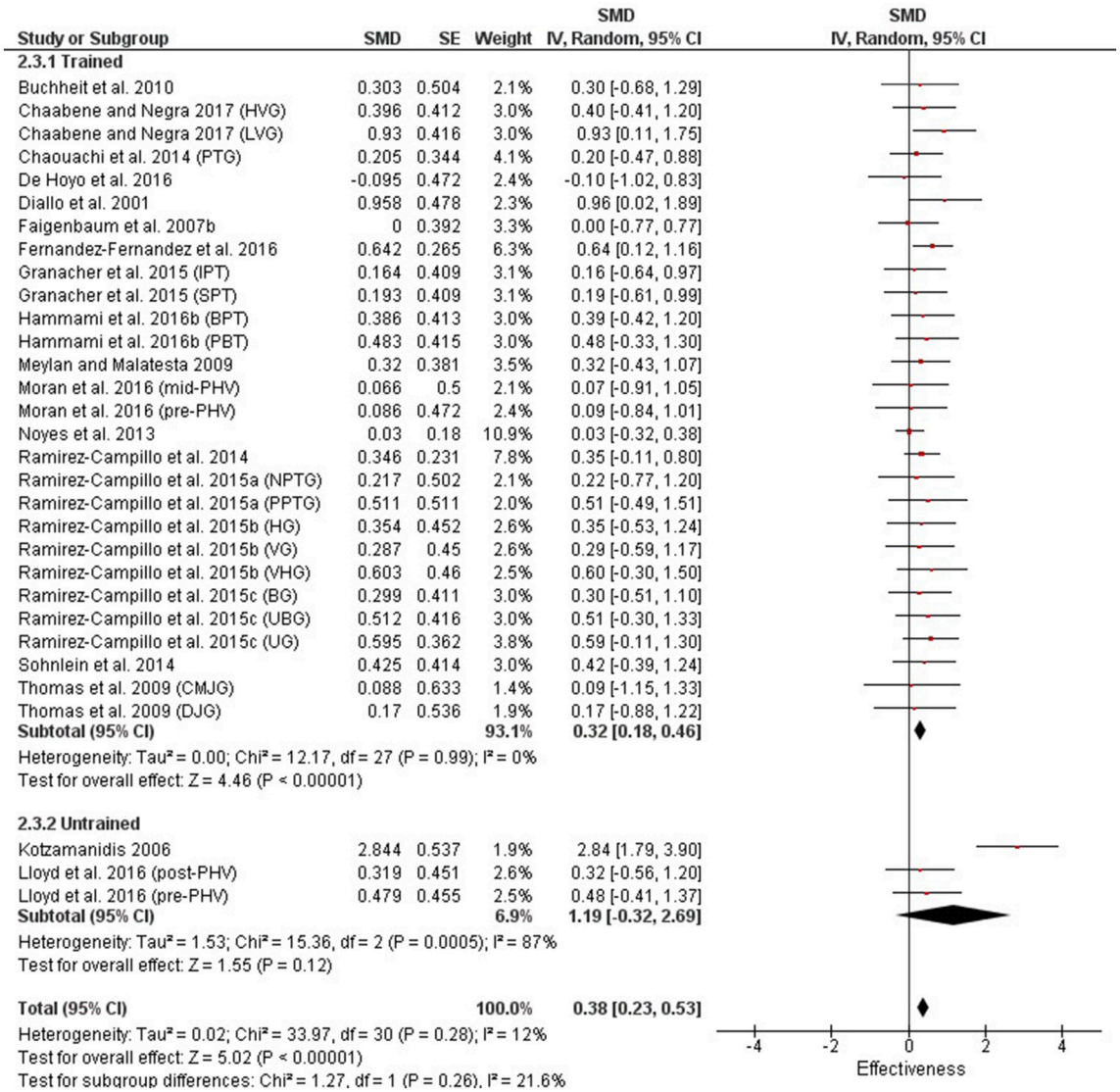


FIGURE 6 | Power training effects on sprint measures for trained and untrained subjects. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

absorbing those forces over a longer time period, which would nullify the advantages of SSC actions (Miyaguchi and Demura, 2008). The lack of sprint training specificity with youth might be attributed to a lack of foundational eccentric (and likely concentric) strength. The effectiveness of traditional RT with youth sprinting would lie in its ability to build this essential strength component allowing youth to take advantage of the SSC mechanical and reflexive power amplification. Plyometric training would not be effective with any individual (youth or adult) who must absorb reaction forces over a prolonged period and thus cannot efficiently transfer the eccentric forces to the concentric power output.

The CMJ, drop, squat and other jumps evaluated in this meta-analysis all involved bilateral take-offs and landings. In contrast, sprinting is a series of rapid, unilateral landings and propulsions which would place greater challenges on the balance capabilities of the individual. Balance is another important contributor to SSC and sprint performance especially in youth (Hammami et al., 2016a). Balance affects force, power output and movement velocity (Anderson and Behm, 2005; Drinkwater et al., 2007; Behm et al., 2010a,b). Since balance and coordination are not fully mature in children (Payne and Isaacs, 2005), the effectiveness of plyometric training could be adversely affected. Hammami et al. (2016a) reported large-sized correlations between balance measures and proxies of power with youth ($r = 0.511–0.827$). These correlation coefficients were greatest with the more mature post-peak height velocity (PHV) youth, suggesting that the poorer postural control of the less

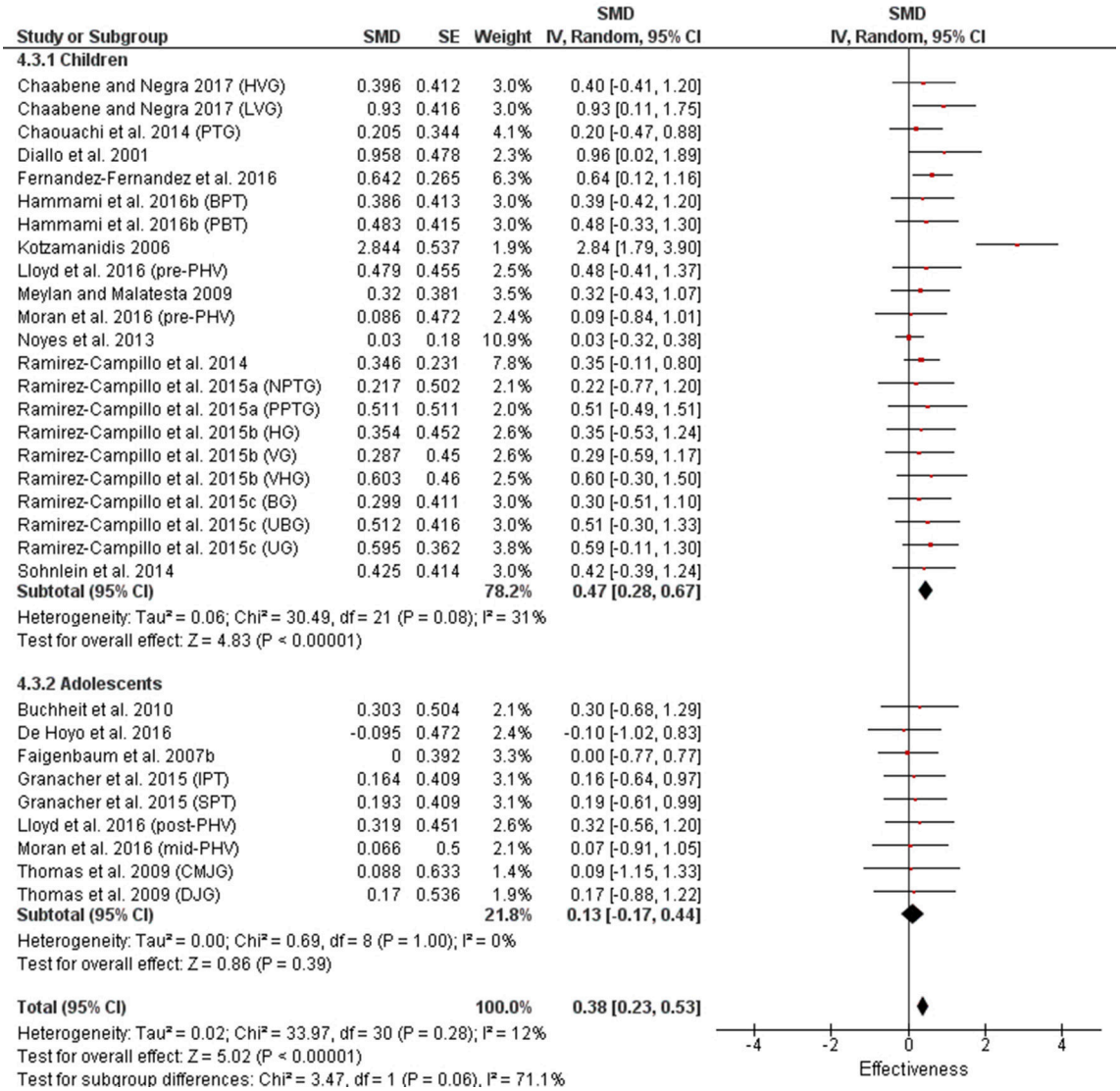


FIGURE 7 | Power training effects on sprint measures for children and adolescents. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

mature pre-PHV and PHV youth had negative consequences upon power output. Similarly, significant positive correlations between maximum speed skating performance and a static wobble board balance test were reported in youth under 19 years of age (Behm et al., 2005). Thus, plyometric training activities are positively augmented with greater balance or postural control. For example, when 4 weeks of balance training was incorporated prior to 4 weeks of plyometric training the training outcomes were significantly better with youth than in the reverse order (Hammami et al., 2016b). Hence, the combination of inadequate strength and balance would inhibit positive sprint training adaptations associated with plyometric training with youth. In conflict with the training specificity principle, traditional RT may be more beneficial for promoting sprint adaptations in youth since it can build a foundation of strength upon which youth can take greater advantage of the SSC. Furthermore, the use of free weight or ground based strength/RT would be highly recommended for youth in order to emphasize initial balance adaptations (Behm et al., 2008, 2010a,b).

The only exception to the strength training advantage for sprint performance was with untrained participants with strength training providing moderate benefits (0.57) compared to large benefits (1.19) with plyometric training. However, upon closer inspection, there were only 3 measures each available for the untrained strength and plyometric training participants vs. 11 and 30 measures for the trained strength and plyometric trained participants, respectively. Hence, with such a sparsity of

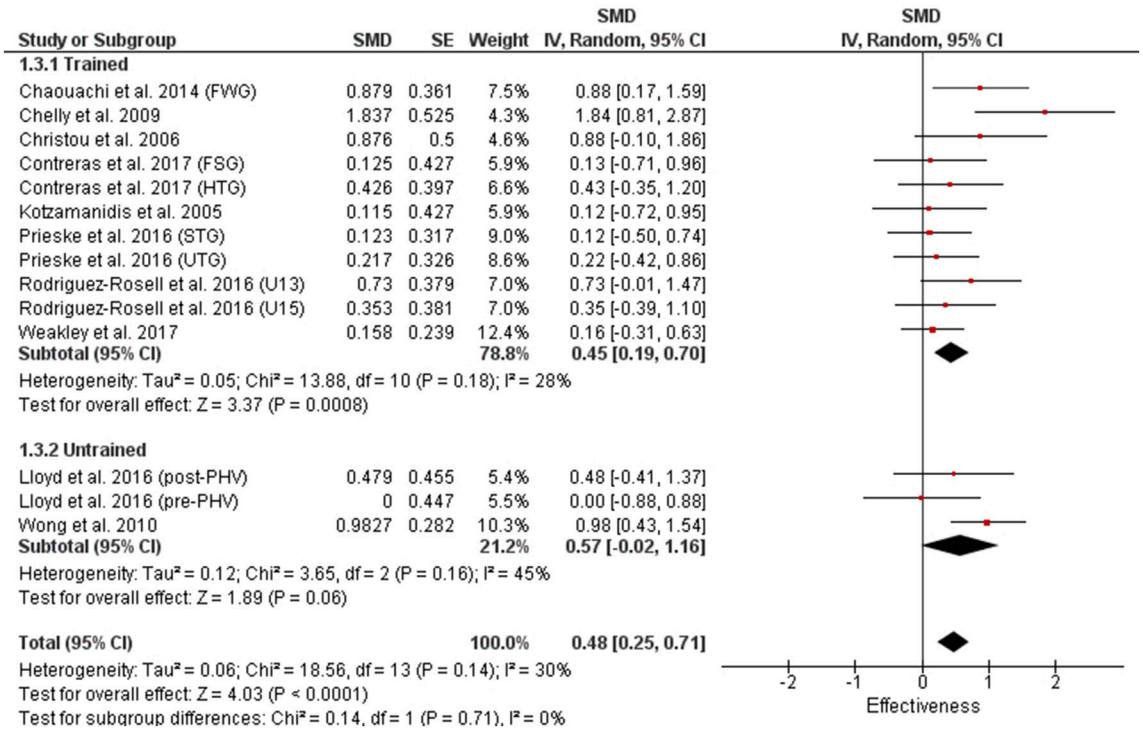


FIGURE 8 | Strength training effects on sprint measures for trained and untrained subjects. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

measures, one must be cautious about interpreting the robustness of this specific result for the untrained youth population.

There are a few youth training studies that combine plyometric and RT. As expected, the combination of plyometrics and RT provided significantly greater improvements in sprint speed and vertical jump height performance than untrained controls with 6 and 12 weeks of training, respectively (Wong et al., 2010; Hopper et al., 2017). Radnor et al. (2017) compared 6 weeks of plyometric, RT and combined training and found more positive responders for 30 m sprint speed with the combined pre-PHV group. In the post-PHV group, the combined training provided more positive responders with acceleration (10 m sprint) and squat jumps vs. the plyometric only and RT groups. Similarly, Kotzamanidis et al. (2005) reported that the combination of 13 weeks of RT and speed training provided greater training benefits for 30 m sprint, squat jump and CMJ than RT alone. The combination of plyometric and RT in these studies did not provide substantially greater training adaptations than the plyometric only training meta-analysis results expressed in this meta-analysis. While Wong et al. (2010) reported small to moderate magnitude improvements for vertical jump height, 10 and 30 m sprint performance, Kotzamanidis et al. (2005) reported 3–7% improvements in sprint and jump performances vs. 1–2% improvements for the RT only group. Thus, the combination of plyometric and strength training exercises did not seem provide additive benefits compared to either plyometric or RT alone.

Untrained youth in this meta-analysis produced greater training gains with jump and sprint measures (for both strength and power training) than trained youth. **Table 2** illustrates that not only were the numerical effect sizes greater but in each case the threshold for the magnitude descriptor was exceeded and moved into a higher category with the untrained (i.e., moderate vs. large, small vs. moderate, small vs. large). Since the untrained individuals are beginning a training program and are situated at a lower baseline of functional performance, the initial degree of improvement would be expected to be greater than with trained individuals whose physical capacities have already progressed beyond their initial baseline. Similarly, Behringer et al. (2011) reported a similar trend and offered there might a ceiling effect of functional adaptations in experienced subjects, whereas novices and non-athletes experience greater adaptations due to greater learning effects. The only exception to the untrained groups training accrual benefits was for the effect of strength training upon lower body strength measures, where both groups had large magnitude changes. The training adaptation emphasis may differ between these two groups with untrained youth optimizing motor control/learning and coordination, whereas trained youth may emphasize more the neural (recruitment, rate coding synchronization) and morphological adaptations. So, although the trained youth may be closer to their training potential ceiling, they may be able to tap into adaptations not yet fully available to the untrained.

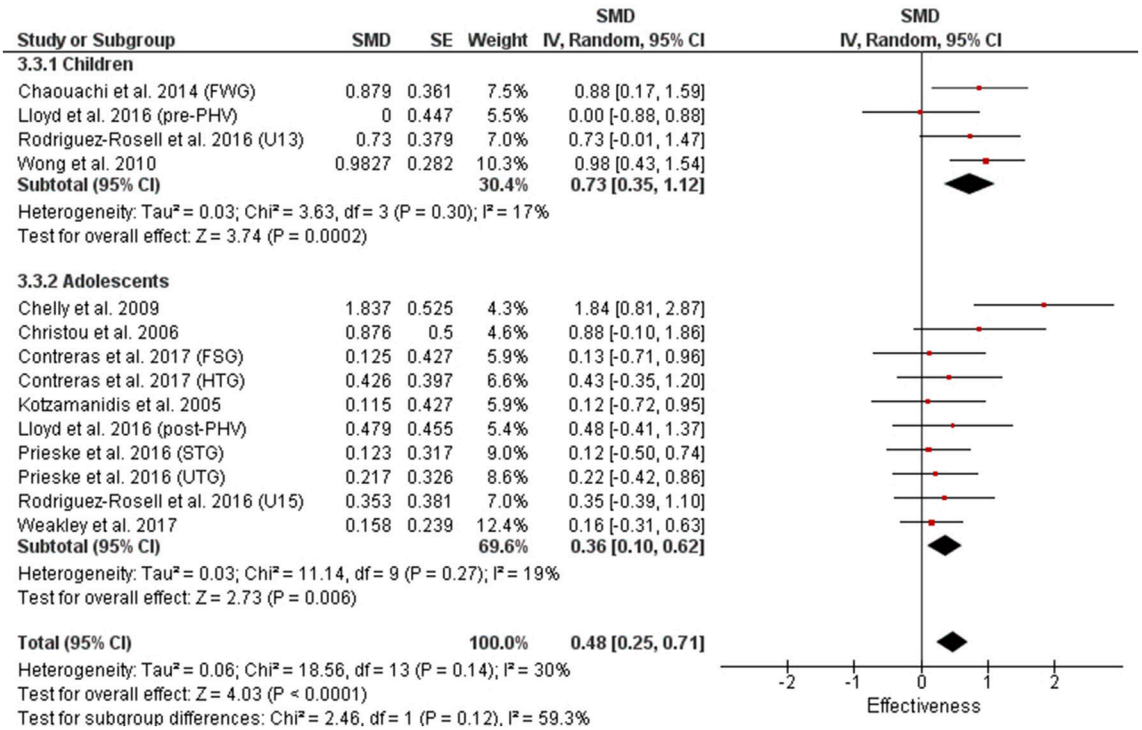


FIGURE 9 | Strength training effects on sprint performance for children and adolescents. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

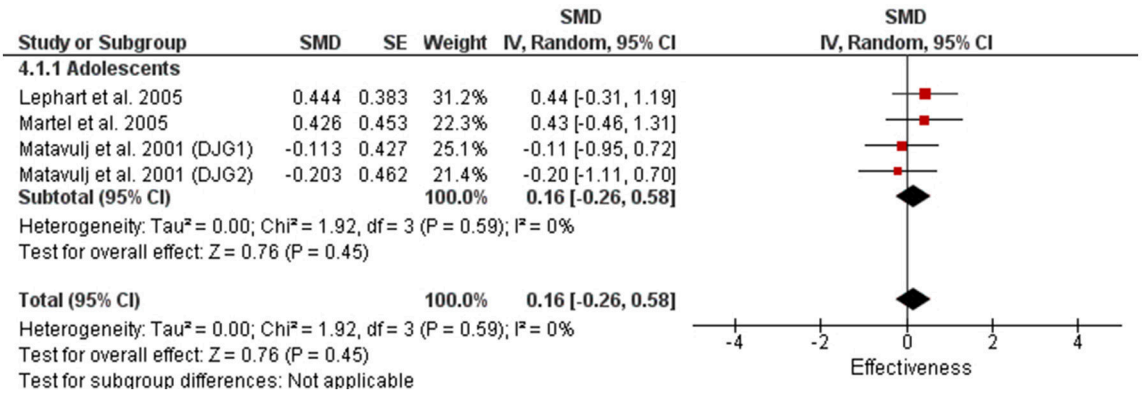


FIGURE 10 | Power training effects on lower body strength for adolescents only. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

A limitation of this meta-analysis is that the involved studies investigated relatively healthy and athletic populations. Future studies should also focus on populations with risk factors. Furthermore, appropriate age or maturation matched power and plyometric training intensities, volumes, durations, frequencies and other factors (e.g., What is the optimal platform height for drop jumps with different youth maturational levels? With the appropriate intensity established, what would be the appropriate volume of power training for each session or each week/cycle?) should be investigated to obtain the greatest benefits.

In conclusion, there was modest evidence for the effect of power training specificity upon power measures (small to moderate magnitudes of change). Plausibly due to the greater

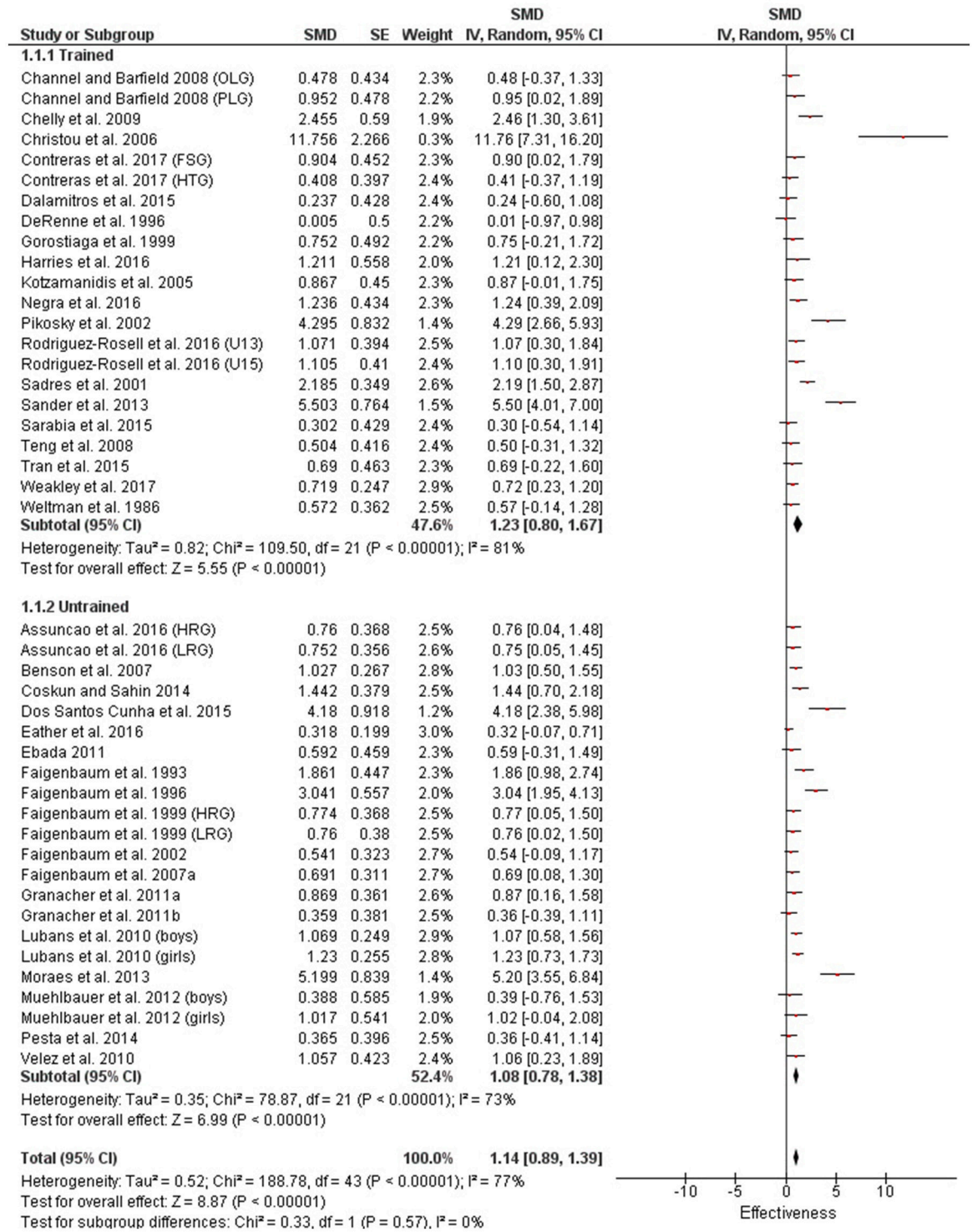


FIGURE 11 | Strength training effects on lower body strength for trained and untrained subjects. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

reaction forces with sprinting, there was no power training specific advantage with sprint results. On the contrary, strength training provided greater sprint training benefits likely due to the development of greater strength allowing the individuals to

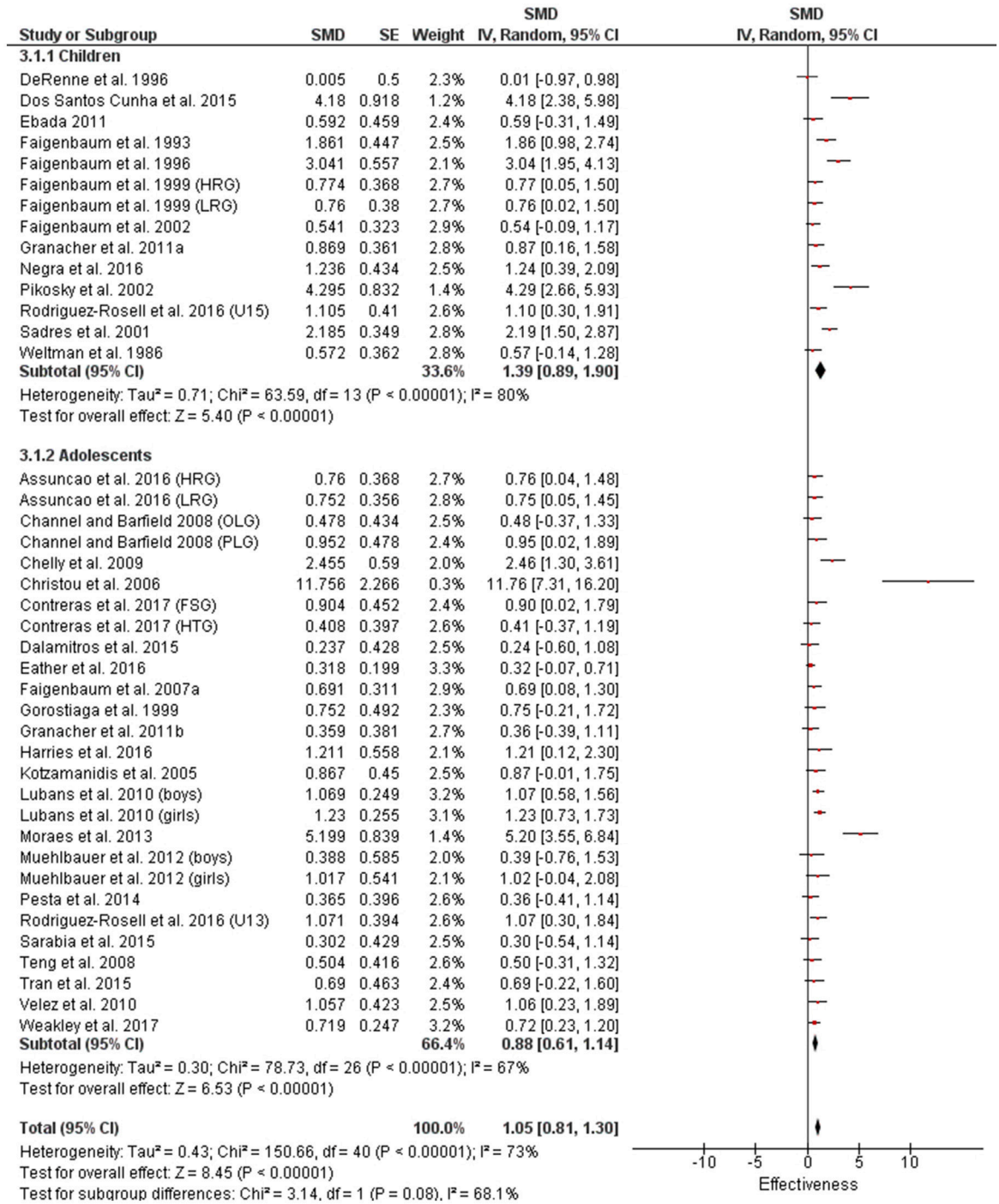


FIGURE 12 | Strength training effects on lower body strength for children and adolescents. Positive SMD values indicate performance changes from pre to post related to training effects, while negative SMDs are indicative of non-effective changes from pre to post. SMD, Standardized mean difference expresses the size of the intervention effect relative to the variability observed in that study. SE, Standard Error. Weight, proportional weight or contribution of each study to the overall analysis.

absorb and react to the ground reaction forces more efficiently to optimize the SSC mechanical and reflexive advantages. Strength training provided the greatest training specific results in youth with consistently large magnitude improvements in lower body strength across trained, vs. untrained, as well as with children vs. adolescents. In addition, untrained youth with their lower baseline of physical capacities (untapped training potentials), immature motor learning (Payne and Isaacs, 2005; Behm et al.,

2010b; Behringer et al., 2011; Hopper et al., 2017) and possibly due to their lack of experience tend to experience greater training benefits for power and sprint measures than trained youth. Based on these findings, resistance training for youth should initially emphasize strength training methods. Prior research has also demonstrated the importance of introducing balance training early in the training process (Behm et al., 2008; Hammami et al., 2016b). Plyometric training can also be included but this training should emphasize lower amplitude movements with low to moderate reaction forces (Behm et al., 2008). Proper form, balance and motor control should be first emphasized before presenting the individual with high reaction forces. As indicated in the Canadian Society for Exercise Physiology position stand (Behm et al., 2008), plyometric training and other forms of power training (e.g., Olympic weight lifting) are not intended to be stand-alone exercise programs, the best approach is to incorporate properly supervised and progressive power training into a well-rounded program that also includes other types of strength and conditioning.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Effects of Soccer Training on Anthropometry, Body Composition, and Physical Fitness during a Soccer Season in Female Elite Young Athletes: A Prospective Cohort Study

Melanie Lesinski[1], *Olaf Prieske*[1], *Norman Helm*[2] *and Urs Granacher*[1]*

[1] Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany, [2] Olympic Testing and Training Center Brandenburg, Potsdam, Germany

The objectives of this study were to (i) describe soccer training (e.g., volume, types), anthropometry, body composition, and physical fitness and (ii) compute associations between soccer training data and relative changes of anthropometry, body composition, and physical fitness during a soccer season in female elite young athletes. Seasonal training (i.e., day-to-day training volume/types) as well as variations in anthropometry (e.g., body height/mass), body composition (e.g., lean body/fat mass), and physical fitness (e.g., muscle strength/power, speed, balance) were collected from 17 female elite young soccer players (15.3 ± 0.5 years) over the training periods (i.e., preparation, competition, transition) of a soccer season that resulted in the German championship title in under-17 female soccer. Training volume/types, anthropometrics, body composition, and physical fitness significantly varied over a soccer season. During the two preparation periods, higher volumes in resistance and endurance training were performed ($2.00 \leq d \leq 18.15$; $p < 0.05$), while higher sprint and tactical training volumes were applied during the two competition periods ($2.22 \leq d \leq 11.18$; $p < 0.05$). Body height and lean body mass increased over the season ($2.50 \leq d \leq 3.39$; $p < 0.01$). In terms of physical fitness, significant performance improvements were found over the soccer season in measures of balance, endurance, and sport-specific performance ($2.52 \leq d \leq 3.95$; $p < 0.05$). In contrast, no statistically significant changes were observed for measures of muscle power/endurance, speed, and change-of-direction speed. Of note, variables of muscle strength (i.e., leg extensors) significantly decreased ($d = 2.39$; $p < 0.01$) over the entire season. Our period-specific sub-analyses revealed significant performance improvements during the first round of the season for measures of muscle power/endurance, and balance ($0.89 \leq d \leq 4.01$; $p < 0.05$). Moreover, change-of-direction speed significantly declined after the first round of the season, i.e., transition period ($d = 2.83$; $p < 0.01$). Additionally, significant medium-to-large associations were observed between training and anthropometrics/body composition/physical fitness ($-0.541 \leq r \leq 0.505$). Soccer training and/or growth/maturation contributed to significant variations in anthropometry, body composition, and physical fitness outcomes

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***Correspondence:**
Urs Granacher
urs.granacher@uni-potsdam.de

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throughout the different training periods over the course of a soccer season in female elite young soccer players. However, changes in components of fitness were inconsistent (e.g., power, speed, strength). Thus, training volume and/or types should be carefully considered in order to develop power-, speed- or strength-related fitness measures more efficiently throughout the soccer season.

Keywords: adolescent athletes, annual training, periodization, training load, strength training

INTRODUCTION

In terms of the estimated number of active players, soccer is the most popular sport in the world with more than 270 million participants (Turner and Stewart, 2014). With regards to performance determinants, soccer is an intermittent high-intensity ball game that involves linear sprints, rapid changes-of-directions, jumps and kicks (Bangsbo et al., 2006; Turner and Stewart, 2014). These sport-specific activities require the development of physical fitness during long-term athlete development for successful performance on an elite level (Lloyd and Oliver, 2012; Balyi et al., 2013). Lloyd and Oliver (2012) introduced a physical development model that provides a logical and evidence-based approach to the systematic development of physical fitness in young athletes. This model demonstrates that most, if not all, components of physical fitness are trainable throughout childhood and adolescence. Of note, resistance training is an important means for stimulating athletic development, tolerating the demands of long-term training and competition, and inducing long-term health promoting effects that are robust over time and track into adulthood (Granacher et al., 2016).

In (adolescent) soccer however, seasons are characterized by long competition and short preparation periods. Thus, the time to develop players' physical fitness, to support motor skill acquisition, and to enhance sport performance is limited. Previous studies with young and adult elite soccer players showed that during the season, players are often exposed to prolonged periods of physiological and psychological stress (Michailidis, 2014; Silva et al., 2014; Noon et al., 2015; Rago et al., 2016). For instance, Silva et al. (2014) examined the effects of training and competition during a soccer season in professional soccer players aged 26 years on biochemical stress markers (e.g., creatine kinase activity, myoglobin content) and found significant increases in the level of creatine kinase and myoglobin content during the competition period. Under such conditions, the maintenance or improvement of players' physical fitness depend on appropriate training stimuli that allow the body systems to recover from and adapt to multiple stressors. Thus, to regularly monitoring training data, anthropometry, body composition, and/or physical fitness throughout the season is key for the structured development of performance and the prevention of overuse injuries. In fact, these data are essential to help coaches evaluate their training on a daily basis by tailoring ongoing decision-making processes (Bourdon et al., 2017). In this regard, several studies examined the relationship between measures of training load, anthropomety, body composition, and/or physical fitness in elite adult soccer players over the course of a soccer season (Silva et al., 2011; Mara et al., 2015; Miloski et al., 2016; Jaspers et al., 2017). Findings from these studies indicate significant variations in body composition and physical fitness according to the demands of the respective training period. Further, significant associations were reported between individual match playing time and changes in physical fitness (Silva et al., 2011; Jaspers et al., 2017). Of note, soccer is a complex sport which demands high performance levels in various components of physical fitness (e.g., muscle power, speed, agility) to increase the likelihood for success in competition. For instance, outfield players (e.g., wing-back, central midfield, striker) require well-developed levels of aerobic capacity, speed, agility, maximal strength, and muscle power (Stølen et al., 2005; Bangsbo et al., 2006). Even though these studies provide important information for coaches and practitioners, elite young athletes are different compared to adult athletes and female athletes are different from male athletes in terms of their metabolic (i.e., lower anaerobic capacities) and neuromuscular performance (i.e., lower ability to fully activate muscles) as well as the risk of sustaining injuries (e.g., anterior cruciate ligament injury) (Zauner et al., 1989; Behm et al., 2008; Alentorn-Geli et al., 2009; Faigenbaum et al., 2009; Clemente and Nikolaidis, 2016). Thus, it is not possible to directly translate research findings from (male) elite adult soccer to (female) youth soccer.

To the best of our knowledge, there are only few studies available that examined the effects of a soccer season on anthropometrics, body composition, and physical fitness in elite young soccer players (Williams et al., 2011; Hammami et al., 2013; Di Giminiani and Visca, 2017). Moreover, there is currently no scientific data published on day-to-day training variations, anthropometrics, body composition, and physical fitness at distinct time points over the course of a soccer season in (female) elite young soccer. Thus, we designed a prospective cohort study (i) to describe and evaluate variations in training volume and types, anthropometrics, body composition, and physical fitness over the course of an entire soccer season (e.g., preparation, competition, and transition period) and (ii) to compute respective associations in female elite young soccer players. In accordance with the relevant literature (Silva et al., 2011; Mara et al., 2015; Miloski et al., 2016; Jaspers et al., 2017), we hypothesized that (i) soccer training (and/or growth/maturation) contribute to variations in body composition and physical fitness during the soccer season according to the demands of the respective training period and (ii) the volume of different training types/individual match playing time is significantly associated with relative changes in the respective components of body composition and physical fitness in female young soccer players.

MATERIALS AND METHODS

Participants

A team of 19 healthy female elite young soccer players aged 14–16 years at baseline (15.3 ± 0.5 years; Tanner stage 4: $n = 17$ post-pubertal; 2.7 ± 0.4 years post-peak height velocity [PHV]: $n = 17$ post-PHV) participated in this study. The monitored team competed in the first German under-17 soccer division (Junior Bundesliga). Two players who were injured and could therefore not participate in over 75% of training days were excluded from our analyses. Thus, 17 players were finally included in this study. Biological age (i.e., pre-PHV, PHV, post-PHV) was determined according to Mirwald et al. (2002) using time from PHV, based on the Tanner 5-point scale (Marshall and Tanner, 1969). Before entering the study, participants were familiarized with the experimental protocol and potential risks. This study was carried out in accordance with the recommendations of the International Committee of Medical Journal Editors. All subjects and their legal guardians gave written informed consent in accordance with the latest version of the declaration of Helsinki. The protocol was approved by the local ethical commission (University of Potsdam: submission No. 5/2014).

Experimental Procedure

A prospective longitudinal study design was applied to systematically monitor training and performance data, anthropometrics, and body composition of a female elite youth soccer team during the season 2015/2016. The team completed the season with the German under-17 championship title. All athletes were tested six times over the experimental period (T1-T6; **Figure 1**) using a large variety of anthropometric, body composition, and physical fitness tests. The fitness test battery included the assessment of muscle strength (i.e., 1-RM of the leg extensors), muscle power (i.e., squat jump [SJ], countermovement jump [CMJ], drop jump [DJ]), muscle endurance (i.e., ventral trunk Bourbon test), speed (i.e., 10-m linear sprint), change-of-direction speed (i.e., T-agility test), dynamic balance (i.e., Y-balance test), endurance (i.e., shuttle run test), and a sport-specific performance test (i.e., kicking velocity). Due to methodological reasons, the tests for muscle strength were conducted only twice over the experimental period (T1 and T6). Prior to physical fitness testing, a standardized warm-up protocol (i.e., 15 min of dynamic stretching, jumping, running and agility/change-of-direction drills) was performed.

Monitoring of Training Data

Team coaches tracked day-to-day training data (i.e., volume, types) for each player and each training session over the entire season using an online database (IED database, Institute of Applied Training Science, Leipzig, Germany). Training types were coded as resistance training, sprint training, coordination training, flexibility training, technical training, tactical training, endurance training, and matches (i.e., individual match playing time). Further, specific types in terms of resistance training methods (e.g., hypertrophy training, muscular endurance training) and types (e.g., machine based training, free weights training) were documented. The entire soccer season was divided into five periods: 1. preparation period (PP1; 4.5 weeks; mid-August [T1] until mid-September 2015 [T2]), 1. competition period (CP1; 12 weeks; mid-September [T2] until beginning of December 2015 [T3]), transition period (TP; 4 weeks; beginning of December 2015 [T3] until beginning of January 2016 [T4]), 2. preparation period (PP2; 8 weeks; beginning of January [T4] until end of February 2016 [T5]) and 2. competition period (CP2; 15 weeks; end of February [T5] until mid-June 2016 [T6]) (**Figure 1**). Before PP1, soccer players returned from a 30-day off-season period in which physical activity was not documented.

Assessment of Anthropometry, Body Composition, and Physical Fitness

Anthropometry and Body Composition

At the beginning of each test session (T1-T6), standardized testing protocols were applied for the assessment of standing/sitting body height and leg length (i.e., iliac height). In addition, body composition was analyzed using the InBody720 system (Biospace, Seoul, South Korea). Tests were always conducted at the same time of day.

Muscle Strength

Maximal leg extensor strength was assessed by means of a 1-RM leg press test on a Cybex Eagle Leg Press (Cybex International, Medway MA, USA). High test-retest reliability was reported previously with an intraclass correlation coefficient (ICC) of 0.997 (Seo et al., 2012). Participants were horizontally positioned on the sledge of the leg-press with hip and knee angles adjusted at 90°. Participants were allowed to stabilize their upper body by holding on to handles attached to the leg-press. Before testing, a warm-up was applied on the leg press using submaximal

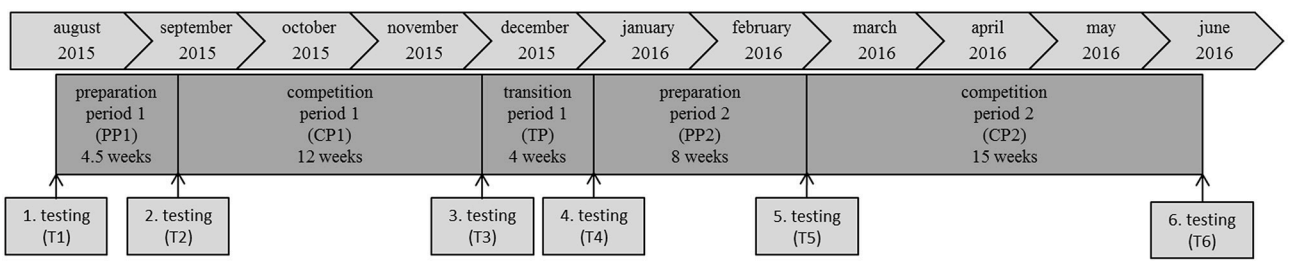


FIGURE 1 | Longitudinal study design. This figure illustrates test sessions over the course of a soccer season.

loads. Subsequently, the 1-RM was determined within five trials using the protocol according to the American College of Sports Medicine (Arena, 2014). Two to four minutes of passive rest were allowed after each trial. All testing procedures were supervised (instructor-to-participant ratio: 1:1). The maximal lifted load (kg) was used for further data analyses.

Muscle Power

Proxies of muscle power were assessed using SJs, CMJs, and DJs. Jump performance was measured by means of an optoelectric cell system (Optojump, Microgate, Bolzano, Italy). High test-retest reliability was previously reported for the SJ and the CMJ height with an ICC value of 0.97 and 0.98 (Markovic et al., 2004). For the SJ, participants stood quietly in a squatted position (i.e., knees bent 90°), feet shoulder-width apart, and hands akimbo. Jumps were initiated with a concentric upward movement. In terms of the CMJ, participants stood in an erect standing position, feet shoulder-width apart, and hands akimbo. Jumps were initiated with a countermovement which was immediately followed by a concentric upward movement. For the DJ, participants stood in an erect standing position on a 40 cm box, feet shoulder-width apart, and hands akimbo. Participants were asked to step off the box with their dominant leg, drop down to land evenly on both feet on the ground, keep ground contact time short, and jump-off the ground with a double-leg vertical jump at maximal effort. All participants were consistently instructed to jump as high as possible (SJ, CMJ, DJ) and to keep ground contact as short as possible (DJ). Following one test trial, three SJs, CMJs, and DJs were conducted with a rest period of 30 s between the single jump trials and a 1 min rest between the different vertical jump types. The best trial in terms of maximal jump height was taken for the SJ and the CMJ. For the DJ, the best trial in terms of the maximal DJ performance index (i.e., ratio of jump height by ground contact time) was taken for further data analyses.

Muscle Endurance

The ventral Bourban test was used to assess trunk muscle endurance. The test can be classified as reliable with a coefficient of variation of 14.1% (Tschopp et al., 2001). Participants were in prone bridge position on their elbows and toes. Legs were extended, elbows shoulder-width apart, and forearms rested flat on a fitness mat. While in the bridged position, the lower horizontal reference rod of the alignment device was attached to the participant' s lower back at the level of the iliac crests and was then fixed in this position. After visual inspection of the participant's starting position, athletes were asked to lift their feet alternately for 2–5 cm according to the beat of a metronome (i.e., 1 s per foot). During testing, participants were instructed to remain in contact with the horizontal reference rod for as long as possible. Warnings were given when participants lost touch to the horizontal rod or failed to lift their feet to the beat. The test was terminated when participants failed to remain in contact with the reference rod for the third time. One trial was performed. Test time until failure was manually measured by the tester using a hand-held stop watch and was taken for further analyses.

Speed

A 10-m linear sprint test was applied for the assessment of speed. Sprint time was measured using double-light electronic barriers (WITTY; Microgate Srl, Bolzano, Italy). High test-retest reliability was reported for the 10-m sprint test with an ICC of 0.93 (Moir et al., 2004). Participants started the test with one foot 15 cm before the starting line in an erect standing position and were instructed to accelerate as fast as possible. A starting signal was not provided in order to avoid the effect of reaction time. The rest period between the single sprint trials amounted to 3–5 min. The best out of two trials in terms of fastest sprint time was taken for further analyses.

Change-of-Direction Speed

Change-of-direction speed was assessed using the T-agility test (Young et al., 2015). Previously, this test showed high test-retest reliability with an ICC = 0.98 (Pauole et al., 2000). Sprint time was measured using double-light electronic barriers (WITTY; Microgate Srl, Bolzano, Italy). Participants were instructed to run and shuffle as fast as possible following a figure-T course that was set up using four cones. Thus, participants had to continuously change direction throughout the testing procedure. A starting signal was not provided. The rest period between trials was 5 min. Following one test trial, the best out of two trials in terms of fastest sprint time was taken for further data analyses.

Dynamic Balance

Dynamic balance was assessed using the lower quarter Y-balance test. High test-retest reliability was reported for the Y-balance test in all 3 movement directions with ICC values ranging between 0.89 and 0.93 (Plisky et al., 2006). Before the test started, participants' left and right leg length was assessed in supine lying position by measuring the distance from the anterior superior iliac spine to the most distal aspect of the medial malleolus. Further, participants practiced 3 trials per reach direction on each foot to get familiarized with the testing procedures. All trials were conducted barefooted. The Y-balance test was performed according to the protocol of Plisky et al. (2006). In brief, participants were positioned in single leg stance while reaching as far as possible with the contralateral leg in three different movement directions (i.e., anterior, posteromedial, posterolateral). Participants always started with the right foot placed at the center of the Y-balance test tool (Move2Perform, Evansville, IN, USA) and the left leg reaching three times in anterior direction as far as possible, lightly touching the farthest point possible on the line with the most distal part of the reach foot. Afterwards, the left foot was placed at the center of the grid and the right leg maximally reached in anterior direction. Thereafter, the same test procedure was conducted for the posteromedial and the posterolateral reach direction (positioned 135° from the anterior scale). The examiner manually measured the distance from the scale of the tool. According to Filipa et al. (2010), a composite score was calculated and taken as dependent variable for further data analyses using the following formula: composite score = [(maximum anterior reach distance + maximum posteromedial reach distance + maximum posterolateral reach distance)/(leg length × 3)] × 100.

Endurance

Endurance was assessed by means of the 20-m shuttle run test. Test-retest reliability was high with ICCs ranging from 0.91 to 0.94 (Lemmink et al., 2004). The 20-m shuttle run test involves continuous running between two lines which are located 20-m apart according to the timed beep that is delivered by a computer program. Participants stood before starting line and accelerated to the second line on the start signal. Speed at the start was set at 8 km/h. Running speed was controlled through acoustic signals that were delivered by the computer program. Participants continued running between the two lines. When reaching one line, they turned around and ran back to the other line. After about 1 min, an acoustic signal indicated an increase in speed of about 0.5 km/h. This continued each minute (level). If the line was reached before the signal, participants had to wait before running toward the other line. If the line was not reached before the signal, participants received a warning and they had to continue to complete the run toward the line. They then turned around, tried to catch up with the pace within the two subsequent "beeps." The test was terminated if participants failed to reach the line (within 3 m) for two consecutive acoustic signals. The total distance (m) covered was used for further data analyses.

Sport-Specific Performance

Sport-specific performance was assessed by analyzing kicking velocity during a penalty kick (i.e., ball-goal distance: 11 m) using a standard soccer ball (i.e., FIFA standard size 5) and a Doppler radar gun (Stalker Sport 2, Applied Concepts, Inc./Stalker Radar, Plano, TX, USA). In terms of maximal ball velocity, high test-retest reliability was previously reported (i.e., $0.87 \leq \text{ICC} \leq 0.93$) (Berjan Bacvarevic et al., 2012). Participants were asked to perform three penalty kicks with their dominant and non-dominant leg. Leg dominance was determined according to the lateral preference inventory (Coren, 1993). Athletes were instructed to target the middle of the goal and to act "as forcefully as possible." Rest between trials was set at 5 min. The best out of three trials for each leg was used for further analyses (i.e., fastest kicking velocity).

Statistics

Data are reported as means and standard deviations (SD) after normal distribution was confirmed by the Shapiro-Wilk test. Separate analyses of variance (ANOVA) with repeated measures on time (i.e., five levels for the training periods [PP1, CP1, TP, PP2, CP2]; six levels for anthropometry, body composition, and physical fitness test dates [T1-6]) were applied to analyze differences in training data, anthropometry, body composition, and physical fitness. If significant main effects of time were found, a Bonferroni *post-hoc* analysis was conducted. In addition, effect sizes were calculated by converting partial eta-squared to Cohen's d. According to Cohen (1988), effect sizes can be classified as small ($0 \leq d < 0.50$), medium ($0.50 \leq d < 0.80$), and large ($d \geq 0.80$). Finally, associations between training data/individual match playing time and relative changes in anthropometry/body composition/physical fitness (i.e., deltas relative to the duration of the respective training period) were assessed using Pearson's product-moment correlation coefficient. Associations are reported by the correlation coefficient r and level of significance (i.e., in case of multiple correlations we used the Bonferroni correction). Based on the recommendations of Hopkins et al. (2009), values of $0.10 \leq r < 0.30$ indicate small, $0.30 \leq r < 0.50$ medium, $0.50 \leq r < 0.70$ large, $0.70 \leq r < 0.90$ very large, $0.90 \leq r < 1.00$ nearly perfect, and $r = 1.00$ perfect correlation. The significance level was set at α level < 0.05. All analyses were performed using Statistical Package for Social Sciences (SPSS) version 24.0 (SPSS Inc., Chicago, Illinois, USA).

RESULTS

Training Volume and Types

Total training volume was 431 ± 21 h (range: 368–458 h) distributed across 339 ± 19 training sessions (range: 284–361 h), and 207 ± 10 (range: 178–220) training days across the soccer season. Training volume for each training period (total and hours per week) is presented in **Table 1**. Our statistical analyses indicated period-specific training volumes. Due to reduced training sessions per week (i.e., PP1 to CP1: 20% [i.e., 2 sessions/week]; PP2 to CP2: 13% [i.e., 1 session/week]) higher training volumes were found during the preparation periods compared to the respective competition periods (i.e., PP1 to CP1: 15% [i.e., 2 h/week]; PP2 to CP2: 10% [i.e., 1 h/week]). The lowest training volume was found during the transition period. In terms of training types, **Figure 2** illustrates the volume of the different training types for each training period. In general, our analyses showed that sport-specific training volume (i.e., technical/tactical training, matches) was significantly larger compared to non-specific training across almost all training periods (52–68% vs. 32–48%), except PP1. Additionally, endurance and resistance training volumes were particularly high during the preparation periods (i.e., PP1, PP2) compared to the competition and transition periods (i.e., CP1, CP2, TP). However, sprint and tactical training volume were particularly high during the competition periods (i.e., CP1, CP2) compared to the preparation and transition periods (i.e., PP1, PP2, TP). The statistical analyses indicated significantly lower training volumes during PP2 compared to PP1 in technique, endurance, flexibility as well as sprint training (Δ30–82%; $2.64 \leq d \leq 18.96$; $p < 0.01$). Further, in CP2 training volume in technique, sprint, and resistance training was significantly lower compared to CP1 (Δ17–35%; $2.18 \leq d \leq 3.30$; $p < 0.05$). In contrast, training volume in flexibility and coordination was significantly higher (Δ22–37%; $2.36 \leq d \leq 4.69$; $p < 0.001$) in CP2 compared to CP1.

More detailed analyses of the different training types according to the applied training methods and types indicated that resistance training comprised muscular endurance training mostly through the application of free weight and stabilization training.

Anthropometry and Body Composition

The seasonal variations in anthropometry and body composition are presented in **Table 2**. Our statistical analyses revealed a significant main effect of time for almost all anthropometric and

TABLE 1 | Seasonal changes in training volume in female elite young soccer players.

	Preparation period I		Competition period I		Transition period		Preparation period II		Competition period II	
	Total (4.5 weeks)	Per week	Total (12 weeks)	Per week	Total (4 weeks)	Per week	Total (8 weeks)	Per week	Total (15 weeks)	Per week
Training volume (h)	61 ± 3	13 ± 1	130 ± 9	11 ± 1	22 ± 2	5 ± 0	79 ± 16	10 ± 2	140 ± 10	9 ± 1
Training sessions (n)	51 ± 3	10 ± 1	99 ± 7	8 ± 1	18 ± 1	4 ± 0	64 ± 14	8 ± 2	106 ± 6	7 ± 0
Training days (n)	27 ± 1	5 ± 0	62 ± 4	5 ± 0	12 ± 1	3 ± 0	34 ± 7	4 ± 1	72 ± 4	5 ± 0

Training sessions = number of sessions (in total and per week) in the respective training period, training days = number of days (in total and per week) in the respective training period.

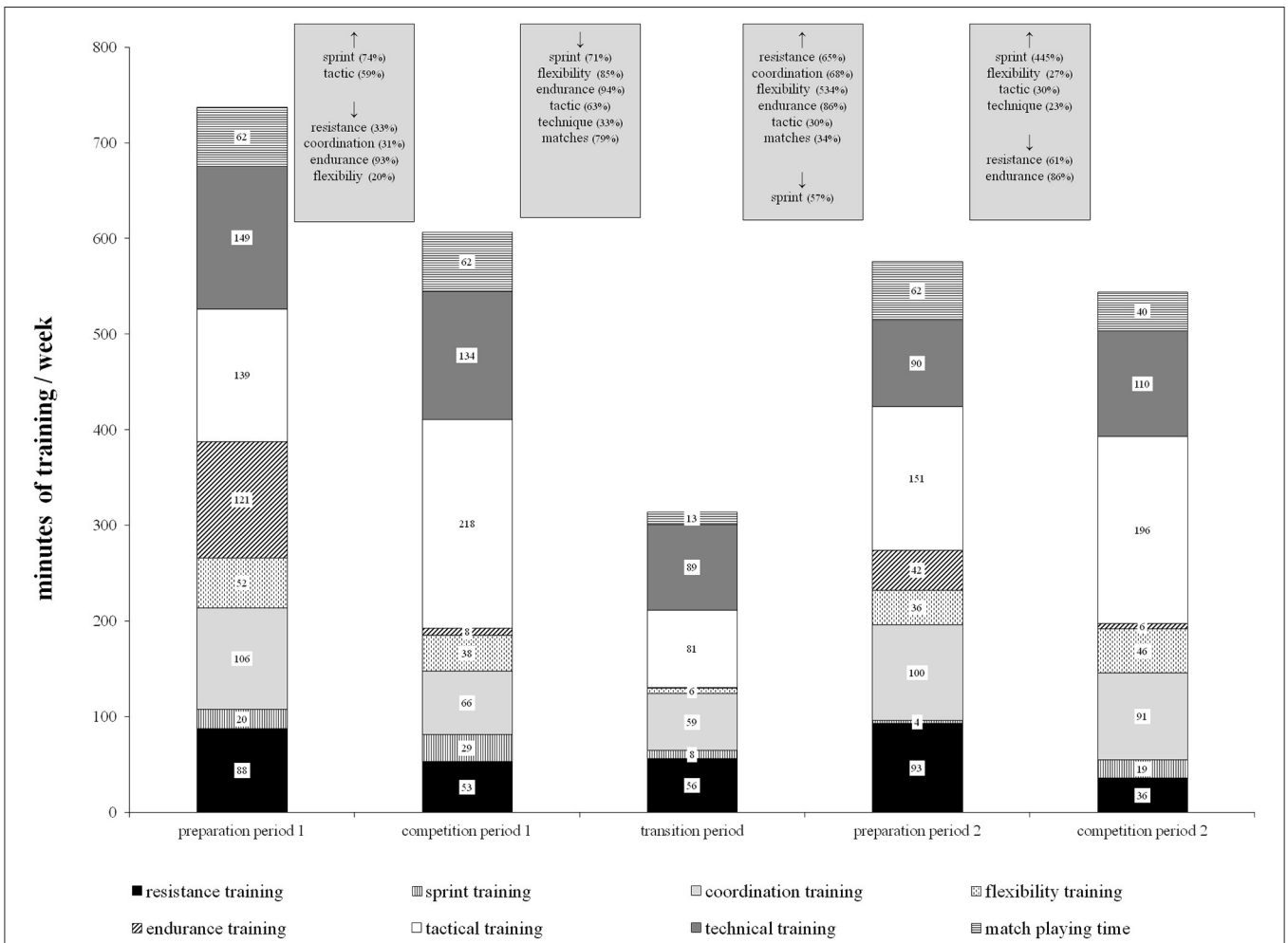


FIGURE 2 | Training volumes classified by training types for each training period in female elite young soccer players. Note that gray boxes denote significant changes. Data are reported as means for the female young soccer team.

body composition measures, except for the body mass index. Body height (Δ1%; $d = 3.39$; $p < 0.001$) and total absolute lean body mass (Δ4%; $d = 2.50$; $p < 0.01$) significantly increased over the course of the season (i.e., T1-T6). *Post-hoc* analyses indicated that relative fat mass significantly decreased (Δ8%; $d = 1.96$; $p < 0.05$), while body height, body mass as well as absolute lean leg and lean trunk mass significantly increased (Δ0.3–4%; $1.80 \leq d \leq 3.36$; $p < 0.05$) during CP1. During TP, absolute lean leg mass significantly decreased (Δ3%; $2.80 \leq d \leq 3.07$; $p < 0.01$). During PP2, absolute lean leg mass significantly increased (Δ3%; $3.02 \leq d \leq 3.03$; $p < 0.01$) and relative fat mass significantly decreased (Δ8%; $d = 1.99$; $p < 0.05$). Finally, body height and absolute lean leg mass (right leg) significantly increased (Δ0.3–2%; $2.22 \leq d \leq 2.25$; $p < 0.01$) during CP2.

Physical Fitness

The seasonal variations in physical fitness are presented in **Figure 3**. The statistical analyses indicated a significant main

TABLE 2 | Seasonal changes in anthropometry and body composition in female elite young soccer athletes.

	N	Main effect (ES_d)	Start of PP1 (T1)		PP1	End of PP1 /start of CP1 (T2)		CP1	End of CP1/start of TP (T3)		TP	End of TP/start of PP2 (T4)		PP2	End of PP2/start of CP2 (T5)		CP2	End of CP2 (T6)		Season 2015/2016 (T1 vs. T6)
			Mean	*SD*	%	Mean	*SD*	%	Mean	*SD*	%	Mean	*SD*	%	Mean	*SD*	%	Mean	*SD*	%
Body height (cm)	14	2.73***	165.2	5.7	0.3	165.7	5.7	0.3*	166.2	5.6	0.0	166.3	5.6	0.1	166.4	5.6	0.3**	166.8	5.8	1.0***
Body mass (kg)	15	1.40***	56.2	6.7	0.6	56.6	6.0	2.1*	57.7	6.2	−0.4	57.5	6.1	0.0	57.5	6.0	1.2	58.2	6.3	3.6
BMI (kg/m^2)	14	0.67	20.4	1.9	0.0	20.4	1.6	1.3	20.7	1.8	−0.4	20.6	1.8	−0.2	20.6	1.6	0.8	20.7	1.6	1.5
Fat mass (%)	15	1.06**	16.4	5.1	2.4	18.5	3.8	−1.4*	17.1	3.9	1.1	18.2	3.2	−1.5*	16.7	3.0	−0.1	16.6	3.0	1.2
Total lean mass (kg)	15	2.04***	26.0	2.8	−1.6	25.5	2.6	4.1	26.6	2.8	−1.8	26.1	2.6	2.2	26.7	2.6	1.5	27.1	2.9	4.4**
Right leg lean mass (kg)	15	1.53***	7.2	0.9	−0.5	7.1	0.9	2.2*	7.3	0.9	−2.5**	7.1	0.8	2.9**	7.3	0.8	2.1**	7.5	0.9	4.0
Left leg lean mass (kg)	15	1.44***	7.1	0.8	−0.4	7.1	0.9	2.3*	7.3	0.9	−2.7**	7.1	0.8	3.0**	7.3	0.8	1.5	7.4	0.9	3.7
Trunk lean mass (kg)	15	1.85***	19.9	1.9	−2.4	19.4	1.8	4.4***	20.2	1.9	−0.5	20.1	1.9	0.1	20.1	1.8	1.3	20.4	2.0	2.8

*$p < 0.05$; **$p < 0.01$; ***$p < 00.1$; *CP1, 1. competition period; CP2, 2. competiton period; PP1, 1. preparation period; PP2, 2. preparation period; SD, standard deviation; TP, transition period.*

effect of time for almost all physical fitness tests, except for the 10 m-sprint. Performances in the y-balance test (Δ5–6%; $2.57 \leq d \leq 3.95$; $p < 0.05$), the DJ performance index (Δ28%; $d = 3.09$; $p < 0.05$), the shuttle run test (Δ16%; $d = 3.11$; $p < 0.01$), as well as kicking velocity of the dominant leg (Δ6%; $d = 2.52$; $p < 0.01$) significantly increased, while maximal leg extensor strength significantly decreased (i.e., 1 RM leg press Δ13%; $d = 2.39$; $p < 0.01$) over the course of the soccer season (i.e., T1 vs. T6). *Post-hoc* tests revealed significant improvements in the ventral Bourban test (Δ27%; $d = 0.89$; $p < 0.05$), the shuttle run test (Δ12%; $d = 3.28$; $p < 0.01$), and the y-balance test of the dominant leg (Δ4%; $d = 3.18$; $p < 0.01$) during PP1 as well as in CMJ height, DJ height, and DJ performance index (Δ19–38%; $2.66 \leq d \leq 4.01$; $p < 0.01$) during CP1. Of note, TP led to significant performance declines in change-of-direction speed (Δ3%; $d = 2.83$; $p < 0.05$). During the second round of the season (i.e., PP2 and CP2), no significant changes in physical fitness were observed.

Associations between Training, Match Playing Time, and Changes in Anthropometry, Body Composition, and Physical Fitness

Significant medium-to-large associations were found between training volumes of different training types/match playing time and the relative changes in anthropometry/body composition ($-0.422 \leq r \leq 0.371$) and physical fitness ($-0.541 \leq r \leq 0.505$) (**Table 3**). During CP1 and 2, no significant associations were found between individual match playing time and the relative changes in anthropometry, body composition, and physical fitness ($p > 0.05$).

DISCUSSION

To the authors' knowledge, this is the first study that examined seasonal variations in training data, anthropometry, body composition, and physical fitness in female elite young soccer players. In addition, we computed associations between training/individual match playing time and relative changes in anthropometry, body composition, and physical fitness. The main findings of this study revealed that (i) training volume was significantly higher during PP1/2 compared to TP and CP1/2, (ii) irrespective of the training period, volume of sport-specific training was significantly higher compared to non-specific training, (iii) volume of endurance and resistance training were significantly higher during the preparation periods, while sprint and tactical training volumes were significantly higher during the competition periods, (iv) body height and lean body mass as well as DJ performance index, Y-balance, shuttle run, and kicking performance significantly increased over the course of the soccer season, particularly due to changes in the first round of the season, while maximal leg extensor strength significantly decreased, (v) associations between the volume of different training types/match playing time and relative changes in anthropometry, body composition and physical fitness were unsystematic and reached medium-to-large magnitudes.

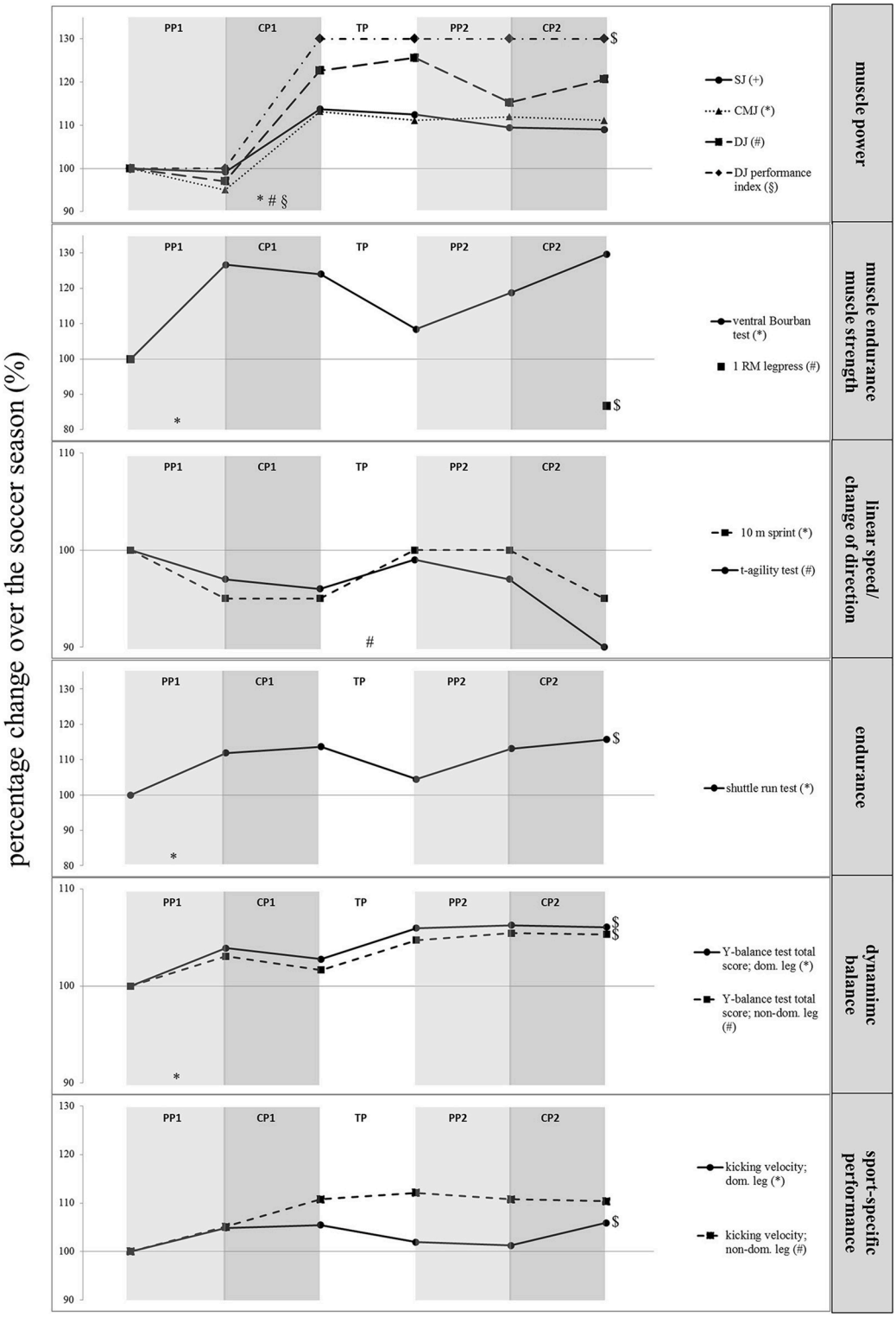


FIGURE 3 | Seasonal changes in physical fitness in female elite young soccer players. For better visual inspection, the vertical axis was not scaled similarly in all charts. Note that improvements in linear sprint and T-agility performances (time) correspond to decreases in percentage changes. CP1, competition period 1 (12 weeks); CP2, competition period 2 (15 weeks); PP1, preparation period 1 (4.5 weeks); PP2, preparation period 2 (8 weeks); TP, transition period (4 weeks); $^{*,+,\#,\S}$Significant differences; $^{\$}$significant differences between pre (T1) and post-season (T6).

TABLE 3 | Associations between changes in anthropometry, body composition, and physical fitness and the relative volume (in %) of the different training types of the respective training periods in female elite young soccer players.

Relative changes	Resistance training	Sprint training	Coordination training	Flexibility training	Endurance training	Tactical training	Technical training	Individual match playing time
ANTHROPOMETRY AND BODY COMPOSITION								
Body mass	−0.143	0.157	−0.197	0.226*	0.209	−0.032	−0.197	0.124
Relative fat mass	0.118	−0.010	0.085	−0.073	0.307**	−0.356**	0.120	−0.163
Absolute lean body mass total	−0.228*	0.095	−0.210	0.195	−0.133	0.300**	−0.239*	0.278*
Absolute lean body mass; right leg	−0.201	−0.036	−0.156	0.361**	0.078	0.141	−0.380***	0.271*
Absolute lean body mass; left leg	−0.212	−0.011	−0.225*	0.371**	0.106	0.158	−0.422***	0.304**
Absolute lean body mass; trunk	−0.166	0.229*	−0.116	−0.002	−0.336**	0.354**	0.017	0.095
PHYSICAL FITNESS								
Countermovement jump height	−0.308**	0.293*	−0.408***	0.054	−0.238*	0.401**	−0.005	0.226
Squat jump height	−0.341**	0.315**	−0.408***	0.032	−0.079	0.208	0.149	0.148
Drop jump height	−0.070	0.331**	−0.272*	−0.152	−0.393**	0.335**	0.230	0.005
Drop jump performance index	−0.028	0.307*	−0.246*	−0.185	−0.362**	0.277*	0.262*	−0.027
Ventral Bourban test	−0.251*	−0.127	−0.311**	0.351**	0.505***	−0.229*	−0.310**	0.400***
1 RM legpress	−0.219	0.239	0.286	−0.264	0.226	−0.333	0.571	0.032
10 m sprint	−0.126	0.075	−0.221	0.056	0.129	−0.096	0.122	0.090
T-agility-test	0.388**	0.058	0.267*	−0.541***	−0.309**	−0.059	0.395***	−0.296**
Shuttle run test	0.122	−0.058	0.089	−0.208	−0.220	0.056	0.276*	−0.182
Y-balance test total score, dom, leg	0.279*	−0.117	0.158	−0.296**	0.256*	−0.454***	0.292**	−0.198
Y-balance test total score, non-dom, leg	0.220	−0.110	0.159	−0.278*	0.293**	−0.451***	0.306**	−0.226*
Kicking velocitiy, dom, leg	−0.271*	0.039	−0.282*	0.310**	0.325**	−0.096	−0.181	0.241*
Kicking velocity, non-dom, leg	−0.117	−0.055	−0.130	0.187	0.299**	−0.146	−0.120	0.105

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Monitoring Training, Anthropometry, Body Composition, and Physical Fitness

Training Volume and Types

The present study indicates that the annual training cycle of female elite young soccer players significantly varied in terms of volume and type according to the respective training period. This is in accordance with Gamble (2006) who highlighted the training principle of periodization for physical preparation during the season. For instance, we found that weekly training volume decreased from the preparation to the subsequent competition periods. This is in accordance with a previous study from Moreira et al. (2015) who examined pre- and in-season training volumes and intensities in 44 professional Australian football players aged 23 ± 3 years. The authors reported that absolute training volume was significantly higher during the pre-season compared to in-season. Further, training volume relative to period duration significantly decreased from 11 to 13 h/week to 9–10 h/week from the first to the second round of the season. In this regard, Jayanthi et al. (2015) observed that young athletes who participate in more hours of sports per week than number of age in years show an increased risk of sustaining overuse injuries compared to athletes with lower training volumes (odds ratio: 2.07). Thus, the reduction in training volume may decrease the risk of injuries during the competition periods.

Further, our statistical analyses indicated that the training types were specific for the different training periods. More specifically, endurance and resistance training volumes were particularly high during the preparation periods (i.e., PP1, PP2) while sprint and tactical training volumes were particularly high during the competition periods (i.e., CP1, CP2). Moreover, sport-specific training volumes (i.e., technical training, tactical training, matches) were significantly higher compared to non-specific training volumes, but particularly during the competition period (64–68% vs. 32–36%). This is in accordance with the literature (Haff and Haff, 2009; Tønnessen et al., 2014) and indicates higher sport-specific training volumes during the competition periods to better prepare for the upcoming demands of the competition period.

Anthropometry and Body Composition

It has previously been demonstrated that anthropometry and body composition change throughout the course of a soccer season (Mukherjee and Chia, 2010; Hammami et al., 2013; Oyón et al., 2016). For instance, Hammami et al. (2013) and Oyón et al. (2016) evaluated the effects of soccer-training on anthropometric and body composition characteristics (i.e., body height, body mass, relative body fat) in young soccer players. Over the season, Hammami et al. (2013) found significant increases in body height (2%) in elite male young soccer players (15 ± 0.5 years). For female young soccer players (12–15 years), Oyón et al. (2016) reported significant increases in body height (1%), body mass (8%), and relative body fat (2%) over the season. In accordance with the findings of Hammami et al. (2013), we observed significant seasonal increases in body height (1%) only.

In contrast to the findings of Oyón et al. (2016), we found no negative changes in body composition (i.e., increase in relative body fat/mass) over the season in the examined sample of female young soccer players. This might be due to differences in training volume in the participants of our study (5–13 h/week) and the study of Oyón et al. (2016) (3 h/week).

Our period-specific analyses indicated no significant changes during PP1 (i.e., T1-T2; 4.5 weeks) in any of the tested anthropometric and body composition data. However, an increase in lean body mass and a decrease in percentage of body fat during CP1 (i.e., T2-T3; 12 weeks) was observed. During TP (i.e., T3-T4; 4 weeks) and at the turn of the year, athletes were granted an active rest in which they conducted non-specific physical activities of their own choice. During this period, training volumes significantly decreased (64–84%) which may have resulted in the observed negative adaptations in body composition that were again compensated during the second round of the season (i.e., PP2, CP2). To the authors' knowledge, there is only one study available (Mukherjee and Chia, 2010) that observed anthropometric and body composition data during the pre-season, the early in-season (i.e., 12 weeks later), and the end mid-season (i.e., again 13 weeks later) in young soccer players. These authors found a significant decrease in relative body fat and a significant increase in lean body mass during the pre-season period in male elite young soccer players aged 18 ± 0.3 years. In contrast, during the competition period Mukherjee and Chia (2010) observed bionegative adaptations (i.e., increase in relative body fat and decrease in lean body mass) in their tested sample. Thus, anthropometry and body composition significantly changed during specific training periods in young soccer players. Additionally, in the present study, small- to-medium sized associations were found between training types and changes in anthropometry/body composition ($r = -0.422$–0.371). Interestingly and in accordance with McManus and Armstrong (2011), female adolescent growth covers a period of 4–4.5 years around PHV until estrogen levels rise and epiphyseal fusion begins which ultimately terminates growth of stature. Even though most of the included female young soccer players were classified as post-PHV, growth can still occur until the age of 17 years (Balyi et al., 2013). All of our study participants were post-PHV with a mean age of 15.3 years. Thus, it is hypothesized that growth and maturation partly contributed to the observed changes in anthropometry and/or body composition. In this regard, Kromeyer-Hauschild et al. (2001) reported similar body height increases (∼1%) for German adolescent females aged 15.5 over a one-year period. These changes were similar in magnitude as the ones that were found in this study over the entire soccer season (see **Figure S1**). Consequently, the reported changes in anthropometry/body composition are multifactorial and can most likely be attributed to training, competition, habitual activity, diet, growth, and/or maturation.

Physical Fitness

Several health- and skill-related components of physical fitness are essential prerequisites for successful performance in (youth) soccer. In fact, earlier studies identified that higher levels of aerobic endurance (Hoff, 2005; McMillan et al., 2005; Castagna et al., 2006), speed (Murphy et al., 2003; Little and Williams, 2005), agility/change-of-direction speed (Gambetta, 1990; Little and Williams, 2005), strength and power (Wisløff et al., 1998) are important determinants of superior soccer performance (Turner and Stewart, 2014). Several authors observed changes in these physical fitness components over a soccer season (Hammami et al., 2013; Sæther and Aspvik, 2014; Silva et al., 2014; Miloski et al., 2016). Similarly, in the present study we were able to show significant improvements over the season in terms of performances in the Y-balance test, the shuttle run test, the DJ performance index and in kicking velocity (6–28%). However, our findings also indicated that several performance measures maintained (i.e., SJ height, CMJ height, DJ height, 10 m-sprint, change-of-direction speed, ventral Bourban test) or even declined (i.e., maximal leg extensor strength) over the season (T1 vs. T6). This somewhat unexpected finding could partly be explained by the specificity of the training types. Of note, the greatest performance changes occur if training follows the principle of training specificity (Behm and Sale, 1993). In the present study, the training documentation revealed that for instance resistance training predominantly focused on muscular endurance. Plyometric and sprint training constituted only a small part of the overall training volume. Thus, it can be speculated that the volume of specific training stimuli to improve jump, speed, change-of-direction speed and/or leg muscle strength was too low to induce sufficient adaptive processes. From a practical point of view, it appears beneficial to include specific means (e.g., resistance training) in the future that focus on the development of leg muscle strength/power, sprint and change-of-direction performances. For instance, a number of studies (Wong et al., 2010; Rubley et al., 2011; Sander et al., 2013; Ozbar et al., 2014; Granacher et al., 2015; Prieske et al., 2016) already examined the effects of different resistance training programs (e.g., plyometric training) in young soccer athletes and found significant improvements in strength, power, linear and/or change-of-direction speed following training. Another possible explanation for the observed inconsistent performance gains over the season could be that body mass status (i.e., body mass index) was inappropriate. In fact, Nikolaidis (2014) argued that physical fitness is related to the body mass index of female soccer players. More precisely, this author reported larger performance output (e.g., leg muscle power) in athletes with a body mass index of ∼22 kg/m^2 compared to those athletes with lower and higher values. In the present study, our athletes' body mass index did not significantly change over the course of the season and it ranged from 20.4 to 20.7 kg/m^2. Thus, it is postulated that the observed inconsistent performance gains in muscle power could be due to their low body mass index.

It appears that during the preparation periods, a particular focus should be laid on the promotion of physical fitness to prepare the athletes for the competition period. In accordance with this approach, our training data indicated a great percentage of sport-specific training especially during the competition periods (64–68%) and less sport-specific training during the preparation periods (48–52%). However, our detailed analyses of the single training periods showed significant

improvements, both during the preparation (e.g., muscle endurance, endurance, and balance performance during PP1 [4–27%]) and the competition periods (e.g., jump performance during CP1 [19–38%]). Thus, it appears that the training stimuli during the competition periods provided sufficient overload for performance enhancements. Further, more in-depths analyses of our data revealed that physical fitness changes occurred during the first round of the season only. This might indicate either less effective training stimuli or less optimal physical and/or psychological conditioning (e.g., imbalance between stress and recovery) during the second round of season. For instance, Noon et al. (2015) found moderate-to-large decrements in perceptions of well-being (e.g., motivation, sleep quality, appetite, fatigue) and several physical fitness tests (e.g., 30 m sprint) in English elite young soccer players aged 17 ± 1 years as the soccer season progressed. They concluded that their findings are indicative of an imbalance between stress and recovery during the season; even if players participate less in training sessions. In terms of the transition period, the present findings indicate a significant performance decline in addition to the impaired anthropometric and body composition characteristics. Hence, our data indicate that a well-designed transition period (e.g., structured home training plan) is very important to prevent anthropometric, body composition as well as physical fitness deteriorations in the middle of the season and create optimal conditions for the onset of the second half of the season.

In this study, correlation coefficients between training types/match playing time and changes in physical fitness ranged between −0.541 and 0.505. Only a few studies examined associations between variations in seasonal training data, match playing time, and changes in anthropometry, body composition, and/ or physical fitness (Castagna et al., 2013; Silva et al., 2014; Los Arcos et al., 2015; Jaspers et al., 2017). For instance, Jaspers et al. (2017) conducted a systematic review and examined the relationship between training load indicators and physical fitness outcomes, injury and illness in adult elite soccer players. Our findings are in accordance with those from Jaspers et al. (2017) in as much as both studies observed positive to negative correlations between training volume and/or match playing time and long-term changes in physical fitness. As one possible explanation, Jaspers et al. (2017) suggested that a non-linear relationship (e.g., U-shaped curve) between the dose of (i.e., workload) and response to training (i.e., changes in physical fitness) may have contributed to the inconsistent findings reported in the literature. However, future research should continuously monitor training data to further our knowledge on these relationships.

Finally, it should be acknowledged that the lack of a passive control group represents a methodological limitation of this study. However, the inclusion of a passive control group (i.e., no soccer training) is impossible in an elite athletic setting because we cannot expect athletes to stop training for an entire season. Moreover, our findings on anthropometry, body composition, and components of physical fitness should be considered with caution because they might also be affected by natural variation of performance and/or maturity-related changes of our sample. Additionally, the sample size appears to be rather small. However, we would like to point out that female elite young athletes were included in the present study which is why the overall population for recruitment is highly limited in an elite athletic setting.

CONCLUSION

The present study clearly showed large variations in training and performance data as well as anthropometrics and body composition in female elite young soccer players who completed the season with the national under-17 championship title. The seasonal soccer training varied with respect to the training periods and thus mainly followed the principles of training variation and specificity. In addition, body composition (i.e., lean body mass, body fat mass) varied according to the demands of the respective training periods which is indicative of biopositive changes (e.g., decreases in fat mass and increases in lean body mass) during the CP1 and bionegative changes (e.g., increases in fat mass and decreases in lean body mass) during TP. Further, anthropometry (i.e., body height) changed due to maturation over the season (T1 vs. T6). Moreover, soccer training and/or growth/maturation contributed to significant gains in a number of physical fitness outcomes (i.e., DJ performance index, Y balance performance, shuttle run performance and kicking velocity) over the soccer season. This is particularly due to adaptations during the first round of the season (i.e., PP1, CP1). It is noteworthy that other performance data did not change (i.e., SJ height, CMJ height, DJ height, 10 m-sprint, change-of-direction speed, ventral Bourban test) or even decline (i.e., maximal leg extensor strength) over the season (T1 vs. T6) which might be caused by fatigue and/or insufficient training stimuli. Thus, it is recommended that coaches and practitioners should carefully consider the training volume of jumping, sprinting, agility/change-of-direction speed and/or heavy-resistance training routines in order to develop speed-, power-, and strength-related fitness measures more efficiently throughout the soccer season in female elite young soccer players.

AUTHOR CONTRIBUTIONS

Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work: ML, NH, OP, UG. Drafting the work or revising it critically for important intellectual content: ML, NH, OP, UG. Final approval of the version to be published: ML, NH, OP, UG. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: ML, NH, OP, UG.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2017.01093/full#supplementary-material

Figure S1 | Baseline mean values and standard deviations of anthropometrics, body composition, and physical fitness measures in female young soccer players relative to the respective measures of representative data reported in the literature. The dotted line (100%) indicates the level of the outcome measures assessed in the respective age-matched reference group. Lower relative values indicate that smaller absolute values (e.g., lower t-agility test time) were assessed in female young soccer players compared to the reference group from the literature. In contrast, higher relative values indicate larger absolute values (e.g., larger squat jump height) in female young soccer players compared to the reference group.

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Effects of Unloaded vs. Loaded Plyometrics on Speed and Power Performance of Elite Young Soccer Players

*Ronaldo Kobal[1], Lucas A. Pereira[1], Vinicius Zanetti[2], Rodrigo Ramirez-Campillo[3] and Irineu Loturco[1]**

[1] Nucleus of High Performance in Sport (NAR), São Paulo, Brazil, [2] Red Bull Brazil, Jarinú, Brazil, [3] Department of Physical Activity Sciences, Research Nucleus in Health, Physical Activity and Sport, University of Los Lagos, Osorno, Chile

The purpose of this study was to investigate the effects of loaded and unloaded plyometric training strategies on speed and power performance of elite young soccer players. Twenty-three under-17 male soccer players (age: 15.9 ± 1.2 years, height: 178.3 ± 8.1 cm, body-mass (BM): 68.1 ± 9.3 kg) from the same club took part in this study. The athletes were pair-matched in two training groups: loaded vertical and horizontal jumps using an haltere type handheld with a load of 8% of the athletes' body mass (LJ; $n = 12$) and unloaded vertical and horizontal plyometrics (UJ; $n = 11$). Sprinting speeds at 5-, 10-, and 20-m, mean propulsive power (MPP) relative to the players' BM in the jump squat exercise, and performance in the squat jump (SJ) and countermovement jump (CMJ) were assessed pre- and post-training period. During the experimental period, soccer players performed 12 plyometric training sessions across a 6-week preseason period. Magnitude based inferences and standardized differences were used for statistical analysis. A *very likely* increase in the vertical jumps was observed for the LJ group (99/01/00 and 98/02/00 for SJ and CMJ, respectively). In the UJ group a *likely* increase was observed for both vertical jumps (83/16/01 and 90/10/00, for SJ and CMJ, respectively). An *almost certainly* decrease in the sprinting velocities along the 20-m course were found in the LJ group (00/00/100 for all split distances tested). Meanwhile, in the UJ *likely* to *very likely* decreases were observed for all sprinting velocities tested (03/18/79, 01/13/86, and 00/04/96, for velocities in 5-, 10-, and 20-m, respectively). No meaningful differences were observed for the MPP in either training group (11/85/04 and 37/55/08 for LJ and UJ, respectively). In summary, under-17 professional soccer players increased jumping ability after a 6-week preseason training program, using loaded or unloaded jumps. Despite these positive adaptations, both plyometric strategies failed to produce worthwhile improvements in maximal speed and power performances, which is possible related to the interference of concurrent training effects. New training strategies should be developed to ensure adequate balance between power and endurance loads throughout short (and high-volume) soccer preseasons.

Keywords: team-sports, football, power output, acceleration, youth athletes

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***Correspondence:**
Irineu Loturco
irineu.loturco@terra.com.br

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INTRODUCTION

In prospective training programs, coaches and sports scientists face the challenge of developing multiple physical and technical capacities in young athletes. In this context, the proper development of speed-related abilities has a determinant role in improving athletic performance. More recently, in professional team sports, a progressive and gradual increase in the demands of maximal sprints and explosive game actions has been observed during training and official competitions (Barnes et al., 2014; Bush et al., 2015). For example, during an official soccer match, between 7 and 12% of the total distance is covered in high-speed running ($>5\,m.s^{-1}$), while from 1 to 4% is covered by sprinting activities ($>7\,m.s^{-1}$) (Bradley et al., 2009; Di Salvo et al., 2010). Importantly, these high-intensity tasks are frequently executed prior to decisive situations (e.g., goal scores) (Faude et al., 2012). As such, previous studies performed over seven consecutive seasons (from 2006 to 2013) in the English Premier League have demonstrated that professional soccer players have gradually become faster and capable of covering greater distances at higher speeds (from 9.12 to $9.55\,m{\cdot}s^{-1}$ for mean sprint velocity; and from 232 to 350 m for sprint distance, respectively) (Barnes et al., 2014; Bush et al., 2015). Thus, the development of neuromuscular abilities in soccer players has become crucial to cope with the progressive match velocity demands. This is especially important for young players initiating their elite careers, who need to focus on the gradual development of their physical abilities to successfully achieve professionalism (Ford et al., 2011; Williams, 2016).

Different training strategies have been effectively implemented to improve jumping and sprinting abilities in soccer players from different age categories (Garcia-Pinillos et al., 2014; Loturco et al., 2015a, 2016b; Silva et al., 2015). In this sense, despite their extensive use, the implementation of "traditional strength training" (i.e., heavy strength training) might be inappropriate when applied to young athletes, due to the limitations naturally imposed by the maturation process (Behm et al., 2008). Conversely, plyometric training seems to be a practical, safe, and efficient strategy for enhancing neuromuscular performance in young athletes (Loturco et al., 2015a; Ramirez-Campillo et al., 2015a,b). In fact, Loturco et al. (2015a) compared the effects of unloaded vertical vs. horizontal plyometrics on sprint performance of U-20 soccer players, revealing distinct performance adaptations in response to each specific training mode. As such, the horizontal jump group presented greater improvements in speed capacity over short distances (0–10 m), whereas the vertical jumps were superior to produce improvements over longer distances (10–20 m).

Alternatively, previous studies have investigated the effects of loaded jumps, with an haltere type handheld (Cronin et al., 2014; McKenzie et al., 2014; Rosas et al., 2016). Cronin et al. (2014) demonstrated acute improvement in jumping performance when using external overloading during plyometric jumps, which can be explained by the significant increase in ground reaction force and impulse promoted by the use of additional loads. More recently, Rosas et al. (2016) analyzed the effects of jumping with or without haltere type handheld loading on vertical and horizontal jump performances of youth soccer players, finding interesting and relevant results. After 6 weeks of training, both groups improved jump performances; however, the loaded jump group presented greater improvements in vertical and horizontal jump capacities. Nevertheless, it remains to be established whether this training strategy is also capable of increasing the maximal sprint capacity of young athletes. Therefore, the aim of this study was to investigate the effects of loaded and unloaded plyometric training strategies on speed and power performance of elite young soccer players.

MATERIALS AND METHODS

Participants

Twenty-three top-level under-17 male soccer players from the same club (age: 15.9 ± 1.2 years, height: 178.3 ± 8.1 cm, body-mass (BM): 68.1 ± 9.3 kg) took part in this study. The athletes were divided in two training groups: loaded vertical and horizontal jumps using an haltere type handheld with a load of 8% of the athletes' BM (McKenzie et al., 2014) (LJ; $n = 12$) and unloaded vertical and horizontal plyometrics (UJ; $n = 11$). Three players from the LJ group were excluded from the sample due to injuries unrelated to the proposed training/testing. Therefore, twenty players completed the study ($n = 9$ and $n = 11$ for LJ and UJ, respectively). The study protocol took place prior to the competitive season, during the preseason training period. The study was approved by the Anhanguera-Bandeirante University Ethics Committee and the participants and their legal guardians signed an informed consent form prior to research commencement.

Experimental Design

In this study, a parallel two-group, longitudinal design was conducted to test the effectiveness of two training programs on speed and power performance of elite soccer players. Players were pair-matched according to their baseline performance in the 20-m sprint test, and group allocation was performed by tossing a coin. All athletes had been previously familiarized with the performance tests. Sprinting speeds at 5-, 10-, and 20-m, mean propulsive power (MPP) relative to the players' BM in the jump squat exercise, and performance in the squat jump (SJ) and countermovement jump (CMJ) were assessed pre- and post-training period. Prior to all testing sessions, a general and specific warm-up routine was performed, involving light running (5-min at a self-selected pace) and submaximal attempts at each testing exercise (e.g., submaximal sprints and vertical jumps). During the experimental period, all soccer players performed 12 plyometric training sessions. A typical weekly training schedule and the detailed power-oriented training program across the 6-week preseason period are presented in **Tables 1**, **2**.

Vertical Jumping Tests

Vertical jumping height was determined using both SJ and CMJ. In the SJ, subjects were required to remain in a static position with a 90° knee flexion angle for 2-s before jumping. In the CMJ, the soccer players were instructed to execute a downward movement followed by a complete extension of the legs. The SJ and CMJ

TABLE 1 | Typical weekly training schedule for the young soccer players.

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning	Tec/Tac 60′	Tec/Tac 70′	Tec/Tac 80′	Tec/Tac 60′	Tec/Tac 60′
Afternoon	LJ/UJ 30′	Rest	LJ/UJ 30′	Rest	Tec/Tac 40′

Tec/Tac, technical and tactical training based on specific technical actions (e.g., goal shooting, corner kick situations) and small-sided games of different formats; LJ, loaded vertical and horizontal jumps using an haltere type handheld with 8% of the players' body mass; UJ, unloaded vertical and horizontal plyometrics.

were executed with the hands fixed on the hips. All jumps were performed on a contact platform (Elite Jump System® S2 Sports, São Paulo, Brazil) (Loturco et al., 2017b). The obtained flight time (t) was used to estimate the jump height (h) (i.e., $h = gt^2/8$). A total of five attempts were allowed for each jump, interspersed by 15-s. The best attempts at SJ and CMJ were retained.

Bar Mean Propulsive Power in Jump Squat Exercise

Bar maximum MPP in the jump squat exercise was assessed on a Smith machine (Hammer Strength, Rosemont, IL, USA). Players were instructed to execute two repetitions at maximal intensity for each load, starting at 40% of their BM. Athletes executed a knee flexion until the thigh was parallel to the ground (≈100° knee angle) and, after a command, jumped as fast as possible without losing contact between their shoulder and the bar. A load of 10% BM was gradually added until a decrease in MPP was observed. A 5-min interval between sets was provided. To determine MPP, a linear transducer (T-Force, Dynamic Measurement System; Ergotech Consulting S.L., Murcia, Spain) was attached to the Smith machine bar. The technical specification of the MPP analysis and its calculation have been previously described (Sanchez-Medina et al., 2010; Loturco et al., 2015c,d, 2016b, 2017a). The maximum MPP value relativized by the players' BM was retained for data analysis purposes.

Sprinting Speed

Four pairs of wireless single-beam light gates (Smart Speed System, Fusion Equipment, AUS) were positioned at distances of 0, 5-, 10-, and 20-m along the sprinting course. The soccer players sprinted twice, starting from a standing position 0.3 m behind the starting line. To avoid weather influences, the sprint tests were performed on an indoor running track. A 5-min rest interval was allowed between the two attempts and the fastest time was considered for the analyses. The average speeds from zero to the respective gates (5-, 10-, and 20-m) were considered for data analysis purposes.

Statistical Analysis

Data are presented as mean ± standard deviation (SD). To analyze the differences in the vertical jumps, sprinting velocities, and MPP in the LJ and UJ groups, pre- and post-training, the differences based on magnitudes were calculated (Batterham and Hopkins, 2006). The magnitude of the within-group changes in the different performance variables, or between-group differences in the changes, were expressed as standardized mean differences (Cohen's *d*). The smallest worthwhile change was set by using the Cohen's principles for a small effect size (ES: 0.2) for each variable tested (Cohen, 1988). The quantitative chances of finding differences in the variables tested were assessed qualitatively as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; >99%, almost certain. A meaningful difference was considered using the mechanistic inference, based on threshold chances of 5% for substantial magnitudes (Hopkins et al., 2009). Therefore, if the chances of having better and poorer results were both >5%, the true difference was assessed as unclear. Additionally, the magnitudes of the standardized differences were interpreted using the following thresholds: <0.2, 0.2–0.6, 0.6–1.2, 1.2–2.0, 2.0–4.0, and >4.0 for trivial, small, moderate, large, very large, and near perfect, respectively (Hopkins et al., 2009). All performance tests used herein demonstrated small errors of measurement, as presented by their high levels of accuracy and reproducibility (CV < 5% and ICC > 0.90 for all assessments) (Hopkins et al., 2009).

RESULTS

Figure 1 depicts the standardized differences between pre- and post-assessments for both LJ and UJ groups of the plyometric-oriented training program. A *very likely* increase in the vertical jumps was observed for the LJ group. In the UJ group a *likely* increase was observed for both vertical jumps. An *almost certainly* decrease in the sprinting velocities along the 20-m course was found in the LJ group. Meanwhile, in the UJ *likely* to *very likely* decreases were observed for all sprinting velocities tested. No meaningful differences were observed for the MPP in either training group. **Table 3** shows the comparisons between the changes observed for LJ compared with those found for UJ.

DISCUSSION

This study aimed to compare the effects of 6-weeks of loaded vs. unloaded plyometric training regimens on neuromuscular abilities of elite young soccer players. The main findings reported here are that: (1) both training strategies could meaningfully improve the vertical jumping ability of these athletes, and (2) independent of the training mode, the soccer players presented considerable impairments in their acceleration and speed capabilities. These outcomes have important implications in the practical field.

To some extent, our findings are in accordance with previous studies which have already reported positive effects of loaded and unloaded plyometric training programs on jumping ability of young soccer athletes (Loturco et al., 2015a; Ramirez-Campillo et al., 2015a,b). For example, Loturco et al. (2015a) observed meaningful (and specific) increases in vertical and horizontal jump performances of elite U-20 players who executed short-term training programs (3-week) exclusively composed of vertical or horizontal plyometrics. Likewise, with a design more similar to the one used in the present investigation, Rosas et al. (2016) showed a superior capacity of loaded jumps (in

TABLE 2 | Training protocols for both groups over the 6-week training period.

Week 1	Week 2	Weeks 3 and 4	Week 4	Week 6
LJ or UJ (2 sessions/week)	LJ or UJ (2 sessions/week)	LJ or UJ (2 sessions/week)	LJ or UJ (2 sessions/week)	LJ or UJ (2 sessions/week)
2 × 6 VJ	3 × 6 VJ	4 × 6 VJ	6 × 6 VJ	4 × 6 VJ
2 × 6 HJ	3 × 6 HJ	4 × 6 HJ	6 × 6 HJ	4 × 6 HJ

LJ, loaded vertical and horizontal jumps using an haltere type handheld with 8% of the players' body mass; UJ, unloaded vertical and horizontal plyometrics; VJ, vertical jump; HJ, horizontal jump.

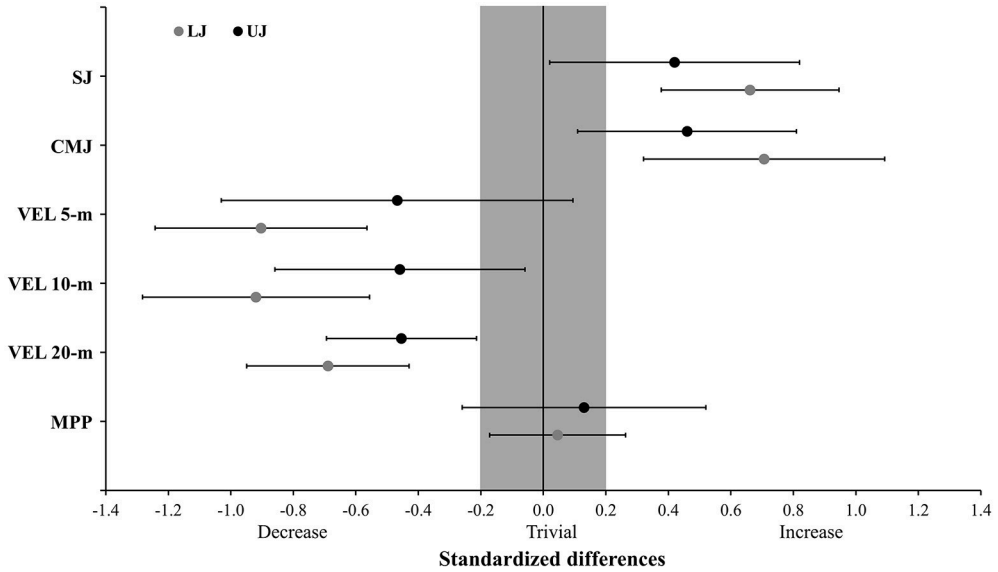


FIGURE 1 | Standardized differences of the performance tests comparing pre- and post- the 6-week preseason period in young soccer players. LJ, loaded jump group; UJ, unloaded jump group; SJ, squat jump; CMJ, countermovement jump; VEL, velocity; MPP, maximum mean propulsive power relative to the players' body mass; error bars represent 90% confidence limits; gray area represents the smallest worthwhile change based on Cohen's units (effect size > 0.2).

comparison with unloaded jumps) to induce functional gains (i.e., kicking velocity and jumping ability) in 63 male youth soccer athletes. The same holds true for our study: the group who trained under loaded conditions reported higher increases in CMJ and SJ heights than the UG (**Table 3**). The reasons behind the apparent superiority of the LG could be related to the overload principle, which states that muscles must be stressed beyond their present capacity to stimulate an adaptive response (Carlson, 2004; Issurin, 2013). Therefore, besides the chronic responses normally expected from a regular plyometric training regimen (e.g., enhanced jump coordination and stretch-shortening cycle efficiency; de Villarreal et al., 2009), it may be speculated that the use of handheld loads enabled players to apply greater amounts of force against the ground in the direction of the intended movement (vertical or horizontal axes) over a longer time period. This mechanical adjustment possibly generates higher impulses (as an "extra overload") during the jumps (Cronin et al., 2014), thus producing superior adaptations in jumping ability in the LG.

Although a previous research has already investigated the effects of handheld loading on neuromechanical capacities of young soccer players (Rosas et al., 2016), this is the first study to analyze its impacts on speed ability. Remarkably, despite the strong correlations already found between jump and sprint performances (Cronin and Hansen, 2005; Loturco et al., 2015b), neither the UG nor LG presented meaningful increases in maximal running speed. Indeed, the proper development of acceleration and speed capacities in elite soccer players throughout age categories and successive training seasons has been demonstrated to be relatively problematic in the literature (Loturco et al., 2015c; Kobal et al., 2016). Partially, it could be elucidated by analyzing the progressive increase in the typical endurance loads that gradually occurs throughout the prospective development of soccer athletes. In fact, due to the congested fixture schedule of elite soccer—which includes high volumes of "predominantly aerobic activities" (i.e., specific soccer training) and relatively low volumes of strength-power training—the players are continuously exposed to concurrent training effects. These interference effects seem to be yet more pronounced during preseasons, where the players usually have to perform a great number of technical and tactical sessions in a short-time period (3–6 weeks) without an appropriate recovery between sessions (Coutts et al., 2007; Coutts and Reaburn, 2008; di Fronso et al., 2013). Also in this study, it is probable that

TABLE 3 | Comparisons of the changes observed for both groups of training in the performance tests after a 6-week preseason period in young soccer players.

	Loaded jump		Unloaded jump		Changes observed for LJ compared with UJ	
	Pre	Post	Pre	Post	Standardized differences (90% CL)	Percent chances of better/trivial/poorer effect
SJ (cm)	36.6 ± 5.2	40.4 ± 4.5	39.2 ± 4.4	41.1 ± 2.9	0.43 (−0.11; 0.96) *small*	76/21/03 *likely*
CMJ (cm)	38.2 ± 4.5	41.7 ± 4.4	40.3 ± 4.4	42.4 ± 3.9	0.33 (−0.21; 0.87) *small*	67/28/05 *possibly*
VEL 5-m ($m \cdot s^{-1}$)	4.93 ± 0.25	4.68 ± 0.29	4.79 ± 0.18	4.69 ± 0.23	0.65 (0.08; 1.21) *moderate*	01/08/91 *likely*
VEL 10-m ($m \cdot s^{-1}$)	5.75 ± 0.20	5.55 ± 0.24	5.66 ± 0.21	5.55 ± 0.20	−0.45 (−0.98; 0.08) *small*	02/19/79 *likely*
VEL 20-m ($m \cdot s^{-1}$)	6.70 ± 0.23	6.53 ± 0.23	6.60 ± 0.23	6.49 ± 0.24	−0.27 (−0.62; 0.09) *small*	01/36/63 *possibly*
MPP ($W \cdot kg^{-1}$)	9.51 ± 1.48	9.58 ± 1.35	9.20 ± 1.14	9.36 ± 1.12	−0.06 (-0.38; 0.51) *trivial*	16/30/54 *unclear*

SJ, squat jump; CMJ, countermovement jump; VEL, velocity; MPP, mean propulsive power relative to the players' body mass in the jump squat exercise; CL, confidence limits.

the young players had some difficulties coping with the high demand of aerobic loads throughout the congested preseason period (**Table 1**), thus presenting impaired speed ability after the training intervention. Therefore, even with the substantial increases reported in vertical and horizontal jump capacities, the soccer players were incapable of sprinting faster. It is reasonable to believe that the neuromuscular stimuli experienced by our youth players was incapable of promoting a positive transference effect between jump performance gains and sprinting speed, as previously reported in the literature (Loturco et al., 2015a, 2016b).

In the same way, for both groups of training the MPP did not increase after the preseason period. This is partially in contrast with a previous study performed in our sports laboratory, which demonstrated meaningful improvements in relative values of muscle power in under-20 soccer players who performed loaded jumps (i.e., jump squats) during an inter-season training period (Loturco et al., 2016b). The lack of improvement in power production observed herein can be explained in different forms. As reported before, the high volume of soccer specific training during preseasons may lead to interference effects from this aerobically predominant training strategy over the specific neuromechanical adaptations. Furthermore, to be effective in improving speed and power abilities, a neuromuscular training strategy for top-level soccer players seems to rely on two important points: reducing the volume of technical and tactical training (Loturco et al., 2016b); and improving the intensity and volume of neuromuscular training (Silva et al., 2015; Loturco et al., 2016a,b). For instance, large improvements in the sprinting speed and in the MPP were observed after an inter-season period of elite soccer players where only low volumes of small sided-games were programmed during the experimental intervention (Loturco et al., 2016b). This respective period comprised resistance training using loaded jump squat performed at the optimum power loads (i.e., workloads able to maximize power output) where athletes trained with loads corresponding to ∼60% of their BM (Loturco et al., 2016b) vs. the load of 8% of the players' BM used in the present study. That said, it is worth highlighting that coaches and sport scientists who are interested in maximizing the speed and power abilities of young athletes pay attention not only to the specific content of neuromuscular training approaches, but also to the total volume of specific soccer sessions executed by the players (Silva et al., 2015; Loturco et al., 2016b). Without an adequate balance between these distinct physical and specific technical-tactical strategies, the proper development of maximal running speed throughout the age categories could be significantly affected (Kobal et al., 2016; Nakamura et al., 2016), compromising the prospective development of elite soccer players.

Accordingly, it has been already shown that the sprinting speed and MPP of professional adult soccer players were not different from their younger counterparts (Loturco et al., 2014; Kobal et al., 2016). Meanwhile, performance in the Yo-Yo intermittent recovery test increased progressively from under-17 to adult age categories (Kobal et al., 2016). This reinforces the notion that since the early stages of development, soccer training programs are focused on the promotion of specific match activities as well as the aerobic capacity, with less importance being paid to neuromuscular abilities, which has an important and pivotal impact on the physical development of these athletes for the older categories, where the physical demands are higher and players need to deal with the competitiveness to achieve success in important professional teams.

According to numerous studies conducted with top-level athletes (Buchheit et al., 2010; Campos-Vazquez et al., 2015; Iacono et al., 2015; Loturco et al., 2016b), this investigation is limited by the absence of a control group (i.e., soccer players maintaining their regular training routine without adding plyometric exercises), the small sample sizes and the inevitable and expected dropouts (3 subjects in the LG and 1 subject in the UG). Even with these limitations, we reported worthwhile improvements in the jumping ability of elite young soccer athletes in response to two different applied plyometric training strategies (i.e., handheld loaded group vs. unloaded group). Lastly, it is worth noting that meaningful increases in neuromechanical capacities of top-level players is not a *commonplace* occurrence in investigations performed during short and high-volume soccer preseasons (Taylor et al., 2012; Meckel et al., 2014; Loturco et al., 2015c).

To conclude, under-17 top-level soccer players could improve their jump performance after a 6-week preseason training program using loaded and unloaded jumps. Nevertheless, this

improvement was not accompanied by meaningful increases in maximal sprinting speed and relative muscle power. Therefore, it is strongly recommended for future studies to better manage specific soccer training content (frequency, volume and intensity) and assess different loading and exercise strategies, to provide sufficient stimulus to increase the different spectrum of neuromuscular abilities in elite youth soccer players. In this respect, it should be emphasized that there is an emergent need to produce faster (and more efficient) players to cope with the increased physical and technical demands of modern soccer.

AUTHOR CONTRIBUTIONS

Designed the work: IL; data acquisition: RK, LP, VZ, and IL; analysis and interpretation of data: LP, RR, and IL; drafting the work: RK, LP, and IL; revising critically the work: LP, VZ, RR, and IL final approval of the version to be published: RK, LP, VZ, RR, and IL; agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work were appropriately investigated and resolved: RK, LP, VZ, RR, and IL.

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Specific Changes in Young Soccer Player's Fitness After Traditional Bilateral vs. Unilateral Combined Strength and Plyometric Training

Rodrigo Ramirez-Campillo[1,2], *Javier Sanchez-Sanchez*[2], *Oliver Gonzalo-Skok*[2,3], *Alejandro Rodríguez-Fernandez*[2,4], *Manuel Carretero*[2] *and Fabio Y. Nakamura*[2,5,6]*

[1] Department of Physical Activity Sciences, Research Nucleus in Health, Physical Activity and Sport, Universidad de Los Lagos, Osorno, Chile, [2] Research Group Planning and Assessment of Training and Athletic Performance, Pontifical University of Salamanca, Salamanca, Spain, [3] Faculty of Health Sciences, University of San Jorge, Zaragoza, Spain, [4] Facultad de Ciencias de la Salud, Universidad Isabel I, Burgos, Spain, [5] The College of Healthcare Sciences, James Cook University, Townsville, QLD, Australia, [6] Department of Medicine and Aging Sciences, "G. d'Annunzio" University of Chieti-Pescara, Chieti, Italy

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***Correspondence:**
Fabio Y. Nakamura
fabioy_nakamura@yahoo.com.br

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The aim of this study was to compare changes in young soccer player's fitness after traditional bilateral vs. unilateral combined plyometric and strength training. Male athletes were randomly divided in two groups; both received the same training, including strength training for knee extensors and flexors, in addition to horizontal plyometric training drills. The only difference between groups was the mode of drills technique: unilateral (UG; $n = 9$; age, 17.3 ± 1.1 years) vs. bilateral (TG; $n = 9$; age, 17.6 ± 0.5 years). One repetition maximum bilateral strength of knee muscle extensors (1RM_KE) and flexors (1RM_KF), change of direction ability (COD), horizontal and vertical jump ability with one (unilateral) and two (bilateral) legs, and limb symmetry index were measured before and after an 8-week in-season intervention period. Some regular soccer drills were replaced by combination of plyometric and strength training drills. Magnitude-based inference statistics were used for between-group and within-group comparisons. Beneficial effects ($p < 0.05$) in 1RM_KE, COD, and several test of jumping performance were found in both groups in comparison to pre-test values. The limb symmetry index was not affected in either group. The beneficial changes in 1RM_KE (8.1%; $p = 0.074$) and 1RM_KF (6.7%; $p = 0.004$), COD (3.1%; $p = 0.149$), and bilateral jump performance (from 2.7% [$p = 0.535$] to 10.5% [$p = 0.002$]) were *possible* to *most likely* beneficial in the TG than in the UG. However, unilateral jump performance measures achieved *likely* to *most likely* beneficial changes in the UG compared to the TG (from 4.5% [$p = 0.090$] to 8.6% [$p = 0.018$]). The improvements in jumping ability were specific to the type of jump performed, with greater improvements in unilateral jump performance in the UG and bilateral jump performance in the TG. Therefore, bilateral strength and plyometric training should be complemented with unilateral drills, in order to maximize adaptations.

Keywords: team-sports, football, strength, change of direction ability, young athletes

INTRODUCTION

Soccer demands high levels of forceful and explosive movements such as heading, shooting and change of direction speed (Stølen et al., 2005), crucial to many game situations (Reilly et al., 2000) and decisive events during competition (Hoff and Helgerud, 2004). Improvements of strength and power may help athletes to improve short-duration maximal efforts during games, most likely contributing to competitive soccer performance (Wong et al., 2010). These traits should be trained independently from aerobic power with an optimal training stimulus (Helgerud et al., 2001), especially among young players during the in-season period (Ramírez-Campillo et al., 2014b, 2015a).

It is believed that by increasing muscular contraction force at high speed, explosive performance can be improved (Bangsbo, 1994). Stretch-shortening cycle muscle actions, such as those induced by plyometric training exercises—particularly as jump drills—do provide such training stimuli and are well-established techniques for enhancing athletic performance (Sáez de Villarreal et al., 2012), especially when combined with resistance training (Markovic and Mikulic, 2010; Meylan et al., 2014; Granacher et al., 2016). Plyometric exercises are widely believed to lead to positive adaptations in terms of power production and corresponding improvements in tasks strongly related with athletic performance in soccer (Arnason et al., 2004), such as maximal strength (Sáez-Sáez de Villarreal et al., 2010), jumping (Markovic, 2007), and change of direction speed (Asadi et al., 2016).

Bilateral-based and solely vertically oriented plyometric strength programs may not maximize training adaptations in young soccer players (Ramírez-Campillo et al., 2014b, 2015a,b). Training strategies must consider the unilateral and multiple-plane nature of most competitive soccer actions (Meylan et al., 2014), with players implicated in predominantly unilateral weight-bearing fundamental movements, such as running, cutting, kicking, vertical and horizontal leaps and changing running direction (Reilly, 1996; McCurdy et al., 2005). Moreover, this consideration is paramount, as soccer demands may impose on players various muscle strength asymmetries (Masuda et al., 2005). Strength asymmetries have been implicated with injuries to the lower limbs (Impellizzeri et al., 2007; Croisier et al., 2008) and may affect performance in tasks such as change of direction (Young et al., 2002). Thus, there is a need for soccer specific strength training interventions that incorporate multidirectional unilateral force production exercises.

Therefore, training programs should focus on unilateral (dominant and non-dominant leg) training to correct for asymmetries and to increase performance during recurrent unilateral actions during competition (Sinclair et al., 2014). However, relatively few studies have addressed this issue. Among females, greater improvements in power and jumping ability was observed after 6 weeks of unilateral plyometric training compared to bilateral training (Makaruk et al., 2011). In another study with males and females (McCurdy et al., 2005), unilaterally-trained subjects improved more than bilaterally-trained ones on unilateral relative power and vertical jump height. In a bilateral test, the improvements in power and jumping ability were similar in both groups. In young soccer players participating in plyometric-only training (Ramírez-Campillo et al., 2015a), an specific training change was observed, where unilateral-training induced greater performance gains in unilateral-dominant tests, whereas bilateral-training induced greater performance gains in bilateral-dominant tests. In a recently published study (Bogdanis et al., 2017) unilateral plyometric training was more effective at increasing jumping performance and maximal strength when compared to bilateral training. However, in the latter studies, plyometric training was not combined with resistance training. Since combination of strength and plyometric training may induce optimal adaptations compared with either training strategy alone (Lloyd et al., 2016), further research is required. In addition, since combination of strength and plyometric training is common among soccer teams (Bedoya et al., 2015; Wallenta et al., 2016; Behm et al., 2017), new research on the topic may offer findings of potential relevance for coaches, trainers, and scientists. Therefore, the purpose of this study was to compare the changes induced by traditional bilateral vs. unilateral combined plyometric and strength training in young soccer player's fitness. We hypothesized that both training approaches would induce beneficial changes in young soccer player's fitness, with improvements specific as the type of training program performed.

MATERIALS AND METHODS

Participants

Eighteen male young (U-19) soccer players with experience in soccer (≥8 years) and bilateral strength training (≥2 years) and from the same regional division team participated in this study. Athletes trained soccer on Monday, Wednesday, Thursday, and Friday, with one competition match on weekends. Soccer players have continually trained for the previous month with absence of musculoskeletal injury. Athletes were divided by simple randomization (Suresh, 2011) into a traditional bilateral strength and plyometric training group (TG; $n = 9$; age, 17.6 ± 0.5 years; height, 174.9 ± 5.3 cm; body mass, 68.3 ± 3.6 kg) and a unilateral group (UG; $n = 9$; age, 17.3 ± 1.1 years; height, 177.1 ± 5.9 cm; body mass, 64.9 ± 5.5 kg). One participant from each group withdrew from the study due to injury taking place during soccer competition. Although some athletes from both groups suffer minor sports trauma (Timpka et al., 2014) during the 8-week intervention, these occurrences did not involve withdraws, nor affected training adherence. The Ethics Committee of the Faculty of Education, Pontifical University of Salamanca, approved the study (Annex II of the Act November 22, 2017). Participants (and guardians for underage players) signed an informed consent document according to the Helsinki Declaration. Underage players provided assent.

The sample size was determined according to changes in vertical jumping performance in a group of soccer players subjected to a control ($\Delta = 0.5$ cm; $SD = 1.1$) or a short-term plyometric training protocol ($\Delta = 2.6$ cm; $SD = 1.6$) (Ramírez-Campillo et al., 2015a) comparable with that applied in this study.

Eight participants per group would yield a power of 95% and $\alpha = 0.01$.

Experimental Design

One repetition maximum strength of knee muscle extensors (1RM_KE) and flexors (1RM_KF), change of direction ability (COD), horizontal and vertical jump ability with one and two legs were measured before and after an 8-week in-season intervention period, where some regular soccer drills were replaced by combination of plyometric and strength training drills. All measurements were performed at the same venue, under identical conditions and by the same researchers, blinded for group's allocation. After a familiarization period, measurements were completed on 2 days separated by 48 h. During the first day the 1RM_KE, 1RM_KF and COD tests were performed. Jump tests were performed in the second day. To avoid measurements outcomes being affected by fatigue during jumping testing, the sequence of jump tests was counterbalanced. A 5-min general warm-up (self-paced jogging; skipping; strides; two acceleration runs) was performed before each testing day.

Maximum Strength Tests

The bilateral 1RM_KE and 1RM_KF were measured in fitness machines (Reebok Fitness Machine®), following previous instructions (Titton and Franchini, 2017). After a standardized general warm-up, athletes perform 10 unloaded repetitions for each exercise, and then 5 repetitions with 50% of the perceived 10RM. After 3 min of rest, athletes completed the 10RM test. It was necessary just one attempt per athlete as they were familiarized with the test. The number of repetitions and the weight lifted were registered in order to obtain the 1RM_KE and the 1RM_KF, calculated from a previously validated equation (Brzycki, 1993). Due to logistical limitations, a unilateral testing procedure was implemented only at pre-intervention for the UG, in order to prescribe initial training loads.

Change of Direction Ability Test

According to previous instructions (Sassi et al., 2009), athletes completed a modified agility *T*-test. A photocell gate system (DSD Laser System®) with its corresponding software (Sport Test, v3.2.1) was used to record the time. The players performed the test using the same directives as the traditional *T*-test, although they were not required to move laterally or face forward (**Figure 1**). The players had to touch the top of the cones instead of its base. A-B displacement (5-m): at his own discretion, each subject sprinted forward to cone B and touched the top of the cone with the right hand. B-C displacement (2.5-m): facing forward the participant shuffled to the left to cone C and touched the top of the cone with the left hand. C-D displacement (5-m): the soccer player then shuffled to the right to cone D and touched its top. D-B displacement (2.5-m): the participant shuffled back to the left to cone B and touched its top. B-A displacement (5-m): the soccer player moved as quickly as possible and returned to line A. Two maximal trials were completed and the best time was used for later analysis.

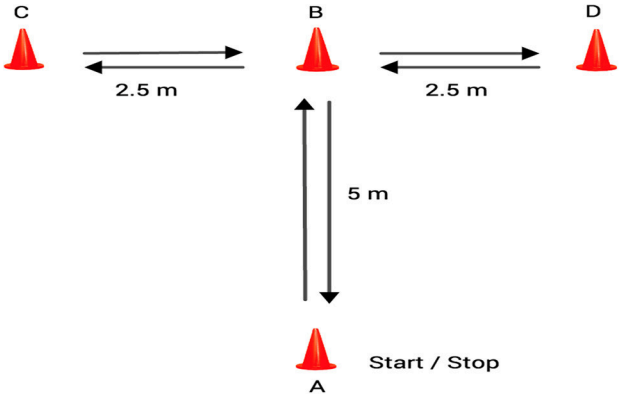


FIGURE 1 | Modified agility *T*-test.

Jumping Tests and Limb Symmetry Index

Athletes completed the countermovement jump (CMJ) and squat jump (SJ) tests following previous suggestions (Maulder and Cronin, 2005), with minimal flexion of the trunk during take-off (Blache and Monteil, 2015). The tests were also performed unilaterally, with dominant (CMJd and SJd) and non-dominant leg (CMJnd and SJnd). Limb dominance was detected by asking the player to kick a soccer ball with their preferred leg. Jumping was measured with a contact mat (Globus Ergo System®, Codogne, Italy). Athletes performed two maximal trials for each test with 1 min of rest in between. The maximal height achieved was selected for analysis.

According to previous validated protocols (Noyes et al., 1991; Rösch et al., 2000), athletes performed a horizontal triple jump with dominant (H3Jd) and non-dominant leg (H3Jnd). Briefly, athletes take three maximal jumps forward as far as possible on the testing leg and land on two legs during the final jump (Maulder and Cronin, 2005). Athletes also performed the horizontal triple jump with dominant and non-dominant leg using a cross-over (HC3Jd and HC3Jnd, respectively) pattern over a 15-cm marking strip, as previously described (Noyes et al., 1991). In short, athletes jumped three consecutive times using the dominant or non-dominant leg, crossing over the center strip on each hop. A bilateral horizontal CMJ with arms (HCMJ) was also performed, as a single jump maximal attempt but also as a triple jump maximal attempt (H3CMJ). For the six horizontal jumping tests, athletes performed two maximal trials, with a recovery of 3 min in between. The maximal distance achieved was selected for analysis. In all jumps, the hands were used freely. At the end of each horizontal jump attempt, athletes maintained the landing position for a brief moment.

As previously suggested (Gustavsson et al., 2006), the limb symmetry index was calculated after unilateral and bilateral jumping tests were completed, as: worse leg/better leg × 100.

Training Intervention

Athletes from both TG and UG groups maintained their regular soccer-training schedule during the 8-week in-season intervention period, including endurance training, small-sided

games, tactical-technical training, friendly games, and injury prevention drills (no injuries associated to the training intervention were observed during the course of the study). Athletes from both training groups attended the same soccer training sessions as they belonged to the same regional division team. Therefore, soccer-training loads were equally distributed between TG and UG groups. However, the strength and plyometric training drills replaced some technical-warm up drills at the beginning of each intervention training session. The intervention was based on previous experience of the team's strength and conditioning coach and from previous reports (McCurdy et al., 2005; Makaruk et al., 2011; Ramírez-Campillo et al., 2015a). Athletes completed strength training on Wednesday and plyometric training on Wednesday and Friday. Between training sessions and competitions, a rest interval of ≥48 h was always allowed. **Table 1** depicts the training program.

Both groups received the same training, volume per leg and coach to athlete supervision ratio. Following previous recommendations (Kraemer and Ratamess, 2004), and in line with the concept of minimal effective dose of training (Moran et al., 2017), during the strength sessions, athletes completed three sets of 10 repetitions for knee extensors and flexors muscles, at 70% 1RM_KE and 1RM_KF in bilateral (TG) or unilateral (UG) exercises. Unilateral 1RM_KE and 1RM_KF testing procedure were implemented only at pre-intervention for UG, in order to prescribe initial training loads. During the plyometric sessions, athletes completed one set of horizontal unilateral or bilateral drop jumps using 20-cm height boxes (10-cm height boxes for the UG) in the first 4 weeks and 25-cm height boxes (15-cm height boxes for the UG) in the last 4 weeks. Athletes completed three repetitions on week 1–3, four during weeks 4–6 and five in weeks 7–8. In addition to drop jumps, athletes completed a set of three consecutive horizontal jumps during the first 4 weeks, and two sets in the last 4 weeks. A low volume of training was deemed appropriate in order to soccer player cope with the rest of their soccer-related training and competitive activities. In addition, the volume applied was very similar to that used in previous effective strength and plyometric intervention with U20 young soccer players (Loturco et al., 2016), where nine jumps per session combined with resistance training induced meaningful improvements in sprint, COD and jumping performance. Each jump repetition was completed with maximal voluntary effort. Athletes were instructed to achieve maximal horizontal jump distance, with minimal ground contact time during drop jumps. Athletes had 2 min of rest between strength and plyometric training sets. Of note, both training groups completed the same total number of sets and repetitions per leg. Each session lasted ∼15 min. Athletes were asked to attend >80% all training sessions during the intervention to be included in the final analysis.

TABLE 1 | Training program*.

Wednesday	Friday
WEEK 1–4	
Knee extensors 3 × 10 (70%) Knee flexors 3 × 10 (70%) 20-cm horizontal drop jumps€ 1 × 3–4 Horizontal jumps 1 × 3	20-cm horizontal drop jumps€ 1 × 3–4 Horizontal jumps 1 × 3
WEEK 5–8	
Knee extensors 3 × 10 (70%) Knee flexors 3 × 10 (70%) 25-cm horizontal drop jumps 1 × 4–5 Horizontal jumps 2 × 3	25-cm horizontal drop jumps 1 × 4–5 Horizontal jumps 2 × 3

*: depicted exercises were performed bilaterally or unilaterally, for the traditional bilateral strength and plyometric training group (TG) and a unilateral group (UG), respectively. €: jump drills were performed with maximal voluntary effort.

Statistical Analysis

Data are presented as mean ± standard deviation (SD). A Shapiro-Wilk test was used to analyse the normally distributed data. Firstly, a traditional null-hypothesis testing was conducted. Within-group comparisons (Student paired *t*-test) were carried out to detect significant differences between the pre-test and post-test in any variable in both groups. In addition, an ANCOVA (general linear model) was used to detect any significant between-group difference at post-test using the pre-test as a covariate (IBM SPSS Statistics 21, IBM Co., USA). Thereafter, all data were log-transformed to reduce bias arising from non-uniformity error (magnitude-based inferences approach). The standardized difference or effect size (ES, 90% confidence limits [CL]) in the selected variables was calculated using the pooled pre-training SD. Threshold values for Cohen's ES statistics were >0.2 (small), >0.6 (moderate), and >1.2 (large) (Hopkins et al., 2009). For within/between-group comparisons, the chances that the differences in performance were better/greater [i.e., greater than the smallest worthwhile change (0.2 multiplied by the between-subject standard deviation, based on Cohen's d principle)], similar or worse/smaller were calculated. Quantitative chances (QC) of beneficial/better, similar/trivial or detrimental/poorer effect were assessed qualitatively as follows: <1%, almost certainly not; >1–5%, very unlikely; >5–25%, unlikely; >25–75%, possible; >75–95%, likely; >95–99%, very likely; and >99%, most likely (Hopkins et al., 2009). If the chance that the true value is >25% beneficial and >0.5% chance that it is harmful, the clinically effect was considered as unclear. However, the clinical inference was declared as beneficial when odds of benefit/harm was >66 (Hopkins et al., 2009). Two specific Excel spreadsheets from sportsci.org were used to examine both the between-group (xCompare2groups.xls) and within-group (xPostOnlyCrossover.xls) comparisons.

RESULTS

Within-Group Changes

Beneficial changes in 1RM_KE (TG: 8 out of 9 individual improvements; UG: 4 out of 9 individual improvements), COD (TG: 9/9; UG: 6/9), CMJ (TG: 8/9; UG: 6/9), CMJd (TG: 5/9; UG: 8/9), CMJnd (TG: 4/9; UG: 7/9), SJnd (TG: 3/9; UG: 6/9), and HC3Jnd (TG: 4/9; UG: 7/9) were found in both groups in comparison to pre-test values. In the TG, beneficial gains were reported 1RM_KF (6 out of 9 improvements), SJ (9/9) and HCMJ

(9/9). In the UG SJd (8/9), H3Jd (8/9), H3Jnd (8/9), and HC3Jd (8/9) were likely to very likely improved (**Table 2**). The limb symmetry index was not affected in either group. Furthermore, significant differences in each group were reported in **Table 2**.

Between-Group Changes

Results from between-group analyses are illustrated in **Figure 2**. The beneficial changes in 1RM_KE (8.1% [CL90%: 4.2; 11.8]; QC = 99/0/0%; p = 0.074) and 1RM_KF (6.7% [CL90%: 2.8; 10.4]; QC = 98/1/0%; p = 0.004), COD (3.1% [CL90%: 0.5; 5.7]; QC = 94/5/1%, p = 0.149), CMJ (2.7% [CL90%: −4.8; 9.7]; QC = 61/23/16%; p = 0.535), SJ (10.5% [CL90%: 3.5; 17.0]; QC = 98/1/1%; p = 0.013) and HCMJ (4.4% [CL90%: 2.7; 6.0]; QC = 100/0/0%; p = 0.002) were possibly to most likely beneficial in the TG than in the UG. However, CMJd (8.4% [CL90%: 4.7; 12.1]; QC = 100/0/0%; p = 0.006), CMJnd (5.9% [CL90%: 0.0; 12.1]; QC = 91/6/3%; p = 0.081), SJd (8.6% [CL90%: 3.6; 13.8]; QC = 99/1/0%, p = 0.018), H3Jd (4.8% [CL90%: 1.4; 8.2]; QC = 98/1/1%, p = 0.023), H3Jnd (5.0% [CL90%: 1.2; 8.9]; QC = 98/2/0%; p = 0.034) and HC3Jd (4.5% [CL90%: 0.1; 9.1]; QC = 89/9/2%; p = 0.090) achieved likely to most likely beneficial changes in the UG compared to the TG.

DISCUSSION

The purpose of this study was to compare the changes induced by traditional bilateral vs. unilateral combined plyometric and strength training in young soccer player's fitness. We hypothesized that both training approaches would induce beneficial changes in young soccer player's fitness, with improvements specific to the type of training program performed. Main findings indicated that both groups improved 1RM_KE, COD and jumping ability, with no changes in limb symmetry index. A specificity was noticed for adaptations, whereby only the TG improved the bilateral maximal strength of the knee flexors and the bilateral jump performance in the SJ and HCMJ, and only the UG improved unilateral performance in the SJd, H3Jd, H3Jnd, and HC3Jd tests. Moreover, improvements in 1RM_KE and 1RM_KF, COD, CMJ, SJ, and HCMJ were greater in the TG than in the UG, while improvements in CMJd, CMJnd, SJd, H3Jd, H3Jnd, and HC3Jd were greater in the UG. Current results are in line with our hypothesis and corroborate previous findings (Behm et al., 2017) related to the efficacy of combined strength and plyometric training in young soccer players, and its specific effects.

Both trained groups improved 1RM_KE, and the magnitude of the improvement is in line with previous findings (Granacher et al., 2016). As previously suggested the specific strength training probably explains most of the improvement (Behm et al., 2017). However, plyometric training might also help to explain the performance gains (Sáez-Sáez de Villarreal et al., 2010). Muscle strength has been significantly correlated with soccer player's sprint, COD and jumping ability (Wisløff et al., 2004). Considering that sprinting, COD and jumping actions are highly demanded during soccer competition (Reilly et al., 2000; Hoff and Helgerud, 2004; Stølen et al., 2005) and are related to team success (Arnason et al., 2004), it might be possible that such strength improvements play a decisive difference during competition. Of note, only the TG improved 1RM_KF. Moreover, the 1RM_KE and 1RM_KF muscles' improvements were greater in the TG compared to the UG. However, these differences might have been artificially created through the implementation of a bilateral maximum strength testing procedure. Due to logistical limitations, the unilateral testing procedure was implemented only at pre-intervention for the UG, in order to prescribe initial training loads. Future studies should seek to clarify this issue.

Regarding COD ability, both trained groups improved performance. Both strength (Sheppard and Young, 2006; Young and Farrow, 2006) and plyometric training (Asadi et al., 2016) might have contributed to improved COD performance. Previous studies have also found COD improvements after strength-plyometric training interventions with young soccer players (Ramirez-Campillo et al., 2014a; Ramírez-Campillo et al., 2014b; Bedoya et al., 2015; Kobal et al., 2017). Improvements in power (Negrete and Brophy, 2000), reactive strength (Young et al., 2002), eccentric strength (Sheppard and Young, 2006), as well as maximal strength (Rouissi et al., 2016) may help explain the COD improvement. Of note, the TG had a likely greater COD improvement compared to the UG. This result contrasts with previous findings, where greater improvements in unilateral-related performance actions were observed after unilateral training programs (McCurdy et al., 2005; Makaruk et al., 2011; Bogdanis et al., 2017). Moreover, current results contrast with a previous study (Ramírez-Campillo et al., 2015a) where young soccer players achieved greater COD improvement after unilateral compared to bilateral plyometric training. It might be possible that the use of different COD test and training programs between studies partially explain the difference. In addition, in the current study only horizontal plyometric drills were used, whereas the combination of both vertical and horizontal drills might optimize adaptations (Ramírez-Campillo et al., 2015b). Considering the unilateral nature of most competitive soccer actions (Meylan et al., 2014), including COD (Reilly, 1996; McCurdy et al., 2005), we deemed prudent to recommend the inclusion of unilateral drills in young soccer training programs.

Current results indicate favorable changes in jumping performance in both training groups. Jumping ability may be considered an independent physical attribute related to soccer performance (Arnason et al., 2004). Further, jumping ability may indirectly positively affect other key physical attributes such as sprint acceleration (Nikolaidis et al., 2016), which may be applicable to players of different positions (Nikolaidis et al., 2014). Although both training groups improved CMJ, CMJd, CMJnd, SJnd, and HC3Jnd, only the TG improved SJ and HCMJ, whereas only the UG improved SJd, H3Jd, H3Jnd, and HC3Jd test results. Moreover, improvements in CMJ, SJ and HCMJ were greater in the TG, whereas CMJd, CMJnd, SJd, H3Jd, H3Jnd, and HC3Jd improvements were greater in the UG. Although the specificity of training is a well-established training principle (Behm et al., 2017), few studies have corroborated this phenomenon in young soccer players, especially after unilateral and bilateral plyometric and strength training approaches (Ramírez-Campillo et al., 2015a). In this sense, replication studies

TABLE 2 | Changes in athletic performance following bilateral combined plyometric and strength training ($n = 9$) or unilateral combined plyometric and strength training ($n = 9$). Data are mean ± SD.

	Bilateral ($n = 9$)						Unilateral ($n = 9$)					
	Pre-test	**Post-test**	**% (CL90%)**	**ES (CL90%)**	**Chances**	**Outcome**	**Pre-test**	**Post-test**	**% (CL90%)**	**ES (CL90%)**	**Chances**	**Outcome**
1RM_KE (kg)	207.9 ± 30.2	237.2 ± 51.0*	12.9 (7.4; 18.6)	0.77 (0.46; 1.09)	100/0/0%	Most Likely	179.8 ± 9.1	182.4 ± 8.4*	1.5 (0.4; 2.6)	0.27 (0.07; 0.47)	73/27/0%	Possibly
1RM_KF (kg)	93.8 ± 11.2	99.8 ± 10.2*	6.6 (2.2; 11.2)	0.48 (0.16; 0.80)	93/7/0%	Likely	86.5 ± 2.9	86.8 ± 2.9	0.3 (−0.3; 1.0)	0.09 (−0.08; 0.25)	12/87/1%	Likely trivial
COD (s)	5.67 ± 0.29	5.46 ± 0.20*	3.7 (1.3; 6.0)	0.66 (0.23; 1.09)	96/4/0%	Very Likely	5.80 ± 0.29	5.67 ± 0.16	2.2 (−0.7; 5.1)	0.41 (−0.13; 0.96)	76/21/4%	Likely
CMJ (m)	0.37 ± 0.05	0.40 ± 0.05*	8.6 (4.2; 13.1)	0.56 (0.28; 0.84)	98/2/0%	Very Likely	0.38 ± 0.04	0.40 ± 0.05	5.2 (−0.8; 11.6)	0.51 (−0.08; 1.11)	82/15/3%	Likely
CMJd (m)	0.22 ± 0.03	0.22 ± 0.03	2.8 (0.1; 5.6)	0.18 (0.01; 0.35)	41/59/0%	Possibly	0.23 ± 0.03	0.26 ± 0.03*	10.0 (6.9; 13.1)	0.85 (0.59; 1.10)	100/0/0%	Most Likely
CMJnd (m)	0.20 ± 0.03	0.20 ± 0.02	2.7 (−0.5; 6.0)	0.19 (−0.03; 0.42)	47/52/1%	Possibly	0.22 ± 0.02	0.24 ± 0.03*	6.4 (2.1; 10.9)	0.50 (0.17; 0.83)	93/6/0%	Likely
LSI_CMJ (%)	90.8 ± 4.6	90.7 ± 4.8	−0.1 (−4.0; 3.8)	−0.02 (−0.71; 0.66)	28/40/32%	Unclear	91.9 ± 6.3	91.1 ± 6.8	−0.8 (−3.2; 1.6)	−0.11 (−0.42; 0.20)	5/65/30%	Possibly harmful
SJ (m)	0.35 ± 0.05	0.37 ± 0.04*	6.5 (2.6; 10.6)	0.36 (0.15; 0.58)	90/10/0%	Likely	0.36 ± 0.05	0.34 ± 0.04	−6.0 (−12.8; 1.2)	−0.45 (−0.99; 0.09)	3/18/79%	Likely harmful
SJd (m)	0.21 ± 0.03	0.21 ± 0.03	1.1 (−1.4; 3.6)	0.08 (−0.11; 0.26)	12/87/1%	Likely trivial	0.22 ± 0.02	0.24 ± 0.02*	8.1 (3.1; 13.2)	0.64 (0.25; 1.02)	97/3/0%	Very Likely
SJnd (m)	0.18 ± 0.02	0.19 ± 0.02	3.1 (−0.1; 6.5)	0.26 (−0.01; 0.53)	66/33/1%	Possibly	0.22 ± 0.03	0.23 ± 0.03*	4.8 (1.3; 8.5)	0.35 (0.09; 0.60)	84/15/0%	Likely
LSI_SJ (%)	87.7 ± 7.9	88.6 ± 9.2	1.0 (−1.3; 3.3)	0.09 (−0.13; 0.32)	20/78/2%	Likely trivial	91.5 ± 8.4	89.8 ± 3.1	−1.5 (−6.3; 3.6)	−0.14 (−0.61; 0.33)	11/48/41%	Possibly harmful
H3Jd (m)	6.49 ± 0.30	6.53 ± 0.28	0.5 (−0.2; 1.2)	0.10 (−0.04; 0.24)	11/89/0%	Likely trivial	6.19 ± 0.32	6.62 ± 0.31*	7.1 (3.7; 10.5)	1.21 (0.64; 1.78)	99/0/0%	Very Likely
H3Jnd (m)	6.29 ± 0.30	6.29 ± 0.31	0.0 (−0.4; 0.3)	−0.01 (−0.07; 0.05)	0/100/0%	Most Likely trivial	5.97 ± 0.33	6.35 ± 0.34*	6.4 (2.7; 10.3)	0.99 (0.42; 1.55)	98/1/0%	Very Likely
LSI_H3J (%)	96.8 ± 4.2	96.1 ± 3.9	−0.7 (−1.4; 0.0)	−0.14 (−0.28; 0.00)	0/78/22%	Likely trivial	96.5 ± 2.8	95.2 ± 3.3	−1.4 (−3.8; 1.1)	−0.43 (−1.20; 0.34)	8/21/71%	Possibly harmful
HC3Jd (m)	5.62 ± 0.40	5.70 ± 0.39	1.5 (−1.9; 4.9)	0.17 (−0.23; 0.57)	45/49/6%	Unclear	5.66 ± 0.42	5.98 ± 0.38*	5.8 (1.7; 10.0)	0.65 (0.20; 1.10)	95/5/0%	Likely
HC3Jnd (m)	5.49 ± 0.47	5.71 ± 0.71	4.0 (−0.8; 9.1)	0.39 (−0.08; 0.87)	76/21/2%	Likely	5.28 ± 0.56	5.70 ± 0.45*	8.2 (2.1; 14.6)	0.64 (0.17; 1.11)	94/6/0%	Likely
LSI_HC3J (%)	95.6 ± 1.6	95.7 ± 2.4	0.1 (−1.7; 1.9)	0.04 (−0.95; 1.03)	39/28/33%	Unclear	93.3 ± 5.9	95.3 ± 3.8	2.2 (−2.5; 7.2)	0.30 (−0.34; 0.94)	61/30/9%	Unclear
HCMJ (m)	2.24 ± 0.08	2.34 ± 0.07*	4.5 (2.5; 6.5)	1.17 (0.67; 1.67)	100/0/0%	Most Likely	2.20 ± 0.15	2.21 ± 0.15	0.7 (0.1; 1.3)	0.09 (0.01; 0.17)	2/98/0%	Very unlikely
H3CMJ (m)	6.56 ± 0.58	6.65 ± 0.56*	1.3 (0.5; 2.2)	0.13 (0.05; 0.21)	8/92/0%	Unlikely	6.67 ± 0.58	6.84 ± 0.52	2.7 (−2.1; 7.6)	0.28 (−0.23; 0.79)	62/33/6%	Unclear

*1RM_KE, one-repetition maximum in knee extensors; 1RM_KF, one-repetition maximum in knee flexors; COD, modified agility test; CMJ, bilateral countermovement jump; CMJd and CMJnd, unilateral countermovement jump with dominant and non-dominant leg; LSI_CMJ, limb symmetry index in unilateral countermovement jump; SJ, bilateral squat jump; SJd and SJnd, unilateral squat jump with dominant and non-dominant leg; LSI_SJ, limb symmetry index in unilateral squat jump H3Jd and H3Jnd, horizontal triple jump with dominant and non-dominant leg; LSI_H3J, limb symmetry index in unilateral horizontal triple jump; HC3Jd and HC3Jnd, crossover horizontal triple jump with dominant and non-dominant leg; LSI_HC3J, limb symmetry index in unilateral crossover triple jump; HCMJ, bilateral horizontal jump with arm swing; H3CMJ, triple bilateral horizontal jump with arm swing. Significant differences ($p < 0.05$) between pre-test to post-test were indicated with *.*

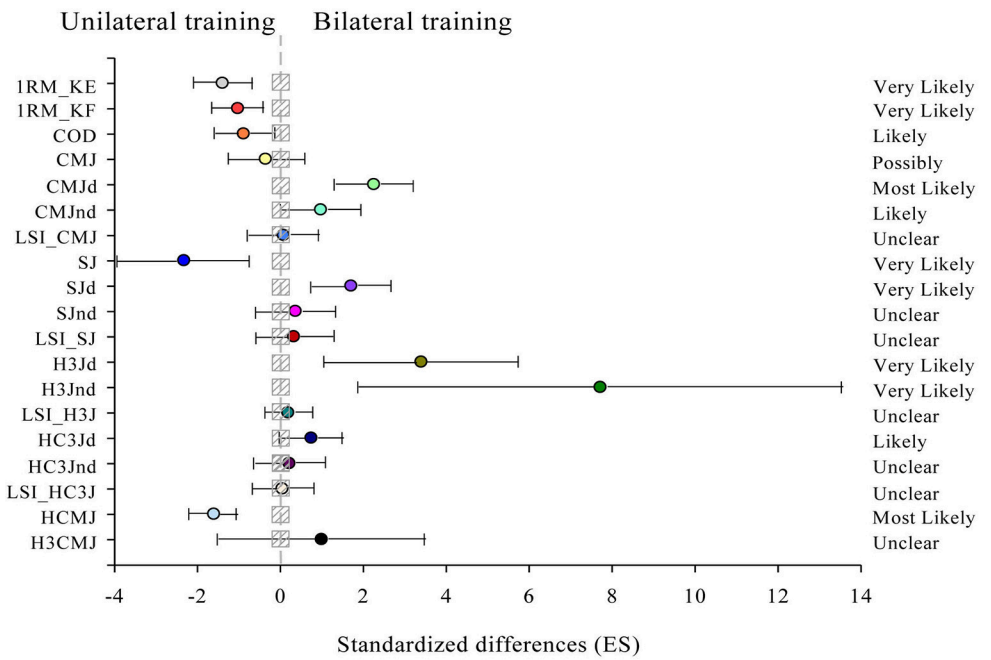


FIGURE 2 | Efficiency of the unilateral (UNI) compared to bilateral (BIL) combined plyometric and strength training to improve one-repetition maximum in knee extensors (1RM_KE), one-repetition maximum in knee flexors (1RM_KF), a modified agility test (COD), bilateral countermovement jump (CMJ), unilateral countermovement jump with dominant and non-dominant leg (CMJd and CMJnd), limb symmetry index in unilateral countermovement jump (LSI_CMJ), bilateral squat jump (SJ), unilateral squat jump with dominant and non-dominant leg (SJd and SJnd), limb symmetry index in unilateral squat jump (LSI_SJ), horizontal triple jump with dominant and non-dominant leg (H3Jd and H3Jnd), limb symmetry index in unilateral horizontal triple jump (LSI_H3J), crossover horizontal triple jump with dominant and non-dominant leg (HC3Jd and HC3Jnd), limb symmetry index in unilateral crossover triple jump (LSI_HC3J), bilateral horizontal jump with arm swing (HCMJ), and triple bilateral horizontal jump with arm swing (H3CMJ) (bars indicate uncertainty in the true mean changes with 90% confidence limits). Trivial areas were the smallest worthwhile change (SWC) (see Methods).

are necessary to increase generalization of findings, with current results aiding to this aim. Motor coordination adaptations may be related to the specificity of movements used during training (Diallo et al., 2001), therefore the changes induced by either unilateral or bilateral jump training drills are higher for actions in which athletes have been specifically trained. Therefore, if athletes require specific unilateral of bilateral improvements in some soccer-related action, coaches should strive to allocate a greater proportion of appropriate drills into the athlete's training schedule. Moreover, current specificity-related results are of paramount importance from a transference point of view, since more specific training approaches offer more transference toward specific performance aims (Loturco et al., 2016). Therefore, current results offer novel results not only from a specificity point of view, but also from a transference point of view.

The limb symmetry index or the between-limbs imbalance is a valid and useful tool to detect players at high risk of lower-limb injury [i.e., 4-fold in players with >10% of asymmetry (Gustavsson et al., 2006), as well as to a successful return to sport after an ACL injury (Ardern et al., 2012)]. Furthermore, functional asymmetries might play a key role in performance (Maloney et al., 2017). To our knowledge, the only study that has analyzed the change of an intervention on limb symmetry index (Gonzalo-Skok et al., 2017) shows that unilateral training might prove effective in reducing between-limb imbalance. However, neither within group nor between-group differences were found in the current study. Therefore, no significant differences in improvements for the dominant compared to the non-dominant leg were observed over time. Between-studies differences might be due to the strength training developed (single-joint vs. multi-joint exercise), the number of repetitions performed (pre-determined vs. post-determined), the athletes' level (regional vs. national/international) or the exercise used to analyse the limb symmetry index. The contrasting changes open a research window to improve our understanding of the effects of unilateral training on reducing the between-limbs differences, and its potential on injury prevention.

As practical recommendations, the replacement of some low-intensity soccer drills with strength and maximal-intensity plyometric drills during the warm-up may positively affect jumping, changing of direction ability and strength during the in-season, even in well trained young soccer players. These improvements might aid performance in competition and may reduce injury risk (Arnason et al., 2004). Current results indicate that bilateral training offer advantages to improve COD, bilateral strength and jumping performance, while unilateral

training induced greater gains in unilateral jumping. However, considering the unilateral nature of most competitive soccer actions, including COD (Rouissi et al., 2016), and to maximize adaptations among young soccer players (Ramírez-Campillo et al., 2015a), it is recommended that during training sessions soccer players combine unilateral and bilateral drills, executed in different planes (Meylan et al., 2014; Ramírez-Campillo et al., 2015b). However, if unilateral or bilateral movements are particularly important for the athlete, due to the specificity of adaptations observed in current study, a high portion of drills should be executed with the required movement pattern. Moreover, practitioners may recommend targeting the worse leg more than the better leg in unilateral training to reduce asymmetry between legs. More research is needed in order to better understand the changes of unilateral training on reducing the between-limbs differences (limb symmetry index), and its potential on injury prevention. Of note, in current study soccer players had extensive experience with strength training. Therefore, in order to better replicable current findings with soccer players, an adequate foundation of strength is advised before introducing plyometric drills (Behm et al., 2017).

A potential limitation of the current study is the lack of a control group. However, in previous seasons soccer players of current study had used the bilateral training program, with significant results. In addition, considering the specific adaptations observed in both experimental groups, it seems evident that the observed changes may be explained by the specific training interventions. However, future studies should aim to replicate current results with a controlled study design, including replication with females, and a greater number of participants. Another potential limitation is related with the bilateral deficit-potentiation phenomenon (Škarabot et al., 2016). In this sense, it may have been possible that different amounts of work-power were completed by the bilateral vs. unilateral trained groups, affecting the outcomes of our study. However, when values of jumping performance (SJ, CMJ) in **Table 2** are considered, when jumping with both legs subjects achieved almost twice the work (body mass × height) compared to jumping with one leg. In this sense, unilaterally and bilaterally trained athletes probably achieved similar values of total work. Of note, due to the large number of comparisons in our study, the risk of type-1 error may have been increased. Although *p*-value adjustments may have reduced the chance of making type I errors (Feise, 2002), this may have increased the chance of making type II errors. Therefore, we also include an ES analysis. In our view, this allows a more comprehensive perspective of the results.

To conclude, both training groups improved maximal strength of knee extensors, change of direction and jumping ability, with no changes in limb symmetry index. The improvements in the maximal strength of knee extensors and flexors, and the change of direction ability were beneficially greater in the traditional bilateral group vs. the unilateral combined strength and plyometric training group. The improvements in jumping ability were specific to the type of jump performed, with greater improvements in unilateral jump in the unilateral training group and bilateral jump performance in the bilateral training group. Therefore, bilateral strength and plyometric training should be complemented with unilateral drills, in order to maximize adaptations throughout the season.

AUTHOR CONTRIBUTIONS

RR-C and JS-S: Designed the work; MC, AR-F, and OG-S: Data acquisition; FN, RR-C, and JS-S: Analysis and interpretation of data; drafting the work; RR-C, JS-S, OG-S, MC, AR-F, and FN: Revising critically the work; final approval of the version to be published; agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work were appropriately investigated and resolved.

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The Effects of Concurrent Strength and Endurance Training on Physical Fitness and Athletic Performance in Youth: A Systematic Review and Meta-Analysis

Martijn Gäbler[1,2]*, *Olaf Prieske*[1], *Tibor Hortobágyi*[2] and *Urs Granacher*[1]

[1] Division of Training and Movement Sciences, Research Focus Cognition Sciences, Faculty of Human Sciences, University of Potsdam, Potsdam, Germany, [2] Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, Netherlands

Combining training of muscle strength and cardiorespiratory fitness within a training cycle could increase athletic performance more than single-mode training. However, the physiological effects produced by each training modality could also interfere with each other, improving athletic performance less than single-mode training. Because anthropometric, physiological, and biomechanical differences between young and adult athletes can affect the responses to exercise training, young athletes might respond differently to concurrent training (CT) compared with adults. Thus, the aim of the present systematic review with meta-analysis was to determine the effects of concurrent strength and endurance training on selected physical fitness components and athletic performance in youth. A systematic literature search of PubMed and Web of Science identified 886 records. The studies included in the analyses examined children (girls age 6–11 years, boys age 6–13 years) or adolescents (girls age 12–18 years, boys age 14–18 years), compared CT with single-mode endurance (ET) or strength training (ST), and reported at least one strength/power—(e.g., jump height), endurance—(e.g., peak $\dot{V}O_2$, exercise economy), or performance-related (e.g., time trial) outcome. We calculated weighted standardized mean differences (SMDs). CT compared to ET produced small effects in favor of CT on athletic performance ($n = 11$ studies, SMD = 0.41, $p = 0.04$) and trivial effects on cardiorespiratory endurance ($n = 4$ studies, SMD = 0.04, $p = 0.86$) and exercise economy ($n = 5$ studies, SMD = 0.16, $p = 0.49$) in young athletes. A sub-analysis of chronological age revealed a trend toward larger effects of CT vs. ET on athletic performance in adolescents (SMD = 0.52) compared with children (SMD = 0.17). CT compared with ST had small effects in favor of CT on muscle power ($n = 4$ studies, SMD = 0.23, $p = 0.04$). In conclusion, CT is more effective than single-mode ET or ST in improving selected measures of physical fitness and athletic performance in youth. Specifically, CT compared with ET improved athletic performance in children and particularly adolescents. Finally, CT was more effective than ST in improving muscle power in youth.

Keywords: child, adolescent, muscle strength, cardiorespiratory fitness, physical conditioning human, resistance training, youth sports

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***Correspondence:**
Martijn Gäbler
mgaebler@uni-potsdam.de

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INTRODUCTION

Physical activity promotes motor development and physical fitness in youth. The World Health Organization recommends at least 60 min of moderate- to vigorous-intensity physical activity daily in youth aged 5–17 years. Most of the physical activity should be aerobic with additional muscle strengthening exercises conducted at least three times per week (WHO, 2010). Thus, the general youth population should regularly perform endurance and strength exercises. While physical activity promotes motor development in youth, young athletes may specifically benefit from endurance training (ET) and strength training (ST) during long-term development of sport-specific athletic performance. Indeed, high levels of muscular strength and aerobic endurance are key determinants of success in many sports (Baar, 2014; Bompa and Buzzichelli, 2015). According to the concept of training specificity (Häkkinen et al., 1989; Behm, 1995), ST improves muscular strength and ET improves cardiorespiratory endurance.

To increase athletic performance, athletes and coaches seek ways to optimize training and minimize risks for injury. A promising way to increase performance is to train both muscle strength and cardiorespiratory fitness within a training cycle [i.e., concurrent training (CT)]. CT could potentiate the individual effects produced by ET and ST and increase athletic performance more than training ET and ST alone. A favorable interaction between ST and ET may reduce time spent on ST and ET and increase time for recovery or training for sport-specific skills. Indeed, CT compared with single-mode ET may produce larger performance improvements in time trials in runners and cyclists (Rønnestad and Mujika, 2014). In addition, when elite cyclists combined cycling and lower limb progressive resistance training, CT improved mean power output during a 45 min cycle-ergometer test more (Δ: 26.4 W, 8.4%) than did ET (Δ: 11.5 W, 3.7%) (Aagaard et al., 2011).

However, ST and ET could also interfere with each other (Docherty and Sporer, 2000) and produce inferior gains in muscular strength compared with ST, resulting in an "interference effect" (Hickson, 1980; Wilson et al., 2012). Interference occurs when strength and endurance stimuli both target peripheral (i.e., muscular) adaptations (e.g., hypertrophy vs. muscle capillarisation) (Docherty and Sporer, 2000) and a meta-analysis confirmed the CT-related "interference hypothesis" (Wilson et al., 2012). That is, ST alone compared to CT produced larger improvements in muscle strength (within group standardized mean differences [SMD]: 1.76 vs. 1.44), muscle hypertrophy (within group SMD: 1.23 vs. 0.85), and muscle power (within group SMD: 0.91 vs. 0.55).

Current theories on the potentiating or interfering effects in CT have been derived from data in adult humans and animals. Because anthropometric, physiological, and biomechanical differences between youth and adults can affect the responses to exercise training, youth compared with adults might respond differently to CT. That is, the physiological processes associated with growth and maturation make the application of adult data to children untenable. For instance, Spurrs et al. (2003) found positive effects of CT compared to ET on 3 km performance {CT: −10 s [1.6%]; ET: −3 s [0.5%]} and running economy at running velocities above 12 km/h (CT: 4–7%; ET: <1%) in 25-year-old distance runners, whereas Bluett et al. (2015) reported a slight decrease in 3 km performance in 10–13 year old distance runners in the CT group (Δ: 6 s, 0.8%), but a slight improvement in the ET group (Δ: −17 s, 2.1%). Further, ST designed to induce hypertrophy in adults (Fleck and Kraemer, 2014) failed to produce hypertrophy in prepubescent children (Ozmun et al., 1994; Granacher et al., 2011). In addition, a 10 week machine-based ST using sub-maximal intensities (70–80% of the 1-repetition maximum [1RM]) increased lower-limb muscle strength but not quadriceps cross-sectional area as measured with magnetic resonance imaging in prepubertal children (Granacher et al., 2011). The apparent inability of children's muscles to hypertrophy following training is attributed to low levels of androgens (Viru et al., 1999; Legerlotz et al., 2016).

Given the anthropometric, physiological, and biomechanical differences between youth and adults and the need to optimize the training stimulus, the present review with meta-analysis aimed to determine whether CT compared with single-mode ET and ST would produce a potentiating or interfering effect in children and adolescents. Specifically, we compared the effects of CT and ET on endurance-related outcomes (cardiorespiratory endurance, exercise economy) and on athletic performance (e.g., time trials) and the effects of CT and ST on strength-related outcomes (maximum muscle strength, muscle power, muscle hypertrophy). We formulated three hypotheses based on previous work. First, given the role of muscle strength in youth physical development and sports (Lloyd and Oliver, 2012; Faigenbaum et al., 2016), we hypothesized that CT is more effective than single-mode ET in improving athletic performance as assessed by time trials. Second, we hypothesized that CT compared to single-mode training results in larger improvements in physical fitness because CT results in adaptations of the muscular and cardiorespiratory systems that are both related to physical fitness outcomes. Third, we hypothesized that CT-related interference effects in strength adaptations are age-dependent and present in adolescents but not in children because prepubescent children appear not to have the physiological basis for training-induced muscle hypertrophy.

METHODS

The systematic literature search and meta-analysis was performed in accordance with the recommendations of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2010).

Literature Search

The electronic databases PubMed and Web of Science were consulted from 1980 until June 7th 2018 using the following Boolean search syntax: "(youth OR young OR children OR adolescents OR pubertal OR boys OR girls OR school) AND (athlete OR sport OR trained) AND (training OR exercise) AND (concurrent OR combined OR combination OR additional) AND (strength OR resistance OR endurance OR aerobic) NOT (elderly OR student OR college OR patient OR disease OR

syndrome OR (cerebral palsy) OR injury OR sedentary OR obese OR animals OR supplementation OR validity)." Where available, we applied filters to limited the output of the search according to the age of participants (Child: 6–12 years; Adolescent: 13–18 years), language (English), article type (no review), and research areas (sport sciences or physiology). Additionally, the reference lists of relevant studies were screened.

Eligibility Criteria

We formed eligibility criteria using the PICOS (Population, Interventions, Comparators, Outcomes, Study design) approach (University of York, Centre for Reviews and Dissemination., 2009). Studies were found eligible for inclusion in the meta-analysis when participants where healthy children or adolescents age 6–18 years. Because biological age is not often reported in studies (Lesinski et al., 2016), participants were categorized based on their chronological age according to Faigenbaum et al. (2009) as children (boys age 6–13 y and girls age 6–11 y) or adolescents (boys age 14–18 y and girls age 12–18 y). Furthermore, we used the definition proposed by Williams (2016) to distinct young athletes from non-athletic youth, namely: "a child or adolescent who is still growing and maturing toward adulthood and who systematically trains (> once per week) and competes (>1-year competition history) in at least one specific sport." With respect to the intervention, studies needed to have applied a CT protocol to at least one group in the study. Furthermore, at least one active control group was required that followed single-mode ET or ST to function as a comparator. For athletes, this meant that a major part of their training consisted of either ET or ST. Studies with two or more different concurrent training protocols, but without a single-mode training group were included in the qualitative analysis of the review but not in the meta-analysis. Means and standard deviations of one or more of the following outcomes had to be reported for all groups before and after intervention: measures of maximum muscle strength, muscle power, muscle hypertrophy, cardiorespiratory endurance, exercise economy, and athletic performance (see also **Table 1**). We defined athletic performance as a sport-specific competitive outcome (e.g., time trial, ball kicking velocity).

The selection process started with the removal of duplicate studies, followed by the screening of titles, abstracts and eventually full texts of the respective studies.

Data Collection

Pre- and post-test means and standard deviations (SDs) were preferably collected from numerical data reported in publications. Authors were contacted in case of unreported data. When authors did not respond, means and SDs were estimated from figures using GetData Graph Digitizer (http://www.getdata-graph-digitizer.com/). Ultimately, SDs were deduced by estimating post-test SD from pre-test SD. Outcomes were excluded when crucial data were still missing.

If more than one outcome measure was reported for a certain variable, only one outcome was included in the analyses to prevent bias. As a general remark, easily administered field tests were preferred over more sophisticated lab measures for the sake of homogeneity, because only few studies reported lab measures.

TABLE 1 | Preferred and alternative outcomes for each outcome measure.

Category	Preferred outcome	Alternative outcome(s)
Maximum muscle strength	1 repetition maximum	>1 repetition maximum Dynamometry
Muscle power	Countermovement jump	Other jump height Dynamometry
Muscle hypertrophy	Muscle cross-sectional area	Muscle mass Muscle thickness
Cardiorespiratory endurance	Peak $\dot{V}O_2$	$\dot{V}O_2$max Estimated $\dot{V}O_2$max
Exercise economy	$\dot{V}O_2$ at submaximal velocity	–
Athletic performance	Relevant sport specific outcome (e.g., time trial, kicking / throwing velocity)	–

An overview of preferred and alternative outcomes can be found in **Table 1**.

Risk of Bias Assessment

Heterogeneity between studies was assessed using I^2 percentages for each outcome and interpreted according to Higgins et al. (2003) as low (>25%), moderate (>50%), or high (>75%). The risk of bias and methodological quality of the included studies were further quantified through the Physiotherapy Evidence Database (PEDro) scale (Maher et al., 2003). The PEDro scale consists of 11 dichotomous questions of which 10 are evaluated. Scoring ranges from 0 to 10 where a higher score indicates a lower risk of bias. A score ≥ 6 is indicative of a high study quality. A score ≥ 4 indicates a fair study quality.

Statistical Analyses

For each study, between-group standardized mean differences (SMD) were calculated for post-test mean values (m) and corrected for sample size (N) according to Hedges and Olkin (1985) $\left(SMD_{between} = \frac{m_{1i}-m_{2i}}{s_i} \cdot (1 - \frac{3}{4N-9})\right)$. SMDs were multiplied by−1 for measures where an improvement in performance was indicated by a negative change (e.g., time trials). Further analyses were performed in Review Manager 5.3.5 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014). To compare the effects of CT to the effects of single-mode ET and ST on different outcome measures, SMDs where weighted with respect to their standard errors and aggregated to compute the overall SMD using a random effects model. Overall SMDs were interpreted according to Cohen (1988) as trivial (SMD < 0.2), small ($0.2 \leq$ SMD < 0.5), moderate ($0.5 \leq$ SMD < 0.8), or large ($0.8 \leq$ SMD). Chi-squared (χ^2) statistics were calculated to determine differences in outcomes between sub-groups. See Deeks and Higgins (2010) for a more detailed description on formulae.

Within group SMDs were calculated as $\left(SMDwithin = \frac{m_{post-}m_{pre}}{sd_{pre}}\right)$. Relationships between within

group SMDs of outcome measures and group characteristics were quantified by Pearson correlation coefficients.

An α of 0.05 was used to determine statistical significance.

RESULTS

The systematic search identified 886 records. **Figure 1** shows the article selection process. Fifteen studies were eligible for inclusion in the meta-analysis with a total of 33 training groups, of which eighteen, eleven, and four groups were categorized as CT, ET, and ST, respectively. Eleven studies examined young athletes (swimming, running, rowing) and compared CT with ET and four studies involved non-athletic youth and compared CT with ET. In total, the number of participants was 518 (268 male, 250 female). Mean ages ranged from 10.7 to 18.2 (median = 14.1) years and fourteen training groups were classified as children and nineteen as adolescents. Two additional records (Enright et al., 2015; Makhlouf et al., 2016) were not eligible for inclusion in the meta-analysis, but were included in the qualitative analysis. **Table 2** characterizes the populations and training programs and shows the quality assessment (PEDro) scores (range: 3 to 7, median = 4).

The meta-analytical comparisons between CT vs. ST and CT vs. ET are presented in the forest plots (**Figures 2**–**4**, **6**) and are described in the next sections. Comparisons between CT and ET involved only young endurance athletes and comparisons between CT and ST involved non-athletic youth only.

Effects of CT vs. ET on Endurance-Related Outcomes

Four studies reported a measure of cardiorespiratory endurance, either as peak $\dot{V}O_2$, or as $\dot{V}O_2$max (**Figure 2**). Compared to ET, CT had a trivial effect on cardiorespiratory endurance in adolescent endurance athletes age 15.9 to 18.2 years (SMD = 0.04; $p = 0.86$; $I^2 = 22\%$). Due to the limited data, sub-group comparisons (trained vs. untrained, children vs. adolescents, boys vs. girls) were not possible.

Five studies reported exercise economy as $\dot{V}O_2$ at a submaximal intensity during swimming, running, skiing on a

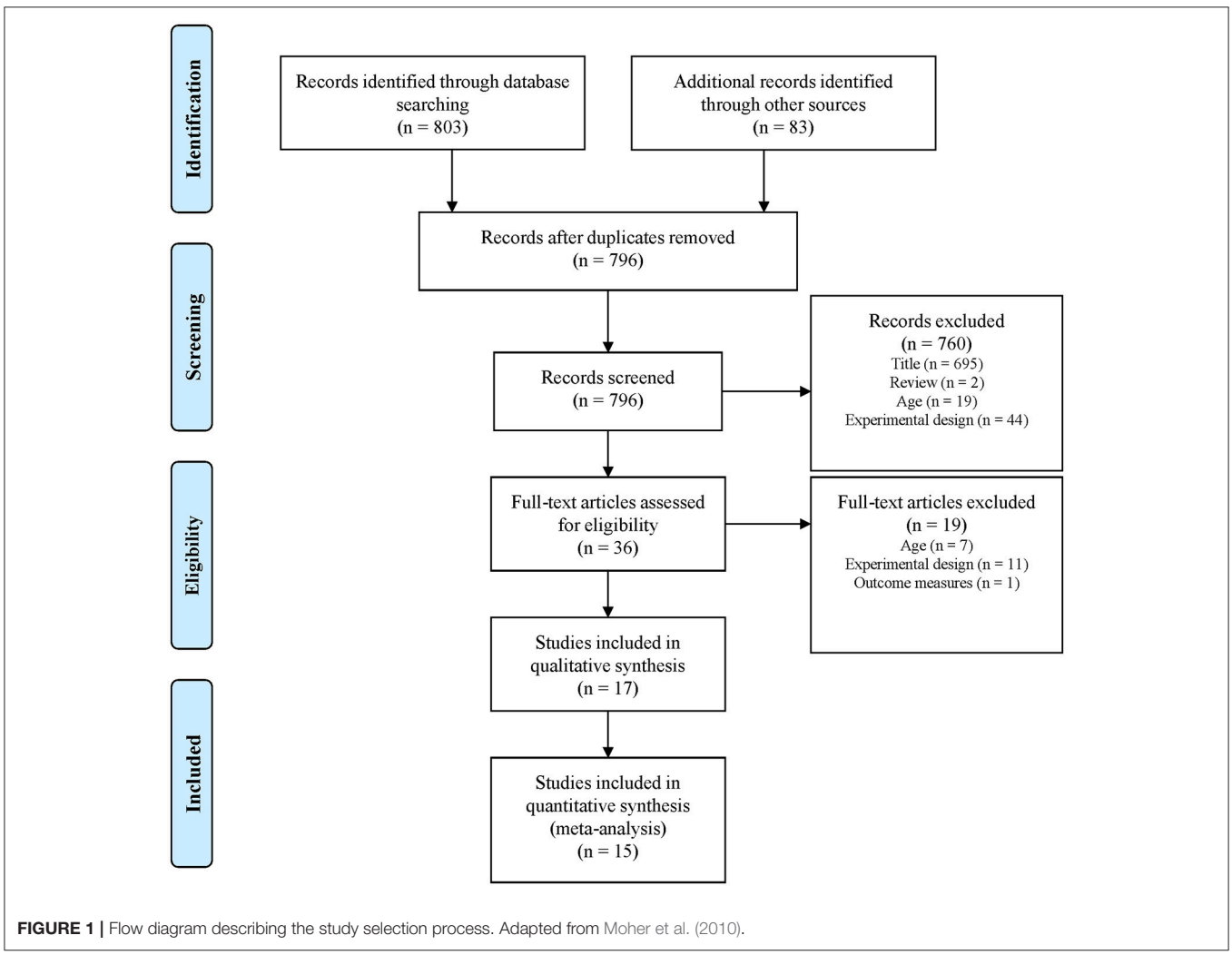


FIGURE 1 | Flow diagram describing the study selection process. Adapted from Moher et al. (2010).

TABLE 2 | Study characteristics.

Author Name, year	Sport	Tr grp	N (m/f)	B. Age	C. Age	Endurance training					Strength training							PEDro
						Contents	W	F	Time or distance	Intensity	Contents	W	F	S	Reps	Rest	Intensity %RM	
Aspenes et al., 2009	Swimming	CT	11 (6/5)	–	17.5 ± 2.9	Interval swimming	11	2	4 x 4 min 3 x 3 min	90–95% HF_{max} 60–75% HF_{max}	Machine	11	2	3	5	2–5	5 RM	3
		ET	9 (2/7)	–	15.9 ± 1.1	Interval swimming	11	2	4 x 4 min 3 x 3 min	90–95% HF_{max} 60–75% HF_{max}								
Amaro et al., 2017	Swimming	CT	7 (7/0)	–	12.7 ± 0.8	Swimming	10	6			Power, core training	6	2	3	6–18	40–90 s	–	7
		CT	7 (7/0)	–	12.7 ± 0.8	Swimming	10	6			Power, core training	6	2	3	10-25s	40–100 s	–	
		ET	7 (7/0)	–	12.6 ± 0.8	Swimming	10	6	4.1 km									
Blagrove et al., 2018	Running	CT	9 (4/5)	3.1	16.5 ± 1.1	Running	10		151 min/week	High volume, low intensity	Plyometric and free weight	10	2	2–4	6–15	90–180 s	–	4
		ET	9 (4/5)	3.9	17.6 ± 1.2	Running	10		213 min/week	High volume, low intensity								
Bluett et al., 2015	Running	CT	6 (3/3)	–	10–13	Continous and interval running	10	2	30 min/300 m 800 m	60–100% of maximal effort	Machine	10	1	3-4	10-12	2	70–75% 1RM	4
		ET	6 (3/3)	–	10–13	Continous and interval running	10	2	30 min/300 m 800 m	60–100% of maximal effort								
Carlsson et al., 2017	Cross country ski	CT	14 (7/7)	–	18.5 ± 0.9	Regular training					Free weight, body weight	6	2	2–3	30–90 s	60 s	6–8RM/ 60–85% BW	4
		ET	19 (9/10)	–	18.1± 0.9	Ski-ergometer	6	2	40 min	90–100% HF_{max}								
Egan-Shuttler et al., 2017	Rowing	CT	8 (8/0)	–	16 ± 0.8	Rowing	4	3	30 min		Plyometric	4	3	2–5	5–20		–	4
		ET	8 (8/0)	–	16 ± 0.6	Cycling + Rowing	4	3	2 x 30 min	Low intensity								
Garrido et al., 2010	Swimming	CT	12 (8/4)	1–2	12.0 ± 0.8	Swimming	8	6	1.5 h	70% $VO2_{max}$	Free weight	8	2	2–3	6–8	2	50–75%/6RM	4
		ET	11 (6/5)	1–2	12.2 ± 0.8	Swimming	8	6	1.5 h	70% VO2max								

(Continued)

TABLE 2 | Continued

Author Name, year	Sport	Tr grp	N (m/f)	B. Age	C. Age	Endurance training					Strength training							PEDro
						Contents	W	F	Time or distance	Intensity	Contents	W	F	S	Reps	Rest	Intensity %RM	
Girold et al., 2007	Swimming	CT	7 (4/3)	–	16.5 ± 2.5	Swimming + cycling	12		8.3 h/week	60–70% HF_{max}	Machine	12	1	3	6	2	80–90% 1RM	4
		CT	7 (3/4)	–	16.5 ± 2.5	Swimming + cycling	12		8.3 h/w	60–70% HF_{max}	Resisted swimming	12	1	2	3	30 s		
		ET	7 (3/4)	–	16.5 ± 1.5	Swimming + cycling	12		10.8 h/w	60–70% HF_{max}								
Mikkola et al., 2007	Running	CT	13 (9/4)	–	17.3 ± 0.9	Running training	8		7.2 h/w	–	High velocity	8	1	2–3	6–10	–	No or low load	4
		ET	12 (9/3)	–	17.3 ± 0.5	Running training	8		8.5 h/w	–								
Potdevin et al., 2011	Swimming	CT	12 (5/7)	3–4	14.3 ± 0.2	Swimming	6	1	5.5 h/w	–	Plyometric	6	2	1–8	1–16	–	BW	4
		ET	11 (5/6)	3– 4	14.1 ± 0.2	Swimming	6	1	5.5 h/w	–								
Weston et al., 2015	Swimming	CT	10 (5/6)	–	15.7 ± 1.2	Swimming	12	8	8 h/w	–	Core training	6	2	2	60 s	60 s	BW	3
		ET	10 (5/6)	–	16.7 ± 0.9	Swimming	12	8	8 h/w	–								
Alves et al., 2016	–	CT	38 (21/17)	–	11.0 ± 0.5	20 m shuttle run	8	2	–	≤ Estimated 75% $V\dot{O}_2max$	Ball throw; jump, sprint	8	2	1–4	4–8	–	–	5
		CT	45 (21/24)	–	10.8 ± 0.5	20 m shuttle run	8	2	–	≤ Estimated 75% $V\dot{O}_2max$	Ball throw; jump, sprint	8	2	1–4	4–8	–	–	
		ST	41 (19/22)	–	10.8 ± 0.4						Ball throw; jump, sprint	8	2	1–4	4–8	–	–	
Marta et al., 2013	–	CT	45 (21/24)	1–2	10.7 ± 0.5	20 m shuttle run	8	2	–	≤ Estimated 75% $V\dot{O}_2max$	Ball throw; jump, sprint	8	2	1–5	3–8	1–2	–	5
		ST	41 (19/22)	1–2	10.7 ± 0.4						Ball throw; jump, sprint	8	2	1–5	3–8	1–2	–	
Santos et al., 2012	–	CT	25 (0/25)	–	13.5 ± 1.0	20 m shuttle run	8	2	–	≤ Estimated 75% $V\dot{O}_2max$	Ball throw; jump, sprint	8	2	1–5	3–8	–	–	5
		ST	21 (0/21)	–	13.5 ± 1.0						Ball throw; jump, sprint	8	2	1–5	3–8	–	–	

(Continued)

TABLE 2 | Continued

Author Name, year	Sport	Tr grp	N (m/f)	B. Age	C. Age	Endurance training					Strength training							PEDro
						Contents	W	F	Time or distance	Intensity	Contents	W	F	S	Reps	Rest	Intensity %RM	
Santos et al., 2012	–	CT	15 (15/0)	–	13.3 ± 1.0	20 m shuttle run	8	2	–	≤ Estimated 75% $V\dot{O}_2$max	Ball throw; jump, sprint	8	2	1–5	3–8	–	–	6
		ST	15 (15/0)	–	13.3 ± 1.0						Ball throw; jump, sprint	8	2	1–5	3–8	–	–	
Enright et al., 2015	Soccer	CT	8 (0/8)	–	17.3 ± 1.6	Soccer specific ET	5	2	3.2	–	Free-weight and body weight	5	2	3–4	6–8	–	85%/ 60–80% 1RM	4
		CT	7 (0/7)	–	17.3 ± 1.6	Soccer specific ET	5	4	3.2	–	Free-weight and body weight	5	2	3–4	6–8	–	85%/ 60–80% 1RM	
Makhlouf et al., 2016	Soccer	CT	14 (14/0)	–	13.7 ± 0.5	Interval running	12	4	15 s	110–120% of aerobic test	23 whole body	12	2	3	5–15	–	Body-weight	4
		CT	15 (15/0)	–	13.7 ± 0.5	Interval running	12	4	15 s	110–120% of aerobic test	23 whole body	12	2	3	5–15	–	Body-weight	

Tr grp, training group; B. Age, biological age; C, chronological age; W, number of weeks; F, training frequency per week; S, number of sets per exercise; Reps, number of repetitions per set; 1RM, one repetition maximum; HF, heart frequency; BW, Body weight (as resistance).

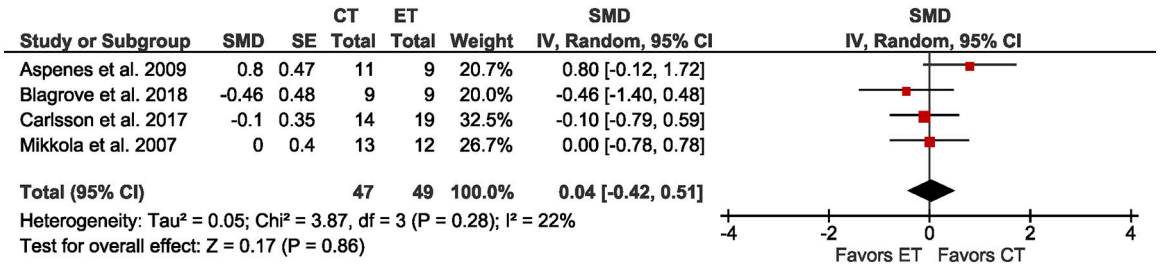


FIGURE 2 | Forest plot for the outcome cardiorespiratory endurance in the comparison between singular endurance training (ET) and concurrent strength and endurance training (CT).

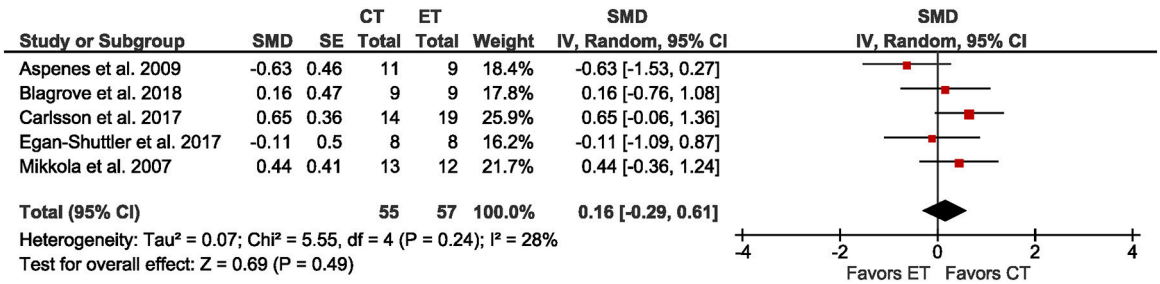


FIGURE 3 | Forest plot for the outcome exercise economy in the comparison between singular endurance training (ET) and concurrent strength and endurance training (CT).

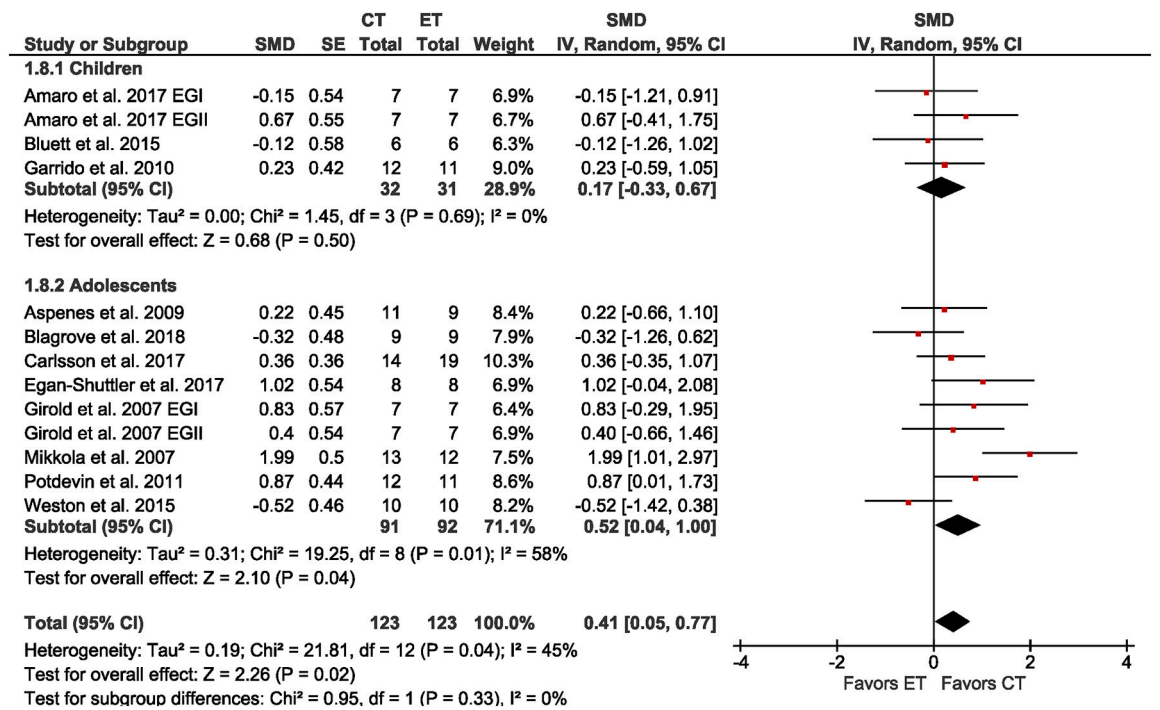


FIGURE 4 | Forest plot for the outcome athletic performance in the comparison between singular endurance training (ET) and concurrent strength and endurance training (CT).

treadmill, or rowing ergometry in adolescent athletes. The meta-analysis (**Figure 3**) revealed a trivial non-significant effect size (SMD = 0.16; $p = 0.24$; $I^2 = 28\%$) of CT compared to ET. Due to small sample sizes, sub-group analyses by age, sex, and training status were not possible.

All eleven studies involving young athletes reported a measure of athletic performance as the time of, or the mean velocity during, a time trial with distances ranging from 30 to 3000 m (median = 275 m). The meta-analysis (**Figure 4**) showed a significant small effect (SMD = 0.41; $p = 0.02$; $I^2 = 45\%$) of CT over ET. A sub-analysis of age revealed a moderate effect of CT over ET in adolescent athletes (SMD = 0.52; $p = 0.02$; $I^2 = 58\%$), but only a trivial effect in child athletes (SMD = 0.17; $p = 0.50$; $I^2 = 0\%$). However, the difference in effect sizes was not significant ($\chi^2 = 0.95$; $df = 1$; $p = 0.33$). Due to small sample sizes, sub-group analyses by sex and training status were not possible.

We found a moderate negative association between chronological age and within group SMDs in athletic performance in young athletes following ET ($r = -0.60$; $p = 0.04$), but only a trivial correlation for CT ($r = 0.02$; $p = 0.94$) (**Figure 5**). In addition to the 11 studies in young endurance athletes we included data from two studies on CT in young soccer players (Enright et al., 2015; Makhlouf et al., 2016) to better be able to evaluate the relationship.

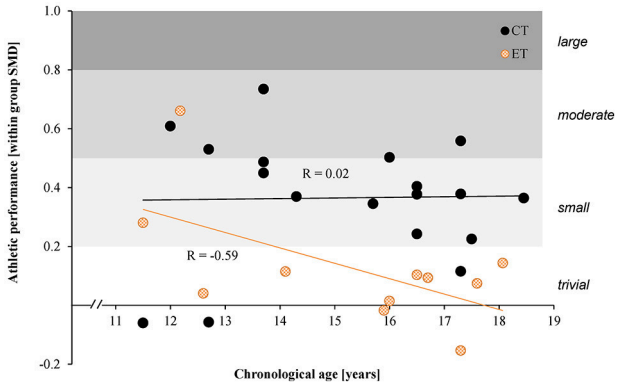


FIGURE 5 | Scatterplot displaying the relationship between chronological age (y-axis) and within SMDs in athletic performance. Each dot represents one concurrent training (CT) or endurance training (ET) group.

Effects of CT vs. ST on Strength/Power-Related Outcomes

Four studies assessed vertical jump height (CMJ) as a proxy for lower extremity muscle power in non-athletic youth age 10.7 to 13.5 years. The meta-analysis (**Figure 6**) revealed a significant but small overall effect size of CT over ST (SMD = 0.23; $p = 0.04$; $I^2 = 0\%$). A sub-analysis did not reveal differences ($\chi^2 = 0.14$; $df = 1$; $p = 0.71$) between SMDs for children (SMD = 0.25; $p = 0.04$; $I^2 = 0\%$) and adolescents (SMD = 0.14; $p = 0.66$; I^2 = n/a). Due to small sample sizes, sub-group analyses by sex and training status were not possible. No studies reported maximum muscle strength or muscle hypertrophy as outcomes.

DISCUSSION

This is the first systematic review that quantified the effects of CT vs. single-mode training (ST, ET) on selected measures of physical fitness and athletic performance in youth. We compared the effects of ET with CT on cardiorespiratory endurance, exercise economy, and athletic performance. We also compared the effects of ST with CT on leg power. CT resulted in larger improvements than single-mode ET on measures of athletic performance, whereas CT compared with ST improved leg power more. Due to small sample sizes, sub-group analyses by age, sex, and training status were not possible. As all comparisons between CT and ET were conducted in young endurance athletes and all comparisons between CT and ST included non-athletic youth, we address the groups in the discussion according to their training status.

Effects of CT vs. ET in Young Endurance Athletes

We hypothesized that CT is more effective than ET for improving athletic performance as assessed by time trials in young endurance athletes because muscle strength is a determinant of athletic performance (Faigenbaum et al., 2016). CT was more effective than single-mode ET to improve athletic performance assessed by time trials (**Figure 4**, SMD = 0.41, $p = 0.04$). This finding is in line with recommendations to include ST in the training of young athletes (Faigenbaum et al., 2009) and with models of long-term athletic development (Lloyd and Oliver, 2012) but direct evidence was limited to a handful of individual studies. Other meta-analyses incorporated young endurance athletes, but grouped them together with adult endurance athletes (e.g., Balsalobre-Fernández et al., 2016) or young athletes from different sports (Lesinski et al., 2016). Lesinski et al. (2016) also found moderate effects (SMD = 0.75) of ST on athletic performance in young athletes, mainly involving soccer players. As Lesinski et al. (2016), we also found low to moderate heterogeneity in outcomes of athletic performance, which suggests that the interpretation may be biased. Methodological differences between studies can increase heterogeneity: the distances of time trials ranged from 30 m to 3,000 m (median = 275 m) in running, swimming, and rowing. The moderate heterogeneity implies that the effectiveness of CT depends on distance and type of sport. The study revealing the largest effect of CT on athletic performance (SMD = 1.99) indeed evaluated athletic performance over the shortest distance (i.e., 30 m) in running (Mikkola et al., 2007). Whereas the study using the longest distance (i.e., 3,000 m) in running showed only a trivial effect (SMD = −0.12) (Bluett et al., 2015).

Sub-group analysis based on chronological age indicated a trend toward higher effects of CT vs. ET on athletic performance in adolescent athletes (**Figure 4**, $SMD_{children} = 0.17$; $SMD_{adolescents} = 0.52$). The relationship between chronological age and athletic performance in the CT groups (**Figure 5**, $r = 0.02$) and ET groups (**Figure 5**, $r = -0.59$) suggests that

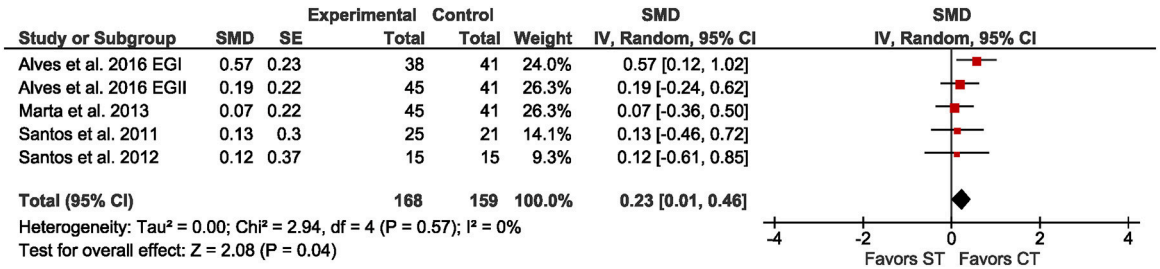


FIGURE 6 | Forest plot for the outcome muscle power in the comparison between single-mode strength training (ST) and concurrent strength and endurance training (CT).

with increasing age the effects of CT on athletic performance do not increase, but the effects of ET alone decrease. This is in line with Lloyd and Oliver's (Lloyd and Oliver, 2012) youth physical development model that recommends using ST throughout developmental stages. Furthermore, previous training experience plays a mediating role in the magnitude of training adaptation (Fleck and Dean, 1987; Fyfe and Loenneke, 2018). The discrepancy in associations between CT and ET could be explained by previous training experience. It could be argued that familiarity with the exercises in the ET groups increased with age, as the ET groups primarily followed their habitual training. As a result, younger athletes with less training experience could benefit more from ET than the older athletes with more experience. The novel exercises in the CT groups could induce adaptations even in older athletes.

Improvements in cardiorespiratory endurance, exercise economy, and performance at lactate threshold may all increase endurance performance (Rønnestad and Mujika, 2014). The limited and heterogeneous data in the present review made it difficult to determine how CT more than ET improved athletic performance in young endurance athletes. The present data suggest that neither cardiorespiratory endurance nor exercise economy improves following CT in young endurance athletes. Previous studies in adults (Aagaard and Andersen, 2010; Sunde et al., 2010; Rønnestad and Mujika, 2014; Balsalobre-Fernández et al., 2016; Denadai et al., 2017) suggested that CT may improve endurance performance by increasing exercise economy, without affecting cardiorespiratory endurance. Of all the studies reporting time trials, not even half of them reported measures on exercise economy or cardiorespiratory endurance (4–5 out of 11). Such paucity of data together with between-group differences at baseline, make it difficult to understand the mechanisms underlying the improvements in time trial performance.

In summary, adding ST to ET seemed to potentiate the effects produced by ET, as CT improved endurance athletes' endurance performance more than did ET. Such a potentiation effect may be greater in adolescents compared to children. However, it is unclear how CT leads to improved athletic performance in young endurance athletes.

Effects of CT vs. ST in Youth

We hypothesized that youth improve physical fitness more when performing CT compared to single-mode training and that the interference effect can be observed in adolescents but not in children because they lack the hypertrophic response to ST (Ozmun et al., 1994; Granacher et al., 2011). The studies that compared CT to ST in non-athletic children (Santos et al., 2012; Marta et al., 2013; Alves et al., 2016) and adolescents (Santos et al., 2011) revealed that CT improved proxies of muscle power slightly more (**Figure 6**, SMD = 0.23, $p = 0.04$).

Unlike in adults (Wilson et al., 2012), combining ST and ET into CT resulted in a potentiating instead of an interference effect on untrained children's leg power. Perhaps the training status played a role in this potentiating effect in non-athletic children and adolescents. According to Coffey and Hawley (2017), "untrained individuals have a greater capacity to activate the molecular machinery in muscle in response to contractile activity, because any overload stimulus induces large perturbations to cellular homeostasis regardless of the mode of exercise." Accordingly, ET produced hypertrophy (Konopka and Harber, 2014) and ST increased oxidative capacity in untrained muscle (Tang et al., 2006). In line with this observation, the studies included in the present meta-analysis showed that ST improved estimated $\dot{V}O_2$max in non-athletic youth (Δ between +0.3 and +1.6 mmol·ml^{-1}·kg^{-1}) (Santos et al., 2011, 2012; Marta et al., 2013; Alves et al., 2016) compared with passive control groups (Δ between −1.1 and +0.3 mmol·ml^{-1}·kg^{-1}). A second explanation may be related to the use of the 20 m shuttle run as an endurance outcome (Santos et al., 2011, 2012; Marta et al., 2013; Alves et al., 2016). These studies used the 20 m shuttle run test as an endurance exercise. The constant acceleration and deceleration of the center of mass could act as a stimulus for leg power measured in the form of jump performance.

The interference effect associated with CT increased with training volume (Rønnestad et al., 2012) and when the form of ET in CT was running in adults (Wilson et al., 2012). Sequencing order of ST and ET elements of CT may affect the magnitude of interference. Muscle hypertrophy might be compromised when ET is performed during the 18 h after ST (Baar, 2014). However, this hypothesis relies heavily on animal data. Meta-analyses of human data seem to favor the ST→ET sequence (Eddens et al., 2017; Murlasits et al., 2017). For instance, the ST→ET compared to the ET→ST sequence produced ∼7% larger gains ($p < 0.01$) in 1RM squat in athletic and non-athletic adults age 18 to 65 y (Eddens et al., 2017). There were no favorable outcomes for either sequence in static strength, muscle hypertrophy or cardiorespiratory endurance. Data in adolescent soccer players (age 17 y) suggest that sequencing can affect improvements in maximum muscle strength, power, and hypertrophy (Enright et al., 2015). Unlike in adults, the

ET→ST vs. the ST→ET sequence was favored in adolescent soccer players. However, one limitation potentially biasing this conclusion was that athletes in the ET→ST group had slightly longer recovery time (2 h) and their lunch between training sessions while the athletes in the ST→ET group had shorter recovery time (<1 h) and a protein shake. Conflicting findings were observed in 13-year-old soccer players (Makhlouf et al., 2016), suggesting that the sequence of ET and ST did not affect improvements in strength-related outcomes in children. The findings of differential responses to sequencing in children and adolescents may be explained by our hypothesis that the interference effect of endurance exercise on strength development is age-dependent. However, it has to be noted that the studies on sequencing effects included no ST groups. It is therefore impossible to determine whether sequencing produced a potentiating or an interfering effect. The available data suggest that responses to sequencing are age-dependent but it is unclear whether this translates to the interference effect. Therefore, more research is needed to test the hypothesis that interfering effects of endurance exercise on strength adaptations are age-dependent and present in adolescent but not in child athletes.

In summary, CT can improve lower extremity muscle power more than ST in non-athletic youth. This finding is indicative of a potentiating effect of CT. Weak evidence in young athletes suggests that age is a factor to consider when manipulating the sequence of ET and ST. It remains inconclusive whether interfering effects of endurance exercise on strength adaptations are age-dependent in youth.

Strengths and Limitations

This is the first review with a meta-analysis to examine the effects of CT in youth with a specific focus on young athletes. The available data allowed us to examine the effects of training on the most relevant outcome for practitioners, namely athletic performance. Furthermore, our data provided some preliminary insights into the interference hypothesis in youth.

The available data from the literature concerning underlying physiological mechanisms such as measures of neuromuscular activity or exercise economy were limited. While there are indications that the responses to CT are greater in adult female compared with male athletes (Barnes et al., 2013), this remains unresolved in young athletes due to insufficient data. In addition, we were not able to clarify whether interference effects in strength adaptations are more pronounced in adolescents compared with children, again due to a lack of data. Moreover, our conclusions are limited because the included studies did not control for training volume between CT and single-mode ST or ET (but see Mikkola et al., 2007). Thus, the observed effects in favor of CT could also be the result of additional training volume. A final limitation was the "fair" methodological quality due to the difficulty in blinding athletes to intervention and investigators to participants' group assignment.

Recommendations

Based on present and past data (Faigenbaum et al., 2016; Lesinski et al., 2016), we recommend that practitioners and coaches include both ST and ET to increase endurance performance in young athletes and to improve physical fitness in non-athletic youth. Both ET and CT could be effective to improve athletic performance in children. However, from a long-term athletic development perspective (Lloyd and Oliver, 2012), CT appears to be favored. CT allows youth to become familiar with ST and learn proper exercise technique from which they may profit at a later age. Coaches should also be aware that sequencing ET and ST within CT affects performance outcomes in young (postpubertal) adolescent athletes. Adhering to previous recommendations could help minimize interference effects (García-Pallarés and Izquierdo, 2011; Baar, 2014; Murlasits et al., 2017). The ST→ET sequence may produce the best results in adolescent athletes but the order does not seem to differentially affect training adaptations in children. This recommendation requires confirmation, as it was based on data from two studies examining young soccer players age 13 and 17 y.

Future studies on CT should control training volume so that any potentiating or interfering effect is not due to differences in training volume between groups. There is a need to report measures quantifying not only athletic performance but also measures that can help understand the underlying processes such as exercise economy or muscle hypertrophy. Biological age should always be reported given their relevance to training adaptations. Finally, data and statistical analyses should be reported separately for boys and girls so that any sex effect on training adaptations can be determined.

CONCLUSIONS

The current systematic review and meta-analysis examined the effects of CT on outcomes of physical fitness and athletic performance in youth. We found at worst no interfering but perhaps a potentiating effect of CT compared with ST or ET alone in endurance athletes age 10 to 18 years and non-athletic youth age 10 to 13 years. A potentiating effect of CT was most visible in adolescent endurance athletes. Preliminary findings from this meta-analysis suggest that CT improves lower body power more than ST in non-athletic youth. This is in contrast to the adult literature and implies an age-dependent interference effect of CT on measures of muscle power. When designing CT programs, training status, sequencing effects, and biological age are factors to consider in future studies.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Influence of Endurance Training During Childhood on Total Hemoglobin Mass

*Nicole Prommer[1], Nadine Wachsmuth[1], Ina Thieme[1], Christian Wachsmuth[1], Erica M. Mancera-Soto[2], Andreas Hohmann[3] and Walter F. J. Schmidt[1]**

[1] Department of Sports Medicine/Sports Physiology, Sports Science, University of Bayreuth, Universitaetsstrasse, Bayreuth, Germany, [2] Department of Physiology, Biological Sciences, Universidad Nacional de Colombia, Bogota, Colombia, [3] Department of Training Sciences, Sports Science, University of Bayreuth, Universitaetsstrasse, Bayreuth, Germany

Elite endurance athletes are characterized by markedly increased hemoglobin mass (Hbmass). It has been hypothesized that this adaptation may occur as a response to training at a very young age. Therefore, the aim of this study was to monitor changes in Hbmass in children aged 8–14 years following systematic endurance training. In the first study, Hbmass, VO2max, and lean body mass (LBM) were measured in 17 endurance-trained children (13 boys and 4 girls; aged 9.7 ± 1.3 years; training history 1.5±1.8 years; training volume 3.5 ± 1.6 h) twice a year for up to 3.5 years. The same parameters were measured once in a control group of 18 age-matched untrained children. Hbmass and blood volume (BV) were measured using the optimized CO-rebreathing technique, VO2max by an incremental test on a treadmill, and LBM by skin-fold measurements. In the second pilot study, the same parameters were measured in 9 young soccer athletes (aged 7.8 ± 0.2 years), and results were assessed in relation to soccer performance 2.5 years later. The increase in mean Hbmass during the period of study was 50% which was closely related to changes in LBM ($r = 0.959$). A significant impact of endurance training on Hbmass was observed in athletes exercising more than 4 h/week [+25.4 g compared to the group with low training volume (<2 h/week)]. The greatest effects were related to LBM (11.4 g·kg^{-1} LBM) and overlapped with the effects of age. A strong relationship was present between absolute Hbmass and VO2max ($r = 0.939$), showing that an increase of 1 g hemoglobin increases VO2max by 3.6 ml·min^{-1}. Study 2 showed a positive correlation between Hbmass and soccer performance 2.5 years later at age 10.3 ± 0.3 years ($r = 0.627$, $p = 0.035$). In conclusion, children with a weekly training volume of more than 4 h show a 7% higher Hbmass than untrained children. Although this training effect is significant and independent of changes in LBM, the major factor driving the increase in Hbmass is still LBM.

Keywords: total hemoglobin mass, blood volume, endurance training, childhood, lean body mass, soccer, talent

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***Correspondence:**
Walter F. J. Schmidt
walter.schmidt@uni-bayreuth.de

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INTRODUCTION

Oxygen transport to muscles involves complex regulation that depends on hemoglobin concentration ([Hb]) and muscle perfusion. Muscle blood flow can be modulated by systemic or local regulation of vascular diameter, as well as by changes in cardiac output; for review, see Montero et al. (2015) and Mortensen et al. (2005). An important factor for a high cardiac

output is a high end diastolic volume in association with a high stroke volume. Furthermore, an efficient muscular pump and fast diastolic filling are prerequisites that are only possible with an adequately high blood volume (BV). In this context, hemoglobin mass (Hbmass) is important in two ways. First, its total mass in combination with the total volume of blood determines [Hb] and O_2 transport capacity. Second, it increases BV via an increase in erythrocyte volume (EV).

During incremental exercise, therefore, Hbmass is important and is one of the major limiting factors of maximum endurance performance. In various studies, a strong correlation between VO2max and Hbmass has been shown at all ages (Astrand, 1952; Schmidt and Prommer, 2010). It has been calculated that a change in Hbmass of 1 g results in a change in VO2max of ∼4 $ml \cdot min^{-1}$ (Schmidt and Prommer, 2010). Therefore, endurance athletes aim to have a high Hbmass either via different training regimens (e.g., altitude training; Wachsmuth et al., 2013) or via prohibited methods (e.g., rhEPO-administration or autologous blood doping; Sottas et al., 2011).

Whether training at sea-level is also an effective way to increase Hbmass is still not entirely clear. Previous studies have found that Hbmass is unaltered in adult elite or highly trained athletes following 3 months (Glass et al., 1969; Gore et al., 1997) and 12 months (Prommer et al., 2008) of endurance training. In contrast, some authors showed a small (3%) increase in elite athletes during intensive training or between training and recovery periods (Garvican et al., 2010b; Eastwood et al., 2012b). In recreational athletes, our group observed a 6.4% increase in Hbmass following a 9-months marathon training program (Schmidt and Prommer, 2008). Their values (12.5 $g \cdot kg^{-1}$), however, were far lower than those observed in elite athletes (∼15 $g \cdot kg^{-1}$) (Heinicke et al., 2001).

Based on available studies, one can conclude that training during adulthood (>21 years), exerts only small effects on Hbmass (Schmidt and Prommer, 2010). The question that arises is whether the high Hbmass observed in elite athletes is primarily inherited and/or possibly achievable through long-term endurance training during childhood and adolescence. In a cross-sectional study, Steiner and Wehrlin (2011) found a 14.5% higher Hbmass in endurance-trained adolescents at the age of 21 than in those at the age of 16 years. However, in longitudinal studies, no effects were reported after 12 months of training by cyclists aged 11–15 years (Eastwood et al., 2009) or following 18 months of endurance training in elite athletes aged 15–17 years (Ulrich et al., 2011). These results lead to the assumption that erythropoietic adaptation occurs at a very young age or during late adolescence or that Hbmass is genetically determined. The latter idea was supported by Martino et al. (2002), who observed naturally high values for Hbmass and BV, which are closely related to VO2max, in adults with no training history.

To provide more information on the possible effects of training on erythropoiesis at a very young age, the present study screened Hbmass in children at prepubertal and pubertal ages (8–14 years) following systematic endurance training over several years (>2 years) and compares the results with those from an age-matched control group. Because Hbmass is closely related to lean body mass (LBM) in adolescence, the second aim was to evaluate how growth-related increases in LBM during maturation are related to increases in Hbmass.

As the third aim, in a separate cohort, the relationship between Hbmass in prepubertal boys (7.8 years) and competition success after 2.5 years of systematic soccer training was investigated in a pilot study. As soccer performance depends to a great extent on the aerobic component of exercise, soccer players need to possess a high VO2max (Manna et al., 2010), which again is to a great extent determined by Hbmass. As the correlation between changes in VO2max and changes in Hbmass after training is low in adults (Eastwood et al., 2012a), it is assumed that Hbmass is mostly genetically determined (Martino et al., 2002) and that it might be used for talent identification not only for specific endurance disciplines, e.g., cycling (Eastwood et al., 2009), but also for team sports played on large fields like soccer.

MATERIALS AND METHODS

Participants

In the first study, 17 endurance-trained children (13 boys and 4 girls) participated in a longitudinal screening for Hbmass and endurance performance. All of them were part of a cross-country skiing training group and regularly participated in competitions. The mean training time per week was 3.5 ± 1.6 h (not including school sports) over the entire study period, and the mean training experience at the beginning of the study was 1.5 ± 1.8 years. During summer, the training included running or biking instead of cross-country skiing. Some of the participants were also part of a soccer or handball team. At the beginning of the study, the youngest participant was 7.6 years and the oldest was 11.5 years, resulting in a mean age of 9.7 ± 1.3 years (see **Table 1**). The control group was composed of 18 children (6 boys and 12 girls) with no experience in endurance sports. Apart from school sports (once per week), some of the subjects engaged in non-endurance sports such as equestrian, gymnastics or combat sports on a non-performance-oriented level. None of the controls had a history of endurance sports. The mean age of the controls was 11.0 ± 1.8 years. As we did not find any significant differences in anthropometric, hematological and performance parameters between male and female control subjects we established one control and one training group and did not differentiate subjects into male and female subgroups. For the anthropometric data of both groups, see **Table 1**. In the second study, 9 male soccer players (mean age 7.8 ± 0.2 years) underwent initial measurements of BV and Hbmass and a longitudinal screening of their performance in soccer competitions. All of the children and their parents signed a written informed consent form prior to participation. Both studies were approved by the local ethics committee at the University of Erlangen-Nuremberg, Germany.

Design of the Study

In the first study, the endurance-trained children were monitored for up to 3.5 years (mean observation period 2.5 ± 1.0 years), with two visits (November and April) per year, which allowed for 97 tests in total. Six of the 17 athletes (all boys) completed the study after 3.5 years and performed all 8 tests, whereas the mean number of tests per subject was 5.8 ± 2.1. At each

TABLE 1 | Anthropometric data (study 1).

	Age (years)	Height (cm)	Body mass (kg)	BMI (kg·m^{-2})	Body surface (m^2)	LBM (kg)
TRAINED ($n = 17$)						
Initial values	9.7 ± 1.3	144 ± 11	35.9 ± 9.5	17.0 ± 2.2	1.19 ± 0.20	29.6 ± 6.4
Final values	12.4 ± 1.5***	158 ± 14***	49.5 ± 14.9***	19.3 ± 3.0***	1.47 ± 0.28**	39.8 ± 10.9***
Mean values	11.1 ± 1.3	151 ± 12	42.7 ± 11.9	18.3 ± 2.7	1.33 ± 0.23	34.9 ± 8.8
Controls ($n = 18$)	11.0 ± 1.8	147 ± 15	42.8 ± 11.2	19.4 ± 2.9	1.32 ± 0.23	32.8 ± 7.9

*BMI, body mass index; LBM, lean body mass. Values are means ± SD. The term "Mean values" indicates the mean of the individual mean values of the trained subjects obtained during the whole monitoring period. Significance of differences within the trained group between initial and final values: **$p < 0.01$, ***$p < 0.001$. In the following tables significance of differences are indicated as follows: Within the trained group between initial and final values: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Between the trained group and the control group: $^{+}p < 0.05$, $^{++}p < 0.01$, $^{+++}p < 0.001$.*

visit, Hbmass, [Hb], hematocrit (Hct), BV and its components (plasma volume (PV) and EV), maximal endurance performance (VO2max), body mass, body height and LBM were measured. The Hbmass and BV measurements were performed 60 min after the performance test to avoid reductions in maximal performance due to blocking the oxygen binding sites by carbon monoxide (CO). For the control group, the same parameters were measured at only one visit.

In the second study, young soccer athletes were tested for BV, Hbmass, [Hb], body mass, body height, and LBM. After 2.5 years of systematic soccer training, competition performance was controlled for and quantified over 5 hierarchical success levels. Competition success was monitored over the full 2.5 years and finally ranked using a scale with the following range: (1) club level, (2) local level, (3) district level, (4) county level, and (5) up to province level.

Procedures and Protocols

In both studies, body mass was measured on a mechanical column scale while wearing shorts, a t-shirt and no shoes. Body surface area was calculated according to the formula by Mosteller (1987). Skinfold measurements (Slimguide® Caliper, Creative Health Products, Plymouth, Michigan, USA) were performed in triplicate at four sites (triceps, biceps, suprailiac, and subscapular). Typical error (TE) was 1.4%. Body fat percentages were calculated using the age-adjusted formulas of Deurenberg et al. (1990). LBM was calculated as the difference between the body mass and amount of body fat.

BVs and Hbmass were measured according to the optimized CO-rebreathing method as described by Gore et al. (2006), Prommer and Schmidt (2007) and Schmidt and Prommer (2005). The CO-bolus was adjusted to a dose of 0.6 ml·kg^{-1} for all children instead of 0.8–1.2 ml·kg^{-1} as used for adults (Prommer and Schmidt, 2007; Garvican et al., 2010a; Alexander et al., 2011). Additionally, filling of the rebreathing bag with pure oxygen was reduced to ∼2 L. After familiarization with the equipment (SpiCO, Blood tec GmbH, Bayreuth, Germany) and the breathing procedure, the children performed the tests without any problems. Leakage, especially around the mouth and nose, was controlled for with a CO detector (Dräger PAC 7000, Dräger Safety, Lübeck, Germany). The typical error (TE) of this method obtained in our laboratory is 1.4%, which is in accordance with the TE published by Gore et al. (2006).

Arterialized blood samples were taken from a hyperemized earlobe to determine the [Hb] and Hct in duplicate. [Hb] was assessed photometrically (HemoCue® HB201+, HemoCue AB, Sweden), and Hct was measured by microhematocrit tube centrifugation (EBA 21, Hettich, Tuttlingen, Germany).

In addition to the blood analysis, an incremental step test to determine VO2max was performed on a treadmill (Ergo XELG2, Woodway, USA) in study 1. The initial speed was set to 6 km·h^{-1} for 3 min and increased to 8 km·h^{-1} for another 3 min. After completing the initial stages, the speed was subsequently increased by 1 km·h^{-1} each min until the subject was exhausted. Measurement of VO2max was performed using a MetaMax II device (Cortex, Leipzig, Germany), which is a portable breath-by-breath indirect spirometry system. The main criterion for the assessment of VO2max was the occurrence of a leveling-off of VO2. At this point, the VO2 values were averaged over a minimum period of 30 s to calculate the VO2max. All the children were familiarized with the treadmill before starting the test. Due to technical reasons (inaccuracy of the spirometry's O2 sensor), performance testing could not be conducted on two girls on the final date.

At each visit, the children from study 1 completed a questionnaire asking about their training volume and frequency, injuries, and illnesses within the previous 3 months. None of the children showed any severe injuries or illnesses that would have been a reason for exclusion. Training volume per week was classified into the following three categories. Category 1: 0–2 h; category 2: 2.1–4 h; category 3: >4 h.

Data Analyses

The sample size for study 1 was calculated according to Hopkins (2006). Based on the literature data of relative Hbmass in adolescents (Eastwood et al., 2009), the between-subject standard deviation was assumed to be 1.0 g·kg^{-1} and the difference between untrained children and the trained group to be 1.2 g·kg^{-1}. For these numbers, the lowest sample size (50% intervention group/50% control group) was 12/12, which was surpassed in the present study (17/18).

To compare the data from the training group with data from the control group, the individual mean of each parameter was calculated for each of the trained subjects. Subsequently, these data were used in unpaired student's tests to determine possible differences between both groups. Additionally, paired *t*-tests

were performed to compare the initial values of the training group with the final values at the end of the observation period.

An analysis of covariance (ANCOVA, mixed model) was performed to evaluate the influence of confounding factors on Hbmass, with the independent effects of sex and training volume as factors and age, LBM and training history as covariates. A special focus was put on the children below 12 years of age. To detect any dependencies between two variables, linear (e.g., Hbmass vs. LBM and VO2max vs. Hbmass) and exponential (age vs. Hbmass) regression analyses were performed.

In study 2, a linear regression analysis was performed to detect any relationship between Hbmass and soccer competition performance 2.5 years later.

RESULTS

Anthropometric Parameters

Changes in the anthropometric parameters of the training group during the period of study 1 are shown in **Table 1**. Body mass increased by ∼5.4 kg per year, which was accompanied by an increase in LBM of 4.1 kg per year. The increase in body height was 5.7 cm per year. The controls were matched according to the mean age of the trained children at all visits, and controls did not show any significant anthropometric differences from the mean values of the training group (**Table 1**).

Training Data

In study 1, the children trained for more than 2 h per week for at least 3 months prior to the tests at 54% of all laboratory visits. For 29%, they had trained for more than 4 h per week, while for 17% of the visits, less than 1 h of exercise per week had been performed due to injury or illness. No endurance training was performed by the controls.

Hematological Data (Study 1, All Subjects)

During the longitudinal part of study 1 (mean of 2.5 years), absolute Hbmass clearly increased by 50%. Hbmass relative to LBM showed a slight increase of 9%. While the mean absolute Hbmass did not differ from the values of the control group, relative Hbmass was elevated in the training group (**Table 2**). **Figure 1** shows the individual Hbmass data relative to the age of the children. Despite broadly scattered results, ∼200 g, there was a uniform increase until the age of 12 years. Beyond this age, no further changes were observed in the girls, although a steep increase, with a much broader spread of up to 600 g, was observed in the boys.

Linear regression analysis with Hbmass as a dependent variable and body mass, body surface, or LBM as independent parameters, showed that the closest relationship was for Hbmass vs. LBM ($r = 0.959$, $y = 14.8x - 96.6$, **Figure 2**) compared to Hbmass vs. body surface ($r = 0.927$) and Hbmass vs. body mass ($r = 0.921$).

Table 3 presents the results of an analysis of covariance (mixed model) for absolute Hbmass in all children below 12 years. As expected, Hbmass was primarily determined by LBM, i.e., 1 kg LBM increased Hbmass by 11.4 g, while age had no effect and sex had only a small effect (28.7 g higher in boys). Additionally,

TABLE 2 | Hematological data (study 1).

	Hbmass (g)	Rel. Hbmass (g·kg^{-1})	Rel. Hbmass (g·kg LBM^{-1})	BV (ml)	Rel. BV (ml·kg^{-1})	PV (ml)	Rel. PV (ml·kg^{-1})	[Hb] (g·dl^{-1})	Hct (%)
TRAINEED (n = 17)									
Initial values	338 ± 74	9.6 ± 1.2	11.5 ± 1.2	2737 ± 570	77.7 ± 8.8	1678 ± 367	47.7 ± 6.5	13.6 ± 1.1	42.5 ± 3.5
Final values	506 ± 191***	10.1 ± 1.3	12.5 ± 1.5*	3930 ± 1318***	79.5 ± 9.3	2391 ± 742***	48.7 ± 5.7	13.9 ± 0.8	42.6 ± 2.8
Mean values	420 ± 129	9.8 ± 1.0++	11.9 ± 0.9+	3364 ± 986+	79.1 ± 7.7+++	2053 ± 579	48.5 ± 5.3+	13.7 ± 0.6	42.7 ± 2.4+
Controls (n = 18)	370 ± 109	8.7 ± 1.1	11.2 ± 1.0	2954 ± 766	69.6 ± 7.3	1859 ± 457	44.1 ± 5.3	13.7 ± 1.0	40.4 ± 2.8

Hbmass, hemoglobin mass; LBM, lean body mass; BV, blood volume; PV, plasma volume; [Hb], hemoglobin concentration; Hct, hematocrit. For explanation of the term "Mean values" and for statistical abbreviations, see ***Table 1****.*

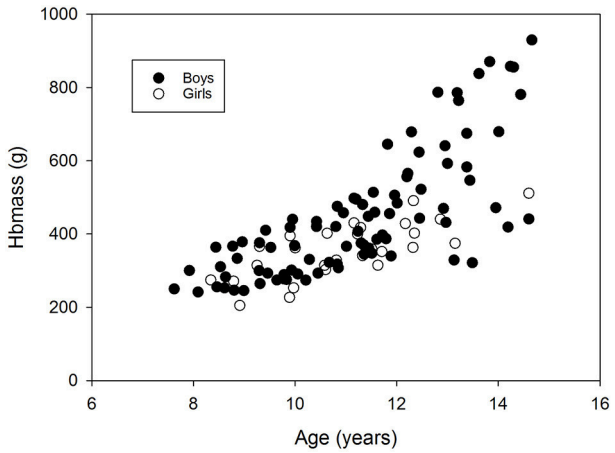


FIGURE 1 | Changes in Hbmass with age. Data are from the longitudinal part of study 1 (trained children) and the cross-sectional sub-study (control group).

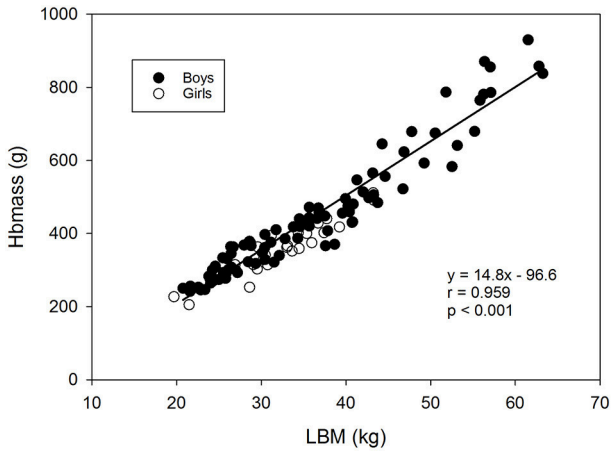


FIGURE 2 | Relationship between Hbmass and lean body mass. Data are from the longitudinal part of study 1 (trained children) and the cross-sectional sub-study (control group).

training volume exerted a small but highly significant effect, with the group with highest training volume (>4 h/week) showing a 25.4 g higher Hbmass than the group with lowest training volume (<2 h/week). Training history did not have a significant influence.

Very similar results were obtained from the mixed model when all the data (i.e., also including those older than 12 years) were included. In this case, the effect of training volume on absolute Hbmass was +22.5 g (>4 h/week, $p < 0.001$), the effect of sex was 25.0 g ($p < 0.025$), and the effect of LBM was 12.4 g·kg^{-1} LBM ($p < 0.001$).

The age-related increase in absolute PV and BV mirrored the time course of changes in Hbmass (**Table 2**), showing an increase in PV by ∼700 ml and in BV by ∼1,200 ml. The volumes in relation to body mass remained constant over the observation period. Additionally, [Hb] and Hct did not change over time (**Table 2**).

TABLE 3 | Results of ANCOVA for absolute Hbmass in children below the age of 12 years (study 1).

	Unit	ANCOVA *p*- value	Regression weights	95% Confidence interval
Base		0.802		
Sex	Males	0.022	28.7	4.5; 53.0
Age	Years	0.93		
Activity level		0.001		
	2 h ≤ 4 h	0.135	11.4	−4.5; 27.3
	> 4 h	0.001	25.4	11.6; 39.2
Training history	Years	0.90		
LBM	(kg)	0.000	11.4	9.0; 13.7

LBM, lean body mass.

Hematological Data From the Male Training Group (Study 1, Longitudinal Data)

The changes in the boys' Hbmass are separately highlighted in **Figure 3**. We found a linear increase in Hbmass until the age of 12 years and an almost exponential increase thereafter ($r = 0.87$, $p < 0.001$, **Figure 3A**). Boys who started the study at a mean age of 8.6 ± 0.6 years increased their Hbmass by 36 g per year, while those who started at 11.1 ± 0.2 years increased their Hbmass by 133 g·yr^{-1} in the following 3.5 years. (**Figure 3B**).

Performance Data (Study 1)

Absolute VO2max increased in the male group by almost 400 ml·min^{-1} but slightly decreased when compared to body mass (**Table 4**). Absolute and relative VO2max were moderately elevated in the training group ($p < 0.05$) compared to values in the control group. The maximum speed attained on the treadmill slightly increased over time and was significantly higher in the training group (**Table 4**).

Anthropometric and Hematological Data From the Group of Soccer Players (Study 2)

Table 5 presents the anthropometric and hematological results from the child soccer players in study 2 at the beginning of the study. We found normal BV and Hbmass levels at the age of 7.8 years. When the hematological data were related to soccer performance after a period of 2.5 years, we found a significant relationship between Hbmass (g·kg^{-1}) and performance ($r = 0.627$, $p = 0.035$).

DISCUSSION

The aim of study 1 was to screen preadolescent children (9.7 ± 1.3 years) for a period of 3.5 years to investigate the influence of systematic endurance training on Hbmass. While comparable studies have investigated older adolescents or shorter intervention times (von Dobeln and Eriksson, 1972; Eastwood et al., 2009; Steiner and Wehrlin, 2011; Ulrich et al., 2011), this study shows that Hbmass might be influenced at a very young age by long-term endurance training. The main finding from the

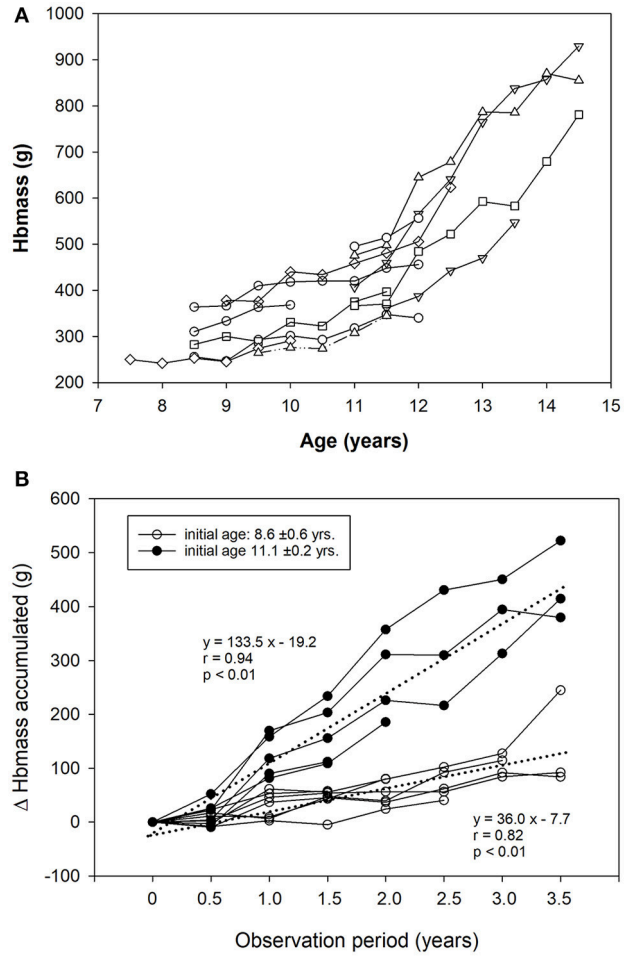


FIGURE 3 | (A) Changes in Hbmass with age in trained boys (longitudinal part of study 1). **(B)** Accumulated increase in Hbmass over the 3.5-year observation period (trained boys only). The dashed lines indicate the regression lines for data from children who entered the study at the age of 8.6 and 11.1 years.

present study, however, is that the increase of Hbmass over time is mostly driven by changes in LBM, which overlaps with the effect of age but is additionally influenced by the sex of the individual and training volume.

Furthermore, study 2 showed that an early high Hbmass might already have a positive influence on later competition success in youth soccer for children between the ages of 7.8 ± 0.2 years and 10.3 ± 0.3 years.

Development of Hbmass During Adolescence

In study 1, the mean values for Hbmass of the athletes (∼420 g) and controls (∼370 g) was similar to published data, showing a mean value of ∼430 g in 11–13-year-old boys (von Dobeln and Eriksson, 1972) and ∼370 g in 12–13-year-old girls and boys (Astrand, 1952).

Below the age of 12 years, Hbmass was slightly higher in boys than in girls (estimate by ANCOVA was ∼25 g), which agrees with the data of Karlberg and Lind (1955). Hbmass showed a very similar increase in both sexes until the onset of puberty (**Figure 1**, ∼36 g·yr^{-1}). Afterwards, the increase became considerably less in girls, while the increase was almost exponential in boys (133 g·yr^{-1}).

Despite the obvious increase in Hbmass with age, ANCOVA did not show any independent statistical effects of age on Hbmass, as the effects fully overlapped with those of LBM. As demonstrated in **Figure 2**, linear regression analysis showed a strong relationship ($r = 0.959$, $p < 0.001$) between both parameters, demonstrating that a 1 kg increase in LBM was associated with a 14.8 g increase in Hbmass. This close relationship has been shown for adults in various recent studies (Sawka et al., 1992; Schumacher et al., 2008) but has not previously been shown for children, and the present results prove that the development of LBM, to a great extent, explains changes in Hbmass. A very similar picture as that for Hbmass was found for BV with respect to the percentage change, time course and statistical dependency on LBM, which is in agreement with previous studies (Astrand, 1952; Karlberg and Lind, 1955; von Dobeln and Eriksson, 1972). We, therefore, conclude that LBM is a strong predictor of Hbmass and BV in children, as this parameter indirectly incorporates age, height, and body mass.

When analyzing the development of Hbmass as a function of age, it is apparent that Hbmass increases exponentially at the age of ∼12 years in most boys (**Figure 3A**). Whether this sharp increase reflects puberty-associated changes in erythropoiesis can only be speculated as more specific data on maturation were unfortunately not obtained in this study. However, data from the literature showing a close relationship between the increase in testosterone levels during puberty and [Hb] (Krabbe et al., 1978; Thomsen et al., 1986; Hero et al., 2005) support our hypothesis that Hbmass is affected by androgens and that the increase in Hbmass in the boys starting at the age of ∼12 years is directly due to increasing testosterone levels.

In females, the lower level of testosterone relative to that in male adolescents is probably the reason for the plateau in Hbmass, which becomes obvious during and after puberty (Astrand, 1952; Tanner, 1962). We consider the lack of capacity for further increases in Hbmass as one reason for the early peak in performance in women, which is frequently observed by the age of 14 years in, for example, swimming (Kojima et al., 2012).

Influence of Endurance Training on Hbmass

It is a well-known fact that elite endurance athletes possess an ∼40% higher Hbmass than sedentary subjects (Heinicke et al., 2001); in top individual athletes, differences in Hbmass greater than 70% have been observed (Heinicke et al., 2001). One important reason is most likely a training-independent genetic predisposition, as subjects with high rel. VO2max (65 ml·kg^{-1}·min^{-1}) but without any training history are characterized by a 24% higher Hbmass and 16% higher BV than subjects with low rel. VO2max (46 ml·kg^{-1}·min^{-1}) (Martino et al., 2002). Therefore, a strong genetic impact can be assumed.

The impact of the training itself on accelerated erythropoiesis has been discussed and the findings are controversial. In adult elite endurance athletes, changes in training volume and intensity showed no (Prommer et al., 2008) or only very small effects (3%, Garvican et al., 2010b) on Hbmass. Higher effects (6.4%) have

TABLE 4 | Performance data (study 1).

	Abs. VO_{2max} ($ml \cdot min^{-1}$)	Rel. VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	Max. speed ($km \cdot h^{-1}$)	Max. heart rate ($b \cdot min^{-1}$)	RER
TRAINED ($n = 17$)					
Initial values	1,969 ± 448	56.0 ± 6.4	15.0 ± 1.7	204 ± 10	1.23 ± 0.08
Final values	2,382 ± 6***	50.1 ± 5.1**	15.6 ± 1.6*	203 ± 11	1.25 ± 0.10
Mean values	2,297 ± 612+	54.4 ± 5.2+++	15.4 ± 1.5+++	203 ± 10	1.23 ± 0.07
Controls ($n = 18$)	1,898 ± 475	44.9 ± 5.6	12.1 ± 1.7	198 ± 6	1.18 ± 0.10

*RER, respiratory exchange ratio. For explanations of the term "Mean values" and for statistical abbreviations, see **Table 1**.*

TABLE 5 | Anthropometric and hematological data of the participants of study 2.

	Age (years)	Height (cm)	Body mass (kg)	LBM (kg)	Hbmass (g)	Rel. Hbmass ($g \cdot kg^{-1}$)	Rel. Hbmass ($g \cdot kg\ LBM^{-1}$)	BV (ml)	Rel. BV ($ml \cdot kg^{-1}$)	Rel. BV ($ml \cdot kg\ LBM^{-1}$)	[Hb] ($g \cdot dl^{-1}$)
Mean ± SD	7.8 ± 0.2	125 ± 5	24.5 ± 2.7	22.6 ± 2.5	250.8 ± 23.7	9.8 ± 0.8	11.3 ± 0.4	2,186 ± 206	85.0 ± 6.1	98.4 ± 3.0	12.6 ± 0.4
Minimum	7.5	119	22.0	19.9	226.8	8.3	10.9	2,017	73.9	94.1	12.0
Maximum	8.1	133	29.7	27.5	298.7	10.7	12.1	2,628	90.4	102.2	13.1

*n = 9; for further explanations, see **Table 1**.*

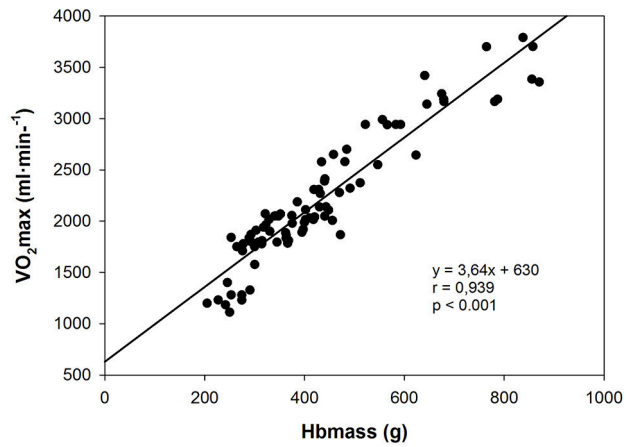


FIGURE 4 | Relationship between VO2max and Hbmass. Data are from the longitudinal part of study 1 (trained children) and the cross-sectional sub-study (control group).

only been demonstrated in recreational athletes preparing for a marathon competition over 9 months (Schmidt and Prommer, 2008). Thus, the available data demonstrates that training during adulthood only yields negligible stimulating effects on Hbmass, which cannot explain the large differences between endurance athletes and sedentary subjects. Therefore, the hypothesis arises that training during adolescence or even childhood may have an essential impact on erythropoiesis. This idea is also supported by the fact that East African runners start with high-volume training at very early stages in life (Prommer et al., 2010).

Today, there are four studies available highlighting this controversial point. Steiner and Wehrlin (2011) compared Hbmass values of elite endurance athletes at 16, 21, and 28 years and reported 15% higher values for the 21-year-old athletes than for the 16-year-old athletes. However, no further increases were observed from 21 until 28 years of age. They concluded that the period between 16 and 21 years is a very sensitive phase for training effects, whereas training at a younger age appeared to have negligible effects with respect to enhanced erythropoiesis. Ulrich et al. (2011) monitored the Hbmass of 15–17-year-old boys and girls during a 1.5-year training period. They found a 15% higher Hbmass in the trained subjects than in the untrained subjects but found no training effects. Very similar results were demonstrated for 11–15-year-old boys and girls; these results showed 10% higher values in the athletic group (cyclists) than in the sedentary subjects. Changes in Hbmass occurring during the one-year training period were attributed to the normal maturation process and not to the training itself (Eastwood et al., 2009). In the only study conducted with younger children (mean age 11.8 years) (von Dobeln and Eriksson, 1972), an increase in Hbmass of 39 g after a 16-week training program was attributed solely to normal growth in the children. These results coincide well with the increase of 133 $g \cdot yr^{-1}$ observed in this study for this age group (**Figure 3B**), corresponding to a change of 41 g/16 weeks. In the present study, which first monitored Hbmass in children between 8 and 12 years and then monitored it over a longer training period of up to 3.5 years, a training effect of approx. 25 g (corresponding to 7%) was demonstrated for Hbmass (**Table 3**). This effect was not statistically related to the effect of LBM, which suggests the existence of an independent training effect not due to normal growth mechanisms. However, as we did not include a longitudinal control group during the training period, we cannot determine whether the 7% increase related to training is due to a direct training effect or due to a selection process that favors children with a naturally high Hbmass (Eastwood et al., 2009; Ulrich et al., 2011). In any case, the 7% higher values related to training cannot explain the large differences between trained and untrained subjects in adulthood. As was shown for VO2max (Bouchard et al., 1998, 1999; Martino et al., 2002), we hypothesize a high basic genetic impact and

a genetically determined influence of endurance training on Hbmass, which, according to Steiner and Wehrlin (2011), may preferentially occur in late puberty.

Aerobic Performance

VO2max in our athletic group was 21% higher than in the control group and 24% higher than in a group of untrained children between 11 and 13 years (von Dobeln and Eriksson, 1972). During the monitoring time, absolute VO2max increased by ∼400 ml, which is in line with a meta-analysis including data from 2100 boys between 6 and 16 years (Bar-Or and Rowland, 2004). In contrast, relative VO2 max decreased by 5.9 $ml \cdot kg^{-1} \cdot min^{-1}$, which is normally observed in girls above the age of 11 years but not in boys. One reason may be the relatively high baseline values obtained during the period when all participants performed intensive endurance training; however, with increasing age, the training volume was reduced in some of the boys.

The strong dependency of VO2max on Hbmass ($r = 0.939$, **Figure 4**) is demonstrated by the slope of the regression line (3.64); this indicates that a 1 g change in Hbmass results in an ∼4 $ml \cdot min^{-1}$ change in VO2max. As nearly identical slopes were found in several studies with adults (Gore et al., 1997; Schmidt and Prommer, 2010), we can conclude that Hbmass exerts the same impact on the oxygen transport system in children as in trained and untrained adults. During incremental exercise, therefore, Hbmass gains importance as a limiting factor, in combination with a high level of muscle perfusion and a high cardiac output, in the maximum supply of oxygen to working tissues.

Prognostic Relevance of Hbmass

The significant relationship ($r = 0.627$, $p = 0.035$) in our pilot study on the prognostic relevance of blood parameters, in this case between Hbmass and performance level in soccer competitions 2.5 years later in prepubertal boys (7.8 years), hints to a possible relevance of the aerobic component of exercise for soccer performance. This is in line with Eastwood's et al. hypothesis of the prognostic validity of Hbmass for talent identification (Eastwood et al., 2012a) not only in pure endurance disciplines but also in soccer, where the long distances covered during a game make high demands on the endurance of the players.

Study Limitations

The main limitation of both studies is the small number of athletic children, especially of girls in study 1. A lack of a control group in study 1 that was monitored over the same time period and with the same frequency as the athletic group makes it difficult to distinguish between real training effects and genetic predispositions. Furthermore, a mean training volume of 3.5 h/week may be too low to achieve relevant increases in Hbmass. In contrast, it is very difficult to monitor young children with regard to a continuous and high training impact over several years as children do not focus on high-performance training groups at this age and the drop-out rate is quite high. Therefore, the data presented here provide valuable insights into changes in Hbmass under a relatively intensive training burden in prepubertal children.

CONCLUSION

Hbmass linearly increases between the ages of 8 and 12 years in both sexes, showing a mean increase of ∼25 $g \cdot yr^{-1}$. Beyond 12 years, increases in Hbmass are almost exponential in boys, with a change of ∼130 $g \cdot yr^{-1}$ probably reflecting the impact of testosterone production during puberty. These age-related changes in Hbmass are mainly promoted by the development of LBM, although long-term endurance training (>4 h/week) exerts additional effects (∼7%). However, this study cannot definitively conclude whether the higher Hbmass found in endurance-trained children below the age of 12 years is due to the training itself or due to genetic preselection. Also, some limitations of this study, such as the low number of female athletes and the lack of collection of cross sectional data in the control group, require a cautious interpretation of our results. However, our data hint at positive effects of a high Hbmass at an early age on subsequent competition performance in, for example, soccer.

AUTHOR CONTRIBUTIONS

NP, IT, AH, and WS: conceived the study; NP, NW, IT, EM-S, CW, AH, and WS: contributed to data collection, with NP and WS performing all statistical analyses; NP, AH, and WS: drafted the manuscript, to which NW, IT, EM-S, and CW then contributed. All authors read and approved the final version of the manuscript; NP, NW, IT, EM-S, CW, AH, and WS: agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Sport-Specific Assessment of the Effectiveness of Neuromuscular Training in Young Athletes

Erika Zemková[1,2]* *and Dušan Hamar*[1]

[1] Department of Sports Kinanthropology, Faculty of Physical Education and Sport, Comenius University in Bratislava, Bratislava, Slovakia, [2] Sports Technology Institute, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Bratislava, Slovakia

Neuromuscular training in young athletes improves performance and decreases the risk of injuries during sports activities. These effects are primarily ascribed to the enhancement of muscle strength and power but also balance, speed and agility. However, most studies have failed to demonstrate significant improvement in these abilities. This is probably due to the fact that traditional tests do not reflect training methods (e.g., plyometric training vs. isometric or isokinetic strength testing, dynamic balance training vs. static balance testing). The protocols utilized in laboratories only partially fulfill the current needs for testing under sport-specific conditions. Moreover, laboratory testing usually requires skilled staff and a well equipped and costly infrastructure. Nevertheless, experience demonstrates that high-technology and expensive testing is not the only way to proceed. A number of physical fitness field tests are available today. However, the low reliability and limited number of parameters retrieved from simple equipment used also limit their application in competitive sports. Thus, there is a need to develop and validate a functional assessment platform based on portable computerized systems. Variables obtained should be directly linked to specific features of particular sports and capture their complexity. This is essential for revealing weak and strong components of athlete performance and design of individually-tailored exercise programs. Therefore, identifying the drawbacks associated with the assessment of athlete performance under sport-specific conditions would provide a basis for the formation of an innovative approach to their long-term systematic testing. This study aims (i) to review the testing methods used for the evaluation of the effect of neuromuscular training on sport-specific performance in young athletes, (ii) to introduce stages within the Sport Longlife Diagnostic Model, and (iii) to propose future research in this topic. Analysis of the literature identified gaps in the current standard testing methods in terms of their low sensitivity in discriminating between athletes of varied ages and performance levels, insufficent tailoring to athlete performance level and individual needs, a lack of specificity to the requirements of particular sports and also in revealing the effect of training. In order to partly fill in these gaps, the Sport Longlife Diagnostic Model was proposed.

Keywords: agility, balance, core stability, muscle strength and power, speed, testing

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Charles University, Czechia

***Correspondence:**
Erika Zemková
erika.zemkova@uniba.sk

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INTRODUCTION

All of us are aware of the importance of reaching the correct diagnosis to identify the illness and craft a prompt treatment. Though sport cannot be compared with clinics, the right and accurate assessment of athlete performance is crucial for designing effective training programs. Getting the right diagnostics is also a key for physical fitness development in general population. It provides useful information on their strengths and weakness and in this way it may reveal potential health risks. By focusing exercise programs on these aspects, it may prevent some type of diseases or injuries before they ever occur.

So far, most of the diseases have been linked to the elderly population; however today, more than ever before they affect middle-aged people (e.g., low back pain), and even the young generation (e.g., diabetes). This issue could be related to workplace conditions (occupational stress, manual operations, etc.) and/or a sedentary way of life. Identifying symptoms associated with a particular disease by assessing the body balance, muscle strength and power or hamstring flexibility may be considered as a "preventive" tool before it starts to become a chronic disease.

Although several field tests have been proposed for various populations, most of them do not meet the requirements of the modern age. One of their main shortcomings is the insufficient reliability and limited number of variables due to the very simple equipment used. Therefore, there is a need to apply portable computerized systems for testing both athletes and untrained subjects of different ages and fitness levels. Only on the basis of relevant variables, their performance capabilities may be evaluated and appropriate exercise programs designed. Testing batteries should include user-friendly, portable and low-cost diagnostic systems well suited for the testing of varied groups in a relatively short time period. These batteries might be applicable in clinical settings, as well as in non-medical institutions, fitness centers or school sports clubs.

In particular, testing batteries for young individuals should get a makeover. So far, a variety of them have been developed for school age children. In Europe, it is the Eurofit Physical Fitness Test Battery, devised by the Council of Europe, that has been used in many European schools since 1988. This test battery includes nine tests assessing speed, strength, endurance and flexibility. Despite the many advantages of field tests, these do not sufficiently reflect various aspects of physical fitness relevant to a particular age and are not sensitive enough to exercise induced changes specific to a particular sport. These traditional methods of assessing the physical fitness of children and adolescents only partially fulfill current needs for testing under sport-specific conditions.

Preliminary analysis of the literature identified the gap in current standard testing methods in terms of their low sensitivity in discriminating between young athletes of varied ages and performance levels and specificity to reveal the effect of training. This study aims (i) to review the existing testing methods used for the evaluation of the effect of neuromuscular training on sport-specific performance in young athletes, (ii) to introduce stages within the Sport Longlife Diagnostic Model, and (iii) to propose future research in this topic.

METHODS

Two specific questions were addressed in this review: (1) Can existing testing methods effectively evaluate changes in sport-specific performance of young athletes following neuromuscular training? and (2) Which of the current tests are suitable to be implemented in the Sport Longlife Diagnostic Model?

In order to answer these questions and to reveal the gaps in the current literature, we provided a literature search. Electronically available literature was searched using the MEDLINE database, PubMed, SportDiscus® and Web of Science. Additional searches were performed on SpringerLink, Elsevier, EBSCOhost and Google Scholar. Besides peer-reviewed journal articles, available conference proceedings were analyzed. Search results were limited to studies closely related to the main topic of this review—to identify methods used for assessment of the effectiveness of neuromuscular training on physical fitness in children and adolescents. Our primary focus was on testing under sport-specific conditions. However, this approach resulted in the identification of a small number of studies that were considered eligible for the review. Therefore other relevant studies that evaluated the effect of training on at least one measure of neuromuscular functions and/or athletic performance were included. This help us to identify the gap in current testing methods using for evaluation of changes in neuromuscular performance after specific training in a particular sport.

The target population was young competitive athletes coupled with other groups of children and adolescents involved in physical activities in sport clubs or schools. The most frequent terms "neuromuscular training," "resistance training," "strength and power training," "plyometric training," "muscular fitness," "muscle strength," "muscle power," and "muscular endurance" used for research procedure were combined with particular sports (basketball, gymnastics, soccer, swimming, tennis, volleyball, etc.). Further searches were conducted using relevant words from each subheading, namely tests used for assessment of muscular fitness. The key inclusion criterion was that studies evaluated the effects of neuromuscular training on sport-specific athlete performance. In consequence of limited research in this field, studies investigating the effects of such a training on traditional measures of muscle strength and power, core stability and strength, body balance, agility and speed were also included. These abilities represent a crucial aspect of performance in many sports, and therefore their assessment should be an integral part of testing in young athletes. Studies were excluded if tests or testing batteries were not sufficiently specified. Studies that failed to meet these conditions were excluded from this review.

RESULTS AND DISCUSSION

Overview of Test Batteries for Assessment of Physical Fitness in Children and Adolescents

Fitness testing is a common part of the curriculum in many schools. These testing programs vary across regions, countries and continents.

One of the first were the American Alliance for Health, Physical Education, Recreation and Dance (AAHPERD) test battery, developed in 1957, which included pull-up, standing long jump, flexed leg sit-up, shuttle run, 50-yard dash, and 600-yard run (option: 1 mile or 9 min run for 10–12 years old, and 1.5 miles or 12 min run for ≥13 years old) (AAHPERD, 1976), and the Canadian Association for Health, Physical Education and Recreation (CAHPER) test battery, which dates back to 1963, and included flexed arm hang, standing long jump, 1 min speed sit-ups, shuttle run, 50 m run and endurance run (800 m run for 6–9 years old, 1,600 m run for 10–12 years old, and 2,400 m run for 13–17 years old) (CAHPER, 1980).

In 1994, AAHPERD adopted FITNESSGRAM as its national fitness testing program. The FITNESSGRAM Health-related fitness test battery consists of following tests: bent arm hang (included in 1987), pull up (included in 1987, removed in 2005), 90° push-up (included in 1992), modified pull up (included in 1992), curl-up (included in 1992), trunk lift (included in 1992), modified sit-up test (included in 1987, removed in 1992), one mile run/walk (included in 1987), one mile walk test (included in 1999), PACER test—a 20 m progressive, multi-stage shuttle run (included in 1992), shuttle run K-3 (included in 1987, removed in 1992), sit and reach test (included in 1987, removed in 1992), shoulder stretch (included in 1992), and back saver sit and reach (included in 1992; Plowman et al., 2006).

However, in September 2012 the New Presidential Youth Fitness Program was launched. This program is focused on assessing health rather than the athleticism of America's youth. The updated version was intended to assess health related fitness of youth with emphasis on their personal goals. This new program was developed in partnership with experts in youth fitness and health promotion including the Amateur Athletic Union, the American Alliance for Health, Physical Education, Recreation and Dance, the Centers for Disease Control and Prevention and the Cooper Institute.

In Europe, the most used is the Eurofit Physical Fitness Test Battery (Council of Europe, Committee for the Development of Sport, 1993) that includes plate tapping—tests speed of limb movement, handgrip test—measures static arm strength, bent arm hang—measures muscular endurance/functional strength, standing broad jump—measures explosive leg power, sit-ups in 30 s—measures trunk strength, 10 × 5 m shuttle run—measures running speed and agility, 20 m endurance shuttle run—tests cardiorespiratory endurance, flamingo balance test—single leg balance test, and sit-and-reach—flexibility test. Another example is the Assessing Levels of Physical Activity (ALPHA) health-related fitness test battery for children and adolescents. This includes a 20 m shuttle run test, handgrip strength test, standing broad jump, and a 4 × 10 m shuttle run test (Ruiz et al., 2011).

Further examples are: International Physical Fitness Test (United States Sports Academic, General Organization of Youth and Sport of Bahrain), Amateur Athletic Union Test Battery (Chrysler Foundation, Amateur Athletic Union), YMCA Youth Fitness Test, National Youth Physical Program (the United States Marines Youth Foundation), Fit-4-Fun test battery, Canadian Physical Activity, Fitness and Lifestyle Approach (Canadian Society for Exercise Physiology), National Fitness Test Program in the Popular Republic China (China's National Sport and Physical Education Committee), Australian Fitness Education Award (the Australian Council for Health, Education and Recreation), New Zealand Fitness Test (Rusell, Department of Education), and so forth.

In general, these batteries include tests assessing endurance (e.g., 20 m shuttle run, Cooper test–12 min run, 9 min run, cycle ergometer sub-maximal test, 1.5 mile run/walk test, 1 mile run/walk test, 1/2 mile run/walk test, 1/4 mile run/walk test, 1,000 m run), speed and agility (e.g., 50 m sprint or 50 yard run, 100 m dash, shuttle run for 4 × 10 m or 10 × 5 m, shuttle run with sponges for 10 × 4 m, plate tapping), muscle strength (e.g., handgrip, medicine ball or basketball throw, bent arm hang, push-ups and their modifications, standing broad jump, vertical jump—countermovement jump, Abalakov jump and Sargent jump—vertical jump tests with the arms swing, sit-ups and their modifications–7-stage, 30, 60 s, or up to failure, trunk lift), balance (e.g., Flamingo balance test), and flexibility (e.g., sit and reach, stand and reach, V sit and reach, and shoulder stretch).

Similar test batteries consisting primarily of strength tests have been used to evaluate the effect of neuromuscular training on physical fitness in children and adolescents (**Table 1**). These batteries include mainly repetition maximum (1, 6, 10 RM) strength test on various exercises (e.g., bench press, squat, leg press, knee extension, elbow flexion), isometric strength tests (e.g., leg extensors on a leg press), medicine ball throwing, push-ups, curl-ups, handgrip, repeated leg press or chest press exercise, standing long jump, vertical jump (e.g., squat jump, countermovement jump, drop jump, jumping sideways, triple hop, single-leg hop, maximal and submaximal hopping), Bourban trunk muscle strength test—assesses core strength endurance, speed and agility tests (sprints at 10, 20, or 30 m, shuttle run, Illinois agility test), PACER test—multistage, 20 m shuttle run, half mile run, one mile run, or other cardiorespiratory fitness tests, static and dynamic balance tests (e.g., standing on a stable platform or those exposed to perturbations, Stork stand balance test, Y balance test, Star excursion balance test), flexibility tests (stand and reach, sit and reach, V sit and reach, shoulder stretch), and other more specific tests based for instance, on coordination tasks.

Overview of Tests for Assessment of the Effect of Neuromuscular Training on Athlete Performance

Analysis of the literature identified (**Table 1**) that the efficiency of neuromuscular training (namely resistance and plyometric or in combination with balance, agility and other exercises) was evaluated mainly by repetition maximum tests (1, 3, 6,

TABLE 1 | Overview of tests for assessment of the effect of neuromuscular training on physical fitness of children and adolescents.

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Alves et al., 2016	Strength/Strength and aerobic	8	Schoolchildren	41, 45, 38/44	F,M	10–11	Medicine ball throwing (1 and 3 kg) Standing long jump Countermovement jump 20 m sprint
Andrejić, 2012	Strength/Plyometric and strength	6	Basketball players	10+11	M	12–13	Vertical jump Long jump Seated medicine ball toss 20 m sprint 4 × 15 m standing start running Stand and reach flexibility test
Annesi et al., 2005	Cardiovascular, resistance, flexibility	12	Schoolchildren	570	F,M	5–12	Push-ups Shoulder stretch 1 mile run/walk
Assunção et al., 2017	Plyometric	10	Track and field athletes, volleyball, basketball, and soccer players	14/15		∼16.79, 16.85	30 m sprint 1600 m aerobic test Running anaerobic sprint test
Barber-Westin et al., 2010	Neuromuscular	6	Tennis players	15	F,M	∼13.0	Single-leg hop for distance test Single-leg triple crossover hop for distance test Baseline speed and agility forehand and backhand tests Service box speed and agility tests Single-court and 2-court suicide runs Abdominal endurance test
Behringer et al., 2013	Resistance/Plyometric	8	Tennis players	12, 12/12	M	∼15.03	10 repetition maximum test Service velocity test Service precision test
Benson et al., 2007	Resistance	8	Intermediate and high-school students	37/41		10–15	1 repetition maximum bench press and leg press Cardiorespiratory fitness test
Bishop et al., 2009	Plyometric	8	Swimmers	11/11		∼13.1, 12.6	Swimming block start test
Brown et al., 1986	Plyometric	12	High school basketball players	13/13	M	∼15.0	Vertical jump without arms swing Vertical jump with arms swing
Buchheit et al., 2010a	Explosive strength/Repeated shuttle sprint	10	Soccer players	7, 8	M	∼14.5	10 and 30 m sprints Repeated shuttle sprint ability test Countermovement jump Hopping test
Buchheit et al., 2010b	Speed-agility/Sprint interval	4	Handball players	7, 7	M	∼16.0, 16.0	Countermovement jump 10 m sprint Repeated sprint ability test Graded intermittent aerobic test (30–15 Intermittent Fitness Test)
Cavaco et al., 2014	Strength and plyometric	6	Soccer players	5, 5/6	M	∼13.8, 14.2/14.2	1 repetition maximum squat 15 m sprint 15 m agility test with the ball Crossing efficiency and shooting efficiency tests

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Channell and Barfield, 2008	Olympic/Traditional resistance	8	High school athletes	11, 10/6	M	~15.9	Vertical jump 1 repetition maximum squat and power clean
Chaouachi et al., 2014	Plyometric/Balance and plyometric	8	Schoolchildren	14, 14/12	M	12–15	1 repetition maximum leg press Horizontal and vertical jumps Triple hop for distance test Reactive strength test Leg stiffness test 10 and 30 m sprints Standing Stork test Star excursion balance test Shuttle run test
Chaouachi et al., 2017	Balance and plyometric	8	Soccer players	26	M	~13.9	Isometric back and knee extension strength tests Countermovement jump Standing long jump Triple hop test Maximal and submaximal hopping test 10 and 30 m sprints 49 m shuttle run test Standing Stork test Y-balance test
Chelly et al., 2009	Strength	8	Soccer players	11/11	M	~17.0	Cycling force-velocity test Squat jump Countermovement jump 5-jump test 40 m sprint 1 repetition maximum back half squat at 90 degrees
Chelly et al., 2014	Plyometric	8	Handball players	12/11	M	~17.4	Force-velocity ergometer tests for upper and lower limbs Squat jump Countermovement jump Video filming of sprint velocities (first step, first 5 m, and 25–30 m)
Chelly et al., 2015	Plyometric	10	Track athletes	14/13	M	~11.9	Cycle ergometer force-velocity test Squat jump Countermovement jump Drop jump Multiple 5-bound test 40 m sprint
Christou et al., 2006	Soocer, strength and soccer	16	Soccer players	9, 9/8	M	12–15	1 repetition maximum leg press and bench press Squat jump Countermovement jump Repeated jumps for 30 s 30 m sprint 10 × 5 m shuttle run Seat and reach flexibility test Soccer technique

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Coutts et al., 2004	Resistance	12	Rugby players	21/21	M	~16.7	3 repetition maximum bench press and squat Maximal chin-ups Countermovement jump with the arm swing 10 and 20 m sprints
da Fontoura et al., 2004	Strength	12	Schoolchildren	7/7	M	~9.4/9.7	1 repetition maximum knee extension and elbow flexion
Diallo et al., 2001	Plyometric	10	Soccer players	10/10	M	12–13	Countermovement jump Squat jump Drop jump Multiple 5-bound test Repeated rebound jumps for 15 s 20, 30, and 40 m sprints Force-velocity cycling test
Drinkwater et al., 2005	Bench press	6	Basketball and soccer players	12+14	M	~18.6, 17.4	6 repetition maximum bench press Smith machine bench throw with 40 kg
Escamilla et al., 2010	Baseball conditioning	4	Baseball players	17/17		11–15	Throwing velocity test
Faigenbaum et al., 1993	Strength	8	Schoolchildren	15/10	F,M	8–12	10 repetition maximum strength test Sit and reach flexibility test Vertical jump Seated ball put
Faigenbaum et al., 1996	Strength	8	Schoolchildren	15/9	F,M	7–12	6 repetition maximum leg extension and chest press Vertical jump Sit and reach flexibility test
Faigenbaum et al., 1999	Resistance	8	Schoolchildren	15, 16/12	F,M	5.2–11.8	1 repetition maximum strength and muscular endurance tests on the leg extension and chest press
Faigenbaum et al., 2001	Resistance	8	Schoolchildren	15, 16, 12, 11/12	F,M	5.2–11.8	1 repetition maximum vertical chest press Local muscular endurance test on the vertical chest press
Faigenbaum et al., 2002	Strength	8	Schoolchildren	21+34	F,M	7.1–12.3	1 repetition maximum chest press and leg press Handgrip strength test Long jump Vertical jump Sit and reach test
Faigenbaum et al., 2005	Resistance	8	Schoolchildren	23+20	F,M	8.0–12.3	1 repetition maximum chest press Local muscular endurance test (15 RM) on the leg press Long jump Vertical jump V-sit flexibility test
Faigenbaum and Mediate, 2006	Medicine ball	6	High-school students	69/49	F,M	15–16	Shuttle run test Long jump Sit and reach flexibility test Abdominal curls Medicine ball push-up Medicine ball seated toss

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Faigenbaum et al., 2007a	Plyometric and resistance/Resistance	6	Baseball and American football players	13, 14	M	12–15	Vertical jump Long jump Seated medicine ball toss 9.1 m (10 yd) sprint Pro-agility shuttle run test V-sit flexibility test
Faigenbaum et al., 2007b	Resistance	9	Schoolchildren	22	M	∼13.9	10 repetition maximum squat and bench press Vertical jump Seated medicine ball toss Sit and reach test PACER test (multistage, 20 m shuttle run)
Faigenbaum et al., 2009	Plyometric	9	Schoolchildren	40/34	F,M	8–11	Standing long jump Sit and reach flexibility test Curl-up test Push-up test Shuttle run test Half mile run
Faigenbaum et al., 2013	Muscular fitness	8	Schoolchildren	20/19	F,M	∼7.5/7.6	Standing long jump Single-leg hop Curl-up test Stork stand balance test
Falk and Mor, 1996	Resistance and martial arts	12	Schoolchildren	14/15	M	6–8	Sit-ups for 20 s Seated ball put Standing broad jump Sit and reach flexibility test 6 × 4 m shuttle run Coordination task
Fernandez-Fernandez et al., 2013	Strength	6	Tennis players	15/15	M	13	Service velocity test Service accuracy test Shoulder internal/external rotation test
Ferrete et al., 2014	Strength and high-intensity	26	Soccer players	11/13		8–9	15 m sprint Countermovement jump Yo-Yo intermittent endurance test Sit and reach flexibility test
Filipa et al., 2010	Neuromuscular	8	Soccer players	13/7	F	∼15.4/14.7	Star excursion balance test
Flanagan et al., 2002	Strength	11	Third-grade students	14, 24/20	F,M	∼8.75, 8.64, 8.65	Two-handed medicine ball put Standing long jump Shuttle run test
Gabbett et al., 2008	Strength, conditioning, and skills	10	Rugby players	14+21		∼14.1, 16.9	Vertical jump 10, 20, and 40 m sprints 505 Agility test Multistage fitness test
González-Badillo et al., 2005	Resistance	10	Lifters	16, 17, 18	M	∼16.4, 16.5, 16.8	1 repetition maximum snatch, clean and jerk, and back squat

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
González-Badillo et al., 2006	Heavy resistance	10	Weightlifters	12, 9, 8	M	~17.1, 16.9, 17.5	1 repetition maximum snatch, clean and jerk, and back squat
Gorostiaga et al., 1999	Heavy resistance	6	Handball players	9, 10/4	M	14–16	Maximal isometric knee extensions and flexions 1 repetition maximum leg press and pec-dec Squat jump Countermovement jump Throwing a handball ball Running test
Gorostiaga et al., 2004	Strength	11	Soccer players	8/11	M	~17.2	Countermovement jump 5 and 15 m sprints Endurance running test
Granacher et al., 2011	Ballistic strength	8	High-school students	14/14		~16.7, 16.8	Isometric strength test of the leg extensors on the leg press Countermovement jump One-legged balance test Mediolateral perturbation test
Granacher et al., 2014	Core strength (stable, unstable)	6	Physically active adolescents	13, 14	F,M	13–15	Bourban TMS test Standing long jump 20 m sprint Stand and reach test Jumping sideways test Emery balance test Y balance test
Granacher et al., 2015	Plyometric (stable, highly unstable)	8	Soccer players	12, 12	M	~15.2, 15.6	Countermovement jump Drop jump Multiple 5-bound test 30 m linear sprint Figure-8 run agility test One-legged balance test Star excursion balance test Mediolateral perturbation test
Hammami et al., 2016	Balance and plyometric	8	Soccer players	24	M	12–13	Medicine ball throw Countermovement jump Maximal and submaximal hopping test 4 × 9 m shuttle run 10, 20, and 30 m sprints Standing Stork balance test Y-Balance test
Häkkinen et al., 1989	Endurance, sprint, strength	1y	Endurance runners, sprinters, weightlifters	4, 4, 4+6/6	M	11–13, 17/11–12	Multistage treadmill run test Isometric strength of the leg extensor muscles Countermovement jump Maximal squat lift

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Keiner et al., 2014	Strength	2y	Soccer players	62/50		13–18	Change of direction sprint test 1 repetition maximum/body mass in the squat
King and Cipriani, 2010	Plyometric	6	High school basketball players	16, 16		14–16	Vertical jump
Klusemann et al., 2012	Supervised or video-based resistance	6	Basketball players	13, 13/12	F,M	14–15	20 m sprint Step-in vertical jump Agility test Sit and reach test Line drill test Yo-Yo intermittent recovery test (level 1) 15-s push-ups and pull-ups Functional movement screening
Kotzamanidis et al., 2005	Combined high-intensity strength and speed	9	Soccer players	12, 11/12	M	∼17.0, 17.1, 17.8	Squat jump Countermovement jump Drop jump from the height of 40 cm 30 m dash 1 repetition maximum for each exercise
Kotzamanidis, 2006	Plyometric	10	School students	15/15		∼11.1/10.9	Squat jump Running at distances 0–10, 10–20, 20–30, and 0–30 m
Lehnert et al., 2009	Plyometric	8	Volleyball players	11	F	∼14.8	Standing vertical jump Vertical jump with an approach Shuttle run for 6 × 6 m
Lehnert et al., 2012	High resistance/Plyometric	5	Soccer players	8/8		∼17.8/17.8	Isokinetic strength of knee flexors and extensors Countermovement jump 10 and 30 m sprints
Lehnert et al., 2017	Pre-season conditioning (jumping, strength)	8	Volleyball players	12	F	∼16.8	Countermovement jump with free arms Squat jump with hands on the hips Drop jump with hands on the hips Isokinetic knee flexion and extension test
Lephart et al., 2005	Plyometric and resistance	8	Athletes	14, 13	F	∼14.5, 14.2	Isokinetic knee flexion and extension torque test Isometric hip abduction torque test Drop-landing test
Lloyd et al., 2012	Plyometric	4	School students	41, 44, 44	M	9, 12, 15	Maximal and submaximal hopping test
Maio Alves et al., 2010	Strength	6	Soccer players	9, 8/6	M	∼17.4	Squat jump Countermovement jump 5 and 15 m sprints 505 Agility test
Martel et al., 2005	Aquatic plyometric	6	Volleyball players	19	F	∼15.0	Vertical jump Knee extension and flexion strength test
Matavulj et al., 2001	Plyometric	6	Basketball players	11, 11/11	M	15–16	Countermovement jump Isometric tests of hip and knee extensors
Meylan and Malatesta, 2009	Plyometric	8	Soccer players	14/11	M	∼13.3, 13.1	10 m sprint Agility test Squat jump Countermovement jump Contact test Multiple 5-bound test

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Michailidis et al., 2013	Plyometric	12	Soccer players	24/21	M	∼10.6, 10.6	Graded exercise test on a treadmill 30 m sprint with a 10 m splits Standing long jump Multiple 5-bound test Squat jump Countermovement jump Drop jump from the height of 30 cm 10 repetition maximum barbell squat 30 s Wingate test Soccer-specific tests (agility, kicking distance)
Muehlbauer et al., 2012	High-velocity strength	8	High-school students	14/14	F,M	16–17	Isometric strength test on the leg press Countermovement jump
Mujika et al., 2009	Sprint and power	7	Soccer players	10, 10	M	∼18.1, 18.5	Countermovement jump without and with arms swing 15 s countermovement jumps 15 m sprint 15 m agility test
Myer et al., 2005	Neuromuscular	6	Basketball, soccer and volleyball players	41/12	F	13–17	Countermovement jump 9.1 m sprint Single-leg hop and hold distance test 1 repetition maximum squat and bench press Three-dimensional biomechanical analysis
Negra et al., 2016	Resistance and soccer/Soccer	12	Soccer players	13, 11		∼12.8, 12.7	1 repetition maximum half-squat Countermovement jump Squat jump Standing long jump Multiple 5-bound test 5, 10, 20, and 30 m sprints *T*-test Illinois change of direction speed test
Negra et al., 2017	Resistance/Plyometric	12	Soccer players	12, 11/11		∼12.8	20 m sprint Illinois change of direction speed test Countermovement jump Squat jump Standing long jump Multiple 5-bound test 1 repetition maximum half-squat
Nikolaidis, 2015	Plyometric	10	Soccer players	11/10	M	∼11.4/11.3	Standing long jump 10 and 30 m sprints
Potdevin et al., 2011	Plyometric	6	Swimmers	12/11	F,M	∼14.3, 14.1	Squat jump Countermovement jump Swim tests (a gliding task, 400 and 50 m front crawl with a diving start) 2 tests with a water start without push-off on the wall (25 m in front crawl and 25 m only with kicks)

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Prieske et al., 2016	Core strength (stable, unstable)	9	Soccer players	20, 19	M	~17.0	Tests of trunk muscle strength/activation Countermovement jump 20 m linear sprint T-agility test Kicking performance test
Ramírez-Campillo et al., 2013	Plyometric	7	High school students	9, 8, 7/5	M	~16.89	Strength tests (5 maximum repetitions) Drop jumps from heights of 20, 40, and 60 cm Squat jump Countermovement jump Timed 20 m sprint Illinois agility test
Ramirez-Campillo et al., 2014a	Plyometric	7	Soccer players	13, 14, 12/15	M	~10.4	Countermovement jump Drop jump from heights of 20 and 40 cm 20 m sprint Change of direction speed test Kicking performance test
Ramírez-Campillo et al., 2014b	Low-volume high-intensity plyometric	7	Soccer players	38/38	M	~13.2, 13.2	20 m sprint Illinois agility test Countermovement jump Drop jump from heights of 20 and 40 cm Multiple 5-bound test Maximal kicking test for distance 2.4 km time trial
Ramírez-Campillo et al., 2015a	Vertical, horizontal, and combined vertical and horizontal plyometric	6	Soccer players	10, 10, 10/10	M	10–14	Vertical and horizontal countermovement jumps with arms Multiple 5-bound test Drop jump from the height of 20 cm Maximal kicking velocity test Sprint test Change of direction speed test Yo-Yo intermittent recovery test (level 1) Balance tests (normal stance, eyes open; normal stance, eyes closed)
Ramírez-Campillo et al., 2015b	Plyometric	6	Soccer players	8, 8/8	M	~13.0	Bilateral and unilateral horizontal and vertical countermovement jumps with arms Drop jump from the height of 20 cm Maximal kicking velocity test 10 m sprint Change of direction speed test Yo-Yo intermittent recovery test (level 1)
Ramírez-Campillo et al., 2015c	Plyometric	6	Soccer players	54, 57/55	M	10–17	Squat jump Countermovement jump Drop jump from the height of 20 cm Broad long jump 20 m sprint 10 × 5 m agility test 20 m multistage shuttle run test Sit and reach test

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Ramírez-Campillo et al., 2015d	Unilateral, bilateral, and combined plyometric	6	Soccer players	16, 12, 12/14	M	10–15	Unilateral and bilateral countermovement jumps with arms Multiple 5-bound test Drop jump from the height of 20 cm Maximal kicking velocity test 15 and 30 m sprints Agility test Yo-Yo intermittent recovery test (level 1) Bilateral balance tests (normal stance, eyes open; normal stance, eyes closed; perturbed stance, eyes open; perturbed stance, eyes closed)
Rhea et al., 2008	Plyometric	12	High school athletes	32, 32	F,M	∼17.4	Countermovement jump
Roden et al., 2014	Strength (squats, CMJs)	6	High school basketball players	20	M	∼15.4	Countermovement jump
Rubley et al., 2011	Plyometric	14	Soccer players	10/6	F	∼13.4	Vertical jump Kicking distance test
Saeterbakken et al., 2011	Core stability	6	High-school handball players	14/10	F	∼16.6	Throwing velocity test
Sáez de Villarreal et al., 2015	Plyometric and sprint	9	Soccer players	13/13		14–15	10 m sprint 10 m agility test with and without the ball Countermovement jump Abalakov vertical jump Yo-Yo intermittent endurance test Ball-shooting speed test
Sander et al., 2013	Strength	24	Soccer players	134		U13,U15,U17	1 repetition maximum front and back squat 30 m linear sprint
Sankey et al., 2008	Plyometric	6	Rugby players	6, 6/6	M	∼14.5	Countermovement jump Drop jump
Santos and Janeira, 2008	Weight and plyometric	10	Basketball players	15/10	M	14–15	Squat jump Countermovement jump Abalakov test Depth jump Mechanical power test Medicine ball throw
Santos and Janeira, 2009	Resistance and plyometric	10	Basketball players	8, 7	M	14–15	Squat jump Countermovement jump Abalakov test Depth jump from a 40 cm platform Mechanical power test Seated medicine ball throw
Santos and Janeira, 2011	Plyometric	10	Basketball players	14/10	M	∼15.0, 14.5	Squat jump Countermovement jump Abalakov test Depth jump Mechanical power test Medicine ball throw

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Santos and Janeira, 2012	Resistance	10	Basketball players	15/10	M	14–15	Squat jump Countermovement jump Abalakov test Drop jump from a 40 cm platform Seated 3 kg medicine ball throw
Siegler et al., 2003	Plyometric, resistance, and high-intensity anaerobic	10	High school soccer players	17/17	F	∼16.5, 16.3	Abridged 45 min shuttle test Vertical jump 20 m running-start sprint 30 s Wingate test
Soh et al., 2007	Aerobic and strength	8	Sport school netball players	21		14–18	SEMO Agility run test Vertical jump
Söhnlein et al., 2014	Plyometric	16	Soccer players	12/11		11.2–14.7	20 and 30 m sprints Hurdle agility run 5 × 10 m shuttle run Multiple 5-bound test Standing long jump
Szymanski et al., 2007a	Resistance plus medicine ball	12	High school baseball players	25/24	M	∼15.4	3 repetition maximum torso rotations at the dominant and nondominant side Sequential hip-torso-arm rotational strength test (medicine ball hitter's throw) 3 repetition maximum parallel squat and bench press
Szymanski et al., 2007b	Resistance plus medicine ball	12	High school baseball players	25/24	M	∼15.4	3 repetition maximum torso rotations at the dominant and nondominant side Sequential hip-torso-arm rotational strength test (medicine ball hitter's throw) 3 repetition maximum parallel squat and bench press
Thomas et al., 2009	Plyometric	6	Soccer players	15	M	∼17.3	Countermovement jump 20 m sprint with a 5 m splits 505 agility test
Thompson et al., 2017	Resistance	6	High school athletes	38	M	15–18	1 repetition maximum back squat Countermovement jump
Tsimahidis et al., 2010	Heavy resistance combined with running	10	Basketball players	13/13		∼18.0/18.0	1 repetition maximum half squat 10 and 30 m sprints Squat jump Countermovement jump Drop jump
Tsolakis et al., 2004	Resistance	8	Untrained preadolescents	9/10	M	11–13	Isometric strength test 10 repetition maximum elbow flexion
Weston et al., 2015	Isolated core	12	Swimmers	10/10	F,M	∼15.7, 16.7	50 m front-crawl swim Straight-arm latissimus dorsi pull-down test Timed prone-bridge test Analysis of EMG activity of the core muscles while performing MVCs

(Continued)

TABLE 1 | Continued

Authors, year	Type of training	Duration (weeks)	Subjects	N (E/C)	Sex	Age (years)	Tests
Wong et al., 2010	Strength and power	12	Soccer players	28/23	M	~13.5/13.2	Countermovement jump Ball-shooting test 30 m sprint Yo-Yo intermittent endurance run (level 1) VO_2max test
Zribi et al., 2014	Plyometric	9	Basketball players	25/26	M	~12.1/12.2	30 m sprint Squat jump Countermovement jump Countermovement jump with arms swing 5-jump test Force-velocity test on the cycle ergometer

10 RM) for different exercises (bench press, squat, leg press, power clean, snatch, clean & jerk, torso rotations, etc.), isokinetic and isometric tests (back, knee extension and flexion), force-velocity test on a cycle ergometer, 30 s Wingate test, standing long and vertical jumps (e.g., squat jump, countermovement jump, Abalakov test, drop jump, multiple 5 bounds test, repeated rebound jumps, triple hop test, maximal and submaximal hopping), standing and seated medicine ball throw, 15 s push-up or pull-up, agility tests (e.g., 505 Agility test, T-agility test, Illinois agility test, hurdle agility run, shuttle run for various distances, i.e., 6 × 6 m, 4 × 9 m, 4 × 15 m, 10 × 5 m) and/or change of direction speed tests, sprints at different distances (5, 10, 15, 20, 30, and 40 m), balance tests (e.g., bilateral stance with eyes open and eyes closed, perturbed stance with eyes open and eyes closed, Standing stork balance test, Y-balance test, Star excursion balance test, etc.), endurance tests (e.g., Yo-Yo intermittent endurance test, Yo-Yo intermittent recovery test, 20 m multistage shuttle run test, multistage running test on a treadmill), and flexibility tests (e.g., stand and reach, sit and reach, V sit and reach).

However, only few sport-specific tests were used for this purpose. These include throwing a handball ball, 10 or 15 m agility test with the ball, service velocity and accuracy tests in tennis, single-court and 2-court suicide runs in tennis, kicking velocity test in soccer, crossing efficiency and shooting efficiency tests in soccer, swim tests (a gliding task, 400- and 50 m front crawl with a diving start), tests with a water start without push-off on the wall (25 m in front crawl and 25 m only with kicks), swimming block start performance test, and so forth.

These findings indicate that moving from traditional field tests to more sophisticated testing methods evaluating athletic performance under sport-specific conditions would be a key step forward. So far, physical fitness of children and adolescents has been assessed using simple equipments (no PC-based), although various portable computerized diagnostic devices are available on the market. Therefore current test batteries should be updated. These novel batteries should be able to objectively assess athletic abilities and skills by means of novel technologies and computational techniques using for data analysis over a long-term period. This should be supported by web-based access to standard and sport-specific test protocols, management of data obtained, and their reporting. This would be the first fundamental step in proposing objective measurement tools that use technological advances in the physical fitness testing of young athletes.

Long-Term Sport Diagnostic Model

The first long-term athlete development (LTAD) model was proposed in Canada in 1998 by Dr. Istvan Balyi and was grounded around three phases: Training to Train, Training to Compete, and Training to Win. Over time, this model was evolved into seven phases: (1) Active Start, (2) FUNdamentals, (3) Learn to Train, (4) Train to Train, (5) Train to Compete, (6) Train to Win, and (7) Active for Life (Balyi et al., 2013).

Recently, Granacher et al. (2016) presented a conceptual model for the implementation of resistance training programs during the stages of long-term athlete development to enhance muscular fitness and athletic performance. According to the

authors, long-term development of muscular fitness (strength, power, and endurance) consists of these stages: "early childhood (female: 6–8 years, male: 6–9 years) including coordination training, agility training, balance training, muscular endurance training with own body mass/training tools (e.g., medicine ball) with a focus on exercise technique; late childhood (female: 9–11 years, male: 10–13 years) including balance training, plyometric training as part of deliberate play (e.g., rope skipping) with a focus on correct jumping and landing mechanics, core strength training, muscular endurance training with own body mass/training tools (e.g., medicine ball), free weight training with a focus on exercise technique; adolescents (female: 12–18 years, male: 14–18 years) including balance training, plyometric training (depth jumps from low drop heights), core strength training, free weight training at light to moderate loads, heavy resistance strength training (hypertrophy), eccentric resistance training, sport-specific resistance training; and adulthood (female: >18 years, male: >18 years) including balance training, plyometric training (depth jumps from moderate drop heights), core strength training, free weight training at moderate to high loads, heavy resistance strength training (neuromuscular activation + hypertrophy), sport-specific resistance training."

Taking this information into account, our previously proposed Long-Term Sport Diagnostic Model (Zemková, 2015) was modified. Age-related stages within this model are as follows: Stage 1 (6–9 years), Stage 2 (10–14 years), Stage 3 (15–18 years), Stage 4 (19–24 years), Stage 5 (25–44 years), Stage 6 (45–64 years), and Stage 7 (65+ years).

Targeting the young population, we have originally developed tests specifically tailored for them. So far, reliable and sensitive parameters were identified that are directly linked to the physical fitness of particular age categories and allow capture of the complexity of the performance by combining multiple parameters. Their combination showed superior results for the accurate assessment of different abilities when compared to current standard field tests. Experience showed that young people participate more intensively and also reach higher exercise goals than with conventional methods when computerized diagnostic and training systems are used. For instance, the task-oriented balance tests based on visual feedback control of body position or the agility test performed under simulated competitive conditions seem to be more suitable for children and adolescents than traditional field tests. Both of them are similar to computerized games which may enhance the attention and motivation of children to exercise. We believe that this approach may also be applied for testing of young athletes under sport-specific conditions.

Besides basic tests of reaction, agility and speed, core and postural stability, muscle strength and power, the Spinal Mouse® device was also used to assess the spinal curvature and pelvic tilt. We have tested 118 children and adolescents for sit-and-reach, passive and active straight leg raise (Muyor et al., 2014). The findings identified that the sit-and-reach test is an appropriate and valid test for the evaluation of the pelvic tilt and lumbar flexion, but not as a measure of hamstring flexibility in school age children. The active straight leg raise test may be an appropriate and easy test for the assessment of their hamstring flexibility. It may be recommended also for young athletes as most of the authors used flexibility tests in their studies evaluating the efficiency of neuromuscular training.

The focus in the present study was given to testing of neuromuscular functions in children and adolescents (**Figure 1**). Proposed tests can be adjusted according to requirements of particular sports and serve as a basis for Sport-Specific Model of Athlete's Performance Testing. The motive for research in this field was our experience with several years of systematic testing of athletes, for instance, those of the National Karate Team (aged from 9 to 27 years). The most used tests were as follows: reaction test (e.g., responses to stimuli of red and blue during the strike of gyaku-cuki), hand and foot tapping, kicking velocity test, agility test, 10 and 60 s jump tests, 10 s exercise bouts at different revolution rates on the isokinetic cycle ergometer, a 30 s load on the isokinetic cycle ergometer or on a treadmill in the form of tethered running, and spiroergometry (Zemková and Dzurenková, 2004). Though these tests were found to be suitable for assessment of performance in karate competitors, prescribed testing protocols used in laboratories only partially fullfil the requirements for testing under sport-specific conditions. Obtaining relevant data on changes in sport-specific athlete performance during the long-term period would provide more useful information for the designing of effective training programs.

Sport-Specific Assessment of Muscle Strength and Power in Young Athletes

The ability to produce power during running, hopping and jumping improves as children grow older. The age-related increase in power production can mainly be ascribed to the increase in muscle size (Kanehisa et al., 1994; Neu et al., 2002). However, Davies and Young (1984) and Ferretti et al. (1994) showed that differences in muscle mass cannot fully explain differences in peak power between pre-adolescent children and adults. According to Ferretti et al. (1994) age-related differences in neural drive could play a role. However, Lambertz et al. (2003) found that the stiffness of the musculotendinous unit increases throughout childhood. This suggests that stiffness of lower limbs may contribute to developmental changes in jump performance (Wang et al., 2004). These findings were extended by Korff et al. (2009) who reported a significant correlation between peak power during the countermovement (CM) jump and lower limb stiffness in adolescents but not in pre-adolescents. When normalized to body mass, the relationship between peak power and stiffness of lower limbs differed similarly between these groups. These findings indicate that leg stiffness may contribute to greater power production during jumps in adolescents. On the other hand, the ability to produce power during vertical jumps in pre-adolescents is not related to the leg stiffness. This weak relationship may be explained by a greater compliance of passive elastic structures in pre-adolescents (Asai and Aoki, 1996; Lambertz et al., 2003). Alternatively, a lesser ability to actively stiffen their joints by antagonistic co-activation (Hortobagyi and DeVita, 2000) may result in lower ability of intersegmental control (Jensen et al., 1994). Taking into account that active (Arampatzis

et al., 2001) as well as passive (Bobbert, 2001) stiffness components influence jump performance, pre-adolescents have a lesser ability to actively stiffen their joints to produce power (Korff et al., 2009). This may be strengthened by the greater compliance of their passive elastic structures (Lambertz et al., 2003). They can benefit from elastic energy storage in the musculotendinous system during CM jumps (Korff et al., 2009).

Therefore, the estimation of the ability to utilize elastic energy across maturational stages could provide useful information on the long-term development of jump performance and reveal potential for its trainability. From the exercise physiology it is known that activation of the stretch-shortening cycle during CM exercise contributes to greater power than the one performed without a prior eccentric contraction (Bosco et al., 1982). Thus, the greater jump height difference between the countermovement and the squat jump indicates an enhanced ability to utilize the elastic energy. Similar parameter can be obtained during resistance exercises performed with and without CM. Using an additional load during jumps or squats enables

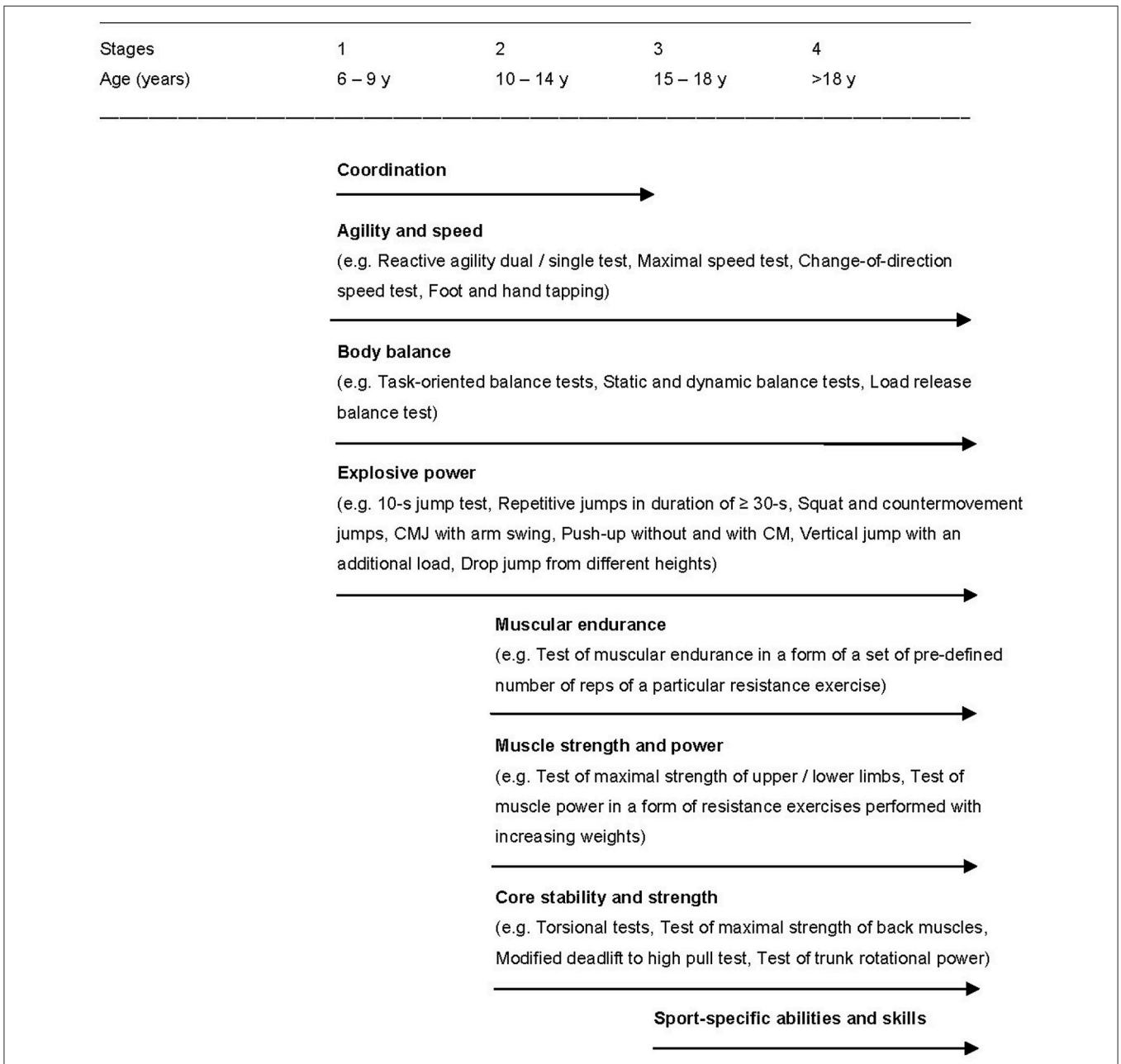


FIGURE 1 | Proposed tests within the abridged Long-Term Sport Diagnostic Model for evaluation of the effect of neuromuscular training on physical fitness in young athletes.

better differentiation of power performance in highly skilled athletes.

However, such an enhancement of power due to CM may differ between jumps and squats, depending on demands on the utilization of elastic energy during athlete performance (Zemková et al., 2017c). While this potentiating effect is greater during jumps than squats in high jumpers and volleyball players, opposite is true for rock & roll competitors in acrobatics and dancing. More specifically, the values are significantly higher during squats than jumps in acrobatic rock & roll competitors, whereas there are no differences in those who dance. On the other hand, the values are significantly higher during jumps than squats in indoor volleyball players, whereas there are no differences in those performing on the sand. Differences in CM potentiation of power in the concentric phase of jumps may also be observed in volleyball players playing different positions (spikers, blockers and setters). However, this enhancement of power during jumps and squats does not differ significantly either in hockey players or in karate competitors. These differences between groups of athletes may be ascribed to specific adaptations to exercise modes used during plyometric and resistance training.

There is a number of variations of plyometric training, including repetitive jumps on and off a box and jumping while wearing weight belts (Bobbert et al., 1996). To determine the height at which the highest power is achieved, one has to perform drop jumps, in random order, from different heights. Then, the relationship between jump height and/or power output and drop height can be described. Alternatively, the optimal drop jump height for plyometric training can be estimated.

During drop jumps, the reactive strength index (RSI), which represents a ratio of jump height and ground contact time (McClymont, 2003), is usually calculated. However, this parameter can also be calculated from repetitive jumps. There is a moderate correlation between RSI calculated from drop jump and repetitive jumps ($r = 0.67$). This method of calculating RSI from repetitive jumps may be used for athletes performing rebound jumps (e.g., aerobic & rock and roll dancers) because it is closer to their specific demands than drop jump.

For instance, appropriate selected tests can reveal the different characteristics of jumping between male and female rock & roll dancers. Boys' jump height is significantly higher when jumps are performed with bent knees than with straight legs. However, jump height does not differ significantly between these test conditions in girls. They achieve significantly higher power in the concentric phase of take off than boys. These differences may be attributed to similar muscle work during jumps in the test and rock & roll performance. While girls perform bounces mainly with legs straight, boys used to jump with knees bent.

Training can lead to specific changes in power production during repetitive hopping in dancers with different forms of muscle activity during rhythmic movements. Rock & roll dancers produce significantly higher power in the concentric phase of take-off than aerobic dancers and synchronized swimmers, concomitant with a significantly lower ground contact time. For them, the beneficial effects of an increased recoil speed from stiffer muscle-tendon units might outweigh the increased energy cost at higher jumps and contribute to lower fatigue index during such an exercise.

The fatigue index represents a decline of power during repeated vertical jumps, usually in a duration of 30, 60, or 90 s, depending on sport specialization. Assessment of muscular endurance is of special interest in sports like aerobic gymnastics or rock & roll, where explosive strength should be maintained for the prescribed period of the performance.

In other sports, shorter 10 s test of maximal jumps can be used to assess the explosive power of lower limbs. It can also be utilized for indirect estimation of muscle fiber distribution in lower limbs because there is a high correlation between the percentage of fast twitch muscle fibers in the vastus lateralis and power produced during 15 s jump test ($r = 0.86$) (Bosco et al., 1983). Such an information can be useful for talent identification.

As can be seen from this analysis, various approaches have been used to assess jump performance, however little is known about their advantages and limitations, particularly when testing children. Their great variability in jumping, a lack of familiarization with proper technique of the jump, or their potential learning effects in a short period of time might influence jump performance and consequently its changes across maturational stages. Therefore, there is a need to design a monitoring tool that would reveal various aspects of jump performance in the particular age, provide reliable data and be sensitive to developmental changes specifically in girls and boys.

Besides plyometric training, most of the authors in the studies analyzed used resistance exercises for the improvement of neuromuscular performance in young athletes. Estimating maximal power using the maximal effort single repetitions with increasing weights is considered as a more suitable alternative for the assessment of strength capabilities in adolescents than traditional 1 RM approach. Subjects usually perform the exercise with stepwise increasing weights up to maximal power. However, one has to be aware that maximal values of peak power and mean power in the acceleration phase of resistance exercises are achieved at lower weights than maximal values of mean power produced over the whole concentric phase, for instance at ∼50 and 60% 1 RM respectively during bench presses and at ∼70 and 80% 1 RM respectively during squats (Zemková et al., 2014).

Currently, instability resistance exercises are often a part of athletic and health-oriented strength training programs (Zemková, 2016c). Therefore, their role in sport-specific performance and general physical fitness is a matter of interest among conditioning specialists and researchers. We have found that measurement of peak and mean power during chest presses on a Swiss ball provides reliable data comparable to those obtained during bench presses under all conditions tested (Zemková et al., 2015a) and may represent an appropriate method for evaluation of the effects of instability resistance training. However, peak values of power measured during chest presses on an unstable surface with weights ≥80% 1 RM should be interpreted with caution.

Besides chest presses and squats, muscle power can be evaluated via many other resistance exercises with free weights or using weight stack machines (e.g., leg press). Some examples are knee extensions and knee flexions. Mean power measured

during these exercises is a reliable and also a sensitive parameter discriminating groups with different levels of physical activity (Zemková et al., 2015b). It can also be used for assessing the differences between the injured and non-injured leg. In addition, muscular endurance of knee extensors and knee flexors can be evaluated using the fatigue index calculated from a set of repetitions (i.e., 15). Such an assessment of muscle power during resistance exercises should be implemented in the functional diagnostics of young athletes and so complement existing testing methods.

Sport-Specific Assessment of Core Stability and Strength in Young Athletes

The importance of the function of the core for body stabilization and force generation in many sports is being recognized. The "core" is described as a box with the abdominals in the front, paraspinals and gluteals in the back, the diaphragm as the roof, and the pelvic floor and hip girdle musculature as the bottom (Richardson et al., 1999). Core strength involves the strength of trunk muscles, whereas core stability reflects the control of trunk position and its motion over the pelvis and leg in order to allow force production to the terminal segment in integrated kinetic chain exercises (Kibler et al., 2006).

Measurement of core stability involves the incorporation of variables of balance and coordination. The majority of core stability tests require the individual to keep a neutral spine in a quadrupedal or supine position (Liemohn et al., 2005; Faries and Greenwood, 2007; Gamble, 2007) that involves activation of local core muscles, such as the transversus abdominus and multifidus. Other tests assess the static muscular endurance of global core muscles, for example external obliques, quadratus lumborum and erector spinae (McGill, 2002; McGill et al., 2003; Faries and Greenwood, 2007). The most used are the Biering-Sørensen test of lumbar extension (Biering-Sørensen, 1984) and the flexor and side bridge endurance tests (McGill, 2001) which are exclusively performed isometrically, usually to task failure.

Another example are instrumented torsional tests, which can be performed under stable or unstable conditions. The task of the subject is to take a correct push-up position with hands on the dynamometric platform while legs are supported on the bench or physioball. Another alternative is that the subject gets into the back bridge position with legs on the dynamometric platform and back supported on the bench or physioball. These tests can also be performed in more difficult conditions with either one hand or one leg placed on the dynamometric platform. During these tests, basic stabilographic parameters are registered using the posturography system based on the dynamometric platform.

Field testing of core strength involves the amount of weight lifted, the number of repetitions performed, and the time of maintenance of neutral stable position (Faries and Greenwood, 2007). In the laboratory, isometric and isokinetic dynamometers are frequently used. In the sporting field, the back dynamometer or a potrable version of the computer-based device allowing the measurement of maximal voluntary isometric strength of predominantly back muscles can be used.

Given that muscle power is a better indicator of athletic performance, the test that measures this parameter during trunk movement may be more specific. The exercise in a form of deadlift to high pull may best mimic the demands imposed by sports comprising of lifting tasks. Muscle power measured during this exercise with free weights and on the Smith machine is a reliable and sensitive parameter able to distinguish the lifting performance in healthy young individuals (Zemková et al., 2016a).

Implements, such as the medicine ball and cable pulleys that allow motion in all three planes, can also be very useful in testing of strength and power performance. Variables of both medicine ball throws and the chop and lift have shown high reliability (Kohmura et al., 2008; Palmer and Uhl, 2011; Rivilla-Garcia et al., 2011; Lehman et al., 2013). Similarly, Andre et al. (2012) reported that a pulley trainer system and an external dynamometer represent a reliable tool for assessing the power during trunk rotations in a sitting position. Such a test may be appropriate for canoeing or kayaking, however for other sports, such as hockey or tennis, standing trunk rotations would be a more relevant alternative. The test adapted from the standing cable wood chop exercise on a weight stack machine is a reliable to assess the maximal power and endurance of core muscles and sensitive to differences among physically active individuals (Zemková et al., 2017a).

Such a computer-based system that can be directly connected to the weights on a stack machine is applicable for testing in fitness centers. Though machines are good for training or testing of muscle strength and power, they neglect key stabilization components of the core. Using free weights is a way to "functional" training and testing because it places greater demands on stabilizing muscles and allows a full range of trunk motion. Besides this, exercises with free weights most closely replicates the upper/lower body rotation movements. A suitable alternative represents a system consisting of an inertia measurement unit in a small box inserted on the barbell placed on the shoulders that allows evaluation of trunk rotational power in either seated or standing position. In such a case, the power is greater during standing than seated rotations of the trunk (Zemková et al., 2017b).

Typically, repetitions of a particular strength exercise with increasing weights up to the 1 RM are performed in order to obtain force-velocity or power-velocity curves. It is known that maximum force production is achieved when the movement speed is very low (Edman et al., 1976; Thorstensson et al., 1976; Binkhorst et al., 1977; Tihanyi et al., 1982; de Koning et al., 1985; De Ruiter and De Haan, 2000). As the movement speed increases, force decreases and is very low at very high speeds. Consequently, maximal values of power occurs at intermediate velocities when lifting moderate weights (i.e., 50–60% 1 RM) during typical resistance exercises such as bench presses or squats, whereas during trunk rotations it is at 30–45% 1 RM. This variation in maximal power production may be ascribed to the specificity of training adaptation.

For instance, Poór (2017) found a significant increase of mean power in the acceleration phase of trunk rotations after both the preparatory and competitive periods in tennis players at almost all weights (10–26 kg and 6–26 kg, respectively). However, its values increased significantly during trunk rotations with weights

≥12 kg in hockey players and with weights ≥10 kg in canoeists after the preparatory period only. These findings indicate that changes in trunk rotational power reflect the specificity of the training program.

Also within and between group differences in trunk rotational power and velocity may be attributed to specificity of the training involving trunk movements of different velocities under different load conditions. In particular, mean power and velocity in the acceleration phase of trunk rotation are sensitive parameters able to identify group and individual differences in athletes of various sports, such as karate, ice-hockey, tennis, golf, ballroom dancing, rock & roll dancing, judo, wrestling, canoeing, rowing, weightlifting, and bodybuilding. This parameter is also specific to asymmetric loading of core muscles during trunk rotations and may identify the likelihood of low back pain. Mean power in the acceleration phase of trunk rotations is significantly higher in the dominant than non-dominant side in golfers (11.9%) and tennis players (9.4%), whereas there are no significant side to side differences in the group of physically fit subjects (6.2%).

Taking into account the importance of core stability and strength in athlete's performance and probably also in the prediction of injuries, their assessment should be included in testing of young athletes. However, these tests involving lifting task or trunk rotations with an additional load must be performed with extreme caution. The exercises are usually performed with increasing weights up to maximal power rather than up to 1 RM. Preadolescents and adolescents should avoid using higher weights.

Sport-Specific Assessment of Body Balance in Young Athletes

Postural stability is maintained by three interrelated systems. The spinal column provides passive support, muscles give active support, and neural control centers coordinate sensory feedback from these systems. Traditionally, postural stability has been assessed under static conditions (bipedal or one-legged stance on a force plate with eyes open and eyes closed); however, these are not sensitive enough in discriminating athletes with good balance. Lower sensitivity of static posturography is a result of multiple sensory inputs involved in balance control that can compensate its small impairment. While standing on an unstable surface, this control mechanisms is taxed to a greater extent so that differences between individuals can be revealed. These conditions include a stance on a foam cushion, external perturbations generated from a platform either shifting in antero-posterior and medio-lateral direction or tilting toes up and down, and applying them directly to the body by pushing/pulling the trunk, shoulders or pelvis. For instance, subjects stand on a force plate connected to a computer with a special program that generates its movement in the horizontal plane. The protocol includes varied determinants of platform translation, such as the direction (forward, backward, left-lateral, and right-lateral), displacement (e.g., from 1 to 14 cm), and velocity (e.g., from 5 to 20 cm/s). Concurrently with measurement of center of pressure (CoP) movement, trunk movement representing roughly the center of mass (CoM) can also be monitored (Zemková et al., 2016b). Experience showed that dynamic posturography is a more sensitive and also more specific alternative for most of the athletes than systems which monitor the CoP in static conditions. Dynamic conditions can also better reveal adaptive changes in sensorimotor functions after the training (Zemková, 2010).

However, most of the dynamic posturography systems have also shortcomings. For instance, some of the platforms are insufficient to destabilize the highly skilled athletes beyond their stability limit. Others produce only unidirectional motions in the antero-posterior plane. In the case of tilting platforms, high learning effect can be observed because the subjects can predict the upcoming perturbations relatively successfully.

Another alternative is to use instrumented tests consisting of trunk repositioning and load release tasks (Reeves et al., 2007; Silfies et al., 2007). The trunk repositioning task requires the subject to passively or actively return to a neutral spine position after a predefined displacement. The load release task requires the subject to perform an isometric contraction of trunk muscles at a predefined intensity against an external load, which is thereafter released, and the trunk displacement is evaluated. Such parameters of the load release balance test measured during standing on a foam surface are able to differentiate between sedentary and physically active adults as early as from 19 years of age (Zemková et al., 2016c).

However, in many sports athletes are forced to keep balance on an unstable surface while performing tasks of various kinds simultaneously. Being able to not only stabilize and maintain balance but also to precisely and efficiently regulate positioning of the CoM may be considered as the essence of functional balance. To assess this ability, task-oriented balance tests, such as a visually-guided CoM target-matching task or a visually-guided CoM tracking task, seem to be promising. While in the first case subjects have to hit the target randomly appearing in one of the corners of the screen by horizontal shifting of CoM in an appropriate direction; in the second they have to trace, by shifting CoM, a curve flowing either in a horizontal or vertical direction. In comparison with static balance tests, task-oriented balance tests showed comparable reliability but better potential for discriminating between groups with different levels of balance capabilities. It can also more sensitively reveal the acute and long-term effect of various sensorimotor exercises on neuromuscular performance (Zemková, 2010).

A moderate correlation between parameters of these task-oriented balance tests ($r = 0.457$) and the common variance of 13% indicates that they assess distinct qualities. This is because voluntary feedback control of body position is performed under different conditions, i.e., the subject is focused either on the goal of the task (i.e., hitting the target) or on movement themselves (i.e., the positioning of the CoM). These test differences allow assessment of accuracy of regulation of body movement that requires less or more feedback processing. This is of special importance for children who regulate their CoM movement in a more conscious, effortful fashion (i.e., observed as a longer CoP trajectory) with their decisions about the action being handled in a slow, attention-demanding way (i.e., shown as a slower response time). Our experience indicates that such an assessment of balance incorporating a functional task is more suitable alternative for children and adolescents than static conditions.

The accurancy of assessment of static balance can be influenced by factors, such as motivation or attentiveness, which are difficult to control in children and adolescents. Providing immediate feedback (based on visual stimuli or statoacoustic signals) may motivate young individuals to exercise as intensively as possible while reducing the level of instructor supervision. Objective feedback also allows for adjustment of the testing protocol to specific individual needs and performance capabilities. An additional benefit is that the systems may be used as the training means. One of the alternatives are computerized balance games. These are effective in speeding the learning process by enhancing the understanding of particular tasks. Indeed, Štefániková (2013) revealed that training programs consisting of visual feedback balance exercises on either a stable or an unstable surface were more effective in improvement of balance functions than exercises on unstable surfaces without visual feedback in early school age children. This novel approach is a natural step to advancing the current state of knowledge by getting objective insight into the changes in postural control system during neuromuscular training in children and adolescents.

Utilizing techniques based on motion analysis or accelerometry recordings while evaluating head, limb and trunk movements could provide additional data and complete functional diagnostics of young athletes. The use of trunk accelerometry is a cost-effective and easily applied solution for measuring body balance and human movement. In particular, the accelerometry is a valid quantitative measure of postural sway which is strongly related to task-based measures (Whitney et al., 2011). With the advent of fast wireless technology and low-cost accelerometers, their use in field-testing of various aspects of balance is now feasible.

All these techniques can be used for assessment of postural stability in sport-specific positions or after aerobic, anaerobic and resistance exercises under laboratory and sport-specific conditions in the sporting field (Zemková, 2014). A better understanding of physiological mechanisms of post-exercise balance impairment and its readjustment to baseline (Zemková and Hamar, 2014c) may serve as a basis for the design of goal-specific balance training programs to improve athletic performance and prevent a risk of injuries.

Sport-Specific Assessment of Agility and Speed in Young Athletes

The ability to perform quick movements, stop and start rapidly while focusing on an opponent or the ball plays an essential role in athlete performance. It involves perception and decision making (cognitive processing), muscle strength and change of direction speed (motor component), in addition to footwork and movement technique (technical skills).

In comparison with traditional agility tests based on pre-planned change of direction speed, novel reactive agility tests address both the cognitive (i.e., anticipation and pattern recognition) and the physical component (i.e., change of direction speed). Such testing is more sensitive in discriminating athletes of different performance levels as compared to pre-planned change of direction speed tests. For instance, Sheppard et al. (2006) discovered that the reactive agility test differentiates between Australian football players of varied performance levels, whereas sprint and sprint with change of direction tests were unable to do so. Similarly, Farrow et al. (2005) found that the highly-skilled group was faster in both the planned and reactive tests than the lesser-skilled group, whereas the moderately-skilled group was faster than the lesser-skilled group in the reactive test only. Adding reactions to given stimuli into agility tests would also reflect sport-specific situations more effectively.

Both speed of decision making and change of direction speed contribute to agility performance, although to a different extent. Agility time strongly correlates with the choice reaction time, regardless of sports specialization of athletes or their previous experience with agility training. This indicates that perception and decision making are the most influential components of agility performance. There is also a significant correlation between agility time and movement time, however only when traveling a short distance. The strength of this relationship decreases with increasing traveling distances. Greater variation in the movement time than two-choice reaction time also makes potentially meaningful differences among athletes (particularly among those of combat sports and sports games) and their differential contribution to the agility performance. For instance, cognitive and motor skills are better in karate-kumite than karate-kata competitors, when only stepping reactions are required. When moving longer distances, better agility time is in players than in goalies of soccer and ball hockey. While the motor component of agility performance seems to be predominant in players in terms of faster movement execution, in goalies it is the sensory component allowing faster decision making (Zemková, 2016b).

Hence, measurements of choice reaction time and movement time or velocity, may provide useful information on these components of agility performance in athletes with different demands on their agility skills. The contribution of movement time to the agility performance may be estimated using the Agility Index (Zemková, 2016a). It is defined as a ratio of reaction time and agility time which is divided by the previously determined coefficient for each distance traveled. This index is useful for agility testing that differs in the number of stimuli and traveling distances.

As shown, agility time significantly improved after 6-week training consisting of balance exercises performed simultaneously with reaction tasks (Zemková and Hamar, 2010). However, simple and two-choice reaction times did not change significantly. On the other hand, there was a significant increase in step initiation velocity. This faster execution of movement most likely contributed to the enhancement of agility performance. In fact, the reduction of agility time correlated significantly with an increase in step initiation velocity after the training ($r = 0.78$). Also of interest was the additional finding that the improvement in agility performance in older basketball players (on average 21 years) was greater than in their younger, less experienced counterparts (on average 15 years). This may be attributed to faster feedback control of movement execution, i.e., as experience level increased with practice, the agility time decreased.

These sports (basketball, soccer, tennis, ice hockey, badminton, racquetball, squash, volleyball, baseball, softball, lacrosse, american football, wrestling, boxing, fencing) which are ranked highest for agility require changes of movement direction while responding to stimuli, such as the ball or a player. These actions in field and court sports are performed alongside the offensive player's movements, which involves some sort of competition.

In order to mimic these sport-specific demands, the agility test should be performed under simulated competitive conditions. In such a case, agility time is significantly shorter when the test is performed by two subjects simultaneously (Agility Dual) than by one subject (Agility Single) (Zemková et al., 2013). Faster agility time recorded under simulated competitive rather than non-competitive conditions (14.3%) may be attributed to enhanced central nervous system arousal in the participants. This factor very likely contributed to a further, but not significant decrease, in agility time in the group that proceeded to the second match. Also, the learning effect may have been a factor; however this would be to a lesser extent because stimuli were randomly generated (temporally as well as spatially). The Agility Dual test should be used for testing of children and adolescents to enhance their attention and motivation. Such an exercise can also be a part of agility training in young athletes. Kováčiková (2012) found a more pronounced improvements in agility time in the Agility Dual test in the group trained under simulated competitive conditions than in the group who participated in a 8-week training without the competitive components. It seems that agility training performed for competition is a more effective method for agility skills enhancement than the training under non-competitive conditions.

This may be beneficial for children and adolescents. It is known that agility time decreases with advancing age up to maturity (Zemková and Hamar, 2014a). Its values decrease markedly from 7 to 10 years (27.1%) and from 10 to 14 years (26.5%). This is followed by a slow period from 14 to 18 years (16.5%). Participating in sport may improve their agility skills. As shown, the best agility times (<350 ms) are in athletes of racquet and combat sports with reactions to visual stimuli (table tennis, badminton, fencing, tae-kwon-do and karate), followed mainly by players of ball sports (ice-hockey, tennis, soccer, volleyball, basketball, and ball hockey with agility time of 350–400 ms), then competitors of combat sports with reactions to visual and tactile stimuli, such as aikido (400–450 ms), and finally judo and wrestling (450–500 ms; Zemková and Hamar, 2014b). In most of these sports, assessment of agility performance requires a specific approach. For this purpose, a number of test alternatives is available depending on the sport specific task (Zemková and Hamar, 2013). Experience showed that assessment of agility performance under sport-specific conditions represents a more appropriate method than the general version of the agility test.

If necessary, a visually-triggered step initiation test can be used to measure the time of foot off (onset of unloading) and foot flight time (from foot-off to foot-contact) of the first step. Alternatively, the speed of step initiation can be measured using the system based on precise analog velocity sensor. Maximal step velocity showed excellent reliability and also sufficient sensitivity to discriminate between individuals of different ages and levels of physical fitness.

In specific conditions, for instance in combat sports where upper and lower body extremities are utilized to punch and kick, the reaction time (onset of unloading in response to visual stimuli) and movement time (from foot-off to bag-contact) during the kick can be measured. The test is reliable and also able to distinguish between athletes of varied sports (tae-kwon-do and karate) and performance levels (kyu and dan) (Zagyi, 2010). The velocity of a punch in karate or box can be measured in a similar way.

The assessment of speed abilities can be completed by measuring the frequency of the movement of upper and lower limbs. The tapping of lower limbs can be performed in the standing or sitting position. The frequency of lower limb movements escalates with increasing age, the maximum recorded by adults, which then began to decline with increasing age ranges. Contact and flight times display a similar tendency, with the lowest values in subjects ranging from 19 to 24 years of age. Participating in sport may improve this ability. For instance, the best foot tapping frequency was recorded in boxers, followed by dancers, karate and taekwondo competitors. Its values were also significantly higher in karate competitors of more advanced (2. kyu to 2. Dan) than less skillful performance levels (7.—4. kyu). This test can be modified by adjusting the contact mats so that specific positions in particular sports can be simulated (e.g., fighting stance in boxing, karate or tae-kwon-do) or by increasing its duration (e.g., close to duration of performance in dancing, rock & roll or aerobics).

Additional information regarding agility and speed can be provided by using wireless timing gate systems. One has to take into account that measurement of change of direction speed may substantially differ from frequently testing straight sprinting speed by many practitioners. There is a weak relationship between change of direction speed and straight sprinting speed in highly skilled athletes. Therefore, sport-specific methods should be addressed in both the testing and training of agility skills and movement speed in young athletes.

Gaps in Current Standard Testing Methods and Proposal for Future Research

Analysis of the literature identified these gaps in current testing methods:

1) inadequacy in particular age periods (early childhood, late childhood, adolescence at pre-PHV, PHV, and post-PHV);
2) a low sensitivity to discriminate between young athletes of various ages and performance levels;
3) insufficent tailoring to athlete performance level (highly skilled athletes vs. their less proficient counterparts);
4) insufficent tailoring to individual needs (most of the studies were focused on groups of athletes rather than on individual's performance assessment);
5) a lack of specificity to the requirements of particular sports, very likely due to scarce information from experimental studies (most of the studies analyzed were related to sports games, namely soccer and basketball);

6) a lack of specificity to reveal the effect of training, especially resistance training (while during plyometric training, a variety of jump tests was applied, in the case of resistance training, only few studies evaluated muscle power during particular resistance exercises);
7) a limited number of variables used, very likely due to diagnostic systems being used rarely, even in recent studies.

In order to partly fill in the gap in recent studies, the Sport Longlife Diagnostic Model was proposed. Its mission is to bring personalized physical fitness testing based on user-friendly computerized systems that enable full performance assessment. It develops novel testing methodologies to address and overcome the today's available field testing. It uses innovative methods to monitor and analyse the physical fitness of individuals of different ages and performance levels in a relatively short-time period. This novel approach enables testing athlete performance under sport-specific conditions. The areas of application and the number of age and sport-specific tests are constantly growing.

The model intends to innovate the assessment of physical fitness in terms of speed, safety, precision, and functionality using new generation diagnostic equipments with the goal of making testing simpler, more effective and objective. The long-term goal is to complement current diagnostic and training methods with self-monitoring devices, virtual coaching and electronic alert in order to evaluate actual athlete performance and/or health state, and the effectiveness of physical activity interventions. The self-testing and data analysis can provide a powerful alternative to current measurement tools as well as new perspectives on applications.

A database platform for the efficient management of long-term testing is being designed. It offers exercise professionals who perform athlete's assessment an integrated application for the analysis and interpretation of subject data. The entire process of the tester-subject relationship is being managed automatically—from data collection, its analysis to the final report. Through this innovative approach, it feeds raw data into the database and fundamentally changes the way users can access, find, and match the results on populations tested. The database has an additional potential in non-sport applications such as schools, fitness and rehabilitation centers, or medical institutions.

Diagnostic centers should serve sport professionals as well as a wide variety of people who wish to protect their health through systematic innovative assessment of their physical fitness. Integrating novel systems and methods into their daily diagnostics can enhance quality, streamline the cost of testing and bring objective data to subjects allowing repeatable evaluation before, during, and after an exercise program, treatment or rehabilitation.

The Sport Longlife Diagnostic Model would represent a significant improvement over existing field testing using computerized portable equipments and applying a set of new diagnostic tools well suited for the testing of various populations. It uses sophisticated systems and methods to detect and assess the prognosis of physical fitness, and to match the subject with objective and more effective exercise testing. It provides a valid proprietary cutting-edge functional assessment platform for athletes and physically active individuals with potential for the untrained population; people with certain diseases and those recovering from injuries. End-users can be not only sport professionals and exercise practitioners but also physical education teachers, physical therapists and physicians. In this way it can be used in gyms, fitness centers and schools, as well as in rehabilitation and medical institutions.

AUTHOR CONTRIBUTIONS

Both authors listed have made a direct and intellectual contribution to the work, and approved it for publication.

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Effects of Sport-Specific Training during the Early Stages of Long-Term Athlete Development on Physical Fitness, Body Composition, Cognitive, and Academic Performances

Urs Granacher and Ron Borde*

Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany

Introduction: Several sports demand an early start into long-term athlete development (LTAD) because peak performances are achieved at a relatively young age (e.g., gymnastics). However, the challenging combination of high training volumes and academic demands may impede youth athletes' cognitive and academic performances. Thus, the aims of this study were to examine the effects of a 1-year sport-specific training and/or physical education on physical fitness, body composition, cognitive and academic performances in youth athletes and their non-athletic peers.

Methods: Overall, 45 prepubertal fourth graders from a German elite sport school were enrolled in this study. Participating children were either youth athletes from an elite sports class ($n = 20$, age 9.5 ± 0.5 years) or age-matched peers from a regular class ($n = 25$, age 9.6 ± 0.6 years). Over the 1-year intervention period, the elite sports class conducted physical education and sport-specific training (i.e., gymnastics, swimming, soccer, bicycle motocross [BMX]) during school time while the regular class attended physical education only. Of note, BMX is a specialized form of cycling that is performed on motocross tracks and affords high technical skills. Before and after intervention, tests were performed for the assessment of physical fitness (speed [20-m sprint], agility [star agility run], muscle power [standing long jump], flexibility [stand-and-reach], endurance [6-min-run], balance [single-leg stance]), body composition (e.g., muscle mass), cognitive (d2-test) and academic performance (reading [ELFE 1–6], writing [HSP 4–5], calculating [DEMAT 4]). In addition, grades in German, English, Mathematics, and physical education were documented.

Results: At baseline, youth athletes showed better physical fitness performances ($p < 0.05$; $d = 0.70$–2.16), less relative body fat mass, more relative skeletal muscle mass ($p < 0.01$; $d = 1.62$–1.84), and similar cognitive and academic achievements compared to their non-athletic peers. Athletes' training volume amounted to 620 min/week over the 1-year period while their peers performed 155 min/week. After the intervention, significant differences were found in 6 out of 7 physical fitness tests ($p < 0.05$; $d = 0.75$–1.40) and

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****Correspondence:***
Urs Granacher
urs.granacher@uni-potsdam.de
orcid.org/0000-0002-7095-813X

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in the physical education grades ($p < 0.01$; $d = 2.36$) in favor of the elite sports class. No significant between-group differences were found after the intervention in measures of body composition ($p > 0.05$; $d = 0.66$–0.67), cognition and academics ($p > 0.05$; $d = 0.40$–0.64). Our findings revealed no significant between-group differences in growth rate (deltas of pre-post-changes in body height and leg length).

Discussion: Our results revealed that a school-based 1-year sport-specific training in combination with physical education improved physical fitness but did not negatively affect cognitive and academic performances of youth athletes compared to their non-athletic peers. It is concluded that sport-specific training in combination with physical education promotes youth athletes' physical fitness development during LTAD and does not impede their cognitive and academic development.

Keywords: long-term, early sport specialization, motor skills, young athletes, scholastic demands

INTRODUCTION

The long-term athlete development (LTAD) is a planned, structured and progressive development of youth's athleticism to achieve elite sport success and to engage in lifelong, health-enhancing physical activity (Balyi et al., 2013). Thus, the structured long-term path of athleticism enables talented youth athletes to achieve success on an elite level. In addition, LTAD should be regarded as key for the prevention of chronic diseases (e.g., metabolic syndrome) and as an important instrument to attain physical literacy and to motivate youth for lifetime engagement in sport and physical activity (Lloyd et al., 2015). Expert-based LTAD recommendations foresee a relative late age (i.e., 12–15 years) to start sport-specific training in disciplines like boxing, canoeing, cycling, weightlifting etc. while other sports (e.g., gymnastics, swimming etc.) demand an early start (i.e., 6–9 years) (Bompa, 2000). In those sports with a relatively young peak performance age (e.g., gymnastics, swimming) promising talents initiate sport-specific training often before they finish primary school (American Academy of Pediatrics, 2000; Myer et al., 2015). To achieve successful performance levels in elite sports, high training volumes are required at an early age (American Academy of Pediatrics, 2000). In swimming and gymnastics, training volumes of 6–18 h per week are frequently observed in child athletes (Deutscher Sport Bund, 2006; Feeley et al., 2016). However, early sport specialization has evidence-based side effects like for instance a higher risk of overuse injuries, burnout, and drop out of sports (DiFiori et al., 2014). DiFiori et al. (2014) summarized extrinsic risk factors for overuse injuries and burnout. They identified high training volumes and intensities and frequent competitions as the most important risk factors related to overuse injuries, burnout, and withdrawals from sports in youth athletes (DiFiori et al., 2014). In addition, high training loads in daily training routines at a young age may result in loss of motivation and a lack of concentration (DiFiori et al., 2014). In this context, Richartz and colleagues (Richartz et al., 2005) interviewed 356 German youth athletes (i.e., gymnasts, swimmers, divers, rhythmic gymnasts) with a mean age of 9.7 years. The authors observed that high training loads together with academic demands represent two main factors related to chronic stress in youth athletes (Richartz et al., 2005).

However, for non-athletic youth, there is evidence from a systematic review including cross-sectional and longitudinal studies that higher levels of physical fitness or training-related improvements in physical fitness are associated with better cognitive and academic performances (Donnelly et al., 2016).

To the best of our knowledge, there is no study available that examined the effects of long-term sport-specific training in combination with physical education on physical fitness, body composition, and cognitive as well as academic performances in prepubertal youth athletes compared to their age-matched non-athletic peers. Thus, the aims of this study were to examine the effects of long-term (1 year) sport-specific training and/or physical education on physical fitness, body composition, cognitive and academic performances in a sample of 9–10 year old athletes from sports with relatively young peak performance age compared to age-matched peers. Based on the relevant literature (Richartz et al., 2005; Donnelly et al., 2016), we hypothesized that sport-specific training in combination with physical education enhances physical fitness but may have a negative effect on cognitive and academic development in youth athletes compared to their peers. Of note, knowledge on long-term effects and demands of early sport-specific training and/or physical education on physical fitness and particularly academic performances are crucial for parents and policy makers responsible for the well-being of their children.

METHODS

Participants

Fourth grade students from a German elite elementary sport school were selected and invited to participate in this study. Local ethical permission was given and all experiments were conducted in accordance with the ethical standards in sports medicine and exercise science (Harriss and Atkinson, 2015). Before the start of the study, parents and teachers were informed about the study purpose and design as well as potential risks. After informed written consent was obtained from all parents or legal representatives, 45 prepubertal children were enrolled in

this study. None of the participants suffered from any form of acute musculoskeletal, neurological, or orthopedic disorders that may have affected their ability to execute sport-specific training, physical education, and/or physical fitness tests. Participants were recruited from an elite sports class (ESC) and a regular class (RC, control group) from the same school.

Twenty students from the ESC aged 9.5 ± 0.5 years performed sport-specific training in combination with regular physical education (PE, 3 lessons/week). Four youth athletes of ESC were gymnasts (male/female = 4/0), three trampoline jumpers (male/female = 1/2), three swimmers (male/female = 2/1), four track and field athletes (male/female = 1/3), one BMX cyclist (male/female = 1/0), and five soccer players (male/female = 4/1). In order to cope with athletic and academic demands, a specific training schedule was developed for ESC. Training included three PE lessons per week (Tuesday to Thursday from 7:00 a.m. to 9:30 a.m.) administered in the form of sport-specific training in addition to after-school sport-specific training.

RC included 25 students aged 9.6 ± 0.6 years who performed four regular PE lessons per week that followed the regular PE curriculum of the state of Brandenburg, Germany (i.e., no sport-specific training). Baseline characteristics of the participating students are presented in **Table 1**.

Experimental Procedure

To assess the effects of sport-specific training and/or physical education on physical fitness, body composition, cognitive and academic performances in youth athletes and their non-athletic peers, a controlled study design with repeated measures (i.e., pre, post) was applied. Pre tests were conducted in January 2014 while our participants attended grade four and post-tests were performed after the 1-year intervention period in January 2015 (grade five). Pre and post-tests of physical fitness and body composition were realized in the local school gym and they were scheduled for the same time of the day (always from 8 am to 11 am). In order not to confound bioimpedance data, subjects were kindly asked to appear in a fasted state on the test day. After the bioimpedance analysis was completed, a rest of 60 min was granted so that subjects were able to have a small breakfast. Physical fitness testing started after the break. Cognitive and academic performance testing was realized at the same daytime on the following day.

TABLE 1 | Baseline characteristics of the study participants by experimental groups.

	ESC (n = 20)	RC (n = 25)
Age (years)	9.5 ± 0.5	9.6 ± 0.6
Sex (m/f)	13/7	13/12
Tanner stages 1/2/3/4/5 (%)		
Pubic hair	95/5/0/0/0	90/10/0/0/0
Genital	53/47/0/0/0	42/42/16/0/0
Years from peak-height-velocity (PHV) (years; male/female)	−3.6 ± 0.2/ −2.0 ± 0.2	−3.1 ± 0.2/ −1.9 ± 0.2

Values are means and standard deviations. ESC, elite sport class; RC, regular class.

Physical Fitness Tests

Health and skill-related components of physical fitness were tested using seven single tests from different motor fitness test batteries (Balogun et al., 1997; Stark, 2000; Bös, 2001; Bös et al., 2009; Golle et al., 2015). Speed was assessed by means of the 20-m sprint test, muscle power was evaluated using the 1-kg ball push test (i.e., upper extremities) and the standing long jump test (i.e., lower extremities), agility was tested by means of the star agility run test, flexibility was assessed using the stand-and-reach test, endurance was evaluated with the 6-min run test, and balance was analyzed using the single-leg stance test. Physical fitness tests were instructed by qualified personnel (Master's degree in sports science) using a standardized test protocol. Before testing, all students conducted a 10-min standardized warm-up program consisting of light running followed by different conditioning activities (e.g., side steps, backward running, skipping, submaximal plyometric exercises, and short distance sprints). After the warm-up, each student received standardized verbal instructions and visual demonstration regarding the test procedure. Prior to testing, all students performed one practice trial for each test (except for the 6-min run test) followed by two test trials. The best trial was taken for further analysis.

Speed

The 20-m sprint test was applied to assess speed. Participants were instructed to stand in a high starting position with one foot right behind the startling line. Children started on the command "ready-set-go" and accelerated at maximum effort. Time was taken with a stopwatch to the nearest 1/10 s. The 20-m sprint test proved to be reliable in 6–10 year old children with an interclass correlation coefficient (ICC) of 0.73 (Bös et al., 2001).

Muscle Power

As a proxy of muscle power for the upper extremities, the 1-kg medicine ball push test was applied. Students were instructed to hold a medicine ball in both hands in front of their chest while elbows were on the same level as the hands. From a parallel standing position, students were asked to push the ball as far as possible. The ball pushing distance was documented using a measuring tape to the nearest 10 cm. The ball push test is a reliable test in 8–10 year old children (r = 0.82) for the assessment of upper-extremity muscle power (Schulz, 2013).

The standing long jump was used as a proxy of muscle power for the lower extremities. From a parallel standing position and with arms hanging loose to the side, students were instructed to jump as far as possible in horizontal direction and to land on both feet. The jumping distance was documented using a measuring tape to the nearest 1 cm. The standing long jump test proved to be reliable (r = 0.96) in 6- to 10-year-olds (Bös et al., 2009).

Agility

Agility was tested using the star agility run test (Golle et al., 2015). Students were instructed to run in different running techniques (e.g., forward, backward, side steps) from the center of a 9 x 9-m star-shaped field to the edge and back with four spikes. Time was taken with a stopwatch to the nearest 1/10th of a second. The star

agility run test proved to be reliable in 8- to 10-year-olds with an ICC of 0.68 (Schulz, 2013).

Flexibility

The stand-and-reach test was applied to analyze flexibility of the lower back and hamstrings (Bös et al., 2009). Students performed the test barefooted and with extended legs and feet close together while standing on an elevated platform. Subjects were asked to bend over using their maximal range-of-motion. Knees, arms, and fingers were fully extended for at least 2 s during the test. A tape measure was attached to the platform with 100 cm corresponding to the upper level of the platform. If students were able to reach beyond their toes, values above 100 cm were measured (i.e., good flexibility). Values below 100 cm indicated that the person was not able to reach the toes (i.e., limited flexibility). In 7–11 years old children, the stand-and-reach test is a reliable test ($r = 0.86$) for the assessment of flexibility (Bös et al., 2009).

Endurance

Endurance was assessed using the 6-min run test (Bös et al., 2009). Students were instructed to run as far as they could on a 54 m circuit in the gym over a time period of 6 min. Split times were provided after 3 and 5 min. The maximal distance achieved during the 6-min run test was used for further data analysis. With an ICC of 0.86 the test proved to be reliable in children aged 6–10 years (Bös, 2001; Bös et al., 2009).

Balance

Balance was tested using the single-leg stance test (Balogun et al., 1997). The dominant leg of our participants was determined with the help of the modified Lateral Preference Inventory Questionnaire (Coren, 1993). Students were asked to stand barefooted in a single-leg stance position with eyes opened. The non-dominant foot was placed against the inside of the dominant leg (i.e., knee) and hands were held akimbo. Students were instructed to stand as long as they could and as quiet as possible during the test, but not longer than 180 s. The test was terminated if students moved their arms or feet in order to achieve stability or if test-operator intervention was required. Time was taken with a stopwatch to the nearest 1/10th of a second. The single-leg stance test is a reliable test ($r = 0.95$) to analyze balance (Balogun et al., 1992).

Anthropometrics and Body Composition

Sitting and standing body height were tested without shoes to the nearest 0.5 cm using a stadiometer (seca 217, Seca, Hamburg, Germany). Biological maturity was estimated by means of assessing years from peak-height-velocity (PHV) derived from sitting and standing body height, body mass, and age (Mirwald et al., 2002). In general, children and adolescents can be classified into three categories according to their maturity status: pre-PHV (-3 years to > -1 years from PHV), circa/around PHV (-1 to $+1$ years from PHV), and post-PHV (>1 to $+3$ years from PHV) (Mirwald et al., 2002). Sexual maturation was determined using Tanner stages (Marshall and Tanner, 1969, 1970). In this regard, parents or legal representatives were asked to choose from photographs and descriptions of the five Tanner stages the stage that was most similar to the present maturation status of their child. Tanner stages were recorded for genital and pubic hair for boys and breast and pubic hair for girls (Marshall and Tanner, 1969, 1970).

A non-invasive bioelectrical impedance analysis system (BIA, InBody 720, BioSpace, Seoul, Korea) was applied to assess students' body composition. According to published BIA guidelines (Shafer et al., 2009), students were instructed to abstain from exercise 12 h prior to testing. Outcome variables included body mass (kg), body mass index (kg/m^2), relative skeletal muscle mass (%), and relative body fat mass (%). Of note, Tompuri et al. (2015) observed excellent agreements between DEXA and BIA (i.e., InBody 720) for lean body mass in children aged 7.7 $\pm$ 0.4 years (ICC: girls = 0.93, boys = 0.92).

Cognitive and Academic Performance Tests

To evaluate cognitive and academic performances, four tests were applied which included the ELFE 1–6 reading test, the DEMAT 4 mathematics test, and the HSP 4–5 spelling test for the assessment of academic performances as well as the d2-test to evaluate cognitive function (i.e., attentional capacity and concentration). The test developer provided age-specific reference values for all tests. In addition, grades in German, Mathematics, English, and PE were documented and used for further analysis (1 = very good, 6 = unsatisfactory).

Reading

The ELFE 1–6 test was used to evaluate reading performance (Lenhard and Schneider, 2006). The test comprises three parts: (i) word understanding (max. 72 points), (ii) sentence understanding (max. 28 points), and (iii) text understanding (max. 20 points).

The sum score of all three parts (max. 120 points) was used for further data analysis. The ELFE 1–6 proved to be reliable with an ICC of 0.91 in primary school children. (Galuschka et al., 2015).

Mathematics

To examine performance in mathematics, the DEMAT 4 test was applied for fourth graders (Gölitz et al., 2006). This test consists of three test items: i) arithmetic tasks (max. 19 points), written math tasks (max. 14 points), and geometric tasks (max. 7 points). The sum score of all three items (max. 40 points) was used for further data analysis. High reliability was reported for the DEMAT 4 test in 4th graders with an ICC of 0.87 (Gölitz et al., 2006).

Spelling

Our students spelling ability was tested using the HSP 4–5 test (May, 2012). For this purpose, students were instructed to write dictated words and sentences on a test sheet. The final score (max. 42 points) was taken from the number of words that were spelled correctly. The HSP 4–5 test showed excellent reliability with an ICC of 0.92 in children aged 9–10 (May, 2012; Galuschka et al., 2015).

Attention and Concentration

The d2-test was applied to evaluate selective attention and concentration of our participants (Brickenkamp et al., 1998). The total score (max. 658 characters) was calculated by subtracting the errors from the total number of edited characters (Brickenkamp et al., 1998). The d2-test is a reliable test ($r = 0.95$) to analyze selective attention and concentration in 9–60 year olds (Brickenkamp et al., 1998).

Documentation of Sport-Specific Training and/or Physical Education

During the intervention period, relevant training modalities such as training volume and intensity were documented for every single sport-specific training session and PE lesson by the responsible teacher and coach. The documented information comprised the type of training (i.e., PE or sport-specific training), training volume (i.e., frequency [PE classes and/or sport-specific training sessions per week], duration of PE classes and/or sport-specific training sessions), main training content of each session (e.g., strength-oriented, endurance-oriented, speed-oriented, technical skills), and number of participating students (i.e., adherence) (Castelli et al., 2014). For the assessment of training intensity, a perceived exertion scale was used for children. The scale contained verbal expressions along a numerical response range of 0 (i.e., very very easy) to 10 (i.e., very very hard) (Faigenbaum et al., 2004). A recently published meta-analysis indicated that the use of perceived exertion scales for children is a valid means to record training intensity with weighted correlation coefficients ranging from 0.84–0.87 between perceived exertion scales for children and physiological outcome measures (e.g., heart rate, oxygen uptake) (Rodriguez et al., 2016). During each lesson or training session, teachers were instructed to ask five randomly selected students for their perceived exertion. The mean score of the five students was used for further analysis.

Statistical Analyses

Normal distribution of data was examined using the Shapiro-Wilk test. If normal distribution was confirmed, descriptive data were presented as group means and standard deviations (SD) otherwise as median and interquartile range. Between-group baseline differences were assessed using either independent sample *t*-tests for interval scaled data or non-parametric Mann-Whitney-U tests for ordinal scaled data. To examine differences between classes at post-test, either an analysis of covariance (ANCOVA) for interval scaled data or the non-parametric Quade test was applied with baseline data entered as covariate. In addition, in a within- and between-subject approach, pre-post-changes in body height and leg length were computed for each participant. Using an independent sample *t*-test, between-group differences from deltas in body height and leg length were calculated to examine whether growth speed/rate differently affected the two experimental groups over the course of the intervention period. Our findings revealed no significant.

The level of significance was set at $p < 0.05$. Effect sizes were calculated by converting partial eta-squared to Cohen's *d* (Cohen, 1988). The effect size is a measure of the effectiveness of a treatment and it helps to determine whether a statistically significant difference is a difference of practical concern. According to Cohen (1988), effect sizes can be classified as small ($0.00 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$) (Cohen, 1988). The SPSS 23.0 package (SPSS Inc., Chicago, IL, USA) was used for statistical analyses.

RESULTS

All participating students received their intervention as allocated. Only one student from the ESC dropped out after baseline testing because his parents moved to a different city. Overall, 45 students completed the study ($n = 20$ ESC, $n = 25$ RC). None of the participating students reported any test- or training-related injuries over the 12 months intervention period. No significant baseline differences were found between classes in terms of age, sex, Tanner stages, and time to PHV (**Table 1**).

Anthropometrics, Body Composition, and Physical Fitness

In terms of anthropometrics, all students were classified as pre-PHV (**Table 1**). At baseline, significant between-group differences were found for body height, body mass, BMI, and body composition (all $p < 0.05$, $d = 1.13$–1.84). More specifically, participants in the ESC were shorter (3%), lighter (31%), had a lower BMI (22%), more relative skeletal muscle mass (6%), and less relative body fat mass (14%) (**Table 2**). After the intervention period, significant between-group differences were found for body height, body mass, and BMI. However, no significant between-group differences were examined for relative body fat mass and relative skeletal muscle mass (**Table 3**).

Table 2 illustrates group specific physical fitness, anthropometrics, and body composition data at baseline. Our analyses indicated significantly better performances at baseline in the ESC compared to the RC in five (i.e., 20-m sprint test, standing long jump test, star agility run test, stand-and-reach test, 6-min run test) out of seven physical fitness tests (Δ5–19%, $p < 0.05$, $d = 0.70$–2.16). No between-group baseline differences were found for the 1-kg ball push and the single-leg stance test. After the intervention period significant between-group differences were observed in six out of seven test items (Δ8–103%, $p < 0.05$, $d = 0.75$–1.40) in favor of the ESC (**Table 3**). However, the ANCOVA analysis did not detect a between-group difference at post for the 1-kg ball push test (Δ0%, $p > 0.05$). No statistically significant between-group differences were detected for deltas in body height ($p = 0.945$) and leg length ($p = 0.498$).

Cognitive and Academic Performance

At baseline, no significant between-group differences were found for all analyzed cognitive and academic parameters (**Table 2**). After completion of the intervention period, the non-parametric Quade test revealed no significant between-group differences in measures of cognitive and academic performance ($p > 0.05$). In addition, post-intervention, no significant between-group differences were found for grades in German, Mathematics, and English ($p > 0.05$). The PE grade was significantly better in

TABLE 2 | Baseline values of anthropometrics, body composition, physical fitness, cognitive and academic performance.

	Variables	ESC		RC		Δ %	*P*-value (*d*)
		M	*SD*	*M*	*SD*		
Anthropometrics, body composition	Body height [cm]	140.5	5.7	144.7	6.2	3	<0.05 (0.68)
	Body weight [kg]	32.0	6.0	41.9	10.3	31	<0.05 (1.11)
	Body Mass Index [kg/m^2]	16.2	2.4	19.7	3.4	22	<0.01 (1.13)
	Relative skeletal muscle mass [%]	46.5	3.0	40.4	4.1	6	<0.01 (1.62)
	Relative body fat mass [%]	10.2	6.2	24.0	8.0	14	<0.01 (1.84)
Physical fitness	20-m sprint [s]	3.9	0.2	4.3	0.4	10	<0.01 (1.16)
	1-kg ball push [m]	4.7	0.7	4.4	0.7	6	n.s.
	Standing long jump [m]	1.5	0.1	1.3	0.3	19	<0.01 (1.20)
	Star agility run [s]	19.5	1.3	22.3	1.7	14	<0.01 (1.77)
	Stand-and-reach [cm]	108.8	9.3	103.6	4.8	5	<0.05 (0.70)
	6-min run [m]	1233.5	97.5	1012.4	100.2	18	<0.00 (2.16)
	Single-leg stance [s]	104.6	55.6	83.9	57.8	20	n.s.
Cognitive/academic performance	ELFE 1–6 (max. 120 points)*	71.0	62–81	76.0	50–93	7	n.s.
	DEMAT 4 (max. 40 points)*	15.0	12–20	17.0	11–21	12	n.s.
	HSP 4–5 (max. 42 points)*	24.0	16–32	30.0	23–36	20	n.s.
	d2-test*	290.5	263–333	313.0	277–372	7	n.s.
	German grade	2.0	2–2	2.0	2–3		n.s.
	Mathematics grade	2.0	2–3	2.0	2–3		n.s.
	English grade	2.0	1–3	2.0	1–3		n.s.
	PE grade	1.0	1–2	3.0	2–3		<0.01 (1.51)

**Values are medians and interquartile ranges. d, Cohen's d effect size; ESC, elite sport class; M, mean; n.s., non-significant; PE, physical education; RC, regular class; SD, standard deviation.*

the ESC compared to the RC at post-test ($p < 0.01$, $d = 2.36$). Even though our analyses revealed no significant between-group differences post-intervention in measures of cognitive and academic performances, ESC showed higher scores in all cognitive and academic measures (Δ5–22%, $p > 0.05$, $d = 0.40$–0.64) (**Table 3**).

Documentation of Training Data

Training and PE data for the ESC and the RC are presented in **Table 4**. Subjects in the ESC realized significantly more sport-specific training sessions and PE classes per week (8.2 vs. 3.4 sessions/week, $p > 0.05$, $d = 2.56$) compared to the RC over the 1-year intervention period. Further, the total duration of sport-specific training sessions and PE lessons per week was significantly larger in ESC compared to RC (620 vs. 155 min/week, $p > 0.05$, $d = 2.50$) over the 1-year training period. The average weekly duration of ESC sport-specific training and physical education is illustrated in **Figure 1**. In terms of ESC training contents, coaches and PE teachers reported technical skill training as the main training content in both, sport-specific training and PE lessons with an average of 390 min/week. Thus, the relative part of movement skill training in ESC amounted to 63% of the entire training volume. In the RC group, endurance training comprised 33% of the overall PE duration and was therefore top ranked in terms of training contents followed by movement skill training (27%). **Figure 2** indicates a significantly higher training intensity in the ESC compared to the RC with 4.8 vs. 3.4 points on the visual analog scale ranging from 0 to 10 ($p < 0.05$, $d = 1.39$). Students of both classes showed high adherence rates in PE lessons and sport-specific training with no significant between-group differences (95.9 vs. 95.6%, $p > 0.05$, $d = 0.28$).

DISCUSSION

This is the first study to evaluate the effects of long-term sport-specific training and/or physical education on physical fitness, body composition, cognitive and academic performances in youth athletes and their age-matched peers. The main findings of this study were: (i) at baseline, ESC compared to RC showed better performances in physical fitness, less relative body fat mass and more relative skeletal muscle mass but no significant differences in cognitive or academic performances; (ii) mean training volume and intensity over the 1-year intervention period were significantly higher in the ESC compared to the RC; (iii) high sport-specific training and physical education volumes proved to be feasible and safe (no training-related injuries) with high adherence rates (96%) in the ESC; (iv) better performance levels in physical fitness were maintained or even enlarged in the ESC compared to the RC over the course of the 12 months intervention period; (v) high volume sport-specific training and physical education did not have any negative effects on cognitive or academic development in the ESC compared to the RC. Given

TABLE 3 | Adjusted post-test values of anthropometrics, body composition physical fitness, cognitive and academic performances.

	Variables	ESC		RC		Δ %	*P*-value (*d*)
		M	*SD*	*M*	*SD*		
Anthropometrics, body composition	Body height [cm]	148.3	6.3	149.6	7.5	1	<0.01 (1.23)
	Body mass [kg]	37.1	7.9	48.1	15.6	23	<0.05 (0.80)
	Body Mass Index [kg/m^2]	17.3	2.9	20.7	4.8	16	<0.05 (0.79)
	Relative skeletal muscle mass [%]	45.5	3.5	41.7	5.0	4	n.s.
	Relative body fat mass [%]	14.6	7.1	22.1	10.0	8	n.s.
Physical fitness	20-m sprint [s]	4.1	0.2	4.5	0.4	9	<0.05 (0.77)
	1-kg ball push [m]	5.1	0.8	5.1	0.8	0	n.s.
	Standing long jump [m]	1.6	0.1	1.4	0.2	13	<0.05 (0.90)
	Star agility run [s]	19.0	1.4	20.6	1.9	8	<0.05 (0.77)
	Stand-and-reach [cm]	105.4	8.8	97.0	7.8	9	<0.01 (1.40)
	6-min run [m]	1214.9	153.2	1076.0	97.7	13	<0.05 (0.75)
	Single-leg stand [s]	139.2	59.1	68.6	60.4	103	<0.01 (1.22)
Cognitive/academic performance	ELFE 1–6 (max. 120 points)*	102.5	86–112	108.0	86–110	5	n.s.
	DEMAT 4 (max. 40 points)*	22.5	16–29	17.5	15–23	22	n.s.
	HSP 4–5 (max. 42 points)*	33.0	29–36	32.5	27–35	2	n.s.
	d2-test*	498.0	393–552	418.0	401–481	16	n.s.
	German grade*	2.0	2–2	2.0	2–3		n.s.
	Mathematics grade*	2.0	1–3	3.0	2–3		n.s.
	English grade*	2.0	2–3	2.0	2–3		n.s.
	PE grade*	1.0	1–1	3.0	2–3		<0.01 (2.36)

**Values are medians and interquartile ranges d, Cohen's d effect size; ESC, elite sport class; M, mean; n.s., non-significant; PE, physical education; RC, regular class; SD, standard deviation.*

TABLE 4 | Documentation of sport-specific training and physical education for both classes.

Variables	ESC			RC	Δ %	*P*-value (*d*)
	PE	SST	total	PE		
TRAINING VOLUME						
Training frequency [ø TS/week]	2.7	5.5	8.2	3.4	141	<0.01 (2.56)
Training duration [ø min/week]	120	500	620 (100%)	155 (100%)	333	<0.01 (2.50)
TYPE OF TRAINING [ø min/week]						
Strength	25	50	75 (12%)	30 (20%)	150	n.s.
Endurance	20	40	60 (10%)	55 (33%)	10	n.s.
Speed	40	30	70 (11%)	30 (20%)	133	n.s.
Coordination	5	20	25 (4%)	0 (0%)		
Technique	30	360	390 (63%)	40 (27%)	975	n.s.
TRAINING INTENSITY						
Perceived exertion [0 = very, very easy; 10 = very, very hard]	3.1	5.1	4.8	3.4	41	<0.01 (1.39)
COMPLIANCE						
Adherence [%]	97.0	95.2	95.9	95.6	0	n.s.

d, Cohen's d effect size; ESC, elite sport class; n.s., non-significant; PE, physical education; RC, regular class; SST, sport-specific training; TS, training sessions.

that we controlled for potential between-group differences at baseline and that we did not detect any significant between-group difference in deltas of body height and leg length, it appears legitimate to ascribe the observed effects to sport-specific training and/or physical education and not to growth speed/rate.

Physical Fitness, Anthropometrics, and Body Composition

At baseline, ESC showed better performances in physical fitness, higher relative skeletal muscle mass and less relative body fat mass compared to RC. These findings could be the result

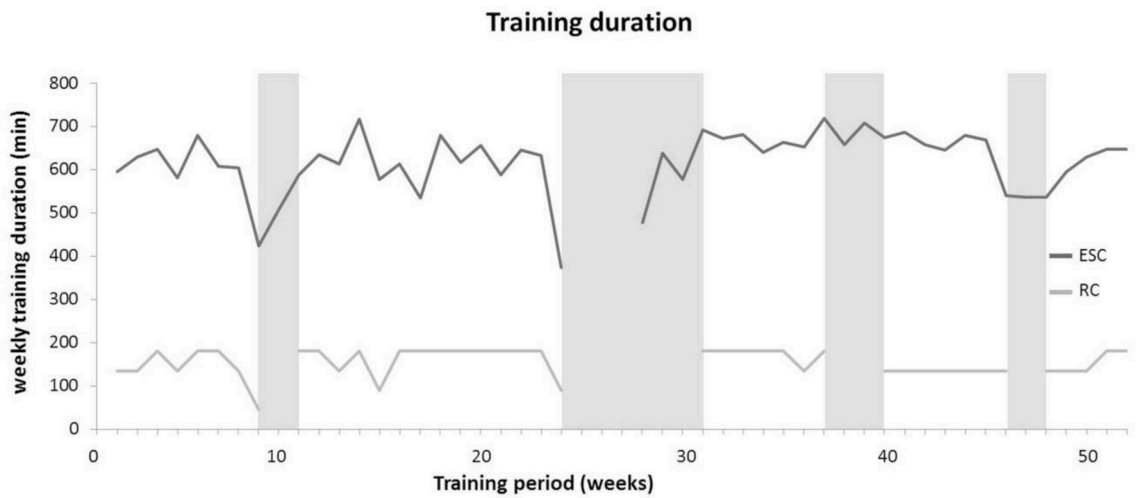


FIGURE 1 | Weekly duration of sport-specific training and physical education for both classes. Gray bars symbolize periods of school holiday. While no physical education classes were conducted in the ESC during school holidays, sport-specific training was performed. *ESC*, elite sport class; *RC*, regular class.

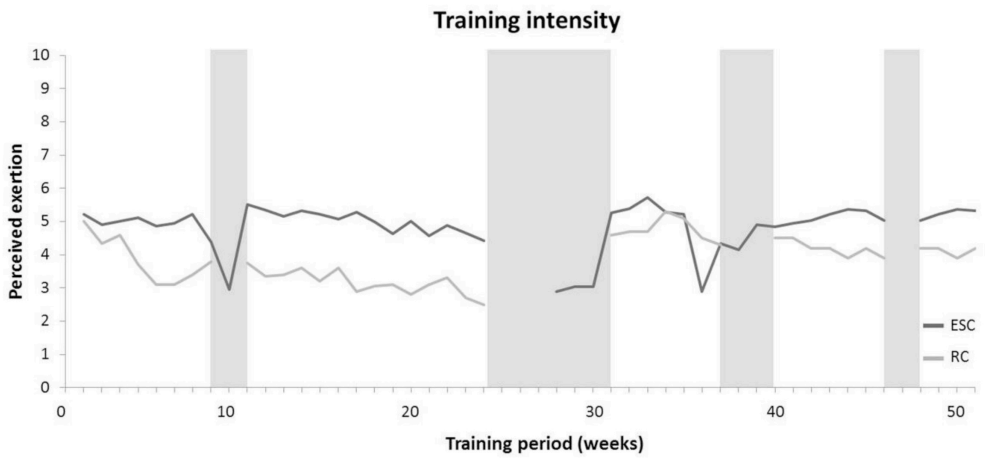


FIGURE 2 | Weekly intensity of sport-specific training and physical education for both classes. Gray bars symbolize periods of school holidays. While no physical education classes were conducted in the ESC during school holidays, sport-specific training was performed. *ESC*, elite sport class; *RC*, regular class.

of an effective talent identification program that enabled the selection of children with better performances compared to their age-matched peers. In fact, the state of Brandenburg, Germany initiated a statewide talent identification program in 2009 (www.emotikon-grundschulsport.de). Each year, between 14,000 and 16,000 children (3rd graders) are tested for their physical fitness in Brandenburg's primary schools (Golle et al., 2015). Children in the ESC were selected based on the results of the talent identification program and through specific recommendations from coaches and PE teachers. Another explanation of between-group baseline differences in physical fitness and body composition might be ESC's participation in sport-specific training right at the beginning of the 4th grade. In other words, ESC students began their sport-specific training 6 months prior to the commencement of this study. Maturational factors did not influence the observed between-group differences in physical fitness and body composition because we did not find any baseline differences in biological maturity between ESC and RC (Goncalves et al., 2012). In summary, it seems that the early start into LTAD and the talent selection program to attend the sport-specific class but not maturation were the main reasons to explain baseline superiority in physical fitness and body composition in the ESC compared to the RC.

After the 12 months intervention period, ESC students showed larger improvements in physical fitness (i.e., 20-m sprint test, standing long jump test, star agility run test, stand-and-reach test, 6-min run test, single-leg stance) after having participated in regular PE and additional sport-specific training compared to RC. These findings are supported by recently published articles (Vanttinen et al., 2011; Drenowatz et al., 2013; Golle et al., 2014;

Granacher et al., 2016). For example, Vanttinen et al. (2011) examined changes in physical fitness and body composition over the course of two seasons in 11 year old soccer players compared to an age-matched control group. The results showed that parameters of physical fitness and body composition of youth soccer players were better than those of the controls, especially in speed (i.e., 10 and 30-m sprint), agility (i.e., Figure 8 run), lower leg muscle power (i.e., countermovement jump), endurance (i.e., VO_2max, shuttle run test), and percentage of body fat. The authors concluded that soccer training resulted in additional behavioral and physiological adaptations which are beyond growth and maturation. Further, Golle et al. (2014) reported significantly better performances in physical fitness tests for children (aged 9–12 years) who continuously participated in sport clubs compared to age-matched peers who did not attend sports club. In another study, it was shown that grade two students participating in organized sport for more than once a week achieved better physical fitness levels and were less likely to be overweight compared to their non-participating peers (Drenowatz et al., 2013).

Cognitive and Academic Performances

Besides the positive effects of sport-specific training in combination with physical education on physical fitness in the ESC, no significant between-group differences were detected for measures of cognitive and academic performances at baseline and post-tests. The lack of training effects on cognitive and academic performances in the ESC compared to the RC is not in agreement with the existing literature. For instance, a systematic review and meta-analysis (Fedewa and Ahn, 2011) examined the effects of physical activity and physical fitness on cognitive and academic performances in 5–16 year old children. Fifty nine cross-sectional and longitudinal studies were included in the analysis (Fedewa and Ahn, 2011). The aggregated findings indicated small but significant effects of physical activity and physical fitness on childrens' cognitive and academic performances with an effect size of 0.32 (Hedge's *g*, 95% confidence interval [CI]: 0.26–0.37, $p < 0.01$) for cross-sectional studies and an effect size of 0.35 (Hedge's *g*, 95% confidence interval [CI]: 0.26–0.43, $p < 0.01$) for longitudinal studies (Fedewa and Ahn, 2011). In accordance with these findings, other systematic reviews of cross-sectional studies showed large positive associations between physical fitness and cognitive as well as academic performances in school-aged children (Chaddock-Heyman et al., 2014; Donnelly et al., 2016). One possible explanation for the lack of training effects on cognitive/academic performances in the present study is the challenging combination of high training volume together with academic demands which may have resulted in stress and academic overload (Richartz et al., 2005). In fact, it has previously been reported that sport-specific demands (e.g., high training volumes, large number of competitions) could be responsible for chronic stress and even burnout (Malina, 2010). These psychological problems together with symptoms such as fatigue, depression, loss of motivation, and lack of concentration may result in a decline in cognitive and academic performances (Kusurkar et al., 2013; Wagner et al., 2015; Rabiner et al., 2016). Interestingly, in the present study, no significant between-group differences were found in terms of cognitive and academic performances at pre and post-test. Nevertheless, it can be postulated that ESC's cognitive and academic performances were not affected by the high training volume. In other words, the observed high training volume of 8.2 training sessions per week with a total duration of 620 min per week at moderate training intensities had no negative effects on the achievements in standardized cognitive and academic tests as well as on school grades in the ESC compared to the RC.

Documentation of Training Data

The training documentation revealed higher training volumes and intensities in the ESC compared to the RC. The contents of the sport-specific training were part of the structured and planned pathway during LTAD. Of note, LTAD consists of seven sequential stages (1. Active Start, 2. FUNdamentals, 3. Learn to Train, 4. Train to Train, 5. Train to Compete, 6. Train to Win, 7. Active for Life) and considers individual maturation level rather than chronological age (Balyi et al., 2013; Granacher et al., 2016). In the present study, ESC students can be categorized in the stage "Learn to Train" that is characterized by a pre-PHV maturation status (>-1 years from PHV) (Lloyd et al., 2015). Sport-specific training of this study was conducted with reference to the "Learn to train" stage of the LTAD. Therefore, coaches implemented movement skill training as the main part of sport-specific training and physical education (63% of the entire training time). Moreover, a recent study examined the time per week spent in organized sports of 1,190 youth athletes aged 7–18 years. The reported time of 636 min per week spent in organized sports was comparable with the findings of the present study (620 min per week) (Jayanthi et al., 2015). However, it was previously reported that early specialization in a single sport increases the risk of sustaining acute and overuse injuries, burnout, and drop out of sports (DiFiori et al., 2014). Of note, the level of sport specialization can be classified as low, moderate, or high depending on the following three factors: (i) participate in year-round training (greater than 8 months per year); (ii) select a main sport, and (iii) quit all other sports to focus on the one main sport only (Myer et al., 2015). According to this classification scheme, all ESC students show a moderate-to-high degree of sports specialization (Jayanthi et al., 2015; Myer et al., 2015). With reference to Jayanthi and colleagues (Jayanthi et al., 2015), ESC's level of sport specialization may increase their risk of sustaining injuries. Of note, the risk of sustaining serious overuse injuries in youth athletes doubles if athletes participate in more hours of sports training per week than number of age in years (OR = 2.07) (Jayanthi et al., 2015). In this study, ESC students mean age was 9.5 years and they exercised on average 10.3 h per week which indicates that injury risk was increased. However, no injuries were reported for the ESC over the course of the 1-year training intervention which is further supported by high adherence rates of 95.9% in sport-specific training and PE. Even though we did not detect any injuries in this study despite the applied high training volumes, coaches and PE teachers are advised to keep training volumes on age and maturation adjusted levels and to conduct neuromuscular training programs to prevent injuries.

Strengths and Limitations

The strengths of this study include the long-term intervention type, the special sample of youth athletes who conducted sport-specialized training at a relatively young age, the detailed training documentation of each conducted training session and PE class over a period of 1 year, and the deduced implications for a structured LTAD. The main limitation of this study was the absence of randomization on a class or school level. However, a randomization process was not feasible because of the unique sports-specific school program. In addition, ESC students started their sport-specific training 6 month prior to our baseline tests. The previous experiences in sport-specific training and the absence of the randomization process resulted in the observed between-group baseline differences.

CONCLUSIONS

In summary, the present study revealed that ESC compared to RC showed better performances in physical fitness, less relative body fat mass and more relative skeletal muscle mass but no significant baseline differences in cognitive and academic performances. The reported sport-specific training in combination with physical education in the ESC resulted in a high mean training volume of 620 min per week and a medium training intensity of 4.8 points on a visual analog scale. We can conclude that ESC's training program is feasible and safe with no training-related injuries and high adherence rates (96%). After the 1-year sport-specific training in combination with physical education, performances in physical fitness were maintained or even increased in the ESC compared to the RC while there were no negative effects of ESC's high training volumes on cognitive and/or academic performances. Thus, it is concluded that sport-specific training in combination with regular school demands promotes physical fitness development and does not impede youth athletes' cognitive and academic performances. The results of the present study represents an example of a sport-specific training program that can be implemented at a relatively young age in schools and sports with early peak performances during the stages of LTAD. Our findings are crucial for parents and policy makers responsible for the well-being of their children. It has to be noted though that more longitudinal studies (>2 years) are needed to achieve in-depths knowledge on the development of youth athletes physical fitness and cognitive/academic performances during the stages of LTAD.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the ethical committee, University of Potsdam, Germany. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the local ethical committee of the University of Potsdam, Germany.

AUTHOR CONTRIBUTIONS

UG was involved in the design of the study, data collection and analysis, statistical computation, and the writing of the manuscript. RB was involved in the design of the study, implementation of the intervention, data collection and analysis, statistical computation, and the writing of the manuscript.

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Postactivation Potentiation of the Plantar Flexors Does Not Directly Translate to Jump Performance in Female Elite Young Soccer Players

Olaf Prieske[1]*, *Nicola A. Maffiuletti*[2] *and Urs Granacher*[1]

[1] Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany, [2] Human Performance Lab, Schulthess Clinic, Zurich, Switzerland

High-intensity muscle actions have the potential to temporarily improve muscle contractile properties (i.e., postactivation potentiation, PAP) thereby inducing acute performance enhancements. There is evidence that balance training can improve performance during strength exercises. Taking these findings together, the purpose of this study was to examine the acute effects of a combined balance and strength (B+S) exercise vs. a strength only (S) exercise on twitch contractile properties, maximum voluntary strength, and jump performance in young athletes. Female elite young soccer players ($N = 12$) aged 14–15 years conducted three experimental conditions in randomized order: S included 3 sets of 8–10 dynamic leg extensions at 80% of the 1-repetition maximum, B+S consisted of 3 sets of 40 s double-leg stances on a balance board prior to leg extensions (same as S), and a resting control period. Before and 7 min after exercise, participants were tested for their electrically-evoked isometric twitches (i.e., twitch peak torque, twitch rate of torque development) and maximal voluntary contraction (MVC) torque of the plantar flexor muscles. Additionally, countermovement (CMJ) and drop jump (DJ) performances (i.e., CMJ/DJ height, DJ ground contact time) were assessed. Significant effects of condition on twitch contractile properties ($p < 0.05$, $d = 1.1$) and jump performance outputs ($p < 0.05$, $1.1 \leq d \leq 1.2$) were found. *Post-hoc* tests revealed that S compared to control produced larger PAP for twitch peak torques by trend ($p = 0.07$, $d = 1.8$, 33 vs. 21%) and significantly larger PAP for twitch rate of torque development ($p < 0.05$, $d = 2.4$, 55 vs. 43%). Following B+S compared to control, significant improvements in CMJ height ($p < 0.01$, $d = 1.9$, 3%) and DJ contact time were found ($p < 0.01$, $d = 2.0$, 10%). This study revealed protocol-specific acute performance improvements. While S resulted in significant increases in twitch contractile properties, B+S produced significant enhancements in jump performance. It is concluded that PAP effects in the plantar flexors may not directly translate to improved jump performance in female elite young soccer players. Therefore, the observed gains in jump performance following B+S are most likely related to neuromuscular changes (e.g., intramuscular coordination) rather than improved contractile properties.

Keywords: sensorimotor training, conditioning activity, twitch torque, power, soccer

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University of Ljubljana, Slovenia
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Lymperis Perry Koziris,
McGill University, Canada

***Correspondence:**
Olaf Prieske
prieske@uni-potsdam.de

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INTRODUCTION

Short bouts of high-intensity exercise induce fatigue and have the potential to acutely improve the muscle's capability of generating high forces over a short period of time, which is usually denoted in the literature as postactivation potentiation (PAP) (Sale, 2002). Alterations in subsequent strength and power output may represent net performance changes due to fatigue and/or potentiation (Tillin and Bishop, 2009). PAP effects may also translate into performance enhancements of physical fitness components (Sale, 2002; Tillin and Bishop, 2009). For instance, Kilduff et al. (2008) reported that countermovement jump height was significantly enhanced by 5% following a loaded squat exercise [i.e., 3 sets of 3 repetitions at 3-repetition maximum (RM)] in male elite rugby players aged 25 years. In another study, Low et al. (2015) observed that repeated sprint performance significantly improved (∼1%) following loaded back squats (91% of 1-RM) in male adolescent soccer players aged 17 years. A recent meta-analysis summarized the acute effects of different types of exercise on subsequent power output in athletes (Wilson et al., 2013). More specifically, Wilson et al. (2013) reported large effect sizes for power enhancement following squat and leg press exercises in athletes (standardized mean difference = 0.81). Consequently, strength exercise (e.g., leg press with 80% 1-RM) appears to be an appropriate means to induce short-term performance enhancements (e.g., jump height) in male (young) athletes. However, there is no study available that has examined the effects of strength exercises on subsequent jump performance in female young soccer players.

Further, it has been reported that balance exercises have the potential to modulate neural activation of the plantar flexor muscles. In fact, cross-sectional studies revealed lower H-reflex amplitudes during the performance of complex postural tasks (e.g., walking on unstable balance beams) compared with tasks that afforded low complexity (e.g., walking on a treadmill) in healthy young adults (Llewellyn et al., 1990; Trimble et al., 2000; Chalmers and Knutzen, 2002; Day et al., 2017). This indicates diminished spinal excitability of the monosynaptic reflex pathway. Moreover, Horslen et al. (2013) found higher Achilles tendon stretch reflex responses under unstable compared to stable conditions (i.e., standing on a tilting platform vs. a firm surface). It was suggested that the observed increases in afferent feedback are related to better muscle spindle sensitivity. Taube et al. (2007) translated these findings to an intervention study. H-reflex amplitudes were significantly reduced after 6 weeks of balance training in adolescent athletes with a mean age of 15 years. In fact, spinal and cortical excitability are reduced following balance training, whereas activity in subcortical regions may increase (Taube et al., 2008). These changes can contribute to more coordinated and/or automatized muscle activation during motor performance (e.g., leg extensions) (Taube et al., 2008). In fact, Taube et al. (2007) observed a balance training induced trend for increased leg muscle activity (e.g., gastrocnemius muscle) in the range of 29–54% during maximal isometric leg extensions. Moreover, following 4 weeks of balance training in healthy young adults, Gruber et al. (2007) reported significant increases in electromyographic median frequency of the triceps surae muscle during maximal isometric plantar flexions (13–45%). These findings from cross-sectional and training studies can possibly be translated to research examining the effects of different types of exercise on acute performance enhancement. In other words, performing balance exercises prior to strength exercises may enhance the potential to improve muscle contractile properties and performance due to a more coordinated muscle activation (e.g., inter-/intramuscular activation) during strength exercises (e.g., leg extensions). To our knowledge, however, no study has previously investigated whether balance exercise performed prior to strength exercise has the potential to acutely facilitate twitch contractile properties (i.e., PAP) and/or jump performance compared to strength only exercise in female young athletes.

Thus, the purpose of the present study was to examine the acute effects of combined balance and strength (B+S) vs. strength only (S) exercise on twitch contractile properties of the plantar flexor muscles, jump performance, and maximum voluntary strength in female elite young soccer players. With reference to the relevant literature (Gruber et al., 2007; Taube et al., 2007; Wilson et al., 2013), we hypothesized that PAP effects and performance enhancements would be more pronounced following B+S compared to S.

METHODS

Participants

Twelve healthy female elite young soccer players aged 14–15 years (body height: 166.3 ± 4.3 cm; body mass: 55.1 ± 5.5 kg; body fat: 17.9 ± 5.6%) volunteered to participate in this study. All study participants were members of a soccer team that completed the season with the German under-17 championship title. With reference to a meta-analysis on the acute effects of strength exercises on proxies of muscle power (Wilson et al., 2013), an a priori power analysis with a type I error rate of 0.05 and 80% statistical power was computed. The analysis indicated that 12 young soccer players are sufficient to observe a medium-sized main effect (Cohen's $d = 0.5$) of condition with multiple sets of high-intensity exercise and rest intervals of ∼7 min on the primary outcome jump performance. Participants' maturity status was determined by calculating years from peak height velocity (PHV) according to the sex-specific formula that was introduced by Mirwald et al. (2002). Ten soccer players were classified as around-PHV (−1 to +1 years from PHV), while two players were defined as post-PHV (>1 to +3 years from PHV) (Hammami et al., 2016). In addition to physical education classes, participants were engaged in supervised competitive soccer training on a regular basis (including unspecific training for muscular endurance or flexibility) with a mean weekly training volume of 9–10 h. None of the participants suffered from acute musculoskeletal, neurological, or orthopedic disorders that might have affected their ability to execute the experimental protocol. The study was approved by the ethics committee of the University of Potsdam (application no. 28/2015). Prior to the start of the study, written informed consent was obtained from all study participants and their legal representatives. All experiments were conducted according to the latest version of the declaration of Helsinki.

Experimental Procedure

A single group, randomized cross-over design was used to examine the acute effects of exercise on twitch contractile properties and maximal voluntary strength of the plantar flexor muscles as well as jump performance (**Figure 1**). Measurements were conducted on a single session at the beginning of the season (i.e., pre-season). To get accustomed to the experimental procedures (e.g., dynamometry), one familiarization session was conducted on a separate occasion before the start of the study. During the familiarization session, participants' body height was assessed using a wall-mounted scale. In addition, body mass and percent body fat were quantified by means of a bioelectrical impedance analysis system (InBody 720, BioSpace, Seoul, Korea). Further, an isokinetic dynamometer (Isomed 2000, D&R Ferstl GmbH, Hemau, Germany) was individually adjusted with the participants lying in the supine position with hip, knee, and ankle joints in neutral position (180°, 180°, and 90°, respectively). Previously, Gago et al. (2017) recommended to use an extended knee position (i.e., 180°) for more pronounced PAP effects. The foot of the dominant leg was firmly attached to the lever arm of the dynamometer with its rotational axis at the level of the malleoli. Foot dominance was assessed using the lateral preference inventory (Coren, 1993). In order to limit upper body contribution to torque production, straps/pads were applied at the hip and shoulder level. This fixed position on the dynamometer was maintained throughout the entire test procedures (i.e., for twitch contractile properties and maximal voluntary strength). Additionally, the individual level of instability was determined on an adjustable balance board system (ARTZT vitality Wobblesmart, ARTZT, Dornburg, Deutschland). The balance board (i.e., balance cone) was unstable in 2 dimensions (i.e., frontal and sagittal plane). The base of support was progressively reduced (six levels available) and thus task difficulty increased by means of a pivot that moved outward of the frame producing a convex base of support. The individual level of task complexity/instability was defined as the smallest base of support that an individual was able to successfully accomplish during bipedal stance for 20 s (i.e., hands akimbo, no frame-ground contact). Finally, the leg press 1-RM (126 ± 19 kg, range: 104–158 kg) was determined for each participant as a reference value for the subsequent exercises (Baechle and Earle, 2008).

The experimental session started by searching the maximal stimulus intensity for electrical muscle stimulation, i.e., the intensity where a plateau in peak twitch torque was reached in a relaxed condition. Twitch torque recruitment curves relating evoked torque to stimulation intensity were obtained by delivering single electrical stimuli of increasing intensity (Neyroud et al., 2015). Subsequently, a brief warm-up was completed just before the pre-tests for twitch contractile properties, maximal voluntary strength and jump performance. The warm-up consisted of 8–10 submaximal isometric plantar flexions at 20–80% of maximum voluntary contraction (MVC) torque (∼5 min) (Neyroud et al., 2015). Following the pre-tests, three different experimental conditions (S, B+S, control) were organized in a randomized order. Each condition was followed by post-tests for twitch contractile properties, maximal voluntary strength and jump performance (same procedure as pre-tests). Seven minutes of rest were provided upon completion of the condition and the respective post-test, so as to obtain the most efficient net effect of fatigue and potentiation on the assessed strength and jump variables (Lesinski et al., 2013). A wash-out phase (∼12–15 min) was provided after each set of the post-tests until twitch torque values returned to baseline (**Figure 1**).

Experimental Conditions

The three experimental conditions comprised S exercise, B+S exercise, and a passive control condition. S consisted of bilateral eccentric-concentric contractions on a horizontal leg press

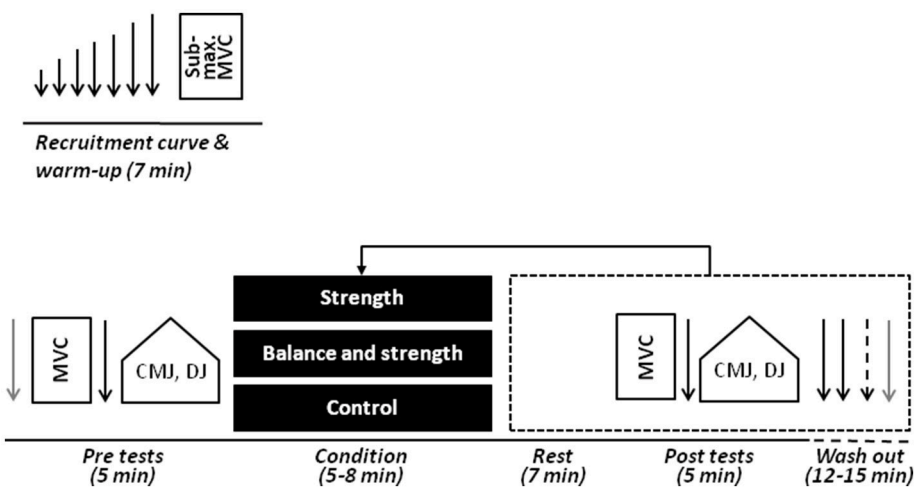


FIGURE 1 | Experimental protocol. The order of experimental conditions (i.e., exercise) was randomized within the same session. Following exercise, a passive rest, post-tests, and a wash-out phase were provided. Arrows depict the application of electrical muscle stimulation (gray arrows = resting twitches). CMJ, countermovement jumps; DJ, drop jumps; MVC, maximal voluntary contraction.

machine (Eagle leg press, Cybex Int., Medway MA, USA). Participants performed three sets of 8–10 repetitions with a load corresponding to 80% of the 1-RM (i.e., 101 ± 15 kg, range: 83–126 kg), and rest periods of 1–2 min between sets. According to Baechle and Earle (2008), 80% of the 1-RM generally corresponds to the 8-RM load. However, repetitions were not performed until failure. The range of motion for knee and ankle joints amounted to 90–175° and 80–100°, respectively. Time under tension during each repetition (1.5 s eccentric phase, 1.5 s concentric phase) was controlled using an electronic metronome. This training protocol proved to be effective in eliciting PAP effects (Lesinski et al., 2013). During B+S, participants performed three sets of double-leg stance balance exercise (eyes open, hands akimbo) on the adjustable balance board for 40 s, with a rest of 20 s between sets (Lesinski et al., 2015). The level of instability was adjusted according to the individual proficiency on the balance board. After balance exercise, leg press exercise was performed similarly to the S condition. During the passive control condition, participants were asked to rest in a seated position for 8 min. This time interval corresponded to the time needed to complete the B+S condition.

Assessment of Twitch Contractile Properties

Twitch contractile properties of plantar flexor muscles were determined by means of electrical muscle stimulation and dynamometry. Excellent test-retest reliability for measures of lower limb twitch contractile properties was reported with an intraclass correlation coefficient (ICC) ranging from 0.85 to 0.93 (Place et al., 2007). Single stimuli were delivered transcutaneously to the plantar flexor muscles of the dominant leg via two 5 × 10 cm rectangular self-adhesive surface electrodes (Compex®, DJO France/Division Compex Sport, Mouguerre, France). The anode was placed over the gastrocnemius muscle (∼5 cm distal to the popliteal fossa) and the cathode over the soleus muscle (∼10 cm proximal to the calcaneus) (Neyroud et al., 2015). Rectangular-wave pulses (200 μs duration) were generated by a high-voltage (max 400 V) constant-current stimulator (Digitimer DS7AH, Hertfordshire, UK). Stimulus intensity was set at 120% of maximal intensity (171 ± 18 mA, range 144–198 mA). As described above, the dynamometer was individually adjusted with the participants lying in the supine position with hip, knee, and ankle joints in neutral position (180°, 180° and 90°, respectively). During pre- and post-tests, twitches were evoked at rest before each experimental condition (i.e., resting twitch) and 2 s after each MVC (i.e., potentiated twitch). The twitch torque signal of the dynamometer was analog-to-digital converted (TeleMyo 2400R G2 Analog Output Receiver, Noraxon®, Scottsdale, AZ, USA), sampled at 1,500 Hz, and stored on a computer running MyoResearch XP Master Edition software (version 1.08.17, Noraxon®, Scottsdale, AZ, USA). Twitch peak torque (twitch PT) and twitch rate of torque development (twitch RTD) were determined from the twitch torque-time curve as the highest torque and the maximal slope between onset of torque and PT, respectively (mean of three trials).

Assessment of Maximal Voluntary Strength

MVC of the plantar flexor muscles of the dominant leg were conducted on the isokinetic dynamometer as described above. Previously, excellent test-retest reliability has been shown for voluntary MVC torque and RTD in leg extensors ($0.80 \leq ICC \leq 0.96$) (Jenkins et al., 2014). Participants performed 3 MVCs each lasting 3 s while they were consistently encouraged to contract "as forcefully and as fast as possible." Trials with an identified initial countermovement were discarded after visual inspection of the torque-time curve. The torque signal was analog-to-digital converted, sampled at 1,500 Hz, and analyzed using MyoResearch XP Master Edition software. MVC torque and voluntary RTD were defined as the highest torque and maximal slope between onset of torque and PT of the torque-time curve, respectively (mean of three trials). For each experimental condition, post-test values were expressed as a percentage relative to pre-test.

Assessment of Jump Performance

To assess jump performance, participants performed maximal vertical countermovement jumps (CMJ) and drop jumps (DJ) on a three-dimensional force plate (type 9286AA; Kistler®, Winterthur, Switzerland). Excellent test-retest reliability was previously reported for the CMJ height with an ICC-value of 0.98 (Markovic et al., 2004). The vertical ground reaction force was sampled at 1,000 Hz. For the execution of CMJ, participants were instructed to begin the jump with a downward movement, which was immediately followed by a concentric upward movement, resulting in a maximal vertical jump. During jumping, hands were kept on the hips and the depth of the downward movement was freely chosen to allow a natural movement. For the execution of DJ, participants stood in an upright position on a 37 cm box, feet shoulder-width apart, with the hands placed on the hips. Participants were asked to step off the box with their dominant leg, drop down to land evenly on both feet and jump-off the ground with a maximal-effort double-leg vertical jump. All participants were instructed to jump as high as possible (for CMJ, DJ) and to keep ground contact time as short as possible (for DJ). Two CMJ and DJ trials were completed with a rest period of 30 s between jumps. Jump height (for CMJ, DJ) as well as ground contact time and performance index (for DJ) were determined and averaged over the two trials. Jump height was calculated according to the following formula: jump height $= 1/8 \times g \times t^2$, where g is the acceleration due to gravity and t is the flight time (Prieske et al., 2013). Performance index was defined as the ratio of jump height and ground contact time (Prieske et al., 2013). For each experimental condition, post-test jump performance was expressed as a percentage relative to pre-test.

Statistical Analyses

Descriptive data are presented as group mean values and standard deviations. Normal distribution was examined using the Shapiro–Wilk test. For strength and jump variables, a one-way (experimental condition: S, B+S, control) repeated measures analysis of variance (ANOVA) was used. For twitch contractile properties, a two-way (time: rested, potentiated; experimental condition: pre-test, S, B+S, control) repeated measures ANOVA

was used. Homogeneity of variance was examined using the Mauchly sphericity test for repeated measures. If homogeneity was violated, the Greenhouse-Geisser correction was applied for further analyses. In *post-hoc* tests, the Bonferroni adjustment was applied to each *p*-value calculated, thereby ensuring the level of significance for all pairwise comparisons. The significance level was set at $p < 0.05$. A trend for statistical significance was deemed at $p < 0.10$. Effect sizes were calculated by converting partial eta-squared to Cohen's *d* to indicate whether a statistically significant difference is a difference of practical concern. According to Cohen (1988), the magnitude of effect sizes can be classified as small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$), and large ($d \geq 0.8$). To assess the relationship between pre-to-post-test changes in twitch contractile properties and performance measures, Pearson correlation coefficients (*r*) were calculated and classified as trivial ($r < 0.1$), small ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), and almost perfect ($r \geq 0.9$) (Hopkins et al., 2009). All analyses were performed using Statistical Package for Social Sciences (SPSS) version 24.0.

RESULTS

Twitch Contractile Properties

Significant, large-sized time by experimental condition interaction effects were observed for twitch PT ($p < 0.05$, $d = 1.14$) and twitch RTD ($p < 0.05$, $d = 1.12$). *Post-hoc* tests indicated that twitch RTD potentiation was significantly higher following S (55%) compared to pre-test (49%) and control (43%) ($p < 0.05$, $1.98 \leq d \leq 2.39$; **Figure 2B**). A statistical trend in the direction of greater twitch PT potentiation following S (33%) compared to control (21%) was also observed ($p = 0.068$, $d = 1.83$; **Figure 2A**).

Maximal Voluntary Strength

Table 1 shows the means and standard deviations for strength parameters. There were small-to-medium sized but non-significant effects of the experimental condition on MVC torque and voluntary RTD ($p > 0.05$, $0.33 \leq d \leq 0.64$). Additionally, trivial-to-moderate correlation coefficients ($-0.38 \leq r \leq 0.32$) were observed between twitch contractile properties and strength variables (**Table 2**).

Jump Performance

Means and standard deviations are displayed in **Table 1** for measures of jump performance. For CMJ performance, a significant and large effect of experimental condition was found for CMJ height ($p < 0.05$, $d = 1.36$). *Post-hoc* tests indicated that CMJ height was significantly larger following B+S compared to control (3%, $p < 0.05$, $d = 1.82$; **Figure 3A**). Additionally, a significant and large effect of experimental condition was found for DJ ground contact time ($p < 0.05$, $d = 1.17$). *Post-hoc* tests indicated that contact time was significantly lower following B+S compared to control (10%, $p < 0.05$, $d = 1.98$; **Figure 3C**). Further, medium-sized but non-significant effects of experimental condition were observed for DJ height and performance index ($p > 0.05$, $0.72 \leq d \leq 0.76$; **Figure 3B**). Finally, the magnitude of correlation coefficients between twitch contractile properties and jump performance variables ranged from trivial-to-large ($-0.61 \leq r \leq 0.35$; **Table 2**).

DISCUSSION

To the authors' knowledge, this is the first study that investigated the acute effects of two different exercise combinations (B+S; S) vs. a passive control condition on twitch contractile properties, jump performance and maximum voluntary strength in female elite young soccer players. The main findings of this study were that (1) S exercise significantly improved plantar flexor muscle contractile properties—but not jump performance—while (2) B+S

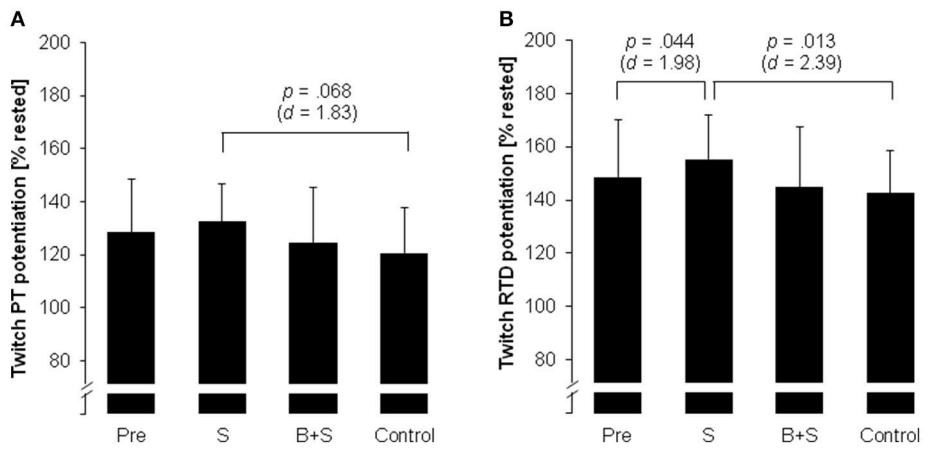


FIGURE 2 | Potentiation of twitch contractile properties of the plantar flexor muscles in female elite young soccer players after the pre-test (Pre) and after the three experimental conditions [strength (S); balance and strength (B+S); passive control]. **(A)** Twitch peak torque (PT) potentiation, **(B)** twitch rate of torque development (RTD) potentiation. Values are displayed in percent relative to the pre-MVC resting twitch and in means ± standard deviation.

TABLE 1 | Performance-related measures at pre-test (Pre) and after strength only exercise (S), balance and strength exercise (B+S), and passive control in female elite young soccer players.

Performance measure	Pre	S		B+S		Con		*p* value (*d*)
		(absolut)	(% Pre)	(absolut)	(%Pre)	(absolut)	(% Pre)	
STRENGTH PERFORMANCE								
MVC torque (Nm)	108.3 ± 40.5	121.1 + 42.0	113.1	117.6 + 41.3	109.4	122.1 + 39.0	115.3	0.336 (0.64)
Voluntary RTD (Nm/s)	331.8 ± 187.7	394.7 + 184.3	127.7	410.1 + 185.0	135.3	379 + 146.6	129.7	0.742 (0.33)
JUMP PERFORMANCE								
CMJ height (cm)	22.9 ± 2.6	23.3 + 2.8	101.7	23.7 + 2.6	103.8	23.1 + 2.7	100.7	0.016 (1.36)
DJ height (cm)	17.8 ± 2.9	17.0 + 3.4	95.5	17.9 + 3.0	101.3	17.8 + 2.7	101.0	0.257 (0.72)
DJ contact time (ms)	219.1 ± 28.7	224.4 + 35.9	102.3	215.9 + 29.6	99.0	239 + 35.7	109.2	0.040 (1.17)
DJ performance index (m/s)	0.83 ± 0.20	0.78 + 0.21	94.1	0.84 + 0.16	103.6	0.77 + 0.20	93.7	0.227 (0.76)

Absolute performance measures are presented for Pre. For S, B+S, and control, performance measures are displayed in percent relative to Pre. Values are presented in means ± standard deviation. CMJ, countermovement jump; DJ, drop jump; MVC, maximal voluntary contraction; PT, peak torque; RTD, rate of torque development.

TABLE 2 | Correlation coefficients (Pearson's *r*) between pre-to-post-test changes in twitch contractile properties and performance measures in female elite young soccer players.

Δ Performance measure	Δ Twitch PT	Δ Twitch RTD
STRENGTH EXERCISE		
MVC torque	−0.38	−0.37
Voluntary RTD	0.31	−0.10
CMJ height	0.06	−0.08
DJ height	−0.21	−0.21
DJ contact time	−0.54	−0.46
DJ performance index	0.15	0.11
BALANCE AND STRENGTH EXERCISE		
MVC torque	0.28	0.27
Voluntary RTD	0.32	0.18
CMJ height	0.31	0.05
DJ height	−0.15	−0.12
DJ contact time	−0.43	−0.35
DJ performance index	0.08	0.37
CONTROL		
MVC torque	−0.19	0.16
Voluntary RTD	−0.01	0.02
CMJ height	0.05	0.07
DJ height	−0.20	0.08
DJ contact time	−0.43	−0.61*
DJ performance index	0.35	0.32

*$p < 0.05$.

exercise significantly enhanced jump performance—but not twitch contractile properties—in female elite young soccer players.

Effects of Balance and Strength Exercise on PAP

It is well-documented that the contractile history of skeletal muscle directly affects its performance characteristics (Sale, 2002; Tillin and Bishop, 2009). Two antagonistic physiological processes take place during the application of a PAP protocol. First, sustained muscle contractions (whether dynamic or isometric) gradually induce muscle fatigue as indicated by decrements in performance output (Enoka and Duchateau, 2008). Second, specific muscle contractions, whether voluntary or electrically evoked, induce short-term PAP effects (i.e., improvements in twitch contractile properties). The net effect of fatigue and PAP in favor of the latter may result in enhanced strength- and power-related performance (Sale, 2002; Tillin and Bishop, 2009). Of note, findings from this study revealed significantly larger PAP (i.e., twitch RTD) following submaximal strength exercise (i.e., three sets of 8–10 leg presses at 80% 1-RM) when compared to a resting control condition (55% vs. 43%). This result is partly supported by studies that examined the effects of submaximal dynamic exercise (i.e., loaded squats) on PAP in lower limb muscles of male trained adults (Mitchell and Sale, 2011; Nibali et al., 2013; Fukutani et al., 2014). For instance, in the study of Mitchell and Sale (2011) rugby union players (mean age: 20 years) performed a set of five squats with a load corresponding to 5-RM which significantly potentiated knee extensor twitch PT (11%) compared to a passive control condition. Further, Fukutani et al. (2014) examined knee extensor twitch PT before and after submaximal squat exercises realized at moderate-intensity (45–75% 1-RM) vs. high-intensity (45–90% 1-RM) in Olympic weightlifters with a mean age of 20 years. Significant twitch PT potentiation was observed after both conditions with larger PAP following high-intensity compared to moderate-intensity exercise (40% vs. 17%). However, only few studies examined the effects of "conditioning" contractions on twitch torque potentiation in preadolescent and/or adolescent youth (Belanger and McComas, 1989; Pääsuke et al., 2000, 2003). For instance, Pääsuke et al. (2003) found significant potentiation of plantar flexor twitch peak force after 5-s MVC in boys (37%) and girls (22%) aged 9–10. Similarly, in this study, exercise-induced potentiation of plantar flexor twitch PT amounted 21–33%. Nevertheless, this is the first study to investigate the effects of submaximal dynamic strength exercise and combined

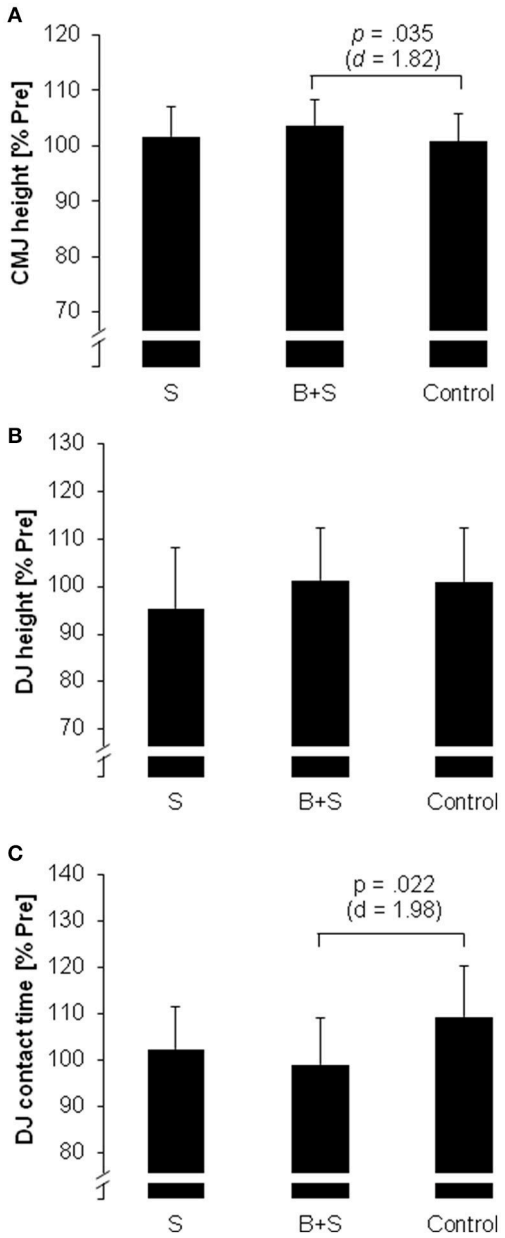


FIGURE 3 | Countermovement (CMJ) and drop jump (DJ) performance in female elite young soccer players after the three experimental conditions [strength (S); balance and strength (B+S); passive control]. **(A)** CMJ height, **(B)** DJ height, **(C)** DJ ground contact time. Values are displayed in percent relative to pre-test and in means ± standard deviation.

balance and strength exercise on PAP in adolescent female soccer players.

Surprisingly, it has to be noted that B+S exercise did not significantly enhance plantar flexor PAP compared to S and control. We therefore hypothesize that twitch contractile properties of the plantar flexors were affected by the volume and/or type of the preceding activity (Tillin and Bishop, 2009). In fact, it was previously demonstrated that volume/duration of both maximal (Vandervoort et al., 1983; Hamada et al., 2003) and submaximal contractions (Fowles and Green, 2003; Morana and Perrey, 2009) of different lower limb muscles is an important determinant of the magnitude of PAP. For instance, Vandervoort et al. (1983) showed the largest potentiation of plantar flexor twitch PT when MVCs were sustained for 10–30 s (45%) compared to 1–3 s or 60 s (<23%) in subjects aged 21–48 years. Additionally, Morana and Perrey (2009) examined the time course of PAP during 10 min of intermittent submaximal (50% MVC) isometric knee extensions in power-trained (i.e., rugby players, weightlifters) and endurance-trained athletes (i.e., distance runners, triathletes) with a mean age of 25 years. They reported that in the rugby players/weightlifters but not in the distance runners/triathletes, twitch PT was significantly enhanced following 1 min of exercise (53%) but decreased (30% below baseline) due to fatigue after 10 min of exercise. Similarly, fatigue-related effects may have occurred following B+S exercise in our participants consisting of power-trained female young soccer players. In terms of activity type, it was argued that balance exercise can enhance neuromuscular function but not muscle contractile properties (Gollhofer, 2007). For instance, Gruber et al. (2007) examined the effects of 4 weeks of balance vs. ballistic strength training on neural (e.g., activation) and muscular adaptations (i.e., contractile properties) in healthy young adults aged 26 years. Both training programs induced specific neural adaptations (e.g., enhanced intramuscular coordination), whereas twitch contractile properties of the plantar flexor muscles remained unchanged. Thus, it can be postulated that the combination of balance and strength exercise as conducted in the present study did not provide an appropriate stimulus to enhance twitch contractile properties of the plantar flexors in female elite young soccer players. This may be attributed to neuromuscular fatigue and/or an inappropriate exercise modality of the preceding activity. It has to be acknowledged that we only examined contractile properties of plantar flexor muscles following S and B+S conditions. Previously, it was shown that PAP effects can occur in other leg muscles (e.g., knee extensors, ankle dorsal extensors) as well following submaximal and maximal lower limb exercises (Hamada et al., 2003; Morana and Perrey, 2009). Thus, future studies need to elucidate whether B+S exercise can enhance PAP effects in other lower limb muscles than plantar flexors.

Effects of Balance and Strength Exercise on Strength and Jump Performance

In contrast to PAP findings, the present study revealed that jump performance (i.e., CMJ height, DJ ground contact time) was significantly improved following B+S exercise compared to the passive control condition. Additionally, MVC torque and voluntary RTD were not significantly enhanced following S or B+S exercise compared to control. Thus, it appears that the observed PAP effects induced by S exercise on the plantar flexors did not directly translate to improved strength and jump performance in female elite young soccer players. Some adult studies indicate that the potentiation of twitch contractile properties (e.g., PT) induced by submaximal and

maximal contractions (Mitchell and Sale, 2011; Requena et al., 2011; Nibali et al., 2013; Fukutani et al., 2014) may partly contribute to acute performance enhancements (e.g., increased jump height). For instance, the studies of Mitchell and Sale (2011) and Fukutani et al. (2014) reported concomitant PAP-related increases in knee extensor twitch PT (11–40%) and CMJ height (3–11%) following submaximal squat exercise in trained men. The authors concluded that PAP effects contributed significantly to the gains in jump performance. However, statistical associations between pre-to-post-exercise changes of twitch contractile properties and strength/jump performance measures are inconsistent in the literature. In fact, a number of studies reported small-to-large sized correlation coefficients ($-0.47 \leq r < 0.50$) between changes in twitch PT and CMJ height/kinetics in recreationally-trained men (Nibali et al., 2013; Pearson and Hussain, 2014) and small-to-large sized correlation coefficients ($0.24 \leq r \leq 0.61$) in male rugby and soccer players (Mitchell and Sale, 2011; Requena et al., 2011). Similarly, in our study correlation coefficients between exercise-induced changes in twitch PT and jump performance ranged from trivial-to-large in female elite young soccer players. Taken together, these correlation-based results indicate that individuals with greater PAP effects are not necessarily those showing the greatest strength/jump performance improvements following acute exercise.

Interestingly, the B+S exercise-induced increases in jump performance without concomitant plantar flexor PAP effects observed here may be attributed to acute neuromuscular adjustments associated to the combination of single-leg stance and leg press exercise. Acute exercise may indeed potentiate selected neuromuscular responses in lower limb muscles. More specifically, H-reflex responses of knee extensor and plantar flexor muscles were significantly potentiated 3–10 min after maximal contractions in adults (Guellich and Schmidtbleicher, 1996; Trimble and Harp, 1998; Folland et al., 2008). Such potentiation at the spinal level appears to be due to the recruitment of larger motor units (Tillin and Bishop, 2009). Additionally, there is evidence that balance exercise has the potential to enhance neuromuscular function (e.g., afferent feedback, motor unit recruitment) during lower limb activities (Gruber et al., 2007; Horslen et al., 2013). For instance, Horslen et al. (2013) reported larger muscle spindle sensitivity under unstable compared to stable conditions. The authors stated that these adaptations may increase afferent feedback to cortical and/or subcortical areas during postural challenges. Further, Gruber et al. (2007) found significant increases in voluntary RTD of the plantar flexors and EMG median frequency of the triceps surae muscle following 4 weeks of balance training in healthy young adults. These authors argued that the observed training-induced RTD improvements are most likely caused by increases in EMG median frequency which is indicative of improved intramuscular coordination (e.g., earlier recruitment of larger motor units). Notably, it was speculated that enhanced recruitment of higher order motor units as a result of preceding muscle activity might increase the contribution of fast fibers to muscle contraction and finally to performance (Tillin and Bishop, 2009). Thus, it is plausible to postulate that short-term neuromuscular adjustments associated to B+S exercise are responsible, at least in part, for the observed enhancements in jump performance.

CONCLUSIONS

Findings from the present study revealed short-term improvements in twitch contractile properties following S but not B+S exercise compared to a passive control condition. In contrast, significant increases in jump performance were observed following B+S but not S exercise with respect to control. Thus, it can be concluded that submaximal leg press strength exercise successfully induced PAP effects in the plantar flexor muscles of female elite young soccer players. However, plantar flexor PAP appears to be affected by the type and/or volume of the preceding activity (i.e., S vs. B+S exercise). Further, PAP effects in the plantar flexor muscles did not directly translate into jump performance improvements, probably because these latter rely more on neuromuscular adjustments (e.g., intramuscular coordination) rather than on intrinsic muscle properties. From a practical point of view, the sequencing of balance and strength exercises (e.g., leg press, loaded squats) is recommended as a procedure to acutely enhance jump performance (e.g., during complex training) in female young athletes.

AUTHOR CONTRIBUTIONS

OP, NM, and UG made substantial contributions to conception, design, and data collection; OP contributed to data acquisition and carried out data analysis and interpretation together with NM and UG; OP wrote the first draft of the manuscript and all authors were involved in revising it critically for important intellectual content; OP, NM, and UG gave final approval of the version to be published and agreed to be accountable for all aspects of the work.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tensiomyographic Markers Are Not Sensitive for Monitoring Muscle Fatigue in Elite Youth Athletes: A Pilot Study

*Thimo Wiewelhove *, Christian Raeder, Rauno Alvaro de Paula Simola, Christoph Schneider, Alexander Döweling and Alexander Ferrauti*

Faculty of Sport Science, Ruhr-University, Bochum, Germany

Objective: Tensiomyography (TMG) is an indirect measure of a muscle's contractile properties and has the potential as a technique for detecting exercise-induced skeletal muscle fatigue. Therefore, the aim of this study was to assess the sensitivity of tensiomyographic markers to identify reduced muscular performance in elite youth athletes.

Methods: Fourteen male junior tennis players (age: 14.9 ± 1.2 years) with an international (International Tennis Federation) ranking position participated in this pre-post single group trial. They completed a 4-day high-intensity interval training (HIT) microcycle, which was composed of seven training sessions. TMG markers; countermovement jump (CMJ) performance (criterion measure of fatigue); delayed onset muscle soreness; and perceived recovery and stress were measured 24 h before and after the training program. The TMG measures included maximal radial deformation of the rectus femoris muscle belly (Dm), contraction time between 10 and 90% Dm (Tc) and the rate of deformation until 10% (V10) and 90% Dm (V90), respectively. Diagnostic characteristics were assessed with a receiver-operating curve (ROC) analysis and a contingency table, in which the area under the curve (AUC), Youden's index, sensitivity, specificity, and the diagnostic effectiveness (DE) of TMG measures were reported. A minimum AUC of 0.70 and a lower confidence interval (CI) >0.50 classified "good" diagnostic markers to assess performance changes.

Results: Twenty-four hours after the microcycle, CMJ performance was observed to be significantly ($p < 0.001$) reduced (Effect Size [ES] = −0.68), and DOMS (ES = 3.62) as well as perceived stress were significantly ($p < 0.001$) increased. In contrast, Dm (ES = −0.35), Tc (ES = 0.04), V10 (ES = −0.32), and V90 (ES = −0.33) remained unchanged ($p > 0.05$) throughout the study. ROC analysis and the data derived from the contingency table revealed that none of the tensiomyographic markers were effective diagnostic tools for detecting impaired muscular performance in elite youth athletes (AUC, 95% CI, DE%; Dm: 0.46, 0.15–0.77, 35.7%; Tc: 0.29, 0.03–0.59, 35.7%; V10: 0.71, 0.27–1.00, 35.7%; V90: 0.37, 0.10–0.65, 35.7%).

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***Correspondence:**
Thimo Wiewelhove
thimo.wiewelhove@ruhr-uni-bochum.de

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Conclusion: The tensiomyographic parameters that were assessed in this study were not sensitive enough to detect muscular performance changes in elite youth athletes.However, due to the preliminary nature of the study, further research is needed to investigate the sensitivity of TMG in this population.

Keywords: muscle contractile properties, fatigue, training monitoring, junior athletes, high-intensity interval training

INTRODUCTION

To help elite athletes to progress, modifications in training load are required, particularly adjustments in frequency, duration and intensity (Halson, 2014). This applies equally to both young and adult athletes. As such, many coaches think that in order to achieve success at the senior level, it is necessary to start intensive training well before puberty. This means that many of the youngsters are already training intensively, and for considerable hours, by the time they reach adulthood (Matos and Winsley, 2007).

Compared with adults, youth athletes are able to resist fatigue better and to recover faster during and after exercise (Ratel et al., 2006). Nevertheless, the incidence of overuse symptoms in pediatric and adolescent athletes is increasing (Brenner, 2007). Especially during excessive amounts of high-intensity, repetitive physical activity without adequate rest, the risk of injury, illness, and/or non-functional overreaching is also serious in the youth athlete for several reasons (e.g., the growing bones, ligaments, tendons and cartilage of the young athletes cannot handle as much stress as the mature, passive structures of adults; Matos and Winsley, 2007). Thus, it is important to titrate fatigue appropriately, and to identify youth at risk of overuse (Halson, 2014; Quarrie et al., 2016; Schwellnus et al., 2016; Soligard et al., 2016).

To determine whether a young athlete can tolerate a training program and to minimize the risk of possible negative outcomes, the routine assessment of fatigue and recovery is viewed by many as important (Halson, 2014). In this context, a potentially effective tool for detecting post-exercise muscle fatigue is tensiomyography (TMG), which was introduced as a non-invasive, motivation-independent, and involuntary measure of muscle contractile characteristics (i.e., peripheral fatigue) designed to work without producing additional fatigue (Hunter et al., 2012; Simola et al., 2016b).

The TMG technique is based on the radial deformation of the isolated muscle belly and the time it takes for this action to occur during an isometric twitch contraction evoked by electrical stimulation (Simola et al., 2016b). The key parameters obtained from TMG are muscle displacement, which is representative of muscle tone and contractile force, and the time of the response, which is related to the speed of force generation (Hunter et al., 2012). It is therefore assumed that the effects of exercise-induced damage to muscle structures and the resulting changes in mechanical capacities and performance capabilities (i.e., peripheral fatigue) can be quantified by TMG measures (García-Manso et al., 2011).

A number of studies have been able to demonstrate fatigue-related changes in TMG measures in adults in cases in which exercise-induced muscle damage and/or muscle soreness as well as a decline in performance, peak force and/or rate of force development was observed (Carrasco et al., 2011; García-Manso et al., 2011; Hunter et al., 2012; Simola et al., 2015, 2016a,b; Wiewelhove et al., 2015b). However, we were unable to find any studies that have examined the usefulness of TMG markers to reflect individual changes in post-exercise muscle fatigue in youth athletes. As such, the purpose of the current study was: (1) to investigate changes of TMG variables in elite youth athletes in response to a 4-day high-intensity interval training period, designed to induce a temporary functional overload; and (2) to assess the sensitivity of TMG measures to identify alterations in performance based on individual changes. We hypothesized that the training program leads to an acute increase in perceived fatigue and soreness accompanied by a reduction in physical capacity and that TMG parameters are sensitive to detect muscular performance changes.

MATERIALS AND METHODS

Participants

Fourteen elite male junior tennis players (age, 14.9 $\pm$ 1.2 years; height: 1.81 $\pm$ 0.09 m; body mass, 69.0 $\pm$ 11.0 kg; and BMI, 19.01 $\pm$ 2.22 $kg \cdot m^{-1}$) with international ITF (International Tennis Federation) ranking positions participated in this study. After being informed about the exercise protocols and all possible risks associated with participation in the investigation, the players and their parents provided written consent to participate in all procedures. Normal electrocardiography findings, as well as the absence of cardiovascular, pulmonary and orthopedic diseases, were confirmed during a preliminary health examination. The study was approved by the ethics committee of the medical faculty of the Ruhr-University Bochum (registration number: 4623-13), and was completed according to the guidelines of the Declaration of Helsinki.

Experimental Design

A pre-post single group design was used to investigate the sensitivity of TMG markers of muscle fatigue. The youth athletes participated in a 4-day training period, which was composed of seven running-based high-intensity interval training (HIT) sessions. At 72 h prior to the HIT program, all players visited the laboratory for a preliminary health examination, to provide data on anthropometrical characteristics, and to complete the 30-15 Intermittent Fitness Test (30-15_{IFT}). TMG markers, countermovement jump (CMJ) performance (criterion

measure of fatigue), delayed onset muscle soreness (DOMS), as well as information on perceived recovery and stress, were then measured 24 h prior to the microcycle (pre) as well as 24 h after completing the training program (post) (**Figure 1**). On both testing days, DOMS, perceived recovery and stress, TMG markers and CMJ were determined (in this order) in the morning between 9 a.m. and 1 p.m. and the testing time was kept constant between days for each player.

Procedures

30-15 Intermittent Fitness Test

The 30-15 Intermittent Fitness Test ($30\text{-}15_{IFT}$) was conducted in a multipurpose indoor training center on a combined elastic flooring system with a PVC surface, and consisted of 30-s shuttle runs interspersed with 15-s passive recovery periods. The speed was set at 8 $km{\cdot}h^{-1}$ for the first 30-s run and was increased by 0.5 $km{\cdot}h^{-1}$ at every 45-s stage thereafter. The players were asked to run back and forth between two lines, set 40 m apart, at a pace dictated by an acoustic signal. The test ended when a player was unable to reach a 3 m zone around each line at the moment of the audio signal for three consecutive times. The speed of the last completed stage that was reached by the athlete (V_{IFT}) was used to calculate the interval intensity of the HIT protocol, and to estimate athletes VO_2max according to the following formula: $VO_2max_{30-15IFT}$ $(ml{\cdot}min{\cdot}kg^{-1}) = 28.3 - 2.15 - 0.741\,A - 0.0357\,W + 0.0586\,A \times V_{IFT} + 1.03\,V_{IFT}$, where A stands for age, and W for weight. The mean V_{IFT} and $VO_2max_{30-15IFT}$ of the athletes were 20.3 ± 0.6 $km{\cdot}h^{-1}$ and 51.2 ± 1.5 $ml{\cdot}min{\cdot}kg^{-1}$ respectively. Previous studies have shown that the $30\text{-}15_{IFT}$ is a valid (V_{IFT} is significantly related to VO_2max ($r = 0.68$, $p < 0.05$), 10-m sprint time ($r = 0.63$, $p < 0.05$), CMJ height ($r = 0.65$, $p < 0.05$), repeated sprint ability ($r = 0.88$, $p < 0.001$), or the final velocity in the University of Montreal track Test ($r = 0.79$, $p < 0.001$) and reliable (V_{IFT} [$km{\cdot}h^{-1}$]: intraclass correlation coefficient (ICC) = 0.96) intermittent aerobic fitness test with a typical error (TE) of measurement of approximately 0.3 $km{\cdot}h^{-1}$ (Buchheit, 2010).

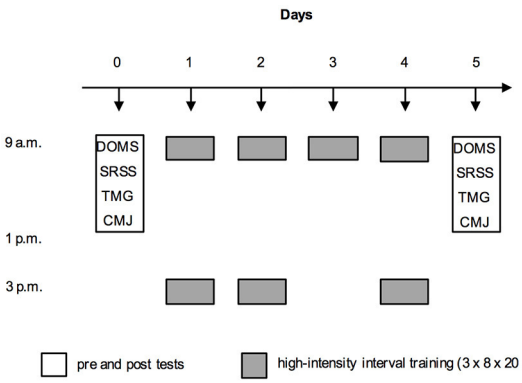


FIGURE 1 | Experimental protocol showing the measurements [delayed onset muscle soreness (DOMS); Short Recovery and Stress Scale (SRSS); tensiomyographic markers (TMG); and countermovement jump performance (CMJ)] and the arrangement of the seven high-intensity interval training sessions during the four-day training period.

Tensiomyography

For the non-invasive assessment of the contractile characteristics of the rectus femoris muscle of the dominant lower limb, TMG was used under laboratory conditions. This technique produces radial displacement of the muscle belly in response to a submaximal (i.e., below voluntary maximal activation) electrical stimulus triggered by a specific electrical stimulator (TMG-S2) that is conducted through the underlying muscle tissue. These displacements are then recorded at the skin surface using a displacement sensor tip with a spring constant of 0.17 $N{\cdot}mm^{-1}$, together with the TMG-OK 3.0 software (TMG-BMC, Ljubljana, Slovenia).

The sensor was positioned perpendicular to the thickest part of the muscle belly, which was established visually and through palpation during a voluntary contraction, and the self-adhesive electrodes were placed symmetrically approximately 5 cm away from the sensor. Once the exact position for the sensor and electrodes was found, it was marked with a dermatological pen and kept constant during the experimental period (Wiewelhove et al., 2015b). Individual maximal electrical stimulation and Dm were found by progressively increasing the electric current by 20 mA until no further displacement of the muscle belly could be produced. Each stimulation was separated by 10-s intervals to minimize the effects of fatigue and potentiation. The average values from the two maximal twitches was used for further analysis. The rectus femoris muscle was assessed in a supine position, and an internal knee angle of 120° was kept by using supporting pads (Simola et al., 2016b).

The TMG measures included Dm, Tc, V_{10}, and V_{90}. Dm is equivalent to the maximal radial deformation of the muscle belly which is representative of muscle tone and contractile force. Tc is the deformation time between 10 and 90% Dm. V_{10} and V_{90} can be understood as the rate of deformation development until 10% Dm (10% Dm/Δtime) and 90% Dm (90%Dm/Δtime), respectively. Tc, V_{10}, and V_{90} refer to the time and velocities of the muscle radial deformation, which in turn indicate the time and speed of force generation (Simola et al., 2016b). It is assumed that the effects of muscle fatigue, especially on the changes in performance parameters like jump height, can be detected by TMG measures (Hunter et al., 2012; Wiewelhove et al., 2015b): If a decline in jump height is observed then a similar response would be expected by Dm, V_{10}, and V_{90}, whereas an increase would be shown in Tc. Moreover, Dm, Tc, V_{10}, and V_{90}were the main parameters in this trial because of sufficient reliability scores (unpublished results, 2013: $n = 20$, Dm [mm]: ICC = 0.87, TE = 0.97, coefficient of variation (CV) = 12.9%; Tc [ms]: ICC = 0.90, TE = 1.86, CV = 5.8%; V_{10} [$mm{\cdot}s^{-1}$]: ICC = 0.86, TE = 4.00, CV = 12.5%; V_{90} [$mm{\cdot}s^{-1}$]: ICC = 0.84, TE = 17.89, CV = 13.7%).

Jump Performance

Following a 5-min standardized warm-up, CMJ were performed on a contact platform (Haynl-Elektronik GmbH, Schönebeck, Germany) with the hands placed on the hips. For CMJ, players dropped down to a self-selected level, before jumping to the

maximum height. Flight time was used to calculate jump height. Three CMJs were performed with ∼10 s of passive recovery between efforts. The best CMJ value over the three attempts was then computed (Al Haddad et al., 2015). Previously measured reliability scores for the CMJ test were regarded as highly reliable (unpublished results, 2013: $n = 38$, CMJ [cm]: ICC = 0.92, TE = 1.86, CV = 3.7%).

Delayed Onset Muscle Soreness

Muscle soreness was assessed using a visual analog scale (VAS). The VAS consisted of a 100 mm line, whose endpoints were labeled as "no pain" (left) and "unbearable pain" (right). Participants were asked to draw a vertical line at a point on the line that best represented their pain at the time of the measurement. Their score was then determined from the distance in mm from the left border of the scale to the point marked (Cleather and Guthrie, 2007).

Perceived Recovery and Stress

Perceived recovery and stress was assessed using the Short Recovery and Stress Scale (SRSS) (Hitzschke et al., 2015). Players were requested to provide responses to eight items on a 0 (i.e., does not apply at all) to 6 (i.e., fully applies) rating scale. Numbers 1–5 on this scale were undefined and were instead used to delineate the degrees of perceived recovery and stress between the two ends of the scale. The items used in this study were "physical performance capability" (PPC) and "muscular stress" (MS). Scores for internal consistencies of the SRSS were previously examined among elite athletes and considered to be sufficient ($n = 574$; $\alpha = 0.70$–0.76).

Training Program

During the 4-day training period, the athletes completed seven HIT sessions (**Table 1**). At each session, the players performed three series involving eight intervals, with 20 s of passive recovery between the intervals and 6 min of passive recovery between each series. Each interval was 15 s in duration and consisted of 20-m shuttle runs at 90% V_{IFT}. The overall distance, which the athletes had to cover during each interval, differed according to their individual V_{IFT}. All sessions were completed in the same indoor training center as the 30-15_{IFT}, and were preceded by a standardized continuous 10-min warm-up. To ensure that the intended training intensity was maintained by the players, all sessions were supervised and the individually calculated running distances were controlled.

Finally, capillary blood samples were obtained from the hyperemized earlobe throughout training sessions 1, 3, 5, and 7 (i.e., before the first interval of the first series and immediately after the last interval of the final series); these were analyzed for blood lactate concentration (La). Blood samples were taken with 20-µl capillaries, hemolyzed in 1-ml micro test tubes, and analyzed by using enzymatic amperometry with the Biosen S-Line Sport (EKF-Diagnostik GmbH, Magdeburg, Germany). In addition, the athlete's perception of the overall difficulty of each training bout as determined 30 min after the completion of an exercise was recorded using a category-ratio scale (Alexiou and Coutts, 2008).

Statistical Analysis

Our statistical analyses were conducted using IMB SPSS Statistics (version 23, IBM Corporation, Amonk, New York, USA) and Microsoft Excel (version 15.17, Microsoft Corp., Redmond, WA, USA). Results are presented as means and standard deviations (SD), and were tested for normal distribution using the Shapiro-Wilk-Test. In cases of non-normal distribution, data was log transformed prior to statistical analysis in order to improve normality and variance homogeneity. All data was first analyzed using the Student's *t*-test for paired data, with significance set at $p < 0.05$. The magnitude of changes between testing days was assessed using the effect size (ES). Threshold values for ES were 0.2 (small), 0.6 (moderate), 1.2 (large), 2.0 (very large), and 4.0 (extremely large) (Hopkins et al., 2009).

Receiver-operating characteristic (ROC) curves were used to investigate the diagnostic accuracy of the TMG measures for the assessment of muscle fatigue in comparison to the criterion measure (i.e., jump performance). A ROC curve plots the true positive rate (i.e., sensitivity) against the true negative rate (i.e., specificity) to produce an area under the curve (AUC). An AUC serves to estimate how high the discriminative power of a test is. The area can have any value between 0.00 and 1.00, and it is a good indicator of the goodness of the test. A perfect diagnostic test has an AUC of 1.00, whereas a non-discriminating test has an AUC of 0.50 (Šimundić, 2008). An AUC > 0.70 and a lower CI > 0.50 have been classified as a "good" benchmark. All ROC curve results were presented as AUC ± 95% CI (Crowcroft et al., 2016).

A 2 × 2 contingency table was used to further evaluate the diagnostic accuracy of TMG measures. The table was composed of horizontal lines to indicate the presence or absence of muscle fatigue (in accordance with changes in TMG parameters) and vertical lines to indicate the "true" condition of a player according to the criterion measure of fatigue. Sensitivity (i.e., the proportion of athletes correctly classified as fatigued), specificity (i.e., the proportion of players correctly categorized as non-fatigued), Youden's index [(sensitivity + specificity) – 1; ranges from 0.00 for a poor diagnostic accuracy and to a value of 1.00 for a perfect diagnostic test] and diagnostic effectiveness (i.e., those who were fatigued and had a positive test plus those who were non-fatigued and had a negative test) were calculated from the constructed table (Šimundić, 2008; Shaikh, 2012).

RESULTS

La was significantly increased immediately after training sessions 1 [$t_{(13)} = 11.73$, $p < 0.001$], 3 [$t_{(13)} = 10.83$, $p < 0.001$], 5 [$t_{(12)} = 9.91$, $p < 0.001$], and 7 [$t_{(12)} = 9.96$, $p < 0.001$] (**Table 1**). The players' ratings of the difficulty of each session ranged from 6.6 to 7.7 (i.e., very hard) throughout the study (**Table 1**).

Twenty-four hours after the training program, CMJ performance was significantly reduced [$t_{(13)} = -6.45$, $p < 0.001$, ES = −0.68] and DOMS, as well as perceived stress (i.e., PPC and MS), had significantly increased [DOMS: $t_{(13)} = 9.21$, $p < 0.001$, ES = 3.62; PPC: $t_{(12)} = -6.88$, $p < 0.001$, ES = −0.66; MS: $t_{(12)} = 7.76$, $p < 0.001$, ES = 1.01] (**Table 2**). In

TABLE 1 | Blood lactate concentration before and after training session 1, 3, 5, and 7 as well as athletes' perception of the overall difficulty of each training bout.

Training day	Training session	Pre training La	Post training La	Δ Pre–post training La	Session-RPE
		(mmol·l^{-1})	(mmol·l^{-1})	*P*	(0–10)
1	1 (9 a.m.)	1.35 ± 0.18	11.03 ± 3.13	<0.001	7.5 ± 1.4
	2 (3 p.m.)				7.4 ± 1.2
2	3 (9 a.m.)	1.40 ± 0.23	10.11 ± 3.01	<0.001	7.7 ± 0.7
	4 (3 p.m.)				6.6 ± 1.3
3	5 (9 a.m.)	1.20 ± 0.22	10.45 ± 3.43	<0.001	7.0 ± 1.0
4	6 (9 a.m.)				7.4 ± 1.1
	7 (3 p.m.)	1.46 ± 0.44	11.10 ± 3.50	<0.001	7.2 ± 1.4

Data are shown as mean ± SD; La: blood lactate concentration; Session-RPE: session rating of perceived exertion.

TABLE 2 | Markers of muscle fatigue before (pre training) and after a 4-day high-intensity interval training program (post training) as well as percentage changes of jump height and muscle contractile properties between testing days.

Variable	Pre training	Post training	Pre–post training		
			%Δ ± CI	*P*	*d*
PERFORMANCE MARKER					
CMJ (cm)	40.2 ± 4.4	36.9 ± 4.6	−8.1 ± 1.0	<0.001	−0.68
SUBJECTIVE MARKERS					
DOMS (mm)	0.4 ± 0.5	3.6 ± 1.9		<0.001	3.62
SRSS PPC	5.4 ± 0.8	3.6 ± 1.2		<0.001	−0.66
SRSS MS	0.5 ± 0.8	3.2 ± 1.5		<0.001	1.01
MUSCLE CONTRACTILE MARKERS					
Dm (mm)	8.8 ± 1.9	8.1 ± 2.0	−8.7 ± 0.9	0.178	−0.35
Tc (ms)	31.3 ± 3.9	31.5 ± 4.6	0.2 ± 2.0	0.896	0.04
V_{10} (mm·s^{-1})	33.2 ± 3.9	30.4 ± 7.2	−8.3 ± 3.8	0.225	−0.32
V_{90} (mm·s^{-1})	137.9 ± 34.9	125.5 ± 29.6	−8.6 ± 15.8	0.189	−0.33

Data are shown as mean ± SD; CI, 90% confidence limits; d, effect size; CMJ, countermovement jump; DOMS, delayed onset muscle soreness; SRSS, short recovery and stress scale; PPC, physical performance capability; MS, muscular stress; Dm, muscle belly displacement; Tc, contraction time; V_{10}, rate of deformation development until 10% Dm; V_{90}, rate of deformation development until 90% Dm.

TABLE 3 | Accuracy of tensiomyographic markers of muscle fatigue in relation to the criterion measure.

Variable	AUC (95% CI)	Sensitivity (%)	Specificity (%)	Youden's index	DE (%)
Dm (mm)	0.46 (0.15 – 0.77)	33.3	50.0	0.17	35.7
Tc (ms)	0.29 (0.03 – 0.55)	33.3	50.0	0.17	35.7
V_{10} (mm·s^{-1})	0.71 (0.27 – 1.00)	33.3	50.0	0.17	35.7
V_{90} (mm·s^{-1})	0.37 (0.10 – 0.65)	33.3	50.0	0.17	35.7

CI, confidence limits; AUC, area under curve; DE, diagnostic effectiveness; Dm, muscle belly displacement; Tc, contraction time; V_{10}, rate of deformation development until 10% Dm; V_{90}, rate of deformation development until 90% Dm.

contrast, Dm, Tc, V_{10}, and V_{90} remained unchanged throughout the study [Dm: $t_{(13)} = -1.42$, $p = 0.178$, ES $= -0.35$; Tc: $t_{(13)} = 0.13$, $p = 0.896$, ES $= 0.04$; V_{10}: $t_{(13)} = -1.27$, $p = 0.225$, ES $= -0.32$; V_{90}: $t_{(13)} = 1.39$, $p = 0.189$, ES $= -0.33$; **Table 2**].

The determination of the AUC ± 95% CI (Dm: 0.46, 0.15–0.77; Tc: 0.29, 0.03–0.59; V10: 0.71, 0.27–1.00; V90: 0.37, 0.10–0.65) showed that none of the TMG markers had an acceptable discriminative ability (i.e., an AUC > 0.70 and a lower CI > 0.50) in detecting impaired muscular performance in elite youth athletes. The data derived from the contingency table also revealed a poor Youden's index of 0.17 and an insufficient diagnostic effectiveness of 35.7% for all TMG measures. This means that only a third of the individuals were correctly categorized by the tensiomyography method, in relation to muscular performance changes. All sensitivity data are reported in **Table 3**.

DISCUSSION

To the authors' knowledge, this is the first trial that examined the sensitivity of tensiomyographic markers of muscle fatigue in elite youth athletes. The major finding of this investigation was that the TMG parameters used were not sensitive enough to detect significant muscular performance changes and, consequently, muscle fatigue induced by a 4-day HIT shock microcycle. As such, these results suggest that tools other than TMG should be implemented in both the scientific and applied environments as a more effective means to measure muscle fatigue in youth athletes. Furthermore, collected data showed that the training program caused an acute increase in symptoms of fatigue. These results confirm the findings of other research studies that have demonstrated significant changes in measures of fatigue following HIT cycles (Halson et al., 2002; Wiewelhove et al., 2015b). Finally, the present findings show that the HIT protocol was extremely demanding, since the players produced high La levels of up to 11.10 mmol·L^{-1}, although young athletes usually accumulate less blood lactate than adults do during intensive exercise (Armstrong and McManus, 2011).

In this study, countermovement jump performance (ES = −0.68; percentage change = −8.1%) and perceived physical performance capability (ES = −0.66) moderately decreased after the training period, while delayed onset muscle soreness (ES = 3.62) and muscular stress (ES = 1.01) were very largely and moderately increased. Since the CV of the

CMJ performance was 3.7%, the magnitude of the change in muscular performance can be considered to be of practical relevance. These results are in line with those of other research studies that have demonstrated a significant increase in the symptoms of fatigue among adult athletes following intermittent high-intensity exercise and partially confirm our hypothesis (Thompson et al., 1999; Halson et al., 2002; Wiewelhove et al., 2015a,b).

Historically, potential mechanisms related to the plethora of fatigue symptoms following HIT can be classified into two categories: (1) central factors involving the central nervous system and nervous pathways; and (2) peripheral factors occurring within the muscle itself. However, the basic assumption is that subsequent fatigue after high-intensity dynamic exercise would account for about 80% from a peripheral origin (Ratel et al., 2006). This includes physical signs such as disrupted sarcomeres and/or damage to components of the excitation-contraction coupling system. During these events, the transient symptoms include prolonged reductions in maximal force, ground reaction force, stretch-reflex sensitivity, muscle joint stiffness regulation and, thus, a decrease in muscular performance as well as an increase in muscle soreness and perceived fatigue (Eston et al., 2003). These symptoms would be consistent with our findings regarding CMJ performance, DOMS, and perceived recovery and stress following the HIT training program.

In contrast, however, we observed no significant alterations in TMG parameters following completion of the HIIT program. Moreover, none of the TMG markers evaluated showed sufficient sensitivity to the detection of the altered muscular performance induced by the HIT microcycle. This is in contradiction with our hypothesis, as well as with a variety of recent studies. For example, Simola et al. (2015) were able to demonstrate that the decreases in maximal voluntary contraction in a half-squat isometric exercise after different dynamic squat training protocols were accompanied by reductions in Dm, V_{10}, and V_{90}. Additionally, following a 6-day running-based HIT-microcycle, Wiewelhove et al. (2015b) observed similar things: namely, that jump and sprint performance had significantly declined together with a simultaneous increase in creatine kinase, muscle soreness, and Tc. Carrasco et al. (2011), García-Manso et al. (2012), Hunter et al. (2012), and MacGregor et al. (2015), as well as Raeder et al. (2016), were also able to show that TMG parameters significantly followed other standard exercise-induced muscle damage and fatigue responses (i.e., changes in maximal voluntary contraction, physical performance, passive muscle tension, creatine kinase, and/or muscle soreness).

The TMG technique involves neuromuscular electrical stimulation, which is delivered using electrodes placed on the skin over a muscle belly. The subsequent muscle response is therefore predominantly generated through the activation of motor axons beneath the stimulating electrodes (Bergquist et al., 2012). Mechanisms of post-exercise muscle fatigue responsible for changes in TMG parameters are thus located peripherally, rather than centrally. In this respect, Hunter et al. (2012) and MacGregor et al. (2015) suspected that a medium-term fatigue related decrease in Dm as well, as an increase in time and velocities of the muscle radial deformation, can be mainly explained by events that occur during primary and secondary exercise-induced muscle damage. This may include excitation-contraction coupling impairment, the redistribution of sarcomere lengths, the loss of membrane integrity and the destruction of cellular structures, which in turn result in an increase in tone or stiffness of the muscle, swelling of the limb, and/or a reduction in the muscle's ability to generate force. Accordingly, the decline in CMJ performance as well as changes in TMG parameters are probably linked to the same occurrences. Nevertheless, TMG markers were not able to effectively track the reduced muscular performance and instead remained unchanged during the training period. The precise reasons for this disparity are unclear; however, there are a number of possible explanations.

As already mentioned above, it is assumed that the immediate and prolonged loss of physical performance capacity (e.g., jump performance) after HIT is primarily caused by factors at or distal to the neuromuscular junction (i.e., peripheral fatigue). Ratel et al. (2015), however, showed that youth athletes experienced no apparent peripheral fatigue and had higher central fatigue than adults similarly induced by repeated maximal contractions. They hypothesized that the greater central fatigue that occurred in the children and adolescents could be related to a strategy of the central nervous system aimed at limiting the recruitment of motor units to prevent any extensive peripheral fatigue. This hypothesis is supported by Chen et al. (2014) as well as Marginson et al. (2005), who observed that adolescent boys have a significantly smaller extent of exercise-induced muscle damage compared with that of adults. They also explained the milder symptoms of exercise-induced muscle damage in youth athletes was due to a greater reliance on slow-twitch muscle fibers and a greater flexibility. In addition, the authors assumed that the ability of adolescents to produce more relative strength than the men at long muscle lengths possibly led to less of an overextension of sarcomeres during damaging exercise bouts. Overall, this may be why a decrease in CMJ performance but no alterations in TMG parameters, which are primarily influenced by peripheral fatigue, could be observed.

Besides, as with any type of physiological measurement, there is a degree of uncertainty or noise in the tensiomyographic test results. In this regard, the findings of a preliminary investigation of our own working group exhibited an excellent level of relative reliability for Dm, Tc, V_{10}, and V_{90} (ICC = 0.84–0.90). Ditroilo et al. (2013) assessed the long-term stability of TMG across a variety of muscle conditions and came to similar conclusions. However, assessing the sensitivity of TMG measures to identify alterations in performance is based on the interpretation of the individual percentage changes in Dm, Tc, V_{10}, and V_{90} in relation to their absolute reliability (i.e., CV), and not to their relative reliability. This means that to make sure that the given magnitude of observed changes is real and physiologically significant, it is necessary to take into account the level of absolute reliability of the TMG parameters. In this context, Ditroilo et al. (2011) and Ditroilo et al. (2013), as well as the results of our preliminary investigation (CV = 5.8–13.7%), have shown that the level of absolute reliability among the TMG parameters examined was questionable. Therefore, since noise of

the tensiomyographic test results is quite high, the assessment of individual changes in TMG markers is problematic. This may be why TMG measures were found to be insufficiently sensitive to adequately detect muscle fatigue in youth athletes.

Finally, some limitations of the study design must be considered. First, there was no control group and the sample size was small, which, in particular, weakens the meaningfulness of the ROC analysis and the data derived from the contingency table. However, we have provided reliability data to indicate typical variation in all measures and effect sizes to indicate trends in the data. In addition, recruiting high-level athletes for standardized research approaches is problematic, especially due to the reluctance of such populations to deviate from their normal training routine. It was therefore not feasible to carry out a controlled trial with an appropriate sample size. Previous studies have also shown that there is acute fatigue following a HIT cycle (Halson et al., 2002; Wiewelhove et al., 2015b), so we believe that the decrements in physical capacity following the treatment were not coincidental. Regardless of this, the purpose of the study was to assess if TMG markers were sensitive to performance decrements, so a control group was not imperative.

Secondly, only the contractile characteristics of the rectus femoris muscle were measured through TMG; however, the effect of muscle fatigue on other muscles that are involved in running-based activities (e.g., gluteus maximus, biceps femoris long head, vastus medialis, vastus lateralis, soleus, or tibialis anterior) might be different. Consequently, it remains to be seen whether TMG markers of other muscles than the recuts femoris have the sensitivity needed to detect reduced muscular performance in elite youth athletes. Nevertheless, it is still important to note that TMG is intended to be a field based measure (Ditroilo et al., 2013). Therefore, the number of different muscles that are examined for the detection of muscle fatigue should be kept as low as possible; otherwise, TMG measurements would take considerably longer, making it impractical for its proposed purpose.

Thirdly, one could question why the recuts femoris muscle was selected for analysis in the present study. Sloniger et al. (1997), for example, showed that the muscles or muscle groups most activated during horizontal running were the adductors, semitendinosus, gracilis, biceps femoris and semimembranosus. However, other studies have also shown that the rectus femoris, together with the vastus lateralis, vastus intermedius, and vastus medialis, are the largest contributors to braking the body mass center during running and to absorbing the shock of the impact during each stance phase (Montgomery et al., 1994; Hamner et al., 2010). This is to be considered, since the training program consisted of 20-m shuttle runs in which the athletes had to undergo numerous changes in directions (COD). Each COD results in considerable decelerations and consequently, in eccentric contractions of the recuts femoris muscle needed in order to brake the body mass center. Therefore, it can be assumed that the recuts femoris was used intensively during the four-day HIT shock microcycle.

Fourthly, the previously reported reliability scores of the tensiomyographic markers used in this study were determined in a study that involved grown-up athletes. However, due to the smaller muscle size of adolescents, the precise positioning of the TMG sensor and the electrodes is more problematic than in adults, and the likelihood that the TMG measures are affected by involuntary contractions of other, nearby muscles is increased. This could further reduce the reliability of TMG when used in young athletes and, as a result, their sensitivity for monitoring muscle fatigue.

CONCLUSION

The number of youth athletes participating in organized athletic activities is increasing. Additionally, the combination of increased exposure and decreased preparedness for sports participation has led to an epidemic of sports-related overuse and injuries in this population (Carter and Micheli, 2011). In this context, TMG was introduced as a potentially effective tool to determine whether athletes can tolerate a certain amount of physical activity and to minimize the risk of possible negative outcomes.

To the best of our knowledge, this is the first study that examined the sensitivity of tensiomyographic markers of muscle fatigue as a means to identify individual alterations in performance in elite youth athletes. The major finding of this study was that the TMG parameters considered were not sensitive enough to detect significant muscular performance changes and, consequently, any muscle fatigue induced by intensified training. Although the precise reasons for these findings are unclear, the performance decrements observed in the youth athletes may be from central rather than peripheral fatigue, which is likely to be undetectable with TMG. Furthermore, TMG measurements are noisy, which makes it difficult to determine if individual changes in tensiomyographic markers are meaningful. These two factors may limit the sensitivity of tensiomyographic markers for monitoring muscle fatigue in youth athletes and highlight that other tools should be implemented to monitor and titrate fatigue appropriately in this population and to identify individuals at risk of overuse injury. However, due to the preliminary nature of the study, which involved a single group design and low number of subjects, further research is needed to investigate the sensitivity of TMG in youth athletes.

AUTHOR CONTRIBUTIONS

TW and AF, Conceived and designed the experimental design; TW, CR, RD, CS, AD, Performed the experiments; TW and CS, Analyzed the data; TW, CR, RD, CS, AD, and AF, Contributed reagents, materials and/or analysis tools; TW and AF, Wrote the paper.

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Long-Term Athletic Development in Youth Alpine Ski Racing: The Effect of Physical Fitness, Ski Racing Technique, Anthropometrics and Biological Maturity Status on Injuries

Lisa Müller[1], Carolin Hildebrandt[1], Erich Müller[2], Christian Fink[3,4] and Christian Raschner[1]*

[1] Department of Sport Science, University of Innsbruck, Innsbruck, Austria, [2] Department of Sport Science and Kinesiology, University of Salzburg, Salzburg, Austria, [3] Research Unit for Orthopedic Sports Medicine and Injury Prevention, Institute of Psychology (ISAG), The Health & Life Sciences University (UMIT), Hall, Austria, [4] Gelenkpunkt – Sports and Joint Surgery, Innsbruck, Austria

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***Correspondence:**
Lisa Müller
lisa.mueller@uibk.ac.at

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Alpine ski racing is known to be a sport with a high risk of injuries. Because most studies have focused mainly on top-level athletes and on traumatic injuries, limited research exists about injury risk factors among youth ski racers. The aim of this study was to determine the intrinsic risk factors (anthropometrics, biological maturity, physical fitness, racing technique) for injury among youth alpine ski racers. Study participants were 81 youth ski racers attending a ski boarding school (50 males, 31 females; 9–14 years). A prospective longitudinal cohort design was used to monitor sports-related risk factors over two seasons and traumatic (TI) and overuse injuries (OI). At the beginning of the study, anthropometric characteristics (body height, body weight, sitting height, body mass index); biological maturity [status age at peak height velocity (APHV)]; physical performance parameters related to jump coordination, maximal leg and core strength, explosive and reactive strength, balance and endurance; and ski racing technique were assessed. Z score transformations normalized the age groups. Multivariate binary logistic regression (dependent variable: injury yes/no) and multivariate linear regression analyses (dependent variable: injury severity in total days of absence from training) were calculated. *T*-tests and multivariate analyses of variance were used to reveal differences between injured and non-injured athletes and between injury severity groups. The level of significance was set to $p < 0.05$. Relatively low rates of injuries were reported for both traumatic (0.63 TI/athlete) and overuse injuries (0.21 OI/athlete). Athletes with higher body weight, body height, and sitting height; lower APHV values; better core flexion strength; smaller core flexion:extension strength ratio; shorter drop jump contact time; and higher drop jump reactive strength index were at a lower injury risk or more vulnerable for fewer days of absence from training. However, significant differences between injured and non-injured athletes were only observed with respect to the drop jump reactive strength

index. Regular documentation of anthropometric characteristics, biological maturity and physical fitness parameters is crucial to help to prevent injury in youth ski racing. The present findings suggest that neuromuscular training should be incorporated into the training regimen of youth ski racers to prevent injuries.

Keywords: injury risk factors, physical fitness, racing technique, biological maturity status, anthropometrics, youth alpine ski racing, neuromuscular training

INTRODUCTION

Alpine ski racing is a physically demanding sport and presents a high risk of injury independent of age and gender (Neumayr et al., 2003; Spörri et al., 2017). In elite alpine ski racing, injury rates of more than 36 injuries/100 athletes have been reported, 36% being severe and partly career ending (Bere et al., 2013; Spörri et al., 2017). The most common injuries were ligament injuries in the knee (35.6%), with the rupture of the anterior cruciate ligament (ACL) being the most frequent diagnosis, representing 13.6% of all injuries in World Cup athletes (Flørenes et al., 2009). To date, most studies have concentrated on elite alpine ski racers. Determining the implications for prepubescent athletes still remains a challenge, despite providing the basis for long-term athletic development (Lloyd et al., 2015; Spörri et al., 2017). The popularity of alpine ski racing in Austria is reflected in the high number of specialized ski boarding schools. However, sport specialization at a young age should not negatively affect skeletally immature athletes (Maffulli et al., 2010). Therefore, epidemiological studies with respect to injuries, and in a further step, studies investigating the injury risk factors in youth ski racing are particularly important as a first and second step of the injury prevention sequence (Van Mechelen et al., 1992).

To date, only two epidemiological studies have been conducted at the adolescent level with ski racers older than 15 years of age (Hildebrandt and Raschner, 2013; Westin et al., 2013) and one study at the youth level among athletes younger than 15 years of age (Müller et al., 2017). Westin et al. (2013) obtained similar results compared with the World Cup level with respect to injury incidence (1.7 injuries/1000 ski hours), severity (49% severe) and the most-affected body part (knee: 41%) among Swedish adolescent ski racers (>16 years). Recently, Müller et al. (2017) observed a relatively low incidence of traumatic injuries (0.86 traumatic injuries/1,000 h of training) in a cohort of ski racers younger than 15 years of age.

In addition to traumatic injuries, overuse injuries represent a problem among adolescent ski racers. Hildebrandt and Raschner (2013) investigated 15–19 year old adolescent ski racers of a ski boarding school over two consecutive school years (September-July). More than half of the investigated athletes had at least one overuse injury during the two-season study period, most of which were low back pain (Hildebrandt and Raschner, 2013). The rate of overuse injuries among ski racers younger than 15 years was much lower (0.21 overuse injuries/athlete) (Müller et al., 2017). However, this study was limited to an epidemiological point of view; scientific research concerning overuse injuries in general and risk factors for overuse injuries among youth ski racers in particular, is still lacking.

Furthermore, a prospective data analysis of skiing-specific risk factors for injuries in youth ski racers who specialize at an early age is also lacking. Previous research has indicated poor physical fitness in youth athletes as a risk factor for sports-related injuries (Carter and Micheli, 2011). Regarding alpine ski racing, Raschner et al. (2012) revealed that insufficient core strength or core strength imbalance was a critical factor for sustaining an ACL injury in adolescent ski racers (15–19 years). However, no data exist about the level of physical fitness of prepubescent athletes and the risk of sustaining an injury, indicating the need for additional data pertaining to possible risk factors for overuse injuries among this youngest age group.

In this context, injury prevention should also include the consideration of biological maturity status because late maturing athletes might be at a higher risk for both overuse and traumatic injuries. It is well known that growth-related factors such as biological immaturity contribute to overuse injuries (DiFiori et al., 2014). The risk of sustaining such an overuse injury is strongly intensified during the adolescent growth spurt (Fort-Vanmeerhaeghe et al., 2016). Additionally, studies of soccer players revealed that late maturing athletes were at a higher risk for overuse injuries (Van der Sluis et al., 2015) or severe traumatic injuries (Le Gall et al., 2007). To date, however, the biological maturity status has not been assessed as a possible risk factor for injuries in youth ski racing.

Furthermore, Spörri et al. (2017) showed in their review article that technical mistakes represent a risk factor for injuries in World Cup alpine ski racers. Training of a stable "skiing technique" in combination with specific neuromuscular training was suggested as a potential preventive measure within this context (Spörri et al., 2017). The combination of frontal bending, lateral bending, and torsion in the loaded trunk has been found to be a potential risk factor for overuse injuries in elite ski racers (Spörri et al., 2015); showing that the ski racing technique has to be well established in order to minimize the load on the trunk in such situations. However, thus far, skiing-technique has not been investigated as a possible risk factor in youth ski racing.

Overall, a suitable screening strategy starting at a young age should focus on the identification of modifiable risk factors (Lloyd et al., 2015). In support of this, Spörri et al. (2017) clearly demonstrated the need for (and lack of) monitoring and preventing injuries at the youth level, and the importance of being able to identify the possible risk factors. Therefore, the aim of the present study was to investigate intrinsic risk factors for injuries such as anthropometrics, biological maturity status, physical fitness and ski racing technique among youth ski racers younger than 15 years of age.

METHODS

Study Design

A two-season prospective study design was used to record injuries and possible risk factors in a cohort of elite youth alpine ski racers younger than 15 years of age. s. An internet-based database (training data base, injury data base) was developed to record all training data and injuries. The coaches recorded all training data including the presence or absence (due to injury) of the athletes immediately after each skiing specific and athletic specific training session. One member of the study team registered all injury data on a weekly basis. The study was performed according to the Declaration of Helsinki and was approved by the Institutional Review Board of the Department of Sport Science of the University of Innsbruck as well as the Board for Ethical Questions of the University of Innsbruck. The athletes and their parents were informed of the study aims, procedures and risks before written informed consent was obtained.

Participants

The study was performed in cooperation with a highly regarded skiing specific secondary modern school in Austria. Participants of the study were pupils of this ski boarding school, aged 9–14 years. Eighty-five athletes who were free of injury at the beginning of the study were enrolled.

Data Collection

Injury Registration

Using the training data base of the ski boarding school, coaches recorded all relevant training data immediately after each training session (skiing specific: technique, race; athletic specific: endurance, neuromuscular, strength training) including among others duration, volume, intensity, contents, presence/absence of athletes due to injury. Exposure time was recorded for each athlete as the number of minutes of all training sessions (skiing- and athletic-specific training). The data entry was user-friendly, because all necessary information was limitative and the coaches only had to mark the appropriate boxes by ticking. If an athlete was absent, the coaches indicated the cause (illness, traumatic injury, overuse injury, others) and an automatic mail was sent to the study team.

One member of the study team (sports scientist and/or physician) then contacted the coaches, physiotherapists and/or physicians of the ski boarding school to get detailed information about the injury. Then all injuries (traumatic and overuse) that occurred in skiing-specific or athletic-specific training sessions, as well as in competitions, and that caused absence from training for at least 1 day, were registered. All data were systematically checked with the coaches, physiotherapists and physician either face-to-face or by telephone. In case of injuries that required medical attention, a detailed medical report was provided. Further details with respect to injuries that occurred and study design are presented in Müller et al. (2017).

A traumatic injury was defined as an injury with a sudden onset based on time-loss definition (Brooks and Fuller, 2006), and the type of traumatic injury, as well as the affected body part were defined according to the injury surveillance consensus paper of the International Olympic Committee (Junge et al., 2008). Injury severity was classified according to Fuller et al. (2006). An injury was classified as minimal with a time loss of 1–3 days, as mild (4–7 days), moderate (8–28 days), severe (>28 days) or career ending (Fuller et al., 2006). Additionally, the mean injury severity of each athlete was calculated (total days of absence/total number of injuries). An overuse injury was defined as any physical complaint without a single identifiable event being responsible (Clarsen et al., 2013). With respect to young athletes, overuse injuries include apophyseal injuries and physeal stress injuries (DiFiori et al., 2014).

Anthropometrics and Biological Maturity

The anthropometric characteristics body height (cm), body weight (kg), leg length (cm), sitting height (cm), and body mass index (BMI; m^2/kg) of the athletes were assessed at the beginning of the study (September). Biological maturity status was assessed by the non-invasive method of calculating the age at peak height velocity (APHV) using gender-specific prediction equations (Mirwald et al., 2002). The validity of this method was previously proven for youth ski racers of the same age (Müller et al., 2015). As proposed by Sherar et al. (2007), the athletes were divided into three maturity groups (early, normal or late maturing) based on the mean (M) ± standard deviation (SD) of the APHV of the total sample (separated by gender; normal: APHV within M ± SD; early: APHV<M-SD; late: APHV>M+SD). The percentiles of body height, body weight and body mass index were classified according to Braegger et al. (2011). Standardized percentile curves of BMI, body weight and height were used to classify each athlete into three categories: <25% percentile=below average, 25–75% percentile=average, >75% percentile=above average.

Physical Fitness Testing

The physical fitness parameters were tested in the sports laboratory at the Department of Sport Science prior to the start of the season (September). Results of the following tests were included: postural stability test (S3-Check), agility test (jump coordination test including 26 jumps), isometric leg extension strength test (unilateral leg press), isometric core strength test (Back-Check, Dr. Wolff Sports & Prevention GmbH, Arnsberg, Germany), power test (Counter Movement Jump, Kistler force plate), reactive strength test (Drop Jump, Kistler force plate) and aerobic endurance test (12-min Cooper test). A detailed description of the testing procedures, materials and test-retest reliability can be found in the studies of Raschner et al. (2012, 2013). **Table 1** shows the appropriate parameters and abbreviations for each test. All tests were performed in a standardized order. Three attempts were allowed for each test, and only the best result was used for the analysis. The values obtained for the athletes were then classified into age- and gender-specific norm data, which were calculated (mean ± ½ standard deviation) based on a comprehensive, sport-specific data pool starting in 1996 (Raschner et al., 2013). Based on their results, the young ski racers were categorized into three groups (average, above and below average).

TABLE 1 | Physical fitness parameters.

Abbreviation	Test	Parameters	Category
JCT	Jump coordination test	Time in s	Coordination
ULST	Unilateral leg press strength test	Relative leg strength (REL LS) in N/kg left and right total	Maximal strength
		Ratio relative left/right leg strength (L:R LS)	
CST	Core strength test	Relative flexion strength (REL FS) in N/kg	Maximal strength
		Relative extension strength (REL ES) in N/kg	
		Ratio relative flexion/extension strength (FLE:EXT S)	
CMJ	Counter movement jump	Jump height in cm	Explosive strength
DJ	Drop jump	Reactive strength index (RSI) in mm/ms	Reactive strength
ST	Stability test (S3 Check)	Stability index (left-right index)	Balance
CT	Cooper test	Total distance in m	Endurance

Ski Racing Technique

The athletes had to pass an entrance exam before they were allowed to frequent the ski boarding school. The entrance exam consisted of skiing-specific exercises and physical performance tests. Among other factors, ski racing technique in three different racing situations (slalom, giant slalom, combi race) was evaluated by three independent experts in youth ski racing according to the Austrian school grading scale (1=perfect; 5=failed). Each expert rated the performance of all athletes by a blinded procedure. The mean of the grades of the three experts and the three racing conditions were calculated and considered in the analyses.

Statistical Analyses

Descriptive statistics are presented as the M ± SD for continuous variables and as frequency counts and percentages for categorical variables. The rates of traumatic and overuse injuries per athlete were calculated as number of injured ski racers divided by the total number. The normal distribution was tested using Kolmogorov-Smirnov tests. Two regression analyses were performed. With respect to occurrence of injury (traumatic and overuse injury combined), a binary logistic regression analysis (backward LR method; dependent variable: injury yes/no) was performed. Regarding injury severity, a multiple linear regression analysis with stepwise backward elimination was performed (dependent variable: days of absence from training due to injury). A gender- and age-specific z-transformation was performed for all variables (Raschner et al., 2012), except for ratios, APHV, BMI and racing technique. The independent variables for the linear regression analyses were the anthropometric characteristics (BMI; z values of height, weight, sitting height, leg length), APHV as an indicator of biological maturity status, the *z*-values of the physical performance test results (see **Table 3**) and the indicator of ski racing technique (mean of grades). The included independent variables were previously tested for collinearity; no collinearity was present. Nagelkerke's R^2 was calculated to determine the power of the model used. Independent *t*-tests were used to assess differences between injured and non-injured athletes with respect to the significant variables of the binary logistic regression analysis. The number of days absent from training per injury (in mean) were additionally calculated to categorize the athletes' mean injury severity (1–7 days: minimal-mild; 8–28 days: moderate; >28 days severe). Multivariate analyses of variance with Bonferroni alpha adjustment were performed (dependent variables: significant variables of regression analyses concerning injury severity; independent variable: categories of severity per injury in mean; contrast: Helmert; *post-hoc*: Scheffé) to assess differences in the significant injury risk factors (assessed by the linear regression analysis) between the three categories of injury severity. The level of significance was set to $p < 0.05$. All calculations were performed using IBM SPSS 23.0 (IBM Corporation, Armonk, NY, USA).

RESULTS

Participants

Over the 2-year study period, three athletes dropped out of school and one athlete had missing values in the physical performance tests; thus, 81 athletes (50 males, 31 females; 11.6 ± 1.4 years) were included in the analyses. The anthropometric data of the 81 participants separated by gender are presented in **Table 2**. The percentiles of body height, weight and BMI are presented according to the three groups of biological maturity status in **Table 3**.

Rate of Injuries

In total, 69 injuries (traumatic and overuse) were recorded from 40 athletes (49.4%; 14 females, 26 males). Traumatic injuries were reported from 34 athletes (42.0%; 14 females, 20 males), representing a rate of 0.63 traumatic injuries/athlete. Nearly half of the traumatic injuries affected the bones and the knee was the most common injured body part (>1/3 of the injuries). Seventeen overuse injuries were described from 13 athletes (16.0%; 2 females, 11 males), representing a rate of 0.21 overuse injuries / athlete. Most of the overuse injuries comprised muscle and tendon structures and similar to the traumatic injuries, the knee was the most affected body part. Further details of the injuries that occurred are presented in Müller et al. (2017). During the two-season study period, 41 athletes (50.6%; 17 females, 24 males) sustained neither an overuse nor a traumatic injury.

Injury Risk Factors

The percentages of injured and non-injured athletes (traumatic injuries, overuse injuries and injuries in total) are presented in **Table 4** according to biological maturity (normal, early and late maturing) and anthropometrics (percentiles of body height, body weight and BMI).

TABLE 2 | Anthropometric data at the start of the study according to gender.

	Male ($n = 50$)	Female ($n = 31$)
	M ± SD	M ± SD
Age [yrs]	11.5 ± 1.5	11.8 ± 1.3
Height [cm]	153.3 ± 9.0	154.9 ± 7.7
Weight [cm]	42.3 ± 8.2	43.8 ± 7.9
BMI [kg/m^2]	17.8 ± 1.8	18.1 ± 2.2
APHV [years]*	13.7 ± 0.5	12.0 ± 0.5

*Significant gender specific difference [$t_{(79)} = 13.856$; $p < 0.001$].
BMI, body mass index; APHV, age at peak height velocity.

TABLE 3 | Percentiles of anthropometric characteristics according to biological maturity status.

	Early ($n = 10$)	Normal ($n = 61$)	Late ($n = 10$)
	M [95% CI]	M [95% CI]	M [95% CI]
Percentile height	71.1 [55.7-84.8]	45.3 [40.8-49.6]	23.6 [15.0-34.2]
Percentile weight	64.2 [49.1-78.0]	41.8 [36.5-46.7]	22.9 [14.2-33.2]
Percentile BMI	53.5 [38.4-69.9]	42.2 [35.6-47.8]	30.7 [19.9-42.3]

Table 5 shows the percentages of injured and non-injured athletes with respect to the physical performance test results based on norm groups.

Ski racing performance was considered by grading racing technique. Overall, the ski racers participated in an average of 17 (±6.3) races per season. The mean grade based on racing technique in three different racing situations (slalom, giant slalom, combi race) was 2.5 ± 0.6 (range: 1.3–3.9).

The multiple binary logistic model explained 47.3% of the variability of the athletes (Nagelkerkes $R^2 = 0.473$); 73.5% of the cases were predicted correctly. With respect to sustaining an injury, the following variables were predictive risk factors in youth ski racers (see **Table 6**): body height, body weight, sitting height, core flexion strength, drop jump (DJ) contact time and DJ reactive strength index (RSI). Athletes with higher body height, higher body weight, higher sitting height, better core flexion strength, shorter DJ contact time and higher RSI were at a lower injury risk. However, independent *t*-tests revealed significant differences between injured and non-injured athletes only with respect to DJ RSI [$t_{(79)} = 2.135$; $p = 0.036$]. Non-injured athletes had a mean *z*-value of 0.18 ± 0.99, whereas injured athletes had a mean *z*-value of −0.13 ± 0.86.

Relationship between Injury Risk Factors and Severity

Most injuries were classified as moderate (44.9%), leading to a time loss of training of at least 8 days. The lowest percentage of injuries was classified as severe injuries (13.1%) with over 28 days of absence from training (**Figure 1**); no injury was career ending. Moderate traumatic injuries accounted for 44.2%, and overuse injuries most frequently caused a loss of training, either for 8–28 days (47.1%) or more than 28 days (17.6%).

The multiple linear logistic model explained 45.5% of the variability of the athletes (Nagelkerkes $R^2 = 0.455$). The following variables were significant predictors of injury severity (see **Table 6**): APHV, ratio relative flexion / extension strength (FLE:EXT S), DJ contact time and DJ RSI. Athletes with lower APHV values (which indicate that they were earlier maturing), a smaller core flexion and extension strength ratio, a shorter DJ contact time and a higher DJ RSI were more likely to miss fewer days of training due to injuries. The multivariate analyses of variance indicated a significant difference between the three groups of injury severity only with respect to DJ RSI ($F = 3.511$; $p = 0.040$). A Helmert test revealed a significant difference between the minimal-mild to moderate severity groups and the severe severity group ($p = 0.021$). Athletes with mean minimal-mild injury severity (1–7 days absence) had a mean *z*-value of 0.29 ± 0.69 with respect to DJ RSI; athletes with moderate injury severity (8–28 days) had a mean *z*-value of 0.27 ± 0.97; and athletes with severe injury severity (>28 days) had a mean *z*-value of −0.61 ± 0.70.

DISCUSSION

The present study supports ongoing research into modifiable risk factors among youth athletes in terms of injury prevention. It is the first study to investigate anthropometric characteristics, biological maturity status, as well as physical fitness parameters in youth alpine ski racers related to risk of traumatic or overuse injuries. The main finding was that biological maturity status, anthropometric characteristics, core strength and reactive strength represent significant injury risk factors in youth alpine ski racing. However, racing technique was not found to affect injury risk.

Anthropometrics and Biological Maturity Status As Injury Risk Factors in Youth Ski Racing

Taller, heavier and more mature athletes have been shown to have performance and selection advantages in youth alpine ski racing (Raschner et al., 1995; Müller et al., 2016). The role of anthropometric characteristics and biological maturity status as injury risk factors in youth ski racing have not been investigated, to date. In the present study, the distribution of early, normal and late maturing athletes did not differ from the expected normal distribution, in line with the study of Müller et al. (2016), in which the biological maturity status of provincial youth ski racers was normally distributed. When examining the classification of early, normal and late maturing athletes and the relationship to the percentiles of body height, body weight and BMI, it can be clearly observed that these two categorization models correspond to each other. On average, early maturing athletes had percentile values of 53.5 (BMI), 64.2 (weight), and 71.1 (height), whereas late maturing athletes had average values of 30.7 (BMI), 22.9 (weight), and 23.6(height). The values of the normal maturing athletes were in between those of the other two maturity groups. Although the validity of the easy feasible method of calculating APHV as an indicator of biological maturity status

TABLE 4 | Affected and non-affected athletes of traumatic and overuse injuries with respect to biological maturity status and anthropometrics.

		Traumatic injuries ($n = 34$)		Overuse injuries ($n = 13$)		Overall injuries ($n = 40$)	
		Yes [%]	No [%]	Yes [%]	No [%]	Yes [%]	No [%]
Biological maturity status	Early ($n = 10$)	30.0	70.0	30.0	70.0	50.0	50.0
	Normal ($n = 61$)	42.6	57.4	11.5	88.5	47.5	52.5
	Late ($n = 10$)	50.0	50.0	30.0	70.0	60.0	40.0
Percentile body height	Above average ($n = 12$)	25.0	75.0	8.3	91.7	33.3	66.7
	Average ($n = 55$)	43.6	56.4	18.2	81.8	50.9	49.1
	Below average ($n = 14$)	50.0	50.0	14.3	85.7	57.1	42.9
Percentile body weight	Above average ($n = 9$)	33.3	66.7	33.3	66.7	55.6	44.4
	Average ($n = 50$)	36.0	64.0	16.0	84.0	42.0	58.0
	Below average ($n = 22$)	59.1	40.9	9.1	90.9	63.6	36.4
Percentile body mass index	Above average ($n = 8$)	37.5	62.5	25.0	75.0	50.0	50.0
	Average ($n = 48$)	41.7	58.3	18.8	81.3	50.0	50.0
	Below average ($n = 25$)	44.0	56.0	8.0	92.0	48.0	52.0

TABLE 5 | Affected and non-affected athletes of traumatic and overuse injuries with respect to norm groups in physical performance tests.

			Traumatic injuries ($n = 34$)		Overuse injuries ($n = 13$)		Overall injuries ($n = 40$)	
Test	**Variable**	**Norm group**	**yes [%]**	**no [%]**	**yes [%]**	**no [%]**	**yes [%]**	**no [%]**
CMJ	Jumping height [cm]	Above average ($n = 9$)	33.3	66.7	11.1	88.9	44.4	55.6
		Average ($n = 53$)	41.5	58.5	18.9	81.1	49.1	50.9
		Below average (n =19)	47.4	52.6	10.5	89.5	52.6	47.4
DJ	RSI [index]	Above average ($n = 12$)	16.7	83.3	8.3	91.7	25.0	75.0
		Average ($n = 57$)	47.4	52.6	15.8	84.2	56.1	43.9
		Below average ($n = 12$)	41.7	58.3	25.0	75.0	41.7	58.3
CT	Distance [m]	Above average ($n = 15$)	40.0	60.0	13.3	86.7	40.0	60.0
		Average ($n = 54$)	42.6	57.4	16.7	83.3	51.9	48.1
		Below average ($n = 12$)	41.7	58.3	16.7	83.3	50.0	50.0
ULST	REL LS [N/kg]	Above average ($n = 6$)	33.3	66.7	33.3	66.7	50.0	50.0
		Average ($n = 47$)	40.4	59.6	14.9	85.1	48.9	51.1
		Below average ($n = 28$)	46.4	53.6	14.3	85.7	50.0	50.0
	L:R LS [ratio]	Norm ($n = 55$)	45.5	54.5	14.5	85.5	52.7	47.3
		Out of norm ($n = 26$)	34.6	65.4	19.2	80.8	42.3	57.7
CST	REL FS [N/kg]	Above average ($n = 47$)	38.3	61.7	14.9	85.1	46.8	53.2
		Average ($n = 32$)	50.0	50.0	18.8	81.3	56.3	43.7
		Below average ($n = 2$)	0	100	0	100	0	100
	REL ES [N/kg]	Above average ($n = 10$)	20.0	80.0	20.0	80.0	30.0	70.0
		Average ($n = 35$)	37.1	62.9	17.1	82.9	45.7	54.3
		Below average ($n = 36$)	52.8	47.2	13.9	86.1	58.3	41.7
	FLE:EXT S [ratio]	Norm ($n = 25$)	44.0	56.0	12.0	88.0	48.0	52.0
		Out of norm ($n = 56$)	41.1	58.9	17.9	82.1	50.0	50.0
ST	Stability Index [index]	Above average ($n = 44$)	45.5	54.5	11.4	88.6	75.0	25.0
		Average ($n = 33$)	39.4	60.6	15.2	84.8	42.4	57.6
		Below average ($n = 4$)	25.0	75.0	75.0	25.0	52.3	47.7
JCT	Time [s]	Above average ($n = 18$)	22.2	77.8	16.7	83.3	38.9	61.1
		Average ($n = 50$)	48.0	52.0	18.0	82.0	54.0	46.0
		Below average ($n = 13$)	46.2	53.8	7.7	92.3	46.2	53.8

TABLE 6 | Regression analyses.

Regression analysis	Dependent variable	Predictor	*p*	Wald/ß
Binary logistic ($R^2 = 0.473$)	Injury occurrence	Body height	0.003	Wald = 8.874
		Body weight	0.017	Wald = 5.680
		Sitting height	0.002	Wald = 9.699
		Core flexion strength	0.044	Wald = 4.050
		Drop jump contact time	0.024	Wald = 5.068
		Drop jump reactive strength index	0.013	Wald = 6.146
Multiple linear ($R^2 = 0.455$)	Injury severity	Age at peak height velocity	0.011	ß = 0.373
		Ratio core flexion: extension strength	0.047	ß = −0.462
		Drop jump contact time	0.039	ß = 0.697
		Drop jump reactive strength index	0.023	ß = −1.092

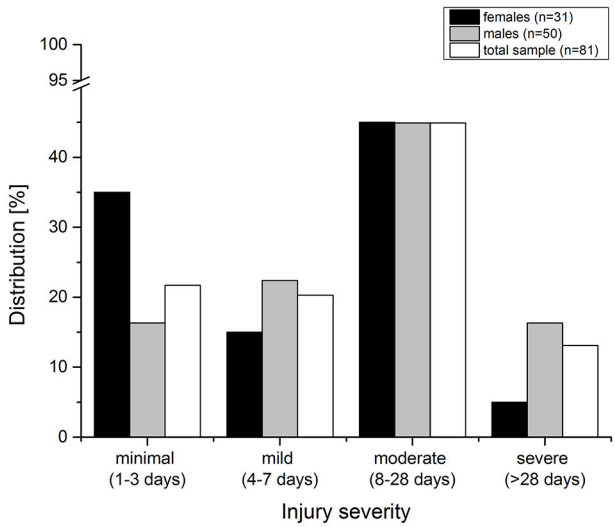


FIGURE 1 | Injury severity and days of absence caused by overuse and traumatic injuries of the total sample and separated by gender.

has been proven (Müller et al., 2015), the method has often been criticized. Nevertheless, the prediction equations of the APHV method include the estimation of leg length and sitting height; consequently, they consider the diverse proportions between the trunk and extremities (the long bones of the legs have a peak growth spurt before the short bones of the trunk) (Lloyd et al., 2014). Therefore, the APHV method appears to be useful in youth talent selection and injury prevention programs because it can be easily applied in a large cohort of young athletes who are not exposed to radiation (Müller et al., 2015), even though X-rays of the left wrist is still the more accurate method (Lloyd et al., 2014).

With respect to injuries, the present results revealed that the athletes who were above average in percentile body height and body weight had descriptively smaller percentages of traumatic injuries compared with the athletes who were average or below average. Additionally, early maturing athletes had descriptively lower percentages of traumatic and overuse injuries compared with normal and late maturing athletes. However, the small percentages of early and late maturing athletes must be considered. Nevertheless, the results of the regression analyses underlined the findings that anthropometric characteristics and biological maturity status play a significant role as injury risk factors in youth ski racing. With respect to occurrence of injuries, body weight, body height and sitting height were significant predictors, of which sitting height (Wald = 9.699) and body height (Wald = 8.874) seemed to have the greatest associations to injury occurrence. Concerning the severity of injuries, APHV was a significant predictor (ß = 0.373); however the association to injury severity was not that high compared to the other variables (ß = −0.462 till −1.092).

The present results are partly in line with previous studies on other sports. Kemper et al. (2015) showed that anthropometric characteristics such as rapid growth rates and BMI increase might help to identify youth athletes at high injury risk, particularly between the year before peak height velocity (PHV) and the year of PHV (DiFiori et al., 2014; Van der Sluis et al., 2015). Additionally, Caine et al. (2014) revealed that the adolescent growth spurt is a time of increased risk for sports injuries; an association between PHV and peak fracture rate was found. Furthermore, the results of Van der Sluis et al. (2015) are in line with those of the present study; the study showed that late maturing soccer players (3.53 injuries/1,000 h of exposure) had a significantly higher overuse injury incidence than earlier maturing athletes (0.49 overuse injuries/1,000 h of exposure), both in the year before PHV and the year of PHV. Moreover, Le Gall et al. (2007) found late maturing athletes at a higher risk of severe injuries and of osteochondral disorders. However, these findings and those of the present study are not in line with the study of Johnson et al. (2009), in which early maturing soccer players showed more injuries than late or normal maturing athletes. It should be noted that in this study, biological age was assessed using X-rays of the left wrist; consequently, actual biological age was calculated (Johnson et al., 2009). Growth timing and diverse proportions were not considered. Additionally, in this study, schoolboy football players were investigated; thus, it might be assumed that they were not top-level youth athletes undergoing a strict selection procedure, as in the present study of youth ski racers, which might explain the differences. Nevertheless, Johnson et al. (2009) emphasized that maturity plus training and playing hours can predict injuries in youth footballers, and consequently, biological maturity status affects the injury risk in young athletes. Jayanthi et al. (2015) additionally found that growth plate tissue may be more vulnerable to injury during periods of rapid growth; consequently, athletes are more susceptible to injuries during more rapid phases of growth. Therefore, it appears particularly important to consider biological maturity status and growth rates in talent development processes to prevent injuries in the future. Additionally, training processes (including volume and intensity) should be commensurate with maturity to prevent late maturing athletes in particular from sustaining injuries.

Physical Fitness Parameters As Injury Risk Factors in Youth Ski Racing

To guarantee the optimal development of talented children into elite athletes, physical fitness is an important component of youth athletic performance (Granacher et al., 2016). To date, limited research has examined the link between physical fitness and injury risk in youth ski racing.

In the present study, most of the athletes were either average or above average relative to the graduation of the norm groups in physical performance tests (Raschner et al., 2013). Thus, the youth athletes already had well-developed physical skills; consequently, the athletes could be considered high-level youth ski racers because Raschner et al. (2008) clearly underlined the necessity of a high level of physical fitness to be successful in ski racing, as well as to be able to cope with the demanding requirements during racing. Although the etiology of sport-specific injuries is multi-factorial, it is important to analyze modifiable risk factors associated with a higher injury risk and severity (Chalmers et al., 2013). Several fitness parameters were included in the present study. Results showed that only small percentages of the athletes who were above average with respect to counter movement jump, drop jump reactive strength index, relative core flexion strength, and jump coordination test had a traumatic and/or overuse injury compared with athletes who were average or below average. Only one-fourth of the athletes who were above average with respect to drop jump reactive strength index had an injury (traumatic and/or overuse). These findings confirm the results of the regression analyses, in which drop jump reactive strength index was a significant predictor of both the occurrence of injury and injury severity. The association of drop jump reactive strength index to injury occurrence was the third highest (Wald = 6.146) in the binary logistic model. The multiple linear regression analyses revealed drop jump reactive strength index having the greatest association to injury severity among the identified significant predictors (ß = −1.092). Additionally, significant differences in drop jump reactive strength index were observed between injured and non-injured athletes and between the three groups of injury severity. Non-injured athletes and athletes with mild-minimal or moderate injury severity (in mean) showed better drop jump reactive strength index values. Consequently, within the context of injury prevention in youth ski racing, drop jump reactive strength index seems to be the most predictable factor and should be especially considered in the future.

The drop jump test represents stretch-shortening cycle muscle loading and allows for conclusions to be made about the neuromuscular ability of an athlete. Several studies have shown that deficient neuromuscular control can increase the risk of injuries in youth athletes (Fort-Vanmeerhaeghe et al., 2016). In the present study, athletes with a longer drop jump contact time were at a higher injury risk and were more likely to miss more days of training due to injury. A longer drop jump contact time often accompanies increased knee valgus loading, which is viewed as an injury risk factor or predictor of knee injuries, particularly in female athletes (Hewett et al., 2005). In alpine ski racing, increased knee valgus loading often leads to neurophysiological injuries (Spörri et al., 2017). Three mechanisms were identified for ACL injuries, among which the dynamic snowplow and the slip catch can be partly attributed to increased knee valgus loading (Bere et al., 2011; Jordan et al., 2017). In the present study, only one male athlete sustained an ACL injury; however, the knee was the most affected body part by traumatic and overuse injuries, and ligament injuries in the knee frequently occurred. The trainability of neuromuscular control is highest in preadolescent athletes (Myer et al., 2011). Consequently, neuromuscular training in young athletes can have a preventative effect in reducing the risk of lower extremity injuries (Hewett et al., 1999; Myer et al., 2005, 2009) and should be regularly implemented in training. During alpine ski racing in particular, the knee is exposed to high moments and external forces acting in different directions. Athletes with below-average drop jump reactive strength index, which can result in inappropriate activation timing, may expose their bodies to harmful loads, which induce a higher risk of severe injuries, as was found in the present study. Consequently, the present findings clearly demonstrate that it is absolutely necessary to incorporate neuromuscular training in the athletic-specific training sessions of youth ski racers, yet. The most effective components of neuromuscular training are not well established, or contrasting results have been obtained. Furthermore, research has focused on team sports, whereas to date, individual sports such as alpine ski racing have been examined less or not at all (Emery et al., 2015).

Next to neuromuscular control, sufficient core strength has been proven to be effective in preventing both traumatic (Raschner et al., 2012) and overuse injuries in alpine ski racing (Spörri et al., 2015). The results of the present study showed that among the athletes who were above average with respect to relative core flexion strength, only 20% had a traumatic injury and 30% had a general injury. The logistic regression model confirmed the finding that young ski racers with better relative core flexion strength were at a lower total injury risk. Moreover, athletes with a higher relative flexion/extension strength ratio were more likely to miss more days of training due to injuries.

Trunk strength is considered to be important in compensating for external forces and loads during alpine ski racing (Spörri et al., 2015). Zazulak et al. (2007) demonstrated a relationship between reduced muscular trunk strength and an increased knee injury risk in young athletes. Knowing that alpine ski racing is a high-risk sport for knee injuries, as it was also shown in the present study, it is crucial to monitor core strength in youth athletes, particularly because the results of Raschner et al. (2012) showed that core strength weakness and core strength imbalances were significant risk factors for ACL injuries in adolescent ski racers. The authors emphasized that coaches must understand the importance of core strength training, and especially the neuromuscular aspects of core training, in the context of injury prevention in youth athletes (Raschner et al., 2012). Because of the importance of well-developed core strength for coping with the unexpected perturbations during racing, a focus should be placed on diverse training contents activating differing reflex activity patterns of the trunk muscles. In this context, Mueller et al. (2016) suggested to use lower leg perturbations of greater magnitude to evaluate the neuromuscular reflex activity patterns

of the trunk muscles. Additionally, Pedersen et al. (2004) argued that in injury prevention programs, perturbations should be implemented with increasing frequency to enhance the level of difficulty of sensorimotor trunk stability exercises and to prepare athletes for compensation of unexpected trunk loading, which seems very important in alpine ski racing. Considering this, next to conventional balance training contents to improve core strength, slackline training could be considered in training sessions of youth ski racers because of the high perturbations and the eventually associated preventative effect, even though statistical evidence has not been found as of yet (Granacher et al., 2010; Keller et al., 2012). However, Keller et al. (2012), underlined the motivational aspect of slackline training compared with classical balance training, because for athletes slacklining may be more joyful and even more demanding. Nevertheless, further research is necessary to prove the preventative effect of slackline training in young athletes (Granacher et al., 2010; Keller et al., 2012). In general, Taube et al. (2008) and Hübscher et al. (2010) emphasized the beneficial effect of diverse balance training contents for injury prevention; it was shown that sensomotoric training leads to an increased motoric control of the musculature responsible for knee and ankle joint stabilization (Gollhofer et al., 2006; Taube et al., 2006), which might be beneficial for a lower injury risk. While all these findings lead to the assumption that neuromuscular core strength training might contribute to the decrease of injury risk in youth ski racing, further research is necessary.

The findings of the present study confirm that there appears to be no relationship between endurance capacity, leg strength and injury risk. At this point, it is important to mention that for coaches, the aim of physical testing is not to make appropriate decisions associated with the future success of their athletes. From a functional point of view, it is more important to discover individual weaknesses and imbalances among young athletes. Results should be used to develop individualized training programs, based on maturational characteristics if necessary, to help prevent injury.

Injury Rate and Severity

In general, smaller rates of traumatic injuries and overuse injuries were found in the present study compared with athletes competing at the adolescent level (1.7 injuries/1,000 h ski training) (Westin et al., 2013) and those competing at the elite level (36.7 injuries/100 athletes) (Flørenes et al., 2009; Bere et al., 2013; Haaland et al., 2016; Spörri et al., 2017). Fort-Vanmeerhaeghe et al. (2016) explained that prepubescent athletes may be at lower injury risk because they have lower body mass and shorter joint lever arms and because they do not generate as much dynamic valgus load as their more mature counterparts. Additionally, most injuries were classified as moderate based on an absence from training between 8 and 28 days. These findings are in line with the results of Hildebrandt and Raschner (2013) among 15- to 19-year old ski racers. In contrast, at the World Cup level, most injuries have been classified as severe (35.6%) (Bere et al., 2013). However, the retrospective study design employed in both studies (Bere et al., 2013; Hildebrandt and Raschner, 2013) should be considered a limitation. It is possible that minimal and moderate injuries were not assessed because of missing data, providing one reason why the results at the World Cup level differ from the results at the youth level.

LIMITATIONS

The diverse sample sizes based on the norm group classification and the three maturity groups must be considered a limitation of the study because direct comparisons are difficult. Furthermore, the rates of injuries were relatively low during the study period. Therefore, in some sub-categories, there were too few cases to yield conclusive results. Further investigations with larger sample sizes and a longer observation period are recommended to detect risk factors between groups. Another limitation of the study was that the potential changes in different parameters (such as changes in height and weight, muscle mass and performance) from the start of the study to the end of the study were not considered as possible risk factors. Within the scope of this study, it was not possible to analyze training-related parameters. Previous research has shown that relative increase of training volume is one of the most important predictors of injuries (Gabbett, 2016; Soligard et al., 2016); therefore, the quantification of training load, variations during the year and the risk of injuries should also be investigated based on a daily monitoring system. Results of the drop jump test were only based on quantitative values. However, a video analysis can provide additional information about valgus lower limb alignment.

CONCLUSION

Although there is no single fitness parameter responsible for determining the risk of injuries, a comprehensive fitness regimen starting at a young age is crucial for coping with the physical requirements of alpine ski racing and minimizing the rate of both traumatic and overuse injuries. The findings of the present study showed that decreased core strength and below-average drop jump ability are accompanied by a higher risk of sustaining a severe injury. DJ RSI was a significant predictor of the occurrence of injury and injury severity. This variable significantly differed between injured and non-injured athletes, as well as between injury severity groups. With respect to both regression models, the DJ RSI showed the greatest (injury severity) or third highest association (occurrence of injury). Thus, these findings underline the importance of neuromuscular training in youth athletes in the context of injury prevention. Additionally, anthropometric characteristics and biological maturity status significantly affected injury risk in youth ski racers. It has to be considered that the two regression analyses could explain only 45–47% of the variability of the athletes and therefore, more than half of the variability remains unexplained. However, Spörri et al. (2017) emphasized the multifactorial nature of injury causes in a changing outdoor environment, which decreases the chance of identifying statistically significant risk factors. In this context, the explained variabilities of the present study seem to be high because nearly half of the variability could be explained by the investigated variables, which seems important for future

injury prevention in youth ski racers. However, in general, the occurrence of injuries was relatively low compared with that of elite alpine ski racers. Therefore, the regression analyses were performed for traumatic and overuse injuries combined. In the future, risk factors should be assessed separately for both types of injuries. Nevertheless, a regular, long-term documentation of changes in anthropometrics, physical fitness and training loads is important to quantify the effect of risk factors on alpine ski racing-specific injuries. Additionally, Fort-Vanmeerhaeghe et al. (2016) emphasized that youth athletes may need longer recovery phases than adults, which also seems important among youth ski racers. Consequently, recovery phases and regeneration measures must be implemented in the training process of young ski racers in order to possibly contribute to the prevention of injuries, particularly of overuse injuries, from occurring.

Based on studies in other types of sport, future research should evaluate the role of leg dominance (Smith et al., 2015) as a potential and modifiable risk factor in youth ski racing and the effects of diverse components of neuromuscular training on injury risk reduction (Emery et al., 2015). All analyses should contribute to injury prevention in young athletes because sports injuries in youth can become a barrier to long-term physical activity and can prevent athletes from enjoying successful careers (Emery et al., 2006, 2015; Caine et al., 2014).

AUTHOR CONTRIBUTIONS

All authors listed have made substantial, direct and intellectual contributions to the work and have approved it for publication.

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frontiers in Physiology

SYSTEMATIC REVIEW
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Dose-Response Relationship of Neuromuscular Training for Injury Prevention in Youth Athletes: A Meta-Analysis

Simon Steib[1]*, *Anna L. Rahlf*[2], *Klaus Pfeifer*[1] and *Astrid Zech*[2]

[1] Department of Sport Science and Sport, Friedrich-Alexander-University Erlangen-Nürnberg, Erlangen, Germany, [2] Institute of Sport Science, Friedrich-Schiller-University of Jena, Jena, Germany

Background: Youth athletes with intensive sports participation are at an increased risk of sustaining injuries. Neuromuscular training programs reduce sports-related injury risk in this population, however, the dose-response relationship is largely unknown. Thus, the aim of this meta-analysis was to identify the optimal frequency, volume, duration, and period of neuromuscular training to prevent injuries in youth athletes.

Methods: Computerized database searches (PubMed, Scopus, SPORTDiscus, The Cochrane Library, PEDro) were conducted in January 2017, with search terms related to youth sports, neuromuscular training, and injury prevention. Eligible trials (i) evaluated a neuromuscular training program; (ii) included youth athletes of 21 years or younger; (iii) had an analytical design (RCTs, quasi-experimental, cohort studies); (iv) contained original data; (v) and provided injury data. Two reviewers independently extracted data and assessed quality of eligible studies. Injury rate ratios (IRRs) for lower extremity injuries were pooled meta-analytically, and moderator analyses examined the effect of training frequency, duration, volume, and period.

Results: Data from 16 trials yielded an overall risk reduction of 42% with neuromuscular training (IRR = 0.58, 95%CI 0.47–0.72). Training frequencies of two (IRR = 0.50; 95%CI 0.29–0.86) or three times (IRR = 0.40; 95%CI 0.31–0.53) per week revealed the largest risk reduction, and a weekly training volume of more than 30 min tended to be more effective compared to lower volumes. Programs with 10–15 min (IRR = 0.55; 95%CI 0.42–0.72) session duration produced effects comparable to those with longer session duration (IRR = 0.60; 95%CI 0.46–0.76). Interventions lasting more than 6 months were not superior to shorter programs.

Conclusion: This meta-analysis revealed that NMT performed in short bouts of 10–15 min, two to three times per week, with a weekly training volume of 30–60 min had the largest preventive effect for lower extremity injuries in youth athletes. These effects can be achieved within 20–60 sessions and training periods of <6 months. The present results are derived from a relatively small number of studies with heterogeneous methodological quality and should be treated with caution.
The study was a priori registered at PROSPERO (CRD42016053473).

Keywords: exercise, sensorimotor training, balance training, injuries, children, youth, adolescent, team sports

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Urs Granacher,
University of Potsdam, Germany

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Lars Donath,
University of Basel, Switzerland
Christian Raschner,
University of Innsbruck, Austria

***Correspondence:**
Simon Steib
simon.steib@fau.de

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INTRODUCTION

The high participation rates as well as a growing specialization and professionalization of sports in young ages entail multiple benefits. However, this comes at the expense of an increased risk of injury and illness. The sport-related injury risk of youth athletes has been demonstrated in a variety of age ranges and sport activities (Pickett et al., 2005; Emery and Tyreman, 2009), with incidence rates of up to 34.4/1,000 h of sport exposure reported in young male ice hockey players for instance (Caine et al., 2008). These data emphasize the urgent need for developing effective strategies to prevent injuries. Hence, a growing number of injury prevention programs have been developed in recent years, with the majority containing multiple exercise components addressing neuromuscular performance (Emery et al., 2015). The positive effects of neuromuscular training (NMT) programs on the incidence of injuries in adults are well established (Hübscher et al., 2010; Lauersen et al., 2014; Schiftan et al., 2015; al Attar et al., 2016). A recent meta-analysis found that a soccer-specific NMT program reduced injury rates by 20–50% (al Attar et al., 2016). Regarding ankle injuries, neuromuscular multi-intervention, and proprioceptive programs have been found to decrease risk by 35–50% in sporting adult populations (Hübscher et al., 2010; Schiftan et al., 2015). Similar effects have also been reported for youth athletes. Two meta-analyses have demonstrated a risk reduction for lower extremity injuries of around 25–35% (Emery et al., 2015; Soomro et al., 2016).

While the preventive effects of neuromuscular interventions in youth athletes are indisputable, little is known with respect to their optimal dose. The investigated programs vary substantially with respect to training content and individual dosage parameters. Neuromuscular injury prevention programs for youth athletes have been examined in various sports, including basketball (Hewett et al., 1999; McGuine and Keene, 2006; Emery et al., 2007; LaBella et al., 2011), handball (Wedderkopp et al., 1999; Olsen et al., 2005), soccer (Hewett et al., 1999; Heidt et al., 2000; Malliou et al., 2004; Mandelbaum et al., 2005; Soligard et al., 2008; Steffen et al., 2008), and volleyball (Hewett et al., 1999; Heidt et al., 2000). Besides sport-specific contents, these programs typically either include multiple components, or focus on balance exercises (Hübscher et al., 2010; Zech et al., 2010). Frequent contents of multi-intervention programs include strength, balance, flexibility, plyometric, speed, and agility exercises (Hübscher et al., 2010), thereby focusing on neuromuscular control and active joint stabilization. Importantly, parameters such as the duration and volume of single training sessions, the training frequency, the intervention volume or training period vary substantially between individual studies (Soomro et al., 2016). Hence, it is difficult to infer the most effective training prescription based on findings from individual studies. A better understanding of dose-response relationships is a fundamental basis for designing well-tailored, population-specific exercise programs.

At present, prospective studies on the analysis of the dose-response relationship in NMT programs are lacking. In adult athletes, preliminary evidence has suggested that a session duration of at least 10 min, and a training frequency of more than once a week for at least 3 months is necessary in order to prevent injuries (Hübscher et al., 2010). In addition, the optimal dose to prevent anterior cruciate ligament injuries in female athletes should include training for at least twice a week, with a minimum of 20 min per session (Sugimoto et al., 2014). Two recent meta-analyses which investigated dosage-effects of balance training, a key component of NMT programs, reported the largest improvements in neuromuscular outcomes with training frequencies of three times a week, session durations of 11–15 min, and training periods of ∼12 weeks (Zech et al., 2010; Lesinski et al., 2015). In youth athletes on the other hand, information on the optimal dose of NMT is scarce. However, such information is particularly relevant in this population, considering the biological and anthropometric inter-individual differences caused by the maturational status. The little data available on dose-response relationships has suggested that training periods of more than 8 months have comparable preventive effects compared to shorter periods (Soomro et al., 2016). From a practical point of view, a deeper understanding of the best training dosage is crucial for tailoring training parameters to the specific population, and would increase coaches' and athletes' confidence in applying NMT programs (van Tiggelen et al., 2008; Zech and Wellmann, 2017).

Taken together, although NMT programs have demonstrated preventive effects in youth athletic populations, no consistent recommendations can be inferred from the current literature with respect to the duration, frequency, volume and training period of such programs. Establishing the minimal and optimal effective dose would not only help practitioners in designing tailored programs, but could also increase coaches' and athletes' compliance to such interventions (van Tiggelen et al., 2008; Zech and Wellmann, 2017). This is particularly relevant in youth athletes, where differences in maturational status can cause large inter-individual variation in anthropometrics and neuromuscular performance. Consequently, this systematic review and meta-analysis aimed to investigate dose-response relationships of NMT programs to prevent lower extremity injuries in adolescent athletes. Specifically, the optimal training frequency, session duration, training volume, and intervention period were targeted to provide recommendations for sports practice.

METHODS

This systematic review and meta-analysis was preregistered (registration number: CRD42016053473) at the international prospective register of systematic reviews (PROSPERO). The registration protocol is accessible at http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42016053473.

Search Strategy

A systematic computerized database search was conducted in five databases (PubMed, Scopus, SPORTDiscus, The Cochrane Library, PEDro) from their inception up until January 12, 2017. Articles in English and published in peer-reviewed journals were considered. We developed a systematic search strategy by clustering key terms according to the PICOS

(Patient/Problem, Intervention, Control/Comparison, Outcome, Study design) strategy. Selected key words related to youth sports, neuromuscular training, and injury prevention were connected using Boolean terms. A detailed list of the exact terms and search strategies used is provided in the Supplementary Material. In addition to electronic database searching, the reference lists of articles were searched during full text screening in an effort to obtain additional eligible studies.

Selection Criteria

Based on the PICOS strategy, the following criteria had to be fulfilled in order for studies to be considered in this meta-analysis: (i) the study population consisted of youths of 21 years or younger (Malina et al., 2015), participating in structured/organized sport programs on a competitive level (P); (ii) a neuromuscular training program (including components such as balance, agility, strength, neuromuscular control) was evaluated with no co-interventions (e.g., education) provided (I); (iii) the study contained a control arm either performing usual practice routine or sham exercises without specific focus on neuromuscular control (C); (iv) data for at least one outcome of lower extremity sports injury was provided (O); and (v) an analytical design was used (RCTs, quasi-experimental trials, cohort studies) (S). Studies without original data (review articles) or without obtainable data for meta-analysis were excluded.

Risk of Bias Assessment

We analyzed risk of bias of included studies using the PEDro scale (Maher et al., 2003). This scale consists of eleven items, addressing internal validity (8 items), interpretability (2 items), and external validity (1 item). A point was scored for each item clearly fulfilling the criterion, allowing a maximal score of 11 points. Two reviewers (SST, ALR) independently performed the quality rating. Disagreements between ratings were discussed and solved via consensus. This process was piloted on three studies not included in the review before actual quality rating was performed.

Data Extraction

Two researchers (SST, ALR) extracted predefined study characteristics from publications and collected the information in tabular form. These characteristics included authors, publication year, study design, participants (age, gender, sports, expertise level, sample size), interventions (types of exercises, training period, training frequency, number of sessions, and session duration for experimental and control groups, respectively), and results (type of injury, injury incidence by type/ location, player exposures).

Outcome Measures

Data was extracted for lower extremity (LE) injury, including any form of muscular, ligamentous or bony injuries (traumatic or overuse). If available, the total number of LE injuries was used for meta-analysis. In cases where studies only reported knee or ankle injuries, this data was used accordingly.

NMT dosage was divided into the following components: training session duration and frequency, weekly volume, and total intervention volume and period.

- *Session duration:* The time (minutes) spent for one NMT session.
- *Training frequency:* The weekly number of NMT sessions.
- *Weekly training volume:* The time (minutes) per week spent for NMT (training frequency x session duration).
- *Intervention volume:* The total number of training sessions, equaling the sum of all sessions throughout the intervention period.
- *Intervention period:* The total intervention duration in weeks.

For moderator analyses, further subgroups were formed within each variable: *session duration* was categorized into low (10–15 min), medium (20–30 min), and high (>30 min); *training frequency* was clustered into 1x, 2x, 3x, and >3x per week; *weekly volume* was categorized as low (<30 min), medium (30–60 min), and high (>60); *intervention volume* was clustered into low (<30 sessions), moderate (30–60 sessions), and high (>90 sessions); and *intervention period* was separated into short term (≤6 months) and long-term (>6 months).

Statistical Analysis

Meta-Analysis

All analyses were performed using the Cochrane review manager (version 5.3.5, The Cochrane Collaboration, Copenhagen). Injury rate ratios (IRRs) with corresponding 95% confidence intervals (CI) were calculated representing an effect estimate for each included study: IRR = (number of injuries in NMT group/player exposures)/(number of injuries in control group/player exposures). In cases where player exposure hours were not available, IRRs were calculated using the players' number of practice and game exposures. The IRR resembles a ratio of the within-group (NMT, control) injury incidence rates. Consequently, a value smaller than 1 indicates an injury risk reduction in favor of NMT, and the closer the value to 0, the larger is the effect. Both cluster RCTs and cohort studies were included in this meta-analysis, and sensitivity analyses indicated that no systematic difference in effect sizes existed between these study designs ($I^2 = 0\%$; $Q = 0.14$; $p = 0.71$).

As significant heterogeneity in individual studies' IRRs was present ($I^2 = 71\%$, $Q = 55.77$; $p < 0.0001$), the assumption of a unified true intervention effect was dismissed. Consequently, a random effect model (inverse-variance) was used for weighting individual studies and estimating the overall pooled effect size (IRR). Z statistics and respective *P*-values were calculated to assess whether this effect was statistically significant. Heterogeneity between studies' IRRs were observed using chi-squared tests, and I^2 values were calculated to quantify the proportion (in %) of observed variance.

Sensitivity analyses were performed for the influence of *study design* (RCT vs. cohort study) and *study quality* on the overall effect, in order to detect potential bias from studies with lower levels of internal validity.

Moderator Analysis

Moderator analyses were performed in order to examine whether specific dosage features would have a stronger effect on injury risk reduction. The following moderators were examined: (i) training frequency; (ii) training session duration; (iii) weekly training volume; (iv) total number of training sessions; (v) intervention period.

For each moderator, subgroups were defined as described above (data extraction). A pooled effect estimate was then calculated for each subgroup containing at least two studies, and differences between subgroups were tested by assessing heterogeneity across subgroup effects using chi-squared tests. Besides statistical comparison, we descriptively compared subgroups IRRs, considering a ≥10% difference as meaningful (Soomro et al., 2016). Meta-regression was not performed due to the limited number of studies and the lack of precision in the continuous data (e.g., training session duration data reported resembled the prescribed duration, rather than the actually performed and precisely measured time).

RESULTS

Trial Flow

Our search strategy identified a total of 1261 records (**Figure 1**). We screened titles and abstracts from 904 articles after duplicate removal. From these, 849 were discarded and full texts obtained from the remaining 55 articles. After full text screening, another 39 articles were excluded, mostly due to lack of original data or inadequate study population. Consequently, 16 trials were included in the final meta-analysis.

Study Characteristics

Table 1 shows the characteristics of the included studies. The sample size varies substantially, from 54 (Cumps et al., 2007) up to 4,546 (Walden et al., 2012). In six studies, both male and female athletes were examined (Hewett et al., 1999; Olsen et al., 2005; McGuine and Keene, 2006; Cumps et al., 2007; Emery et al., 2007; Emery and Meeuwisse, 2010), while two studies focused on male athletes (Longo et al., 2012; Owoeye et al., 2014), and seven trials on females only (Wedderkopp et al., 1999; Mandelbaum et al., 2005; Pfeiffer et al., 2006; Soligard et al., 2008; Steffen et al., 2008; LaBella et al., 2011; Walden et al., 2012). The mean age of the participants varied between 14 (Walden et al., 2012) and 17 years (Steffen et al., 2008; Owoeye et al., 2014), and age groups typically ranged from 12 to 18 years. With respect to players' competitive level, 12 studies focused on sub-elite athletes organized in clubs (Mandelbaum et al., 2005; Olsen et al., 2005; Soligard et al., 2008; Emery and Meeuwisse, 2010; Walden et al., 2012) or high-school sports (Hewett et al., 1999; McGuine and Keene, 2006; Pfeiffer et al., 2006; Emery et al., 2007; McHugh et al., 2007; Steffen et al., 2008; LaBella et al., 2011). Three studies investigated elite players (Cumps et al., 2007; Longo et al., 2012; Owoeye et al., 2014), and one study included a mixed sample (Wedderkopp et al., 1999). All trials studied team sport athletes, with soccer (Mandelbaum et al., 2005; Pfeiffer et al., 2006; Soligard et al., 2008; Steffen et al., 2008; Emery and Meeuwisse, 2010; Walden et al., 2012; Owoeye et al., 2014), and basketball (Cumps et al., 2007; Emery et al., 2007; Longo et al., 2012) being the most common. The NMT programs typically consisted of either multiple components (generally strength, balance, and agility) or balance exercises only. The most commonly investigated standardized multi-component programs were FIFA "the 11" (Steffen et al., 2008) or FIFA "11+" (Soligard et al., 2008; Longo et al., 2012; Owoeye et al., 2014). Balance training only was used in six studies (Wedderkopp et al., 1999; McGuine and Keene, 2006; Cumps et al., 2007; Emery et al., 2007; McHugh et al., 2007).

The training parameters reported in the included studies were as follows: The duration of NMT sessions varied from 5 to 10 (Cumps et al., 2007) up to 60–90 min (Hewett et al., 1999), but the majority of trials ($N = 12$) implemented sessions of 15–20 min length (Wedderkopp et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005; Pfeiffer et al., 2006; Emery et al., 2007; Soligard et al., 2008; Steffen et al., 2008; Emery and Meeuwisse, 2010; LaBella et al., 2011; Longo et al., 2012; Walden et al., 2012; Owoeye et al., 2014). Training frequencies of two and three times a week were most common, however, three studies reported one (Olsen et al., 2005; Steffen et al., 2008) or five (Emery et al., 2007) weekly sessions. The intervention period varied between 6 (Hewett et al., 1999) and 40 weeks (Wedderkopp et al., 1999), and the total number of scheduled training sessions ranged from 18 (Hewett et al., 1999) to 140 sessions (Wedderkopp et al., 1999).

Methodological Quality

Table 2 presents the methodological quality assessment of included studies. The majority of studies were of moderate (PEDro score 5–7; $N = 5$) or high (PEDro score ≥ 8; $N = 5$) methodological quality. Six studies presented low methodological quality (PEDro score 1–3). Statistical between-group comparisons were reported in all trials, and all but one study provided point and variability measures for key outcomes. Other criteria that were fulfilled in the majority of studies include random group allocation ($N = 11$), intention-to-treat analysis ($N = 10$), specification of eligibility criteria ($N = 10$), and allocation concealment ($N = 8$). Similarity of experimental groups at baseline was ensured in only six trials. Similarly, only six trials reported assessor blinding and follow-up data from more than 85% of participants.

Sensitivity analyses (**Table 3** and Supplementary Material) revealed that the study design (randomized vs. non-randomized) had little impact on the effect estimate ($I^2 = 0\%$; $Q = 0.14$; $p = 0.71$). There was a significant difference between study quality subgroups ($I^2 = 66.1$; $Q = 5.90$; $p = 0.05$), with higher effect estimates in studies with low internal validity (Pedro score <5; IRR = 0.37, 95% CI 0.23–0.60), compared to moderate (IRR = 0.60, 95% CI 0.44–0.82) and high (IRR = 0.74, 95% CI 0.56–0.98) PEDro scores. This was further supported by inspection of the funnel plot (**Figure 2**).

Meta-Analysis Results: Overall Effect of NMT

A summary of the individual studies' IRRs and the meta-analysis is provided in **Figure 3**. Data was pooled from a total of 16 studies to establish the overall effect of NMT interventions, representing 1,417,730 player exposures, and 1,724 LE injuries.

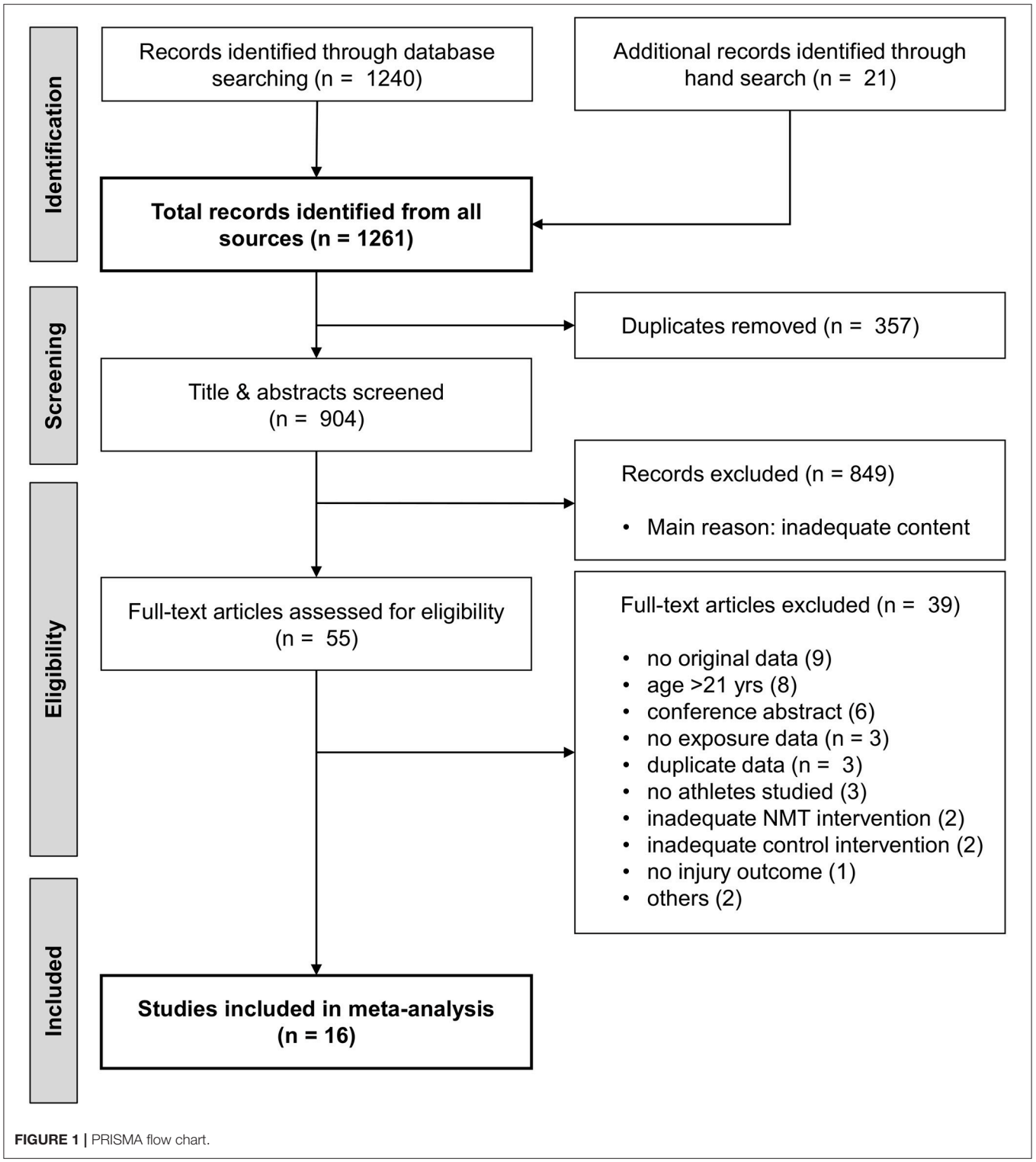


FIGURE 1 | PRISMA flow chart.

The pooled IRR was 0.58 (95% CI 0.47–0.72; $Z = 4.94$; $p < 0.001$), indicating a statistically significant LE injury risk reduction of 42%. A substantial amount of heterogeneity existed in individual studies' effect estimates ($I^2 = 71\%$; $Q = 55.77$; $p < 0.001$).

Moderator Analysis: Dose-Response Relationships of NMT

Results from the moderator analyses are provided in **Table 3** and **Figures 4–8**. We found a significant heterogeneity between *training frequency* subgroups ($I^2 = 74.0$; $Q = 7.69$; $p = 0.02$),

TABLE 1 | Characteristics of included studies.

Author, year	Sample size (n)[a]	Age (years), mean ± SD[b,e]	Sport	Level[d]	Intervention group	Control group	Period (weeks)	Duration (minutes)	Frequency (per week)	Primary outcome	Number of injuries[b]
Cumps et al., 2007	F:17, M:37	IG:17.7 ± 3.9, CG:18 ± 2.7	Basketball	Elite	Balance training intervention (warm-up including basketball-skills on balance semi-globes, progressive difficulty)	Normal routine	22	5–10	3	Ankle injury	IG:5, CG:10
Emery et al., 2007	F:456, M:464	12–18 (range)	Basketball	Sub-elite	Balance training (10 min warm-up routine including aerobic and stretching and 5 min sport-specific balance training warm-up + 20 min home training on wobble board)	Standardized warm-up (specified by research team)	18	15–20	5	Any LE injury, ankle injury	IG:106, CG:111
Emery and Meeuwisse, 2010	F/M:1018	13–18 (range)	Indoor soccer	Sub-elite	Soccer-specific neuromuscular training program (5 min aerobic and stretching and 10 min neuromuscular components including strength, agility, and balance + 15 min home-based balance training on wobble board)	Standardized warm-up (specified by research team)	20	15	No data	Any LE injury, knee injury, ankle injury	IG:42, CG:60
Hewett et al., 1999	F:829, M:434	No data	Soccer, volleyball, basketball	Sub-elite	Pre-season neuromuscular training program (jump technique and performance, stretching and weight training)	No preseason neuromuscular training program	6	60–90	3	Knee injury	IG:2, CG:10
LaBella et al., 2011	F:1,558	IG:16.2 ± 1.5, CG:16.2 ± 1.1	Basketball, soccer	Sub-elite	Neuromuscular warm-up training program (progressive strengthening, plyometric, balance, and agility exercises)	Usual warm-up	9–18[c]	20	3	Any LE injury, knee injury, ankle injury	IG:50, CG:96
Longo et al., 2012	M:221	IG:13.5 ± 1.2, CG:15.2 ± 4.6 11–24 (range)	Basketball	Elite	Neuromuscular warm-up training program—FIFA 11+ (running, strength, balance, jumping exercises, and agility)	Usual warm-up	36	20	3–4[f]	Any LE injury, knee injury, ankle injury	IG:10, CG:11
Mandelbaum et al., 2005	Year 1: F:2,946, year 2: F:2,757	14–18 (range)	Soccer	Sub-elite	Prevent Injury and Enhance Performance (PEP) program (warm-up activities, stretching techniques, strengthening exercises, plyometric activities, soccer-specific agility drills)	Usual warm-up	16	20	2.18	ACL injury	Year 1: IG:2, CG:32; year 2: IG:4, CG:35
McGuine and Keene, 2006	F:523, M:242	IG:16.4 ± 1.2, CG:16.6 ± 1.1	Basketball, soccer	Sub-elite	Balance training program (single- and double-limb balance training on balance board, including 5 phases)	No balance training program	No data	10	3 (preseason 5)	Ankle injury	IG:23, CG:39
McHugh et al., 2007	125	15–18 (range)	American football	Sub-elite	Balance training intervention (single-limb balance training on a foam stability pad)	No control group	13	10	2 (preseason 5)	Ankle injury	IG:20, CG:21
Olsen et al., 2005	F:1,586, M:251	IG:16.3 ± 0.6, CG:16.2 ± 0.6, 15–17 (range)	Handball	Sub- elite	Neuromuscular warm-up training program (exercises with ball, wobble board and balance mat to improve technique, balance and strength)	Usual warm-up	32	15–20	1	Any LE injury, knee injury, ankle injury	IG:66, CG:115

(Continued)

TABLE 1 | Continued

Author, year	Sample size (n)[a]	Age (years), mean ± SD[b,e]	Sport	Level[d]	Intervention group	Control group	Period (weeks)	Duration (minutes)	Frequency (per week)	Primary outcome	Number of injuries[b]
Owoeye et al., 2014	M:416	IG:17.8 ± 0.9, CG:17.5 ± 1.1, 14–19 (range)	Soccer	Elite	Neuromuscular warm-up training program—FIFA 11+ (running, strength, balance, jumping exercises and agility)	Usual warm-up	24	20	2	Any LE injury, knee injury, ankle injury	IG:26, CG:76
Pfeiffer et al., 2006	F:1,439	No data	Soccer	Sub-elite	Knee Ligament Injury Prevention (KLIP) program (plyometric and agility exercises)	No KLIP program	24	20	2	ACL injury	IG:3, CG:3
Soligard et al., 2008	F:1,892	15.4 ± 0.7, 13–17 (range)	Soccer	Sub-elite	Neuromuscular warm-up training program- FIFA 11+ (running, strength, balance, jumping exercises and agility)	Usual warm-up	32	20	2-6[f]	Any LE injury, knee injury, ankle injury	IG:121, CG:141
Steffen et al., 2008	F:2,100	17.1 ± 0.8, 13–18 (range)	Soccer	Sub-elite	Neuromuscular warm-up training program—FIFA "the 11"(core stability, balance, eccentric hamstrings strength and dynamic stabilization)	Usual warm-up and training	32	20	1	Any LE injury, knee injury, ankle injury	IG:181, CG:173
Walden et al., 2012	F:4,564	IG:14.0 ± 1.2, CG:14.1 ± 1.2, 12–17 (range)	Soccer	Sub-elite	Neuromuscular warm-up training program (focus on knee control and core stability in six exercises)	Usual training and play	28	20	2	Knee injury	IG:49, CG:47
Wedderkopp et al., 1999	F:237	16–18 (range)	Handball	Mix	Balance training + functional activities for the upper and lower extremities (ankle disk training, warm-up and training of all muscle groups)	Usual practice and play	40	10–15	3	Any LE injury, knee injury, ankle injury	IG:10, CG:37

[a] *If data available distributed by sex (F, Female; M, Male).*
[b] *If data available distributed in IG: intervention group and CG: control group.*
[c] *9–12 weeks in soccer, 15–18 weeks in basketball.*
[d] *Sub-elite and elite organized in club or high-school sports, mix includes different levels.*
[e] *For missing mean ± SD the range is specified.*
[f] *Depending on the number of training sessions per week; ACL, Anterior Cruciate Ligament.*

TABLE 2 | Quality assessment (PEDro) of included studies.

First author, year	Eligibility criteria specified	Randomization	Concealed allocation	Baseline comparability	Patients blinded	Care provider blinded	Assessor blinded	Adequate follow up	Intention-to-treat	Between-group comparisons	Point estimates and variability	Score
Cumps et al., 2007	–	–	–	–	–	–	–	✓	–	✓	✓	3
Emery et al., 2007	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	9
Emery and Meeuwisse, 2010	✓	✓	✓	✓	–	–	✓	–	✓	✓	✓	8
Hewett et al., 1999	–	–	–	–	–	–	–	–	–	✓	–	1
LaBella et al., 2011	✓	✓	–	–	–	–	–	✓	✓	✓	✓	6
Longo et al., 2012	✓	✓	✓	–	–	–	✓	✓	✓	✓	✓	8
Mandelbaum et al., 2005	✓	–	–	–	–	–	–	–	–	✓	✓	3
McGuine and Keene, 2006	✓	✓	–	✓	–	–	–	–	✓	✓	✓	6
McHugh et al., 2007	–	–	–	–	–	–	–	–	–	✓	✓	2
Olsen et al., 2005	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	9
Owoeye et al., 2014	–	✓	✓	✓	–	–	–	✓	✓	✓	✓	7
Pfeiffer et al., 2006	–	–	–	–	–	–	–	–	–	✓	✓	2
Soligard et al., 2008	✓	✓	✓	–	–	–	✓	–	✓	✓	✓	7
Steffen et al., 2008	✓	✓	✓	–	–	–	✓	✓	✓	✓	✓	8
Walden et al., 2012	✓	✓	✓	✓	–	–	–	–	✓	✓	✓	7
Wedderkopp et al., 1999	–	✓	–	–	–	–	–	–	–	✓	✓	3

✓ *Criterion fulfilled; – Criterion not fulfilled.*

TABLE 3 | Results of subgroup analysis.

Moderator	Within-subgroup comparison						Heterogeneity (Chi^2 test)		
	No. of effect sizes[a]	Total player exposures	IRR	95% CI	*p*-value	Possible risk reduction, %	*Q*-value	*p*-value	I^2
STUDY DESIGN AND QUALITY (SENSITIVITY ANALYSIS)									
Study design									
Cluster RCTs	13	1,277,433	0.59	0.47–0.74	<0.001	41	49.81	<0.001	76
Cohort studies	4	147,324	0.52	0.27–1.00	0.050	48	4.4	0.22	32
				Test for subgroup differences			0.14	0.71	0
Study quality									
Low (PEDro ≤ 4)	7	389,003	0.37	0.23–0.6	<0.001	63	9.3	0.1	46
Medium (PEDro 5–7)	5	577,713	0.6	0.44–0.82	0.002	40	14.41	0.006	72
High (PEDro ≥ 8)	5	458,041	0.74	0.56–0.98	0.040	26	14.72	0.005	73
				Test for subgroup differences			5.9	0.05*	66.1
MODERATOR ANALYSIS (DOSE-RESPONSE)									
Neuromuscular training dosage									
Session duration									
Low (10–15 min)	5	175,445	0.55	0.42–0.72	<0.001	45	4.34	0.36	8
Medium (20–30 min)	10	1,152,336	0.6	0.46–0.76	<0.001	40	44.56	<0.001	80
High (<30 min)	1							*Not estimable*	
				Test for subgroup differences			0.21	0.65	0
Training frequency									
1x/wk	3	408,770	0.76	0.53–1.10	0.140	24	12.71	0.002	84
2x/wk	6	695,605	0.5	0.29–0.86	0.010	50	16.96	0.005	71
3x/wk	5	157,332	0.4	0.31–0.53	<0.001	60	1.02	0.91	0
>3x/wk	1							*Not estimable*	
				Test for subgroup differences			7.69	0.02*	74
Weekly training volume									
Low (20–30 min)	6	500,196	0.67	0.51–0.90	0.007	33	17.83	0.003	72
Medium (30–60 min)	6	688,655	0.45	0.25–0.81	0.008	55	19.16	0.002	74
High (>60 min)	4	188,258	0.54	0.32–0.90	0.020	46	11.41	0.01	74
				Test for subgroup differences			1.7	0.43	0
Intervention volume and period									
Total number of training sessions									
Low (18–29 sessions)	2	83,681	0.48	0.27–0.85	0.010	52	0.67	0.41	0
Moderate (30–60 sessions)	8	1,055,386	0.57	0.41–0.79	0.001	43	42.17	<0.001	83
High (90+ sessions)	4	140,348	0.51	0.28–0.90	0.020	49	9.13	0.03	67
				Test for subgroup differences			0.29	0.87	0
Intervention period									
Short term (1.5–6 months)	6	324,742	0.57	0.41–0.79	0.001	43	11.21	0.05	55
Long term (7–12 months)	10	1,043,399	0.57	0.42–0.76	<0.001	43	42.21	<0.001	79
				Test for subgroup differences			0	0.95	0

**Significant subgroup difference; [a]Number of individual IRRs considered for each subgroup comparison; IRR, injury rate ratio; CI, confidence interval; RCT, randomized controlled trial; wk, week.*

indicating differences in subgroups' pooled effect estimates (**Figure 4**). IRRs in trials with training frequencies of two (IRR = 0.5; 95%CI 0.29–0.86) or three times (IRR = 0.40; 95%CI 0.31–0.53) per week were lower (indicating higher risk reduction) compared to frequencies of once a week (IRR = 0.76; 95%CI 0.53–1.10). Programs with low (IRR = 0.55; 95%CI 0.42–0.72) NMT *session duration* produced effects comparable to those with medium session duration (IRR = 0.60; 95%CI 0.46–0.76; **Figure 5**). Further, a *weekly training volume* of more than 30 min tended to be more effective (30–60 min: IRR = 0.45; 95%CI 0.25–0.81; >60 min: IRR = 0.54; 95%CI 0.32–0.90) compared to lower volumes (20–30 min: IRR = 0.67; 95%CI 0.51–0.90; **Figure 6**).

Little differences existed between effect estimates of studies with moderate (IRR = 0.57; 95%CI 0.41–0.79) or high (IRR = 0.51, 95%CI 0.28–0.90) *total number of training sessions*,

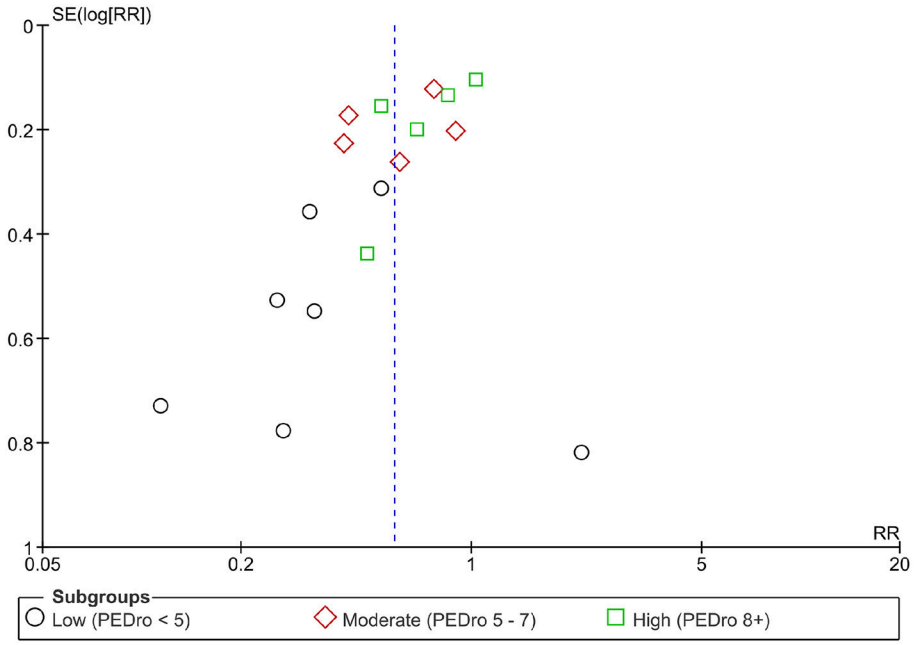


FIGURE 2 | Funnel plot; SE, standard error, RR, relative risk.

Study or Subgroup	Training period (weeks)	Training duration (minutes)	Training frequency (sessions per week)	Weight	Risk Ratio IV, Random, 95% CI
Cumps et al., 2007	22	5-10	3	2.9%	0.34 [0.12, 0.98]
Emery et al., 2007	18	15-20	5	9.1%	0.85 [0.65, 1.11]
Emery and Meeuwisse, 2010	20	15	NA	7.8%	0.69 [0.46, 1.02]
Hewett et al., 1999*#	6	60-90	3	1.7%	0.27 [0.06, 1.23]
LaBella et al., 2011	NA [1]	20	3	8.3%	0.43 [0.30, 0.60]
Longo et al., 2012	36	20	3-4	3.9%	0.48 [0.21, 1.14]
Mandelbaum et al., 2005 (year 1)*	16	20	2.18 [3]	1.9%	0.11 [0.03, 0.48]
Mandelbaum et al., 2005 (year 2)*	16	20	2.18 [3]	3.1%	0.26 [0.09, 0.73]
McGuine and Keene, 2006§	NA [2]	10	3	6.6%	0.61 [0.36, 1.02]
McHugh et al., 2007§#	13	10	2	5.7%	0.53 [0.29, 0.98]
Olsen et al., 2005	32	15-20	1	8.7%	0.54 [0.40, 0.72]
Owoeye et al., 2004	24	20	2	7.3%	0.41 [0.26, 0.64]
Pfeiffer et al., 2006*#	24	20	2	1.5%	2.15 [0.43, 10.67]
Soligard et al., 2008	32	20	1.3 [3]	9.3%	0.77 [0.60, 0.98]
Steffen et al., 2008	32	20	1	9.6%	1.04 [0.84, 1.27]
Walden et al., 2012*	28	20	2	7.7%	0.90 [0.60, 1.35]
Wedderkopp et al., 1999	40	10-15	3	5.0%	0.33 [0.16, 0.65]
Total (95% CI)				**100.0%**	**0.58 [0.47, 0.72]**
Total events	720		1019		

Heterogeneity: Tau² = 0.11; Chi² = 55.77, df = 16 (P < 0.00001); I² = 71%
Test for overall effect: Z = 4.94 (P < 0.00001)

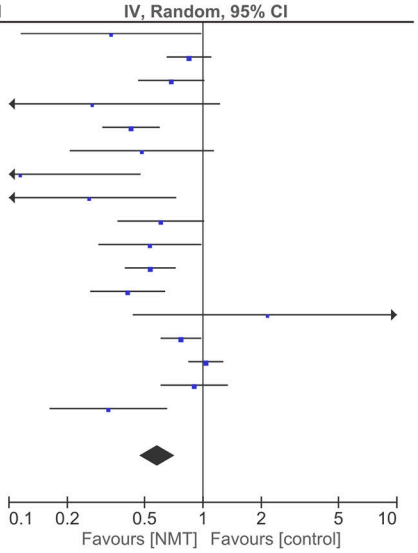


FIGURE 3 | Forest plot with individual studies' injury risk ratios (IRRs) and the overall pooled IRR; IV, inverse variance; CI, confidence interval; NMT, neuromuscular training. *Knee injury data only; §Ankle injury data only; #Cohort studies; [1]15–18 (basketball); 9–12 (soccer); [2]One highschool preseason + season (soccer, basketball); [3]Data provided by the author.

and studies with a low number of total sessions tended to have lower IRRs (IRR = 0.48; 95%CI 0.27–0.85; **Figure 7**). The *intervention period* had a negligible effect on pooled IRRs (0–6 months: IRR = 0.57, 95%CI 0.41–0.79; 7–12 months: IRR = 0.57, 95%CI 0.42–0.76; **Figure 8**).

DISCUSSION

The main aim of this meta-analysis was to identify the optimal training dose of NMT programs to reduce lower extremity injury risk in youth athletes. Overall, and consistent with previous

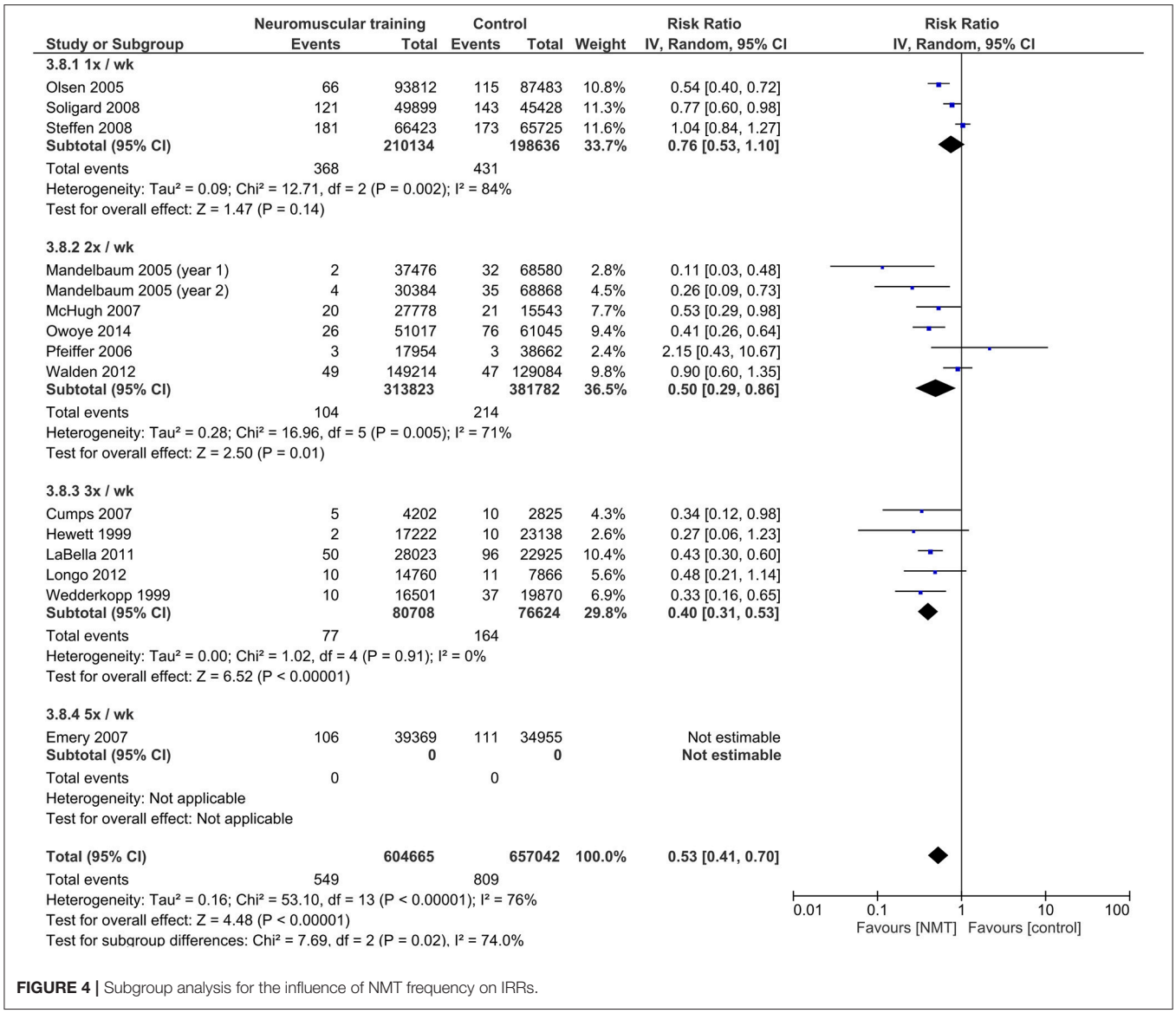


FIGURE 4 | Subgroup analysis for the influence of NMT frequency on IRRs.

reports, the included studies revealed a substantial preventive effect of NMT (IRR 0.58, 95% CI 0.47–0.72), with a 42% risk reduction for lower extremity injuries. Examination of dosage parameters indicated that the highest risk reductions were attained by NMT performed for two to three times per week, and a weekly training volume of 30–60 min. Consequently, injury prevention in youth athletes can be achieved with relatively modest training volumes. Pooled effects of training session durations indicated that short bouts of 10–15 min sessions may be sufficient to achieve this volume for a strong preventive impact. In terms of intervention period, preventive effects were already observed with fewer than 30 sessions and interestingly intervention periods of more than 6 months did not lead to an additional injury risk reduction. The results from the present meta-analysis should be interpreted with caution and considered a first step in understanding dose-response relationships, since comparisons are based on a relatively small number of studies with heterogeneous methodological quality.

Duration, Frequency, and Volume

The results of this meta-analysis revealed that *training frequency* significantly affected the preventive effect of NMT. Programs with frequencies of two or three times a week demonstrated a substantially larger risk reduction compared to training once a week. Similar findings were demonstrated in a recent meta-analysis which investigated dose-response relationships of NMT to reduced ACL injury risk in young and adult female athletes (Sugimoto et al., 2014), which also suggested that the preventive effect increases with increasing numbers of weekly training sessions. Lesinski et al. (2015) reported that neuromuscular adaptations to balance training, a key component of NMT injury prevention programs, were high when conducted for two to three times a week. Thus, these training frequencies seem to

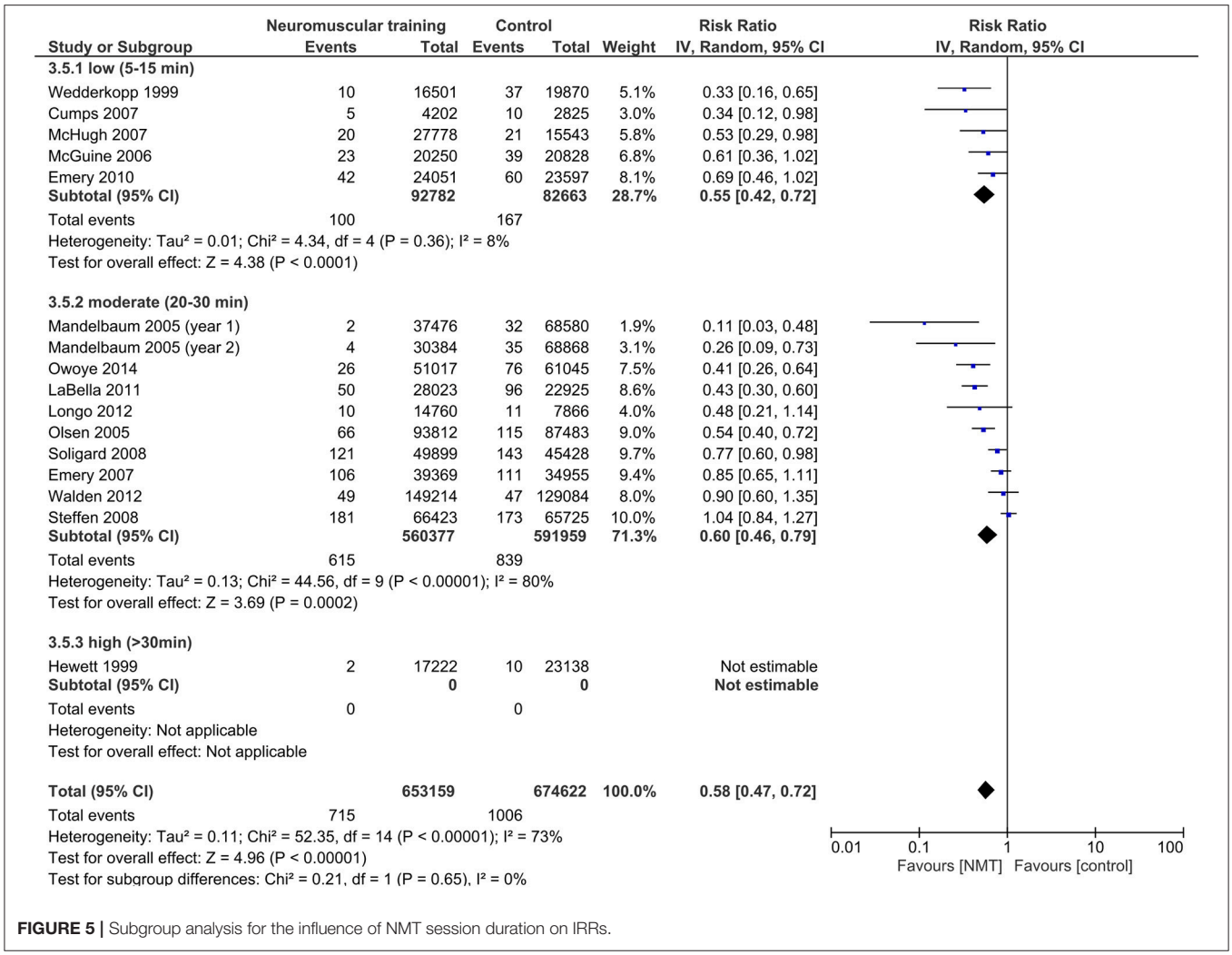


FIGURE 5 | Subgroup analysis for the influence of NMT session duration on IRRs.

be particularly effective for improving neuromuscular control, which has been proposed as a modifiable injury risk factor (Alentorn-Geli et al., 2009). From a practical point of view, this finding emphasizes the importance of regular implementation of NMT into an athlete's training routine. Since NMT programs, such as the "FIFA 11+" (Soligard et al., 2008), are typically designed as warm-up programs, this is easily achievable even in amateur level teams with less frequent training.

With respect to the optimal *NMT session duration*, our results indicate that session lengths of 10–15 min are sufficient to achieve a substantial risk reduction of 45%, with durations up to 30 min not appearing to have any additional effect. This is an important finding with respect to the practicability and feasibility of these programs, since it demonstrates that large preventive effects can be achieved with very short bouts of NMT. This makes exercise based injury prevention easily applicable for athletes and coaches, particularly in team sports settings where practice time is limited. While it is not possible to infer about the optimal timing within a practice session based on our meta-analysis, the integration of NMT bouts into athletes' warm-up routine was the most commonly chosen strategy. The efficacy of such NMT warm-up programs, such as the FIFA 11+, are well-established (Thorborg et al., 2017). Training effects may also be age-dependent, with Sugimoto et al. (2014) finding that session durations of more than 20 min were more effective for ACL injury prevention in both youth as well as adult female athletes. Thus, our results might point at a potential window of opportunity in young ages, where athletes might already benefit from short training bouts of <20 min, whereas longer sessions may be needed in older ages. This is further supported by a meta-analysis from Myer et al. (2013) who found an age effect for the effectiveness of NMT interventions, demonstrating a higher efficacy of NMT programs in young age groups. With respect to the underlying mechanisms, this finding could be explained by neuromuscular performance improvements, which have been shown to respond particularly well to short bouts of neuromuscular training sessions of 11–15 min (Lesinski et al., 2015). It is conceivable that the sensorimotor system in youth age has a greater potential for reorganization, which would consequently lead to more efficient and rapid adaptations during neuromuscular interventions. A

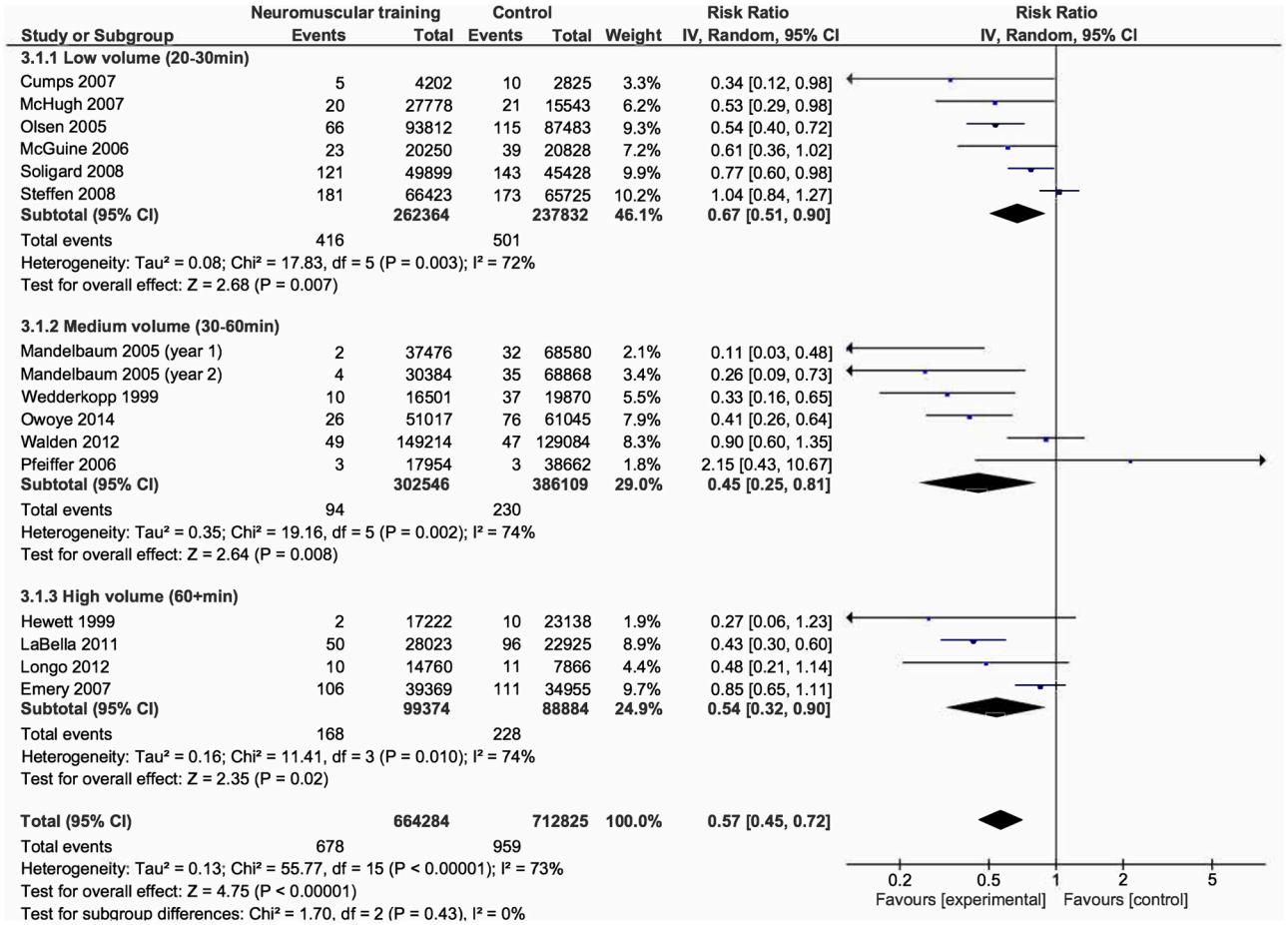


FIGURE 6 | Subgroup analysis for the influence of weekly NMT volume on IRRs.

second reason for the discrepancy between our findings and those of Sugimoto et al. (2014) may be related to the fact that they exclusively reviewed studies on female athletes. Thus, female athletes may respond better to training durations of more than 20 min, while young males might already adapt to shorter training stimuli. A previous meta-analysis by Rössler et al. (2014) demonstrated gender differences in the efficacy of exercise-based injury prevention programs, which would support this idea. However, it remains speculative based on the currently available data.

Our analysis revealed that a *weekly volume* of 30–60 min produced the highest injury risk reduction (IRR = 0.45; 95%CI 0.25–0.81), which equals two to three weekly sessions of 10–20 min duration. This finding confirms the aforementioned dosage effects for training frequency and duration, emphasizing the efficacy of short but frequent NMT sessions. In consequence, injury prevention is achievable with a modest volume of weekly training, which is a strong argument for the practicability of these intervention strategies. Coaches should aim at a regular incorporation of short NMT bouts in multiple practice sessions a week, which adds particular relevance to programs that can be incorporated in regular warm-up routines. Another strategy to ensure the required weekly volume is to have athletes perform additional sessions at home, since NMT programs are typically designed to require little space and equipment.

In summary, the results from this meta-analysis suggest that neuromuscular injury prevention programs should be conducted for at least two to three times a week, in short bouts of 10–15 min, ensuring a weekly volume of 30–60 min. This allows athletes and coaches to easily incorporate NMT contents into regular practice routines or in additional home training programs. Although, it is difficult to conclude on the optimal timing of NMT within a practice session based on the existing data, the majority of effective programs implement the training during athletes' warm-up.

Intervention Volume and Period

The *total volume* and *period of NMT* interventions are additional important factors to consider. We found the largest preventive effects in studies with a low amount of sessions (IRR = 0.48; 95%CI 0.27–0.85). However, this category only contained two studies, which both demonstrated poor methodological quality (Hewett et al., 1999; McHugh et al., 2007). Thus, an overestimation of this effect is likely. More importantly, there

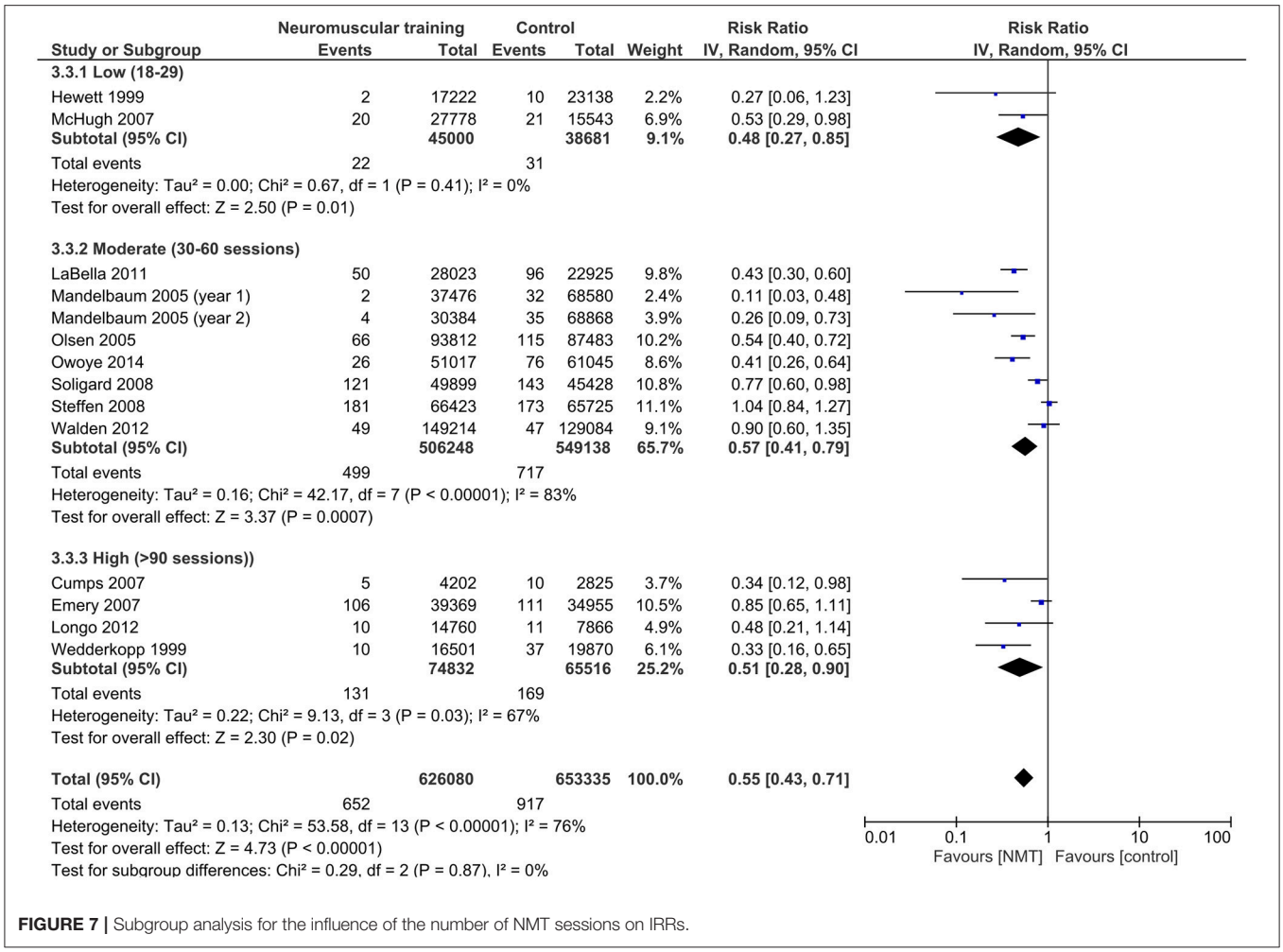


FIGURE 7 | Subgroup analysis for the influence of the number of NMT sessions on IRRs.

was no difference in the preventive effects between studies with moderate (30–60) and high (>60) total numbers of training sessions. Our findings suggest that about 20–60 training sessions may already induce a considerable injury risk reduction provided a frequent incorporation into practice, which will then be sustained with further regular practice. In addition, analysis of the *total intervention period* revealed that studies with short-term interventions of 1.5–6 months demonstrated similar effects compared to studies with longer training periods of 7–12 months. A possible explanation for these findings might be the specific time course of training-induced neuromuscular adaptations: Neuromuscular performance improvements, including increased balance, muscular power, and strength, have recently been demonstrated after NMT injury prevention programs in youth athletes (Faude et al., 2017). These adaptations were consistently demonstrated within only a few weeks of training (Steffen et al., 2013; Zech et al., 2014; Rössler et al., 2016; Steib et al., 2016), and the meta-analysis by Lesinski et al. (2015) reported a peak after 11–12 weeks of training in healthy adults. Consequently, rapid initial adaptations in neuromuscular abilities might lead to the fast reductions of injury risk, potentially reaching a plateau after the first months of training. However, it is noteworthy that this comparison only considers the prescribed, but not the actual number of sessions completed by the athletes. This would obviously provide more valuable information (Stevenson et al., 2015), but was not available in most cases.

In summary, the present evidence indicates that substantial injury prevention can be expected with just a moderate amount of 20–60 training session, within a period of <6 months. From a practical point of view, this further emphasizes the value of incorporating NMT contents into regular practice at any time of the competitive season. Further, the data suggest that these early adaptations will be sustained with continuing training, which emphasize the value of a continuous incorporation of neuromuscular contents into the athletes' long-term training process.

Limitations

We decided to include randomized and non-randomized as well as cohort designs in order to obtain more data for investigating dose-response relationships. A sensitivity analysis revealed that the study design (randomized vs. non-randomized) had no substantial effect on the studies' effect sizes, which

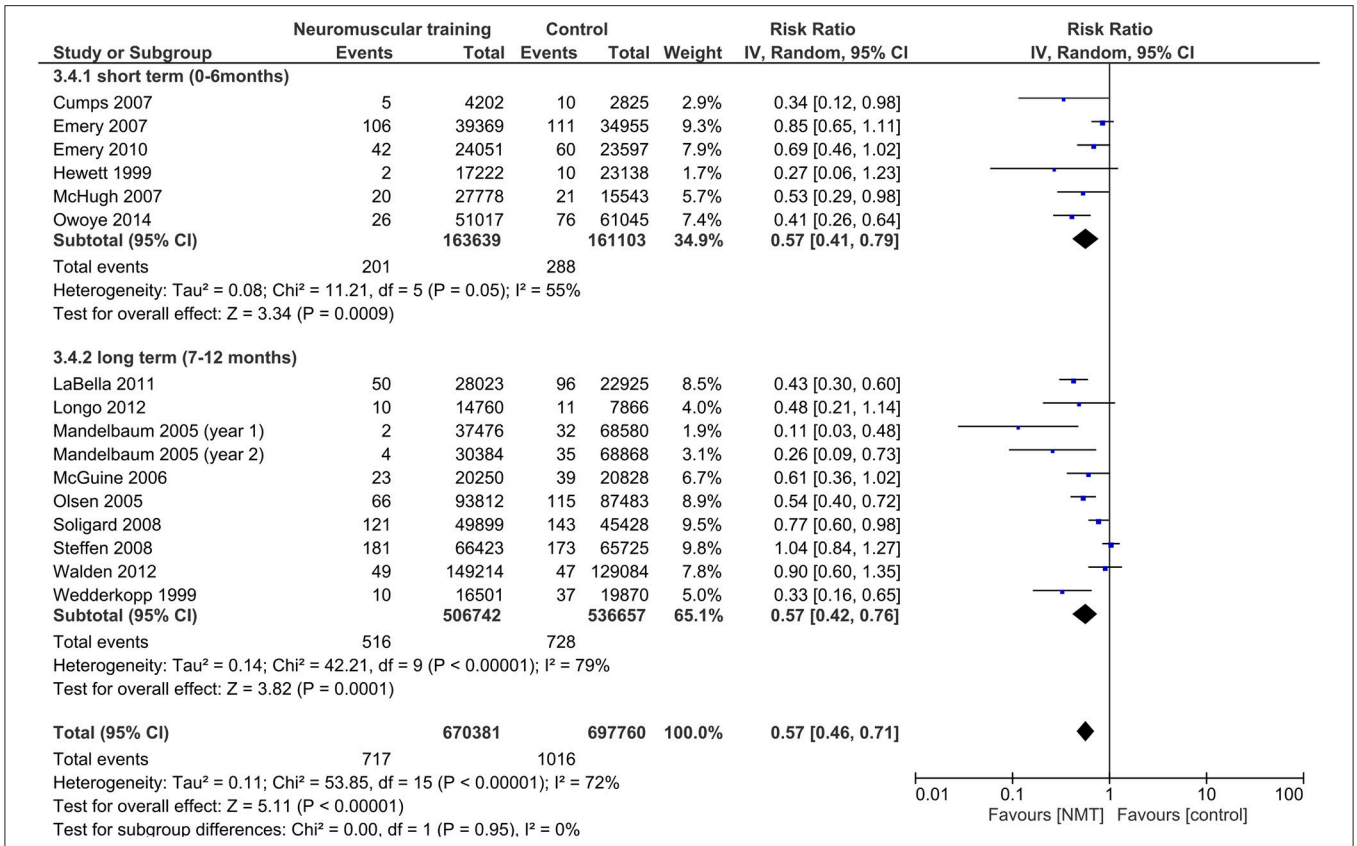


FIGURE 8 | Subgroup analysis for the influence of NMT intervention period on IRRs.

is in accordance with the findings from a previous meta-analysis (Rössler et al., 2014). However, the methodological quality of included studies varied substantially, and one third of the included studies scored poorly on the PEDro scale. Inspection of the funnel plot as well as a sensitivity analysis of trial quality revealed a tendency for smaller sampled and low-quality studies to report greater risk reductions than larger trials with moderate to high quality. This may have affected some of our moderator analyses, particularly when subgroups contained only few studies. In addition, even where substantial differences for effect estimates existed between subgroups, confidence intervals showed considerable overlap. Thus, on the basis of the current existing data, results can only serve as a first step in understanding dose-response relationships and need to be treated with some caution.

Study populations were diverse with respect to the type of sport, the gender and competitive level of participants. Seven studies investigated female and two trials male athletes only. Participants' competitive level ranged from amateur to high school or elite levels. While Soomro et al. (2016) did not find differential effects of injury prevention programs on male and female youth athletes, Rössler et al. (2014) reported that girls benefit more substantially from exercise-based injury prevention programs compared to boys. Further, they demonstrated that studies including sub-elite level athletes tended to show greater risk reductions compared to studies on elite athletes (Rössler et al., 2014). Consequently, the heterogeneity of effects we observed in the meta-analysis is likely not only attributable to difference in the NMT programs' content and dosage, but may at least partly be explained by specific differences in study populations.

In addition, our meta-analytical approach cannot consider the influence of specific program contents and the interactions between individual training modalities (e.g., duration, frequency, intervention period). Hence, subgroup analyses for selected dosage parameters neglect differences between studies in other training modalities. This may also explain why there was still considerable heterogeneity in some of the subgroups investigated. Where possible, we made efforts to account for this aspect by combining several parameters (i.e., weekly volume). In addition, training intensity, which is difficult to specify in multi-component NMT programs, was not addressed due to the lack of reported data. Further, athletes' compliance data was not available for many studies, and thus, is not considered in the analyses. This however is an important aspect influencing the efficacy of injury prevention programs (Soligard et al., 2010; Hagglund et al., 2013). Lastly, a differentiation between the effects of NMT programs on different types of injuries (e.g., overuse vs. traumatic; ankle vs. knee injuries) would add additional value to the dose-response

analysis. This, however, was not possible in the present study due to the little data available at present.

CONCLUSION

In conclusion, this meta-analysis revealed that NMT performed in short bouts of 10–15 min, two to three times per week, with a weekly training volume of 30–60 min had the largest preventive effect for lower extremity injuries. These effects were already observed within 20–60 sessions and training periods of <6 months, and seem to be sustainable with continued regular practice. Consequently, our results emphasize the value of short NMT bouts, such as structured warm-up protocols or home-training programs, which foster the regular incorporation of NMT in athletes practice routines. The fact that even modest weekly training volumes achieve desirable effects should encourage coaches to implement NMT contents into their practice regimes. The conclusions from this meta-analysis mainly represent results from studies including youth athletes between the ages of 12 and 21 years, and inferences for injury prevention in children are not possible at present. Further, the data underlying the dose-response analyses are derived from a limited number of studies with partly low methodological quality, which reduces the strength of the present recommendations. Further studies are needed to better understand the optimal program contents and training dosage, and the underlying mechanisms. Studies directly comparing the effects of individual dosage components are lacking. More work in this field is important in order to better educate athletes and coaches with respect to designing effective injury prevention programs.

AUTHOR CONTRIBUTIONS

SS had the idea, designed, and conducted this meta-analysis. ALR and SS developed the search strategy and conducted the systematic literature screening and quality assessment. ALR and SS were also responsible for data extraction and synthesis. ALR, KP and AZ assisted in designing the moderator analyses and were involved in discussing the results of the meta-analysis. SS wrote the manuscript draft. ALR, KP, and AZ critically revised the draft with respect to the intellectual content and approved the final version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2017.00920/full#supplementary-material

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Neuromuscular Adaptations to Multimodal Injury Prevention Programs in Youth Sports: A Systematic Review with Meta-Analysis of Randomized Controlled Trials

Oliver Faude[1], Roland Rössler[1,2], Erich J. Petushek[3], Ralf Roth[1], Lukas Zahner[1] and Lars Donath[1,4]*

[1] Department of Sport, Exercise and Health, University of Basel, Basel, Switzerland, [2] Department of Public and Occupational Health & Amsterdam Movement Sciences, VU University Medical Center, Amsterdam, Netherlands, [3] College of Human Medicine, Michigan State University, East Lansing, MI, United States, [4] Institute of Training and Computer Science in Sport, German Sport University Cologne, Köln, Germany

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***Correspondence:**
Oliver Faude
oliver.faude@unibas.ch

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Objective: Neuromuscular injury prevention programs (IPP) can reduce injury rate by about 40% in youth sport. Multimodal IPP include, for instance, balance, strength, power, and agility exercises. Our systematic review and meta-analysis aimed to evaluate the effects of multimodal IPP on neuromuscular performance in youth sports.

Methods: We conducted a systematic literature search including selected search terms related to youth sports, injury prevention, and neuromuscular performance. Inclusion criteria were: (i) the study was a (cluster-)randomized controlled trial (RCT), and (ii) investigated healthy participants, up to 20 years of age and involved in organized sport, (iii) an intervention arm performing a multimodal IPP was compared to a control arm following a common training regime, and (iv) neuromuscular performance parameters (e.g., balance, power, strength, sprint) were assessed. Furthermore, we evaluated IPP effects on sport-specific skills.

Results: Fourteen RCTs (comprising 704 participants) were analyzed. Eight studies included only males, and five only females. Seventy-one percent of all studies investigated soccer players with basketball, field hockey, futsal, Gaelic football, and hurling being the remaining sports. The average age of the participants ranged from 10 years up to 19 years and the level of play from recreational to professional. Intervention durations ranged from 4 weeks to 4.5 months with a total of 12 to 57 training sessions. We observed a small overall effect in favor of IPP for balance/stability (Hedges' g = 0.37; 95%CI 0.17, 0.58), leg power (g = 0.22; 95%CI 0.07, 0.38), and isokinetic hamstring and quadriceps strength as well as hamstrings-to-quadriceps ratio (g = 0.38; 95%CI 0.21, 0.55). We found a large overall effect for sprint abilities (g = 0.80; 95%CI 0.50, 1.09) and sport-specific skills (g = 0.83; 95%CI 0.34, 1.32). Subgroup analyses revealed larger effects in high-level (g = 0.34–1.18) compared to low-level athletes (g = 0.22–0.75),

in boys (g = 0.27–1.02) compared to girls (g = 0.09–0.38), in older (g = 0.32–1.16) compared to younger athletes (g = 0.18–0.51), and in studies with high (g = 0.35–1.16) compared to low (g = 0.12–0.38) overall number of training sessions.

Conclusion: Multimodal IPP beneficially affect neuromuscular performance. These improvements may substantiate the preventative efficacy of IPP and may support the wide-spread implementation and dissemination of IPP. The study has been a priori registered in PROSPERO (CRD42016053407).

Keywords: exercise training, sensorimotor, leg strength, balance, power, efficacy, risk factor, team sport

INTRODUCTION

Physical inactivity is a major public health burden and an independent risk factor for non-communicable diseases as well as increased mortality (Blair, 2009; Kohl et al., 2012). Already in childhood, inappropriate physical activity levels can cause considerable health problems on individual as well as society level (Janssen and Leblanc, 2010; Andersen et al., 2011). Consequently, the World Health Organization recommends at least 60 min of moderate to vigorous physical activity on top of everyday physical activity to counter harmful cardiovascular, neuromuscular, and metabolic developments (WHO, 2010). As a side-effect, however, sport and high levels of physical activity are associated with a high prevalence of injuries (Caine et al., 2006; Emery, 2010). For instance, there is evidence from several countries (Switzerland, United States, Canada, France, the Netherlands, the United Kingdom and Sweden) that (organized and non-organized) sports is the main cause of injury in children and adolescents with more than 50% of all injuries caused by sports (Bijur et al., 1995; Mummery et al., 1998; Belechri et al., 2001; Michaud et al., 2001; Hedstrom et al., 2012).

In order to reduce injury incidence while being physically active and, therefore, supporting the beneficial health effects of sport and physical activity, injury prevention programs (IPP) have been developed and evaluated. There is convincing evidence that exercise-based prevention programs can reduce the overall injury rate by about 40% in child and adolescent sport (Rössler et al., 2014). IPP are usually designed as multimodal exercise interventions targeting potential deficits in neuromuscular abilities, such as, leg muscle strength and power or postural stability. Neuromuscular performance can be regarded as the ability of the neuromuscular system to functionally control and drive movements by an appropriate use and coordination of muscular strength and endurance, muscle recruitment pattern, proprioceptive feedback, and reflex activity (Huston and Wojtys, 1996; Zech et al., 2010). Neuromuscular deficits may potentially increase the risk of injury, although evidence in this regard is not conclusive to date (Bahr and Holme, 2003; Emery, 2003; Meeuwisse et al., 2007; Lehr et al., 2017). Successful prevention programs usually include exercises targeting static and dynamic balance, plyometrics, as well as lower limb strength and power (Mandelbaum et al., 2005; Abernethy and Bleakley, 2007; Soligard et al., 2008; Kiani et al., 2010). There are studies, which analyzed the extent to which potential neuromuscular risk factors for injuries were affected by such programs. Some of these studies, however, suffer from low sample sizes, the results appear heterogeneous and definitive conclusions on the expectable effect sizes of potential adaptations are not possible. A systematic analyses of the existing scientific literature in this regard is missing to date.

From a practical perspective, improvements of neuromuscular performance are relevant regarding sport-specific performance (Lesinski et al., 2015; Granacher et al., 2016). In consequence, performance improvements can be a relevant argument—next to the injury prevention perspective—to convince coaches and athletes to implement IPP in their training routine. As deficits in neuromuscular control are considered relevant risk factors for injuries to the lower limbs (Bahr and Holme, 2003; Meeuwisse et al., 2007; Alentorn-Geli et al., 2009; Frisch et al., 2009; Myer et al., 2011), data on adaptations in neuromuscular performance may additionally provide insights in mechanisms underlying the preventative efficacy of multimodal IPP. It can be further argued that the adaptive potential of athletes is limited at higher performance levels, as physical capacities are already well-developed. Therefore, it is of particular interest whether adaptations to prevention programs designed for a large mass of mainly recreational-level children and adolescents can be transferred to high-level youth athletes. Moreover, there is consistent evidence that age and sex affect injury risk (Emery, 2003; Frisch et al., 2009; Faude et al., 2013) and that training dose determines the size of training adaptations to neuromuscular training programs (Lesinski et al., 2015, 2016).

The aims of our systematic review with meta-analysis were: (a) To summarize the scientific literature on neuromuscular performance adaptations resulting from multimodal IPP in organized child and adolescent sport, (b) to quantify the effect sizes of adaptations in neuromuscular performance measures, and (c) to perform sub-group analyses in order to evaluate potential influences of performance level, sex, age-group, training volume, and potential differences between specific IPP. We hypothesized that multimodal, neuromuscular IPP can improve several neuromuscular performance parameters and that these effects were greater in low-level as compared to high-level youth athletes.

METHODS

We conducted and reported this systematic review in accordance with the Preferred Reporting Items for Systematic Reviews

and Meta-Analyses (PRISMA) statement (Moher et al., 2009). The study has been a priori registered in PROSPERO (CRD42016053407). In contrast to the primary registration, we extended the age-range of includable youth athletes from 18 to a maximum of 20 years of age, as we noticed during the literature search process that a part of the athletes, particularly at the highest performance level, competing in the oldest youth age groups are older than 18 years and we aimed to present a comprehensive overview in organized youth sports.

Literature Search

A systematic literature search was conducted independently by two researchers (OF, LD) until May 8th, 2017 in the following electronic databases: PubMed, Web of Science, EMBASE, CINAHL, and SCOPUS. The search strategy was adopted using the PICOS (population, intervention, comparison, outcome, study design) approach. Selected search terms related to youth sports, injury prevention, and neuromuscular performance were combined in Boolean logic. No restriction with regard to publication date was applied. Only full-text articles written in English language were considered. Our search strategy is described in detail in Appendix 1 (Supplementary Material). In addition, we screened the reference lists of the selected articles as well as the authors' own bibliographies. Finally, we searched Google Scholar with the same search terms in order to control for potentially overseen relevant articles.

Eligibility Criteria and Study Selection

Inclusion criteria (according to the PICOS approach) were: (i) healthy participants, up to 20 years of age, who were involved in organized sport (club, high school, college, sports associations) (P), (ii) the study included an intervention arm performing a multimodal neuromuscular training program focusing on injury prevention (I) as well as a control arm following a common training or a sham treatment without a specific neuromuscular focus (C), (iii) at least one neuromuscular performance parameter (static or dynamic balance/stability, power, strength, sprint ability) was assessed (O), and (i) the study was designed as a (cluster-) RCT (S).

Exclusion criteria were: (i) any intervention outside organized sport (for instance, unorganized recreational or leisure time sport, physical education classes), (ii) any neuromuscular intervention without a specific injury prevention focus (e.g., general strength and conditioning programs focusing on performance enhancement), (iii) the control group performing another structured neuromuscular training program outside common training routine, and (iv) athletes suffering from systemic neurological or neuromuscular disease or disability or being injured or undergoing rehabilitation after injury. Studies were independently selected by two investigators (OF, LD). A final decision on eligibility was achieved by consensus.

Data Extraction and Outcome Parameters

Data extraction was independently performed by two investigators (OF, RoR). In case of discrepancies a third researcher (LD) was consulted. Relevant study information regarding author, year, number of participants, intervention (weeks, frequency, duration per session) and passive control condition were extracted and transferred to an excel spread sheet.

Main outcome parameters for this analysis were measures of neuromuscular performance, which have been associated with injury risk and/or which have been assumed to be associated with sport-specific performance. We analyzed parameters indicating balance/stability (sub-categories static and dynamic balance as well as dynamic stability, i.e., the ability to stabilize the center-of-pressure after a dynamic movement, e.g., a jump), leg power (basic and reactive vertical as well as horizontal jump performance), and strength (isokinetic hamstrings and quadriceps strength as well as strength ratios) as these measures might be related to injury risk (Lehr et al., 2017). In addition, we analyzed parameters related to sprint ability (basic straight sprint performance, acceleration, and change-in-direction speed) and sport-specific skills (here: soccer-specific skills like slalom dribbling and the wall-volley test). All analyzed parameters, the particular sub-categories as well as the specific tests, which were integrated in each sub-category, are presented in Appendix 2 (Supplementary Material). We purposely did not analyze potential anatomical or biomechanical risk factors for injuries, which are not directly related to sports performance (e.g., lower limb joint angles or moments or ground reaction forces). If more than one potential parameter for a particular sub-category was reported in a single study, we chose the following procedure for statistical analyses: (i) in case of two parameters (e.g., single leg stance with opened and closed eyes as an indicator of static balance performance) we used the one showing the smaller effect in order to arrive at a conservative estimate; (ii) in case of three parameters (e.g., if only the three reaching directions, but no average or composite score was reported in the Y-balance test) we used the reaching direction showing the medium effect for further analysis.

Means and standard deviations (SD) of pre- and post-tests were available in most studies and par for par extracted. In two studies (Vescovi and VanHeest, 2010; Reis et al., 2013), data were only available as graphs. In these two studies, means and SD were independently extracted from the figures by two investigators (OF, RoR) and the average value was used for further analysis. In three studies (Steffen et al., 2008, 2013; Zech et al., 2014), only pre-test values and change scores were available. In these cases, we calculated the post-test mean by adding the change score to the pre-test mean and used the pre-test SD for statistical analysis.

Risk of Bias Assessment

The methodological quality of the included RCTs was rated using the PEDro scale. This scale comprises 11 dichotomous items (either yes or no). Studies were rated by two reviewers independently (LD and OF). After completing the evaluation, both examiners came to a consensus on every item. The raters were not blinded to study authors, place of publication, and results.

In order to examine a potential publication bias, we performed a risk-of-bias related sensitivity analysis between "weak" (score 5 and 6 on PEDro scale) and "strong" (score 7 on PEDro

scale) studies for all main outcome parameters. Furthermore, we conducted a qualitative funnel plot evaluation.

Meta-Analysis

We conducted a quantitative synthesis of the included studies. We calculated the sample size adjusted standardized mean differences [Hedges' g with 95% confidence intervals (CI)] from pre- to post-test for each variable and for each study arm. The difference of the target outcome between the intervention and the respective control group including the pooled standard deviations was computed. Negative effects in favor of the control arm were symbolized with a minus sign. As we analyzed studies, which were basically different in many ways (e.g., regarding participants, interventions, researchers, etc.), data were analyzed using an inverse-variance model with random effects (Borenstein et al., 2010; Deeks and Higgins, 2010). We used the Cochrane Review Manager Software (RevMan 5.3, Cochrane Collaboration, Oxford, UK) for statistical analyses. Forest plots with 95% CI were created. The magnitude of g was classified according to the following scale: 0–0.19 = negligible effect, 0.20–0.49 = small effect, 0.50–0.79 = moderate effect and ≥0.80 = large effect (Cohen, 1988).

Subgroup and Exploratory Analyses

We conducted a subgroup analysis with regard to different performance levels of participants. Thereby, performance level was classified as high, if it was explicitly stated that players competed on the highest youth level in the corresponding age group or on national level and that athletes trained three or more times per week with additional competitions at the weekend. Performance level was classified as low, if most players competed on a sub-elite level or that they trained maximally two times per week. Further exploratory analyses referred to potential differences related to sex, the effects of a particular IPP, age-group, and the number of overall training sessions. Age-group was analyzed by comparing studies, which investigated participants being 14 years or younger, with studies investigating participants being older than 14 years of age. This cut-off was chosen based on the available studies in order to arrive at two distinct age-groups. Studies with overlapping age ranges were not considered in this analyses. For the analysis regarding the overall training sessions, we divided the study sample according to the median split technique. All meta-analytical subgroup and exploratory analyses were only conducted, if at least two data points were available (Valentine et al., 2010). In all exploratory analyses, we carefully rated effects being different as indicated by a qualitative analysis of the change magnitude (i.e., effects being small, moderate, or large).

RESULTS

Trial Flow

In total, 12,113 potentially relevant articles were initially found (**Figure 1**). After removing duplicates, 9,976 article titles and abstracts were carefully screened for relevance. The full-texts of the remaining 100 potentially relevant articles were thoroughly studied and 82 papers were excluded as not meeting the inclusion or fulfilling the exclusion criteria.

Study Characteristics

In total, data from 14 different RCTs (comprising 704 participants) published in 18 different scientific articles were finally included in the quantitative meta-analysis (**Table 1**). All studies were published in 2008 or later. Seventy-one percent of all comparisons analyzed soccer players with basketball, field hockey, futsal, Gaelic football, and hurling being the remaining sports. The average age of the study populations ranged from 10 years up to 19 years and the level of play from low amateur to professional. Intervention duration ranged from 4 weeks to 4.5 months with a total of 12 to maximal 57 training sessions.

Four studies were classified as high-level (Steffen et al., 2008; Daneshjoo et al., 2012a,b, 2013; Heleno et al., 2016; Ayala et al., 2017), eight as low-level (Kilding et al., 2008; DiStefano et al., 2010; Vescovi and VanHeest, 2010; Lindblom et al., 2012; Reis et al., 2013; Steffen et al., 2013; Zech et al., 2014; Rössler et al., 2016) and in two studies (Lim et al., 2009; O'Malley et al., 2017) the performance level could not be definitely estimated and, thus, these studies were not included in this particular sub-analysis.

Eight studies reported data on boys only (Kilding et al., 2008; Daneshjoo et al., 2012a,b, 2013; Reis et al., 2013; Zech et al., 2014; Heleno et al., 2016; Rössler et al., 2016; Ayala et al., 2017; O'Malley et al., 2017) and five studies on girls only (Steffen et al., 2008, 2013; Lim et al., 2009; Vescovi and VanHeest, 2010; Lindblom et al., 2012).

The following IPP were analyzed in at least two studies (Valentine et al., 2010): "11+" (Daneshjoo et al., 2012a,b, 2013; Reis et al., 2013; Steffen et al., 2013; Ayala et al., 2017), "The 11" (Kilding et al., 2008; Steffen et al., 2008), "HarmoKnee" (Daneshjoo et al., 2012a,b, 2013; Ayala et al., 2017) or the "Prevent Injury Enhance Performance" program (PEP or a modified version; Lim et al., 2009; DiStefano et al., 2010; Vescovi and VanHeest, 2010). Further programs used either a combination of exercises extracted from these established programs (Zech et al., 2014; O'Malley et al., 2017), adapted versions for younger children (DiStefano et al., 2010; Rössler et al., 2014) or applied sensorimotor training combined with plyometrics (Heleno et al., 2016).

Three studies analyzed participants being 14 years or younger (Kilding et al., 2008; DiStefano et al., 2010; Rössler et al., 2016) and in six studies athletes were 15 years or older (Steffen et al., 2008; Lim et al., 2009; Daneshjoo et al., 2012a,b, 2013; Reis et al., 2013; Ayala et al., 2017; O'Malley et al., 2017).

Seven studies had a large (>23 sessions; Kilding et al., 2008; Steffen et al., 2008, 2013; DiStefano et al., 2010; Vescovi and VanHeest, 2010; Daneshjoo et al., 2012a,b, 2013; Reis et al., 2013) and the remaining studies a low (<23 sessions; Lindblom et al., 2012; Zech et al., 2014; Heleno et al., 2016; Rössler et al., 2016; Ayala et al., 2017; O'Malley et al., 2017) number of training sessions during the study period.

Risk of Bias

The funnel plot evaluation (Appendix 3 in Supplementary Material) showed no obvious risk of bias in balance/stability,

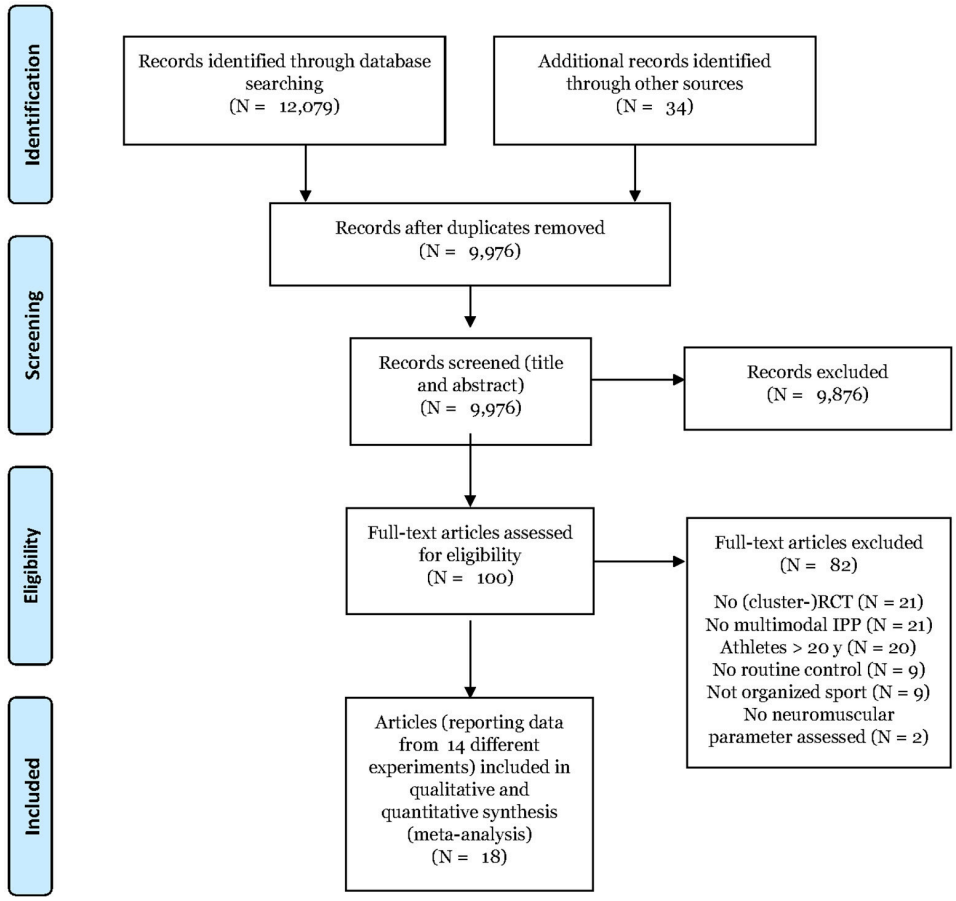


FIGURE 1 | PRISMA flow diagram.

leg power, and strength measures. In sprint abilities and sport-specific tests a slight overrepresentation of small studies with large effects seems apparent.

The results of the study quality assessment are presented in Appendix 4 (Supplementary Material). Seven studies obtained the PEDro score 7 (Steffen et al., 2008; DiStefano et al., 2010; Zech et al., 2014; Heleno et al., 2016; Rössler et al., 2016; Ayala et al., 2017; O'Malley et al., 2017), six studies a score of 6 (Kilding et al., 2008; Lim et al., 2009; Vescovi and VanHeest, 2010; Daneshjoo et al., 2012a,b, 2013; Lindblom et al., 2012; Reis et al., 2013) and one study was rated as PEDro 5 (Steffen et al., 2013).

When comparing studies, which were rated as PEDro 7, with all other studies, we observed no relevant differences between "strong" and "weak" studies in balance/stability, leg power, and sprint abilities, whereas effects were larger in the "weak" studies for isokinetic strength and sport-specific tests (Appendix 5 in Supplementary Material). However, the latter analyses were based on merely two "strong" studies (Steffen et al., 2008; Rössler et al., 2016).

Main Analysis—Intervention Effects

We observed a small overall effect in favor of IPP for balance/stability outcomes including static and dynamic balance measures [g = 0.37 (95%CI 0.17, 0.58); **Figure 2**]. For dynamic stability measures we found a moderate effect (g = 0.72), but CI overlap zero. Similarly, a small overall effect was present for leg power outcomes [g = 0.22 (95%CI 0.07, 0.38); **Figure 3**], particularly for basic (g = 0.31) and reactive power (g = 0.29) parameters, but not for horizontal power (g = 0.04). Further, we found small to moderate effects for isokinetic hamstrings (g = 0.56) and quadriceps strength (g = 0.49) as well as for hamstrings-to-quadriceps ratio (g = 0.40) at low movement speed (60° per second), but not at fast movement speed (240° per second; g = 0.13 to 0.31; **Figure 4**).

We observed a large overall effect for sprint abilities [g = 0.80 (95%CI 0.50, 1.09); **Figure 5**], which was particularly present in acceleration (g = 0.92) and change-in-direction speed (g = 0.88). Basic speed abilities were moderately improved (g = 0.66). With regard to sport-specific skills (here: soccer-specific) we found a moderate effect for slalom dribbling (g = 0.54) and a large effect for the wall-volley test (g = 1.46) with CI including the zero (**Figure 6**).

Subgroup and Exploratory Analyses

Table 2 displays the effects for the different levels of play. We found consistently larger effects in the high-level group

TABLE 1 | Characteristics of included studies.

Study; publication date; country	Design	Participants (analyzed); sport; age; level of play	Parameters (included in quantitative analyses)	Intervention
Ayala et al., 2017 Spain	RCT	*N* = 40 male soccer players; 16.8 (SD 0.7) y; first national juvenile league	Y-balance test; 10 and 20 m sprint; Drop jump; Illinois agility test	"11+" vs. Harmoknee vs. control; 4 weeks, 3 × per week (max. 12 sessions)
Daneshjoo et al., 2012a,b, 2013 Iran	RCT	*N* = 36 male soccer players; 17 to 20 y; professional level (daily training)	Isokinetic hamstring and quadriceps strength (ratios); Single leg stance; Star excursion balance test; 20 m sprint; Squat jump; Illinois agility test; Wall-volley test; Slalom dribble	"11+" vs. Harmoknee vs. control; 8 weeks, 3 × per week (max. 24 sessions)
DiStefano et al., 2010 USA	Cluster-RCT	*N* = 65 soccer players (*N* = 39 boys; *N* = 28 girls); 10 (SD 1) y; local soccer association	Time-to-stabilization; Countermovement jump	Pediatric vs. traditional IPP (PEP) vs. control; 9 weeks, 3 × per week (max. 27 sessions)
Heleno et al., 2016 Brazil	RCT	*N* = 22 male soccer players; 14 to 16 y; State and national competitions (5 training sessions per week)	Y-balance test; Single leg stance	Sensorimotor + plyometric IPP vs. control; 5 weeks, 3 × per week (max. 15 sessions)
Kilding et al., 2008 New Zealand	RCT	*N* = 24 male soccer players; 10.4 (SD 1.4) y; Local soccer club	Countermovement jump; 3-step jump; 20 m sprint; Illinois agility test	"The 11" vs. control; 6 weeks, 5 × per week (once per week supervised; max. 30 sessions)
Lim et al., 2009 Korea	RCT	*N* = 22 female basketball players; 15 to 17 y; Highschool basketball	Countermovement jump	Modified PEP vs. control; 8 weeks, frequency n.a.
Lindblom et al., 2012 Sweden	Cluster-RCT	*N* = 41 female soccer players; 12 to 16 y; Local soccer clubs (2 training sessions per week)	Star excursion balance test; Countermovement jump; 3-step jump; 10 and 20 m sprint; Modified Illinois agility test	Knäkontroll vs. control; 11 weeks, 2 × per week (max. 22 sessions)
O'Malley et al., 2017 Ireland	Cluster-RCT	*N* = 56 male Gaelic football and hurling players; 18.1 to 18.8 y; First year collegiate level	Y-balance test	"GAA 15" vs. control; 8 weeks, 2 × per week (max. 16 sessions)
Reis et al., 2013 Portugal	RCT	*N* = 36 male futsal players; 17.3 (SD 0.7) y; 5.8 h futsal activity per week	Isokinetic hamstring and quadriceps strength (ratios); 5 and 30 m sprint; T-test; Countermovement jump; Single leg stance; Slalom dribble	"11+" vs. control; 12 weeks, 2 × per week (max. 24 sessions)
Rössler et al., 2016 Switzerland	Cluster-RCT	*N* = 122 male soccer players; 7 to 13 y; 2 training sessions per week	Single leg stance; Y-balance test; Drop and countermovement jump; Standing long jump; 20 m sprint; Agility parcours; Slalom dribble; Wall-volley test	"11+ Kids" vs. control (sham treatment); 10 weeks, 2 × pre week (max. 20 sessions)
Steffen et al., 2008 Norway	RCT	*N* = 31 female soccer players; 17.1 (SD 0.8) y; Elite sport high schools, competitive level (13.3 h soccer activities per week)	Isokinetic and isometric hamstring and quadriceps strength (ratios); Drop and countermovement jump; 40 m sprint; Slalom dribble	"The 11" vs. control; 10 weeks, 3 × per week (max. 30 sessions)

(Continued)

TABLE 1 | Continued

Study; publication date; country	Design	Participants (analyzed); sport; age; level of play	Parameters (included in quantitative analyses)	Intervention
Steffen et al., 2013 Canada	Cluster-RCT	*N* = 148 female soccer players; 13 to 18 y; Minor and youth soccer associations, 3 highest levels	Single leg stance; 3-step jump; Y-balance test	Regular "11+" vs. control; 4.5 months; 2–3 × per week (max. 57 sessions)
Vescovi and VanHeest, 2010 USA	Cluster-RCT	*N* = 31 female soccer players; 13 to 18 y; Local soccer community (3 training sessions per week)	9.1, 18.3, 27.4 and 36.6 m sprint; Countermovement jump; Modified Illinois agility test	PEP vs. control; 12 weeks, 3 × per week (max. 36 sessions)
Zech et al., 2014 Germany	RCT	*N* = 30 male field hockey players; 14.9 (SD 3) y; Highest regional youth division (2 training sessions per week)	Y-balance test; Time-to-stabilization	Neuromuscular IPP vs. control; 10 weeks, 2 × per week (max. 20 sessions)

SD, standard deviation; RCT, randomized controlled trial; IPP, injury prevention program; PEP, prevent injuries enhance performance.

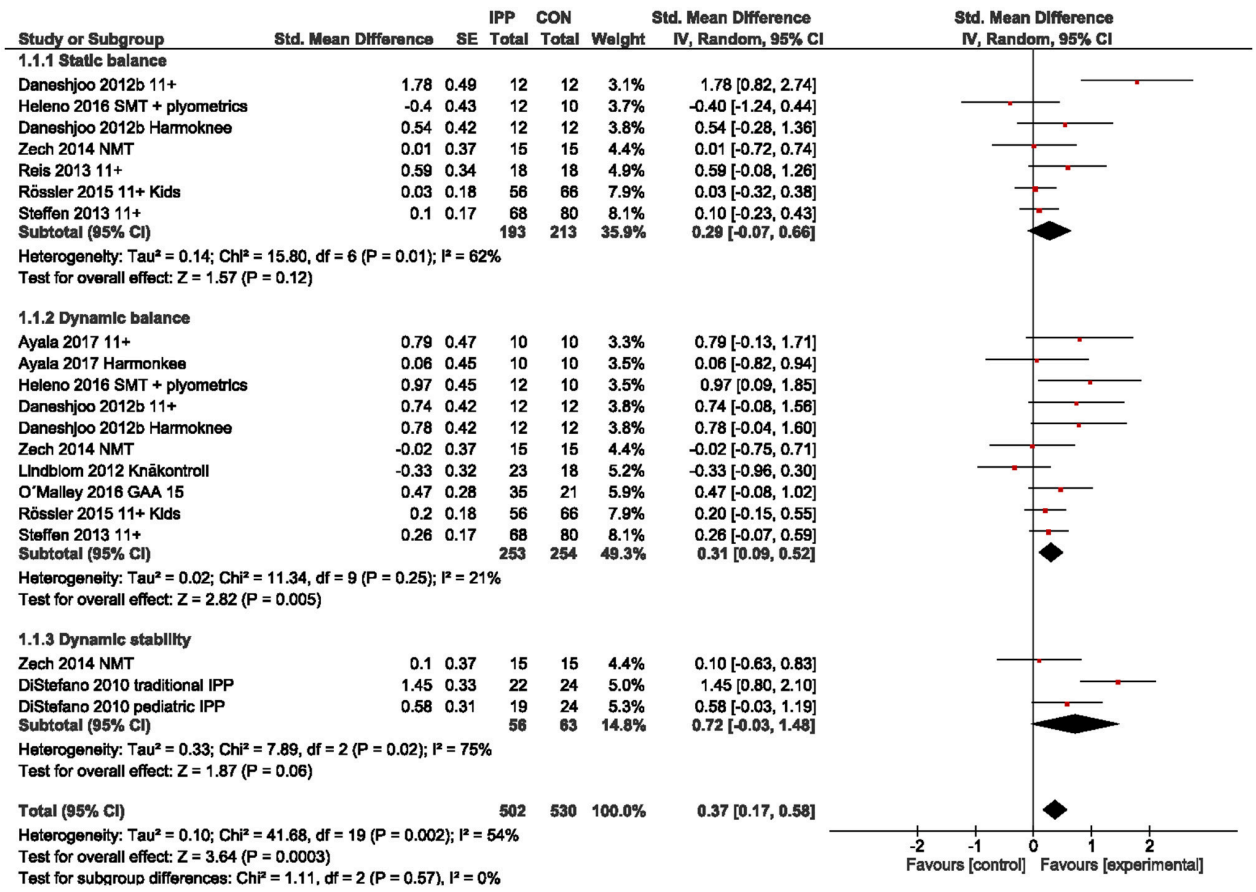


FIGURE 2 | Standardized mean effects of injury prevention programs (IPP) on balance and stability parameters as compared to a control (CON) group. Data are separately presented for static and dynamic balance as well as dynamic stability measures. SE, standard error; IV, inverse variance model; CI, confidence interval; SMT, sensorimotor training; NMT, neuromuscular training.

(g = 0.34–1.18) compared to the low level group (g = 0.22–0.75), with large effects in sprint abilities and sport-specific tests and moderate effects in balance/stability measures. The low-level group showed small to moderate effects in all categories. However, CI largely overlapped.

Boys showed small to moderate effects for balance/stability, leg strength and power, whereas girls showed negligible to small effects (**Table 3**). Particularly for sprint abilities, we found large effects in boys. With regard to the different IPP, we found small to moderate effects for "11+" and "HarmoKnee" in balance/stability

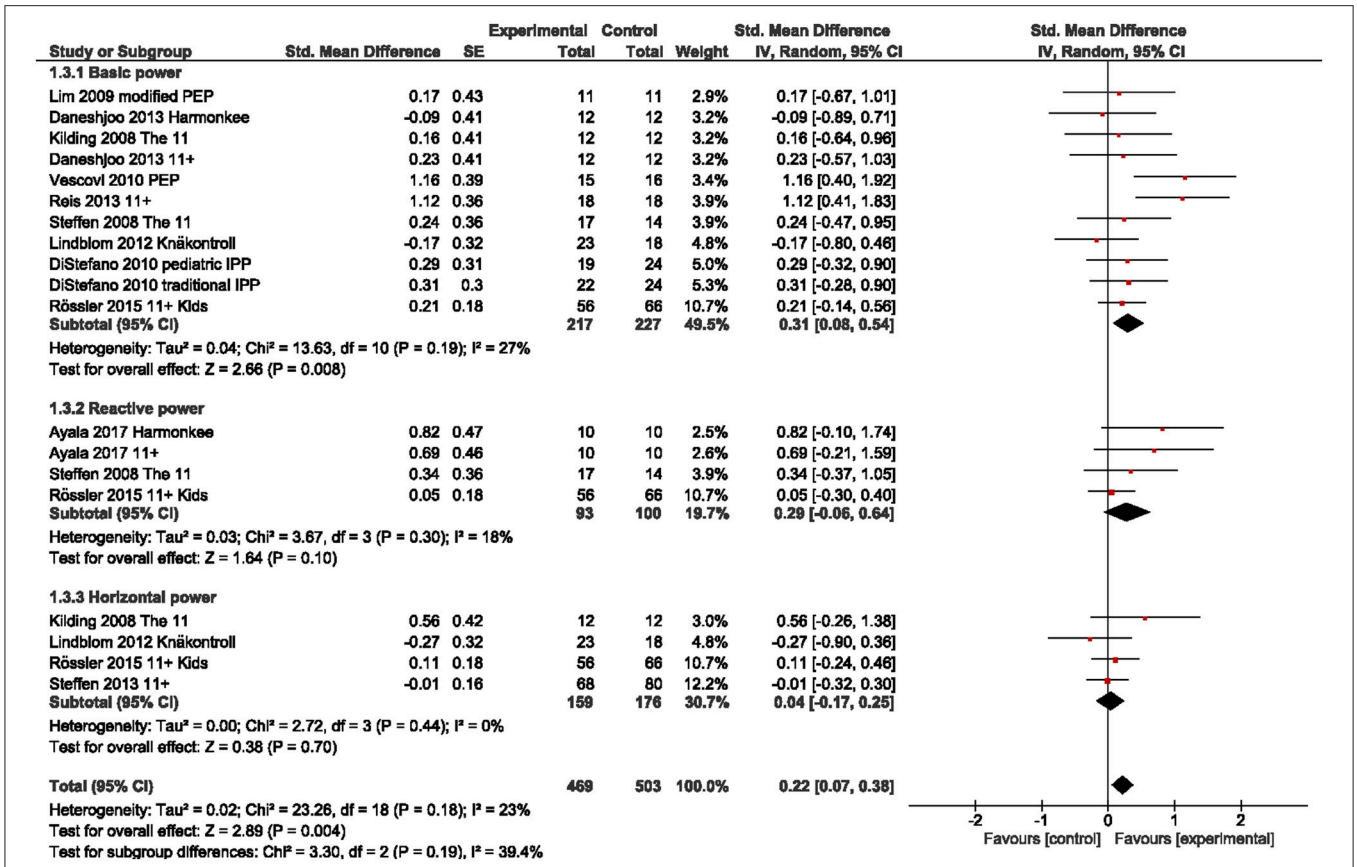


FIGURE 3 | Standardized mean effects of injury prevention programs (IPP) on leg power parameters as compared to a control (CON) group. Data are separately presented for basic, reactive and horizontal power measures. SE, standard error; IV, inverse variance model; CI, confidence interval; PEP, Prevent Injury Enhance Performance.

as well as leg power and strength parameters and large effects for sprint abilities and sport-specific skills for these IPP (**Table 4**). PEP showed moderate effects for leg power and sprint abilities. The effects for "The 11" were negligible to small. While we observed similar moderate effects in balance/stability measures in both the younger and older age-group, the older athletes showed a large effect in sprint abilities (**Table 5**). The studies with <23 training sessions showed in all categories negligible to small effects, whereas those studies with more than 23 sessions showed a small effect in leg power, a moderate effect in balance/stability and large effects in sprint abilities and sport-specific skills (**Table 6**).

DISCUSSION

The main aim of present meta-analysis was to summarize the scientific literature on neuromuscular performance adaptations resulting from multimodal IPP in organized child and adolescent sport and to quantify the effect sizes of adaptations in various neuromuscular performance measures. Furthermore, we performed subgroup analyses regarding potential differences in adaptations between performance levels, sex, age-groups, specific IPP, and number of training sessions.

Key Results

With regard to our main study question we found that multimodal IPP improved several neuromuscular performance measures. We observed small effects for balance/stability measures as well as leg power and a medium effect for isokinetic leg strength at low movement velocities. For sprint abilities and sport-specific tests we found large effects.

Regarding subgroup and exploratory analyses, we obtained slightly larger effects in athletes of a higher performance level. There were differences in adaptations between different IPP, greater adaptations in boys, older players and in studies with higher number of training sessions during the study period.

Overall Interpretation and Generalizability

Neuromuscular deficits, for instance regarding balance, stability, leg power, and leg strength, are considered potential intrinsic risk factors for injuries (Meeuwisse, 1994; Bahr and Holme, 2003; Myer et al., 2011; Lehr et al., 2017). These risk factors are modifiable by appropriate neuromuscular training regimens (Alentorn-Geli et al., 2009; Myer et al., 2011; Bizzini and Dvorak, 2015). IPP, which have been shown to reduce injuries, target these risk factors within a multimodal training approach (Mandelbaum et al., 2005; Soligard et al., 2008; Kiani et al., 2010; Walden

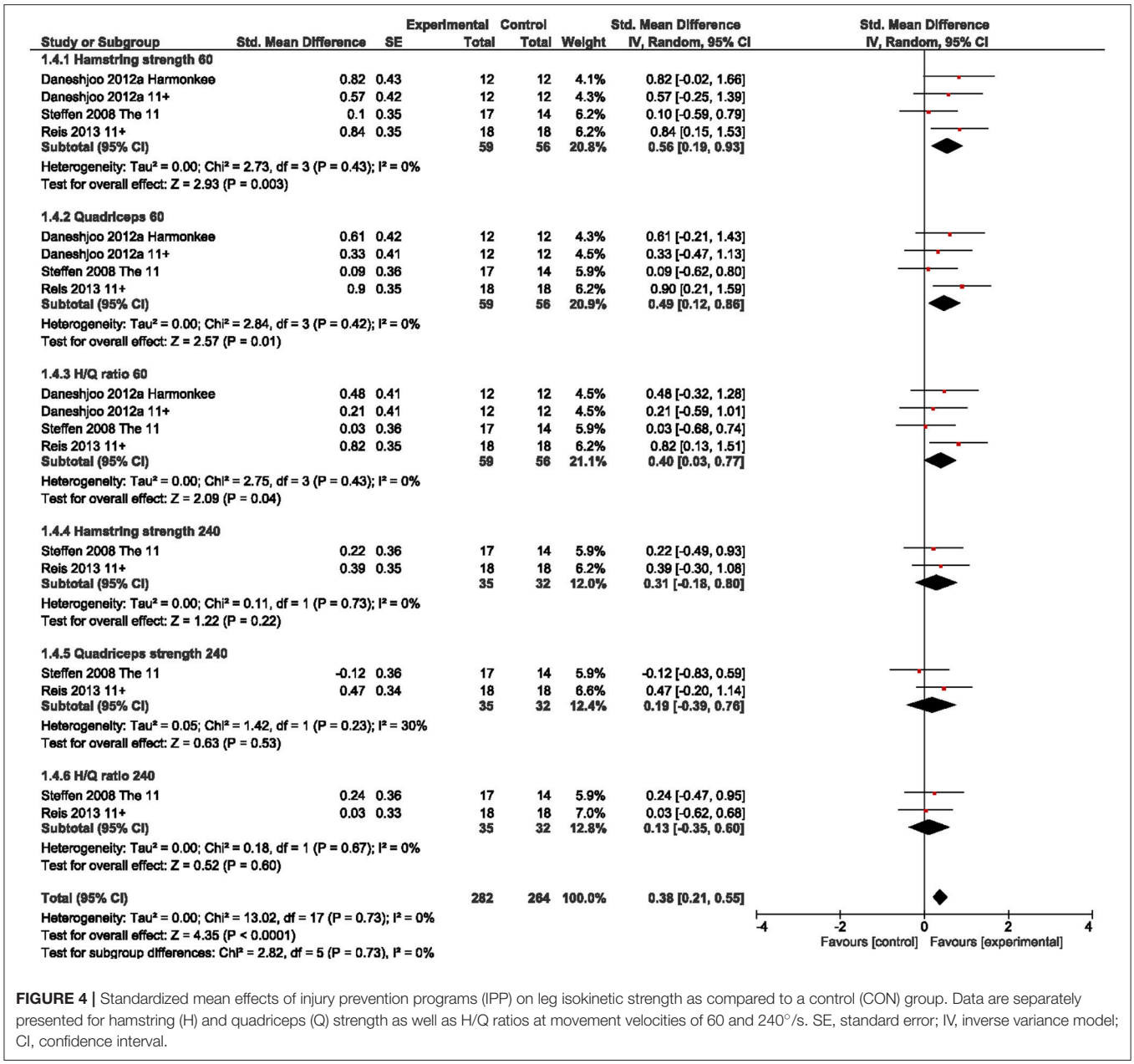


FIGURE 4 | Standardized mean effects of injury prevention programs (IPP) on leg isokinetic strength as compared to a control (CON) group. Data are separately presented for hamstring (H) and quadriceps (Q) strength as well as H/Q ratios at movement velocities of 60 and 240°/s. SE, standard error; IV, inverse variance model; CI, confidence interval.

et al., 2012). Our analysis showed that parameters in relevant neuromuscular domains, such as, balance, postural stability, or leg strength and power, notably benefit from IPP. Effects were, however, small to moderate. It can be speculated, that small effects may be sufficient to relevantly reduce the risk for injury, particularly, as small effects in different domains (e.g., power, strength, balance) may act synergistically (Myer et al., 2005). For instance, an improvement of neuromuscular joint control, e.g., resulting from slightly improved balance and an increased strength of thigh musculature, may reduce forces and moments on muscles and ligaments in situations with high biomechanical loads (e.g., cutting maneuvers) sufficiently in order to avoid traumatic events. Interestingly, time-to-stabilization after single leg landing as an indicator of the ability to stabilize the body in a dynamic situation showed a large effect. As time-to-stabilization was assessed in only two studies (DiStefano et al., 2010; Zech et al., 2014), the confidence interval slightly overlapped the zero and the reliable assessment is methodologically and technically challenging, this result should be cautiously interpreted. However, it might be regarded as an interesting parameter for future injury prevention studies as exercises including one leg standing and landing situations are a main part of IPP. Similarly, we also found large improvements in agility tests. Such tests aim at rapid de- and accelerations while changing movement direction, i.e., the ability to stabilize the joints under large biomechanical loads. Such an ability may allow for an

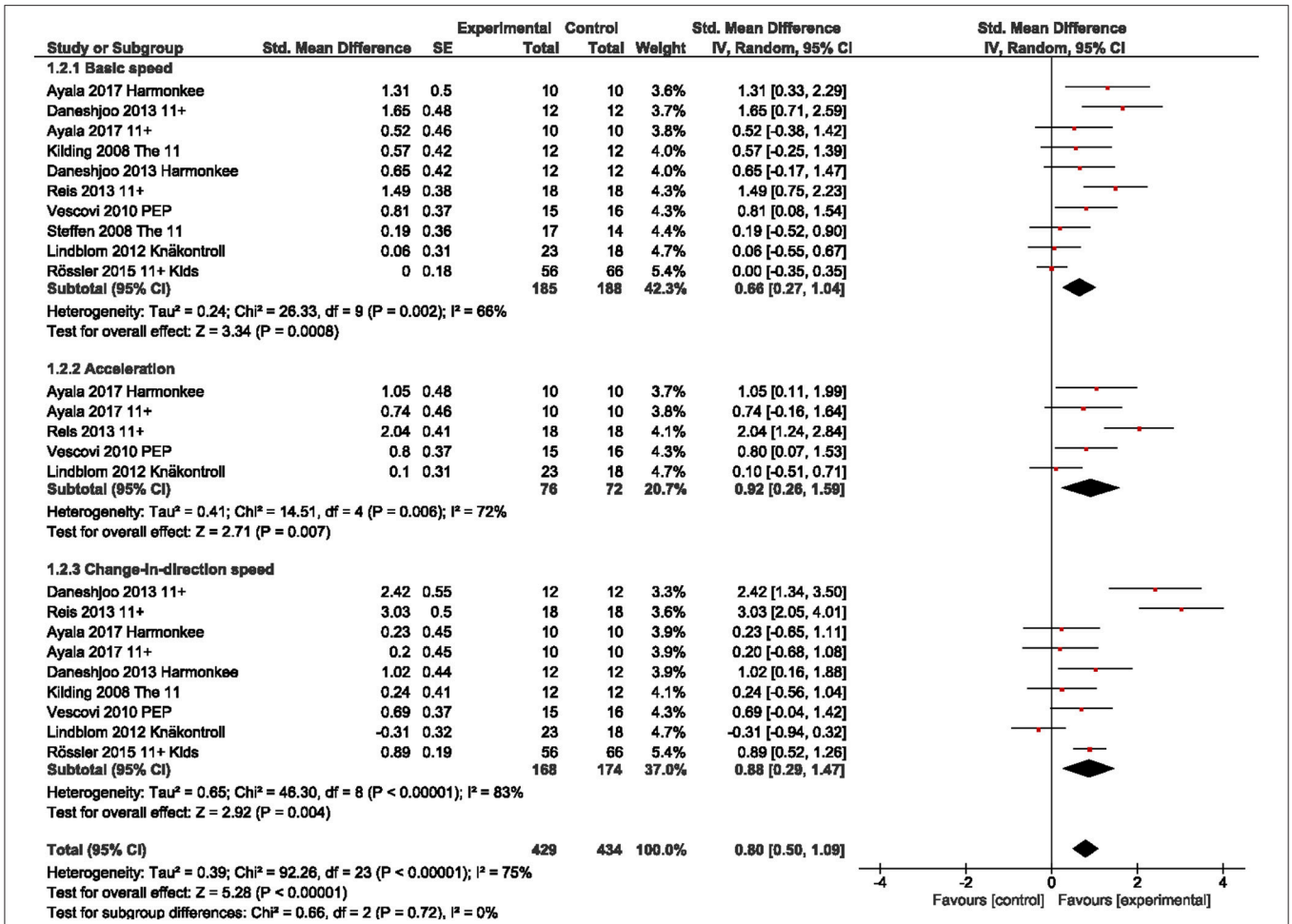


FIGURE 5 | Standardized mean effects of injury prevention programs (IPP) on sprint abilities as compared to a control (CON) group. Data are separately presented for basic speed, acceleration and change-in-direction speed. SE, standard error; IV, inverse variance model; CI, confidence interval; PEP, Prevent Injury Enhance Performance.

efficient transfer of forces and moments and, consequently, has high relevance for performance and likely also for the prevention of injuries.

In addition, we also observed large improvements in straight sprinting speed as well as in the ability to accelerate rapidly. Whereas, it is questionable whether straight sprinting is relevant from an injury prevention perspective, it is generally considered one of the most important physical abilities in team sports from a performance perspective. For instance, Faude et al. (2012) showed that straight sprinting is the most important powerful action preceding goal situations in professional soccer. Particularly, the "11+" program revealed large effects on sprint performance. This may be due to exercises such as, the Nordic hamstrings, plyometrics, or the bounding jumps. Evidence suggests that these exercises and, particularly, combinations of it can effectively improve sprinting abilities (Rumpf et al., 2016). As many coaches in team sports accentuate the development of sprinting speed, our findings may contribute to convincing coaches to implement IPP in their training routine.

Improvements in sport-specific tests like slalom dribbling or the wall-volley test may have a similar effect on coaches' willingness to implement IPP. The underlying reasons why athletes enhance their sport-specific skills through IPP is unclear. One might speculate that improved neuromuscular control during sport-specific skills may enable athletes to better and faster process the ball and, thus, have more attentional capacity to control movements. In this regard it is interesting to note that inappropriately developed sport-specific skills are also considered a potential intrinsic risk factor (Meeuwisse, 1994; Bahr and Holme, 2003). Therefore, the observed large improvements in sport-specific skills may contribute to a decreased injury risk.

IPP are frequently designed as warm-up programs lasting about 15–20 min. Bizzini et al. (2013) showed, for instance, that the "11+" fulfills the requirements of a warm-up program in soccer players. Furthermore, there is a large body of evidence that the "11+" program can reduce injury rate considerably (Barengo et al., 2014; Bizzini and Dvorak, 2015; Thorborg et al., 2017).

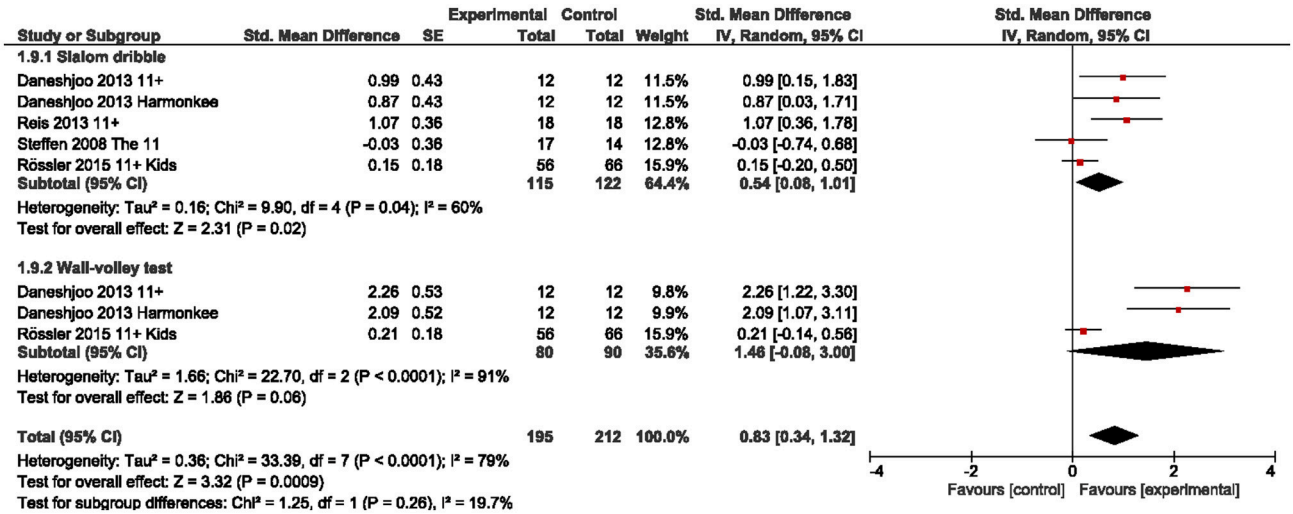


FIGURE 6 | Standardized mean effects of injury prevention programs (IPP) on sport-specific skills as compared to a control (CON) group. Data are separately presented for slalom dribbling and the wall-volley test. SE, standard error; IV, inverse variance model; CI, confidence interval.

TABLE 2 | Training adaptations (pooled standardized mean differences with 95% confidence intervals; qualitative assessment of effect magnitude) for high- vs. low-level players.

	High-level players	Low-level players
Balance/stability	**0.64** (95% CI 0.21,1.07); **moderate**	0.25 (95% CI 0.02,0.47); small
Leg power	**0.34** (95% CI 0.01,0.66); **small**	0.22 (95% CI 0.02,0.42); small
Sprint abilities	**0.86** (95% CI 0.47,1.24); **large**	0.75 (95% CI 0.33,1.17); moderate
Sport-specific tests	**1.18** (95% CI 0.34,2.02); **large**	0.37 (95% CI −0.05,0.79); small

Bold values indicate larger effects for the corresponding measure.

TABLE 3 | Training adaptations (pooled standardized mean differences with 95% confidence intervals; qualitative assessment of effect magnitude) between sexes.

	Girls	Boys
Balance/stability	**0.38** (95% CI −0.07,0.84); **small**	0.37 (95% CI 0.14,0.60); small
Leg power	0.15 (95% CI −0.16,0.46); negligible	**0.27** (95% CI 0.07,0.48); **small**
Isokinetic leg strength	0.09 (95% CI −0.19,0.38); negligible	**0.54** (95% CI 0.32,0.75); **moderate**
Sprint abilities	0.30 (95% CI–0.02,0.62); small	**1.02** (95% CI 0.64,1.40); **large**
Sport-specific tests	–	0.97 (95% CI 0.42,1.51); large

Bold values indicate larger effects for the corresponding measure.

Taken this evidence together, appropriately designed IPP lasting only 15–20 min per session can serve as appropriate warm-up programs. Thereby, these programs are able to improve potential risk factors for injury as well as performance indicators and, simultaneously, to reduce injury rate. This might be a strong point toward a broad implementation of such programs in sports practice.

An interesting finding was that high-level players showed slightly larger effects compared to low-level players. Intuitively, one would assume that the adaptive potential in low-level players is greater and, consequently, adaptations in these players should have been larger. In high-level players a ceiling effect in training adaptability seems reasonable as the stimuli provided by IPP may not be appropriate to induce further improvements. Our results are contradictory to these assumptions. We cannot definitely conclude on the underlying reasons for this finding. It might be speculated that in the high-level teams the coaching staff is better qualified and, thus, the training stimulus was applied in a more appropriate or suitable manner. In contrast, coaches on lower levels of play are frequently not appropriately qualified and, hence, it might be more difficult for them to instruct a correct execution of exercises for the sake of an adequate training stimulus. However, the results should be carefully interpreted as CI were wide and overlapping. Therefore, future research seems necessary.

We found also larger effects in older players as compared to their younger counterparts. This result might be related to the differences in adaptations with different playing levels as the high-level players were older (14–20 years) than the low-level players (7–18 years). Therefore, we cannot definitely distinguish between both factors. Age has been consistently shown to be an important non-modifiable risk factor for injuries (Emery, 2003). Thus, the observed adaptations in the older players might be particularly relevant from an injury prevention perspective.

We obtained larger effects in boys than in girls, particularly, in isokinetic leg strength and sprint abilities. The performance

TABLE 4 | Training adaptations (pooled standardized mean differences with 95% confidence intervals; qualitative assessment of effect magnitude) for the different injury prevention programs.

	"11+"	"The 11"	HarmoKnee	PEP
Balance/stability	**0.55** (95% CI 0.17,0.94); **moderate**	–	0.48 (95% CI −0.01,0.96); small	–
Leg power	0.45 (95% CI −0.12,1.02); small	0.32 (95% CI −0.06,0.69); small	0.34 (95% CI −0.55,1.23); small	**0.54** (95% CI −0.04,1.12); **moderate**
Isokinetic leg strength	0.51 (95% CI 0.27,0.75); moderate	0.09 (95% CI −0.19,0.38); negligible	**0.63** (95% CI 0.16,1.11); **moderate**	–
Sprint abilities	**1.49** (95% CI 0.84,2.14); **large**	0.03 (95% CI −0.13,0.76); negligible	0.82 (95% CI 0.43,1.22); large	0.77 (95% CI 0.35,1.19); moderate
Sport-specific tests	1.37 (95% CI 0.65,2.08); large	–	**1.44** (95% CI 0.25,2.64); **large**	–

Bold values indicate the largest effect for the corresponding measure. PEP, prevent injury enhance performance.

TABLE 5 | Training adaptations (pooled standardized mean differences with 95% confidence intervals; qualitative assessment of effect magnitude) between young and old players.

	Players < 15 years	Players ≥ 15 years
Balance/stability	0.51 (95% CI −0.02,1.03); moderate	**0.66** (95% CI 0.37,0.95); **moderate**
Leg power	0.18 (95% CI 0.00,0.35); negligible	**0.32** (95% CI 0.05,0.60); **small**
Sprint abilities	0.43 (95% CI −0.10,0.95); small	**1.16** (95% CI 0.72,1.60); **large**
Sport-specific tests	0.18 (95% CI −0.07,0.43); negligible	**1.15** (95% CI 0.49,1.81); **large**

Bold values indicate larger effects for the corresponding measure.

TABLE 6 | Training adaptations (pooled standardized mean differences with 95% confidence intervals; qualitative assessment of effect magnitude) relative to the total number of training sessions.

	<23 Training sessions	>23 Training sessions
Balance/Stability	0.14 (95% CI −0.05,0.33); negligible	**0.67** (95% CI 0.33,1.01); **moderate**
Leg power	0.12 (95% CI −0.07,0.31); negligible	**0.35** (95% CI 0.10,0.59); **small**
Sprint abilities	0.38 (95% CI 0.07,0.69); small	**1.16** (95% CI 0.72,1.59); **large**
Sport-specific tests	0.18 (95% CI −0.07,0.43); negligible	**1.15** (95% CI 0.49,1.81); **large**

Bold values indicate larger effects for the corresponding measure.

effects in girls were negligible to small. A recent meta-analysis (Rössler et al., 2014) has shown that IPP are efficacious in organized youth sports in both sexes. Based on our results we cannot conclude on possible mechanisms for this finding. Faude et al. (2013) reported that joint-ligament injuries (sprains), particularly knee sprains, are more frequent in girls compared to boys in youth soccer. Thus, injury prevention studies in female youth sports often focus on knee injuries, whereas this is not the case in studies on boys (Rössler et al., 2014). One might speculate that anatomical and biomechanical risk factors (leg alignment, knee valgus moments, knee internal rotation, cutting task biomechanics, etc.) contribute more to the risk for knee injuries and, consequently, are more important regarding injury prevention in females. There is evidence that such biomechanical risk factors are also modifiable by IPP (Pappas et al., 2015). Future research regarding sex-specific training adaptations is warranted.

When comparing the different IPP it is obvious that the performance effects were comparable between the "11+," the "HarmoKnee" and the PEP program. The effects of the "The 11," the predecessor of the "11+," were considerably smaller. This finding is in line with meta-analytical data showing that the application of "11+" resulted in large reductions in injury incidence, whereas the preventative efficacy of "The 11" could not be substantiated (Al Attar et al., 2016; Thorborg et al., 2017).

Regarding the total number of training sessions our results clearly demonstrate that the effect is larger as with a greater total training volume. Thus, it is advisable to conduct IPP over a longer period of time in order to increase efficacy. This finding strengthens the results of Sugimoto et al. (2014) showing that there is a relationship between dosage and ACL injury reduction in female athletes. Similarly, Lesinski et al. (2015) showed that strength training adaptations in youth athletes are larger when training duration exceeded 23 weeks emphasizing the relevance of longer training durations. There is also evidence that training compliance had a relevant effect on program efficacy (Sugimoto et al., 2012). Similarly, Steffen et al. (2013) showed that a high compliance to the "11+" program resulted in improvements in functional balance and a reduced injury risk. Currently, it is recommended to perform the program at least 1.5 times per week in order to optimize training effectiveness (Barengo et al., 2014). These recommendations were exceeded by all studies included in our analyses. Information on the compliance in the included studies was limited. Thus, we cannot conclude on the influence of compliance on our results. It has to be mentioned that the evidence on the appropriate training frequency is currently limited.

Methodological Considerations

Within the present meta-analysis, we focused on (cluster-) RCTs published in peer-reviewed scientific journals. All studies were of sufficient to high methodological quality (PEDro score $\geq$ 5). Thus, the present results are based on high-quality research. We did not include non-randomized studies or gray literature, thus, accepting the potential for a publication bias. However, a risk of bias analysis did only show a slight risk for the sprint and sport-specific test categories. We analyzed studies, which used evidence-based IPP or blends of such programs. Studies applying other neuromuscular or strength and conditioning programs focusing on performance improvements and not on injury prevention were not analyzed, although such programs also have the potential to reduce injury risk in youth sport (Myer et al., 2011; Granacher et al., 2016). Most studies in our analysis were conducted in soccer. Evidence in other sports and the transferability of our results is, therefore, currently limited. Finally, it has to be mentioned that the statistical power of our analyses was low for some subgroup and exploratory analyses. As CI were large and overlapping, these results should be carefully interpreted. Also, the separation of age-groups in being older and younger than 14 years of age was due to practicality. It would have been better to apply a measure of maturational status, but such information was not available.

CONCLUSIONS, PRACTICAL IMPLICATIONS AND PERSPECTIVES

Multimodal IPP, which have been shown to reduce the risk of injury, improve several neuromuscular performance parameters, which have been associated with injury risk. Although effects were partly small, this may give an explanation for the preventative efficacy of these programs. The general improvements in neuromuscular performance may also support the wide-spread implementation and dissemination of IPP as performance improvements are a strong argument for coaches to use particular training programs. The implementation of IPP as a routine 15–20-min warm-up can effectively prepare for the following training session, can improve performance and reduce the risk of injury. The optimal IPP may fulfill the following requirements: (i) It should be effective with regard to injury prevention and performance enhancement; (ii) it should be efficient with regard to time and resources needed to apply the program; (iii) it should be feasible and practical; (iv) it should be specific, i.e., targeted with regard to the specific sport, age, sex ,and performance level.

Future research is needed to analyze which parts of multimodal programs are most effective. This may allow for optimizing existing programs or making them more efficacious and time efficient. Further, it may allow for adapting programs to other sports and settings. Furthermore, it seems warranted to adapt programs particularly for girls in order to improve performance parameters also in female youth athletes. Studies in younger children are underrepresented. Injury incidence in the youngest children is lower as compared to older athletes and injury characteristics partly differ (Faude et al., 2013). Only two studies used a program, which was specifically adapted for the youngest athletes. This is of particular interest as Myer et al. (2013) suggested to introduce prevention programs before the onset of neuromuscular deficits. Early preventive measures might be important as children make up a large part of the active population, as it may be of particular importance to prevent or at least delay the first injury and as it may support the sensitization of young athletes with injuries and appropriate preventive means.

AUTHOR CONTRIBUTIONS

OF had the idea, designed and conducted this meta-analysis. RoR, EP, RaR, LZ, and LD assisted in the design of this study. OF, LD, and RoR developed the search strategy. LD and OF conducted the literature search and the study quality assessment. RoR and OF extracted study information and outcome data. OF performed the statistical analyses and wrote the first paper draft. All authors revised the manuscript for important intellectual content and approved the final version of the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2017.00791/full#supplementary-material

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frontiers in Physiology

REVIEW
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Muscle Activation During ACL Injury Risk Movements in Young Female Athletes: A Narrative Review

Jesper Bencke[1], Per Aagaard[2] and Mette K. Zebis[3]*

[1] Human Movement Analysis Laboratory Section 247, Department of Orthopedic Surgery Section 333, Hvidovre Hospital, Copenhagen University Hospital at Amager-Hvidovre, Copenhagen, Denmark, [2] Department of Sports Science and Clinical Biomechanics, Research Unit for Muscle Physiology and Biomechanics, University of Southern Denmark, Odense, Denmark, [3] Department of Physiotherapy and Occupational Therapy, Faculty of Health and Technology, Metropolitan University College, Copenhagen, Denmark

Young, adolescent female athletes are at particular high risk of sustaining a non-contact anterior cruciate ligament (ACL) injury during sport. Through the last decades much attention has been directed toward various anatomical and biomechanical risk factors for non-contact ACL injury, and important information have been retrieved about the influence of external loading factors on ACL injury risk during given sports-specific movements. However, much less attention has been given to the aspect of neuromuscular control during such movements and only sparse knowledge exists on the specific muscle activation patterns involved during specific risk conditions. Therefore, the aim of this narrative review was (1) to describe anatomical aspects, strength aspects and biomechanical aspects relevant for the understanding of ACL non-contact injury mechanisms in young female athletes, and (2) to review the existing literature on lower limb muscle activation in relation to risk of non-contact ACL-injury and prevention of ACL injury in young female athletes. Studies investigating muscle activity patterns associated with sports-specific risk situations were identified, comprising cohort studies, intervention studies and prospective studies. Based on the retrieved studies, clear gender-specific differences in muscle activation and coordination were identified demonstrating elevated quadriceps activity and reduced hamstring activity in young female athletes compared to their male counterparts, and suggesting young female athletes to be at elevated risk of non-contact ACL injury. Only few studies (n = 6) examined the effect of preventive exercise-based intervention protocols on lower limb muscle activation during sports-specific movements. A general trend toward enhanced hamstring activation was observed during selected injury risk situations (e.g., sidecutting and drop landings). Only a single study examined the association between muscle activation deficits and ACL injury risk, reporting that low medial hamstring activation and high vastus lateralis activation prior to landing was associated with an elevated incidence of ACL-injury. A majority of studies were performed in adult female athletes. The striking paucity of studies in adolescent female athletes emphasizes the need for increased research activities to examine of lower limb muscle activity in relation to non-contact ACL injury in this high-risk athlete population.

Keywords: adolescent, female, athlete, ACL, injury risk, muscle activation, hamstrings, injury prevention

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Dominic Gehring,
Albert Ludwigs Universität Freiburg, Germany

****Correspondence:***
Jesper Bencke
jesper.bencke@regionh.dk

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INTRODUCTION

Acute knee injury, especially injury to the anterior cruciate ligament (ACL), represents a serious problem in ball sports and racket sports that involve abrupt changes of direction, i.e., landing, turning, and sidecutting (Myklebust et al., 1997; Faude et al., 2006; Beynnon et al., 2014; Pasanen et al., 2017). Most of these injuries occur in non-contact conditions, and in contrast to acute contact injuries the risk of sustaining non-contact injuries appears to be related to neuromuscular factors influencing the biomechanical loading of the knee (Hewett et al., 2005a), as these factors in turn affects the magnitude and timing of muscular force production that can serve to stabilize the knee (Hewett et al., 2005b; Zebis et al., 2009). Adolescent female athletes appear to be at particular high risk of sustaining non-contact ACL injury (Renstrom et al., 2008; Lind et al., 2009). Across sports, the overall incidence of a first-time non-contact ACL rupture in female high school and college athletes have been reported to be as high as 0.112 per 1000 athlete exposures compared with 0.063 per 1000 athlete exposures in males (Beynnon et al., 2014), and ACL injury incidence rates for women seems to peak during adolescence (age 14–18 years) with 227.6 (per 100,000 person years) compared to 113.2 (per 100,000 person years) for the following age group (age 19–25 years) (Sanders et al., 2016). After ACL rupture, the consequences for the individual may be severe, both in short term when the activity in the given sport is paused and potentially have to be terminated, but also in the long term reflected as an increased risk of early onset of osteoarthritis (Molloy and Molloy, 2011) and long-term quality of life (QOL) impairment (Filbay et al., 2017). ACL injury prevention therefore seems of outmost importance in young female athletes, which prompts for a strong need for optimized prophylactic training regimes targeting this specific age- and sex- group.

In order to design effective injury prevention programs, influential risk factors must be identified (van Mechelen et al., 1992). Describing the anatomy of the ACL and the internal lever arms of relevant muscles around the knee joint will yield relevant information about movements in all three planes that impose stress forces on the ACL, and enable to identify which muscles could act as antagonist or synergists to the ACL in different movements and joint positions. Also, gender and age dependent development of muscle strength in these muscle groups would aid to understand the challenges facing young female athletes in sports-specific injury risk situations. Furthermore, analyzing the magnitude and timing of biomechanical loading on the knee joint and the ACL during such risk situations and their relationship to age or gender would also help to improve our understanding of which muscle groups that need to be strong and/or highly active during specific injury risk situation in order to reduce the risk of non-contact ACL injury in young female athletes. A large number of reviews have examined selected anatomical, strength-related and biomechanical aspects (currently 32 review papers can be identified on PubMed using the search terms: ACL AND "injury risk" AND (anatomical OR biomechanical OR physiological) AND (Review[ptyp])) whereas only few review studies have investigated how specific patterns of muscle activation may influence the risk of ACL injury (three review papers retrieved, when adding "EMG" to the previous search string). Even less is known about the effect of specific training intervention on adapting muscle activation patterns that are more in favor of protecting the ACL from non-contact injury in young female athletes.

Thus, the purpose of this narrative review was (1) to describe anatomical aspects, strength aspects and biomechanical aspects relevant for the understanding of ACL non-contact injury mechanisms in young female athletes, and (2) to review the existing literature on lower limb muscle activation in relation to risk of non-contact ACL-injury and prevention of ACL injury in young female athletes. The findings and conclusions of this review are expected to help health care professionals including physiotherapists and exercise physiologists, coaches and physical trainers to design and implement more efficient and varied exercise programs for ACL injury prevention in young female athletes.

Anatomical Aspects

From cadaveric studies it has been shown that the anatomical function of the ACL is to add to the passive stability of the knee joint in all three planes (Markolf et al., 1995). In the sagittal plane forward translation of the tibia is restrained by the ACL, and the resulting anterior forward pull on the ACL decreases with increased knee flexion (Markolf et al., 1995; Fleming et al., 2001), while active quadriceps contraction force is a major contributor to this anterior shear force (Renstrom et al., 1986; Draganich and Vahey, 1990; More et al., 1993; Durselen et al., 1995). Due to the patella ligament angular attachment to the tibia, the contribution of quadriceps muscle contraction force to anterior shear force is most pronounced at more extended knee joint angles of 0–35 degrees of flexion (Beynnon et al., 1995; Durselen et al., 1995; Fleming et al., 2001). Thus these data show, from a biomechanical-anatomical perspective, that large force generation in the knee extensors concurrent with more extended knee joint angles during forceful landing or sidecutting increase the magnitude of loading (strain) in the ACL in the sagittal plane and hence contribute to an increased risk of ACL injury.

In the frontal plane, the ACL restrains knee abduction and adduction movement, as seen by increased ACL strain when loading the knee in either valgus or varus direction in combination with anterior tibial shear force production (Markolf et al., 1995). In the transverse plane internal rotation of the tibia has been shown to add to the loading of the ACL (Durselen et al., 1995; Markolf et al., 1995; Fleming et al., 2001), while external rotation in combination with valgus may cause similar effects when the ACL is restrained by the medial-anterior aspect of the lateral condyle (Ebstrup and Bojsen-Moller, 2000; Olsen et al., 2004). Anatomical and computer modeling studies have demonstrated that the hamstring muscles play an important role as ACL synergists by providing posterior tibial stress forces that countermeasure anteriorly directed stress forces in the knee joint (Renstrom et al., 1986; Draganich and Vahey, 1990; Pandy and Shelburne, 1997; Li et al., 1999; MacWilliams et al., 1999). The importance of the hamstring muscles for providing dynamic knee joint stability is further elaborated by the fact that ACL serves a neural function as an important site of

proprioceptive feed-back in the control of muscles around the knee joint. Dyhre-Poulsen and Krogsgaard (2000) demonstrated that reflex pathways are present in humans, where long-latency (∼120 ms) reflex responses were recorded in the hamstring muscles following electrical intra-articular stimulation of the ACL (Dyhre-Poulsen and Krogsgaard, 2000; Krogsgaard et al., 2002).

Muscle Strength Aspects

Gender differences in maximal lower limb muscle strength are strongly manifested in adult athletic populations, however these differences are not apparent among immature children (McKay et al., 2017). In general, females are not found to improve maximal lower limb strength expressed relative to body mass during maturation (DiStefano et al., 2015). For thigh muscle strength, boys appear to increase strength more than girls during maturation, and in addition strength development in the hamstrings compared to the quadriceps seems to be less favorable developing in girls, leading to decreased H/Q strength ratios in post-pubertal girls (Ahmad et al., 2006). These changes in mechanical muscle properties may put young female athletes at elevated risk of ACL injury compared to their male counterparts.

Biomechanical Aspects

A viable biomechanical approach to investigate the mechanistic causes of a non-contact ACL injury could be to analyze the specific sports movements recognized as high risk situations for sustaining ACL injury, in order to examine various biomechanical factors that may result in an increased ACL strain during specific types of movement. Increased insight into gender specific differences in biomechanical loading and/or neuromuscular activation patterns during such sports specific risk situations may further elucidate why young female athletes appear more susceptible to non-contact ACL injury (Renstrom et al., 2008), and more importantly provide guidance toward more effective countermeasures to prevent such injuries.

Landing from a jump, run-to-stop and sidestep cutting maneuvers are frequently occurring situations that all have been associated with increased risk of ACL injury in a variety of sports (Myklebust et al., 1997; Faude et al., 2006; Krosshaug et al., 2007; Beynnon et al., 2014; Pasanen et al., 2017), and advanced biomechanical analyses of individual injury cases have shown that ACL rupture typically occurs within the first 50 ms after initial ground contact (Krosshaug et al., 2007). In order to identify which biomechanical risk factors that may be represented in various risk movement tasks, previous experiments primarily have been carried out in biomechanical laboratories and often using combined recordings of 3D kinematics/kinetics, ground reaction forces and electromyography (discussed below in the section on muscle activation).

Based on the available data, female athletes tend to demonstrate more extended knee and hip joint angles than their male counterparts during vertical and horizontal landings as well as in lateral sidecutting maneuvers (Malinzak et al., 2001; Lephart et al., 2002; Fagenbaum and Darling, 2003; McLean et al., 2004, 2005; Ford et al., 2005; Chappell et al., 2007; Schmitz et al., 2007). This gender difference seems to emerge during maturation, where post-pubertal girls are noted to land with more extended knee joint angles compared to pre-pubertal girls (DiStefano et al., 2015). Use of extended knee joint positions during landing has been associated with elevated anterior shear forces in the knee joint and hence presumably elevated ACL strain in female study participants (Chappell et al., 2002; Shultz et al., 2009; Tsai and Powers, 2013; Tsai et al., 2017). Likewise, computer model analysis of landings have uniformly indicated that landing/cutting at more extended hip and knee joint angles are predictive of elevated anterior tibial shear forces most likely resulting in increased strain in the ACL (Sell et al., 2007; Southard et al., 2012; Tsai and Powers, 2013; Tsai et al., 2017). Conversely, landing or sidecutting with more flexed knee joint angles has been reported to reduce the magnitude of anteriorly directed strain in the ACL, but also to facilitate the hamstrings to act as ACL synergists as demonstrated in cadaveric studies and using computer modeling (Li et al., 1999; Kernozek and Ragan, 2008; Southard et al., 2012). A recent study stressed the importance of avoiding extended knee joint angle during foot strike by prospectively investigating drop jump landing and showing that landing with more extended knee joint angles and increased ground reaction forces were associated with subsequent ACL injury in a cohort of young female basketball and floorball athletes (Leppanen et al., 2017).

Besides causing unfavorable strain effects in the ACL in the sagittal (anterior–posterior) plane, landings performed with more extended knee joint angles may also affect knee joint loading in other planes. Thus, landing with a more extended knee increases the magnitude of vertical ground reaction impact forces, causing increased compression of the knee joint, which due to the posterior slope angle of the tibial plateau may induce internal tibial rotation that leads to increased strain in the ACL (Torzilli et al., 1994; Kernozek and Ragan, 2008). In addition, performing landing with more extended knee joint positions have been associated with elevated external knee abduction moments in the frontal plane (Pollard et al., 2010), and gender differences in frontal plane kinematic and kinetic differences have often been observed during landing or sidecutting (Ford et al., 2003, 2005; McLean et al., 2004, 2005) (**Figure 1**). These observations have led to the hypotheses that frontal plane biomechanics are important to consider as separate and significant risk factors for non-contact ACL injury, especially in female athletes (Quatman and Hewett, 2009).

In strong support of this notion, using a prospective study design Hewett et al. (2005a) observed an increased risk of subsequent ACL injury in young female athletes who demonstrated increased external knee abduction moment and increased valgus angle at initial contact during drop jump testing. Further, although no differences in knee joint flexion were noted at initial contact, the degree of maximal knee flexion (i.e., functional range of motion) during the landing was reduced in athletes later sustaining ACL injury (Hewett et al., 2005a). On the other hand, prospective data obtained in elite female football and handball players have not been able to verify this relationship to ACL injury incidence despite also using drop jump testing (Krosshaug et al., 2016). Studies examining sidestep cutting maneuvers generally have reported elevated external moments

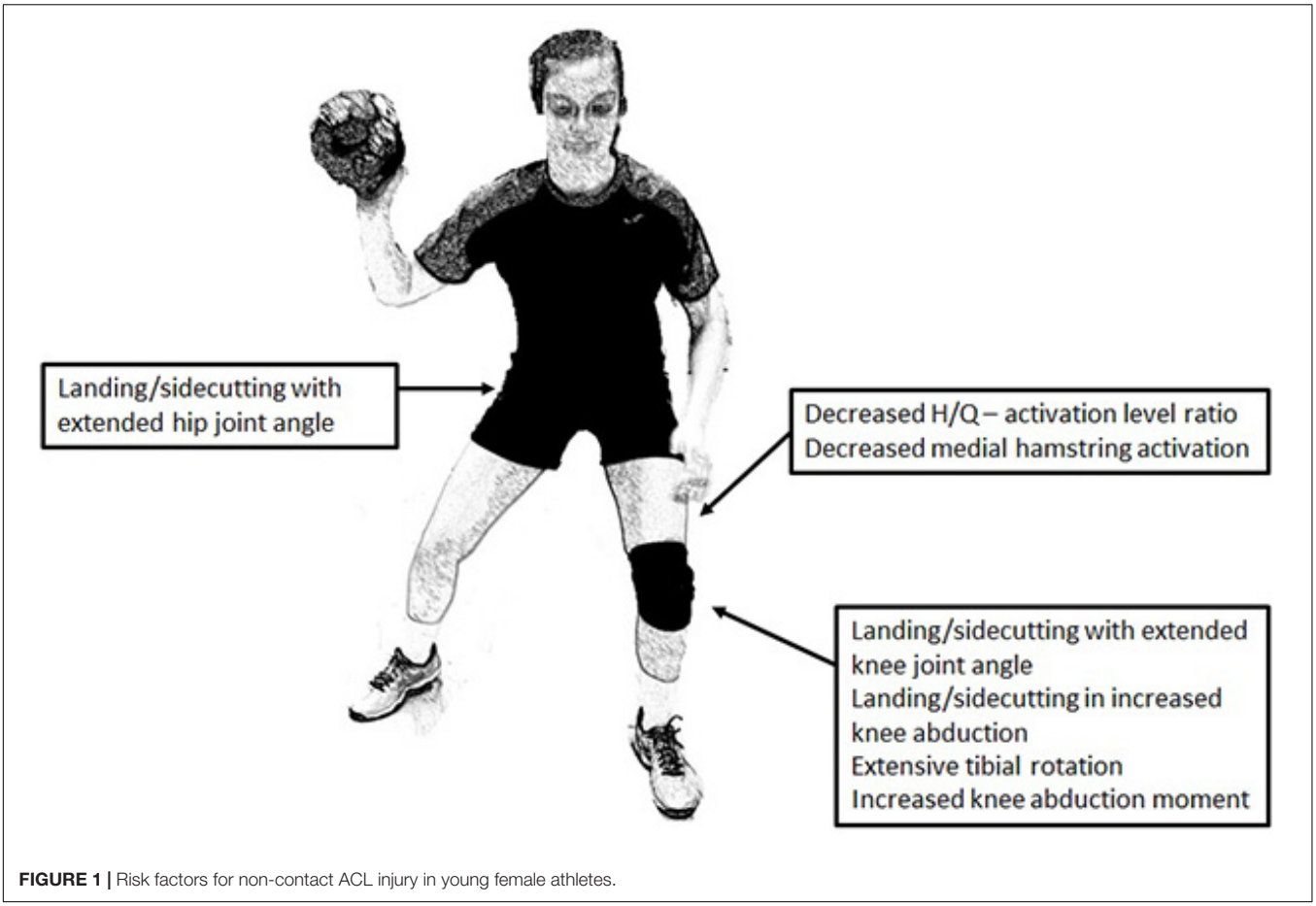


FIGURE 1 | Risk factors for non-contact ACL injury in young female athletes.

around the knee joint compared to studies examining drop jumps, while also displaying coinciding peaks of external knee flexion moments, knee abduction moments and tibia rotational moments within the first 50 ms after landing in female athletes (Bencke et al., 2013; Kristianslund and Krosshaug, 2013). It is likely that a combination of all of these potentially ACL-stressing joint moments may increase the risk of sustaining a non-contact ACL-injury.

While the above biomechanical risk factors can be considered general across all age groups, specific gender differences do not seem to appear until after puberty where distinct sex differences in landing biomechanics become noticeable (Hewett et al., 2004; Quatman et al., 2006). The resulting modifications in knee loading patterns may be more challenging for young adolescent female athletes, given that the concurrent deficit in hamstring strength development relative to the quadriceps (Ahmad et al., 2006) may reduce the ability to generate synergistic joint forces that are protective to the ACL. However, much less data exist on the influence of muscle activation patterns on the risk of ACL injury, especially in young female athletes despite that this population is at particular risk of sustaining such type of injury.

Muscle Activation

The present narrative review intended to examine the significance of muscle activation on the risk of non-contact ACL injury, and to investigate the effect of preventive measures on a reprogramming in muscle activation patterns in young female athletes. Retrieved study papers were divided into three categories: (i) studies investigating muscle activation patterns related to biomechanical risk factors or gender differences in muscle activation patterns (**Table 1**); (ii) studies directly associating muscle activation patterns to the risk of sustaining non-contact ACL injury using prospective designs (**Table 2**), and (iii) studies investigating the effect of preventive exercise training on the reprogramming in muscle activation patterns (**Table 3**).

As discussed above the assessment of selected kinematic and kinetic variables during standardized landing and sidecutting maneuvers may be useful to identify gender differences in external loading of the knee joint during sports specific movements. Importantly, in the laboratory setting the magnitude and direction (i.e., frontal, sagittal, and rotational) of external loading can be sensitively quantified, while concurrently counteracted by a host of internal passive (i.e., ligaments and capsule tissue) and active (i.e., musculo-tendinous) forces that in turn can be estimated. From such experiments, the pattern of muscle activation appear to be an important factor to consider when discussing ACL injury risk factors in female athletes (Kaufman et al., 1991).

TABLE 1 | Studies relating neuromuscular activation to biomechanical risk factors or gender comparisons.

Study	Female/male	Age [years (SD)]	Outcome parameters	Results
Beaulieu et al., 2009	*N* = 15/15	F: 21.1 (3.6) M: 22.9 (3.7)	Sidecut 3D kinematics and quadriceps, hamstring and gastrocnemius EMG. Gender differences	Females more gastrocnemius activity than males, and a more VL-to-VM dominated activity than males
Bencke and Zebis, 2011	*N* = 12/12	F: 22.7 (3.1) M: 23.1 (3.4)	Sidecut preactivity EMG of quadriceps and hamstring, and pre-activity H/Q-ratio	Females showing less hamstring preactivity and smaller H/Q-ratio
Chappell et al., 2007	*N* = 19/17	F: 22.3 (2.2) M: 22.6 (2.2)	Stop jump 3D biomechanics and averaged and normalized quadriceps and hamstring EMG	Females more quadriceps activation than males, and more hamstring activation before landing
Colby et al., 2000	*N* = 6/9	F+M: 22.2 (1.7)	Sidecut and landing kinematics and quadriceps and hamstring EMG	High quadriceps activity and low hamstring activity before ground contact
Ebben et al., 2010	*N* = 12/12	F: 19.9 (0.9) M: 21.0 (1.2)	Sidecut and drop landing quadriceps and hamstring EMG	Females showing less hamstring activity than males after contact, and lower EMG H/Q-ratio
Fagenbaum and Darling, 2003	*N* = 8/6	University athletes	Jump landing knee kinematics and quadriceps and hamstring EMG	No gender differences in EMG activity
Hanson et al., 2008	*N* = 20/20	F: 19.8 (1.1) M: 19.4 (1.4)	Sidecut quadriceps and hamstring and hip EMG	Females showing greater pre-activity VL and gluteus medialis activation and lower H/Q-ratio than males
Landry et al., 2007	*N* = 21/21	F: 16.7 (1.0) M: 17.0 (0.6)	Sidecut 3D biomechanics and EMG of quadriceps, hamstring and gastrocnemius	Females demonstrating higher quadriceps and gastrocnemius activity in stance
Malinzak et al., 2001	*N* = 9/11	F: 24.6 (1.0) M: 24.5 (2.5)	Running, cross-cutting, and sidecutting 3D biomechanics and quadriceps and hamstring EMG	Females tending to have elevated quadriceps and reduced hamstring activity during stance phase in all movement task examined
Myer et al., 2005	*N* = 10/10	F: 22.3 (3.7) M: 25.5 (2.7)	Slow lateral knee flexion and extension measuring VL and VM activity	Females having lower VM/VL ratio
Nagano et al., 2007	*N* = 19/18	F: 19.4 (0.9) M: 19.8 (4.6)	Single leg drop landing 3D biomechanics and quad-riceps and hamstring EMG	Pre activity EMG H/Q-ratio was lower in females compared to males
Pollard et al., 2010	*N* = 58/0	13.5 (range: 11–20)	Drop landing 3D biomechanics. Quadriceps and hamstring EMG	Female subjects with more extended knee joint angle at landing impact showing increased quadriceps EMG
Russell et al., 2007	*N* = 28/27	Children: 9.5 (0.9) Adults: 23.9 (2.8)	Drop landing 3D biomechanics and H/Q-activation ratio between children and adults	Children showing smaller EMG H/Q-ratios compared to adults
Sell et al., 2007	*N* = 17/19	F: 16.1 (1.3) M: 16.3 (1.5)	Stop jump 3D biomechanics and VL and ST EMG	VL activity related to anterior shear force
Shultz et al., 2009	*N* = 39/39	F: 22.2 (2.9) M: 22.6 (2.6)	Drop Jump 3D biomechanics and quadriceps and hamstring EMG	Females having more quadriceps and hamstring activity than males. Greater peak quadriceps activity in subjects with high anterior shear forces, regardless of sex. Low strength was moderately related to high quadriceps activity in females.
Sigward and Powers, 2006a	*N* = 30/0	F: 15.4 (1.0)	Sidecutting 3D biomechanics and quadriceps and Hamstring EMG differences between experienced and novice athletes	Novice athletes showed greater antagonist-agonist muscle co-activation at the knee
Sigward and Powers, 2006b	*N* = 15/15	F: 19.4 (1.5) M: 19.6 (1.9)	Sidecutting 3D biomechanics and quadriceps and hamstring EMG	Females displayed greater average quadriceps EMG
Zazulak et al., 2005	*N* = 13/9	Division I athletes (United States)	Drop landing hip and thigh EMG	Females showed less gluteus max activity after landing and more quadriceps pre activity

Only neuromuscular study data are summarized.
VM, m.vastus medialis; VL, m.vastus lateralis; H/Q-ratio, Hamstring-to Quadriceps ratio.

TABLE 2 | Studies directly associating muscle activation patterns to risk of ACL injury using prospective study designs.

Study	Cohort/follow-up	Age (SD)	Outcome parameters	Results
Zebis et al., 2009	Fifty five female non-injured athletes were followed for two seasons	24 (5) years	Sidecutting EMG of quadriceps and hamstrings	Five ACL injuries registered at follow-up. At baseline, the injured group showed less medial hamstring activity and greater VL activity, along with an elevated VL-ST EMG difference

Only muscle activation study data are summarized.

GENDER DIFFERENCES IN NEUROMUSCULAR ACTIVATION PATTERNS (Table 1)

Numerous studies have reported that female athletes may systematically demonstrate increased quadriceps activation during landing and cutting maneuvers compared to male athletes (Colby et al., 2000; Malinzak et al., 2001; Zazulak et al., 2005; Sigward and Powers, 2006b; Chappell et al., 2007; Landry et al., 2007; Pollard et al., 2010). Increased quadriceps activation *per se* has been associated with increased anterior tibia shear forces and elevated ACL strain (Sell et al., 2007; Brown et al., 2009; Shultz et al., 2009) and therefore likely is a contributing factor to the elevated risk of non-contact ACL injury observed in female athletes. Further, by means of EMG recordings it has been documented that female athletes tend to have a dominance of lateral quadriceps (VL) activation during side-cutting in contrast to male athletes who tend to demonstrate medial quadriceps (m.vastus medialis) dominance (Myer et al., 2005; Beaulieu et al., 2009). Given that knee abduction is a well-known risk factor for sustaining non-contact ACL injury (Hewett et al., 2005a), elevated activity of the lateral quadriceps would be expected to increase the risk of such injury. However, as discussed in detail above, the hamstrings can play a role as functional ACL synergists, and thus co-activation and/or pre-activation of the medial hamstring muscles (frontal plane antagonist to lateral quadriceps forces) may serve an important stabilizing and protective purpose during landing and rapid side-cutting maneuvers (Ebben et al., 2010; Zebis et al., 2016). When examining the magnitude of agonist-antagonist muscle co-activation during risk movements, gender specific muscle activation (EMG amplitude) patterns characterized by reduced hamstring-to-quadriceps co-activation ratio (H/Q-ratio) have been observed in female athletes compared to male athletes in the pre-touch down phase prior to ground contact when performing sidecutting or vertical drop landings (Nagano et al., 2007; Hanson et al., 2008; Bencke and Zebis, 2011), while also observed in sidecutting during the subsequent contact phase (Hanson et al., 2008; Ebben et al., 2010). In contrast, a single study failed to observe any gender differences in thigh muscle activation when examining college athletes during landing from a jump, which might at least in part be due to a very small sample sizes (8 female vs. 6 male subjects) (Fagenbaum and Darling, 2003).

It remains unclear why female athletes demonstrate a lower H/Q-ratio of muscle activity during risk situations for non-contact ACL injury in sports, where an elevated hamstring activity otherwise would be beneficial for providing dynamic knee joint stability. One potential explanation could be that reduced magnitude of hamstring-quadriceps muscle co-contraction would favor a more explosive jumping movement, as the knee extensors would be able to more efficiently produce high eccentric landing- and elevated concentric push-off force and power. Indeed, high school novice female soccer players demonstrated increased amounts of hamstring-quadriceps co-contraction during sidecutting, which was suggested to reflect an immature pattern of muscular activation (Sigward and Powers, 2006a). In terms of maturation *per se*, children appear to display substantially less muscle co-contraction prior to landing from a jump compared to adults, arguably as a result of using different landing strategies (Russell et al., 2007).

NEUROMUSCULAR ACL INJURY RISK FACTORS IDENTIFIED BY PROSPECTIVE DESIGNS (Table 2)

Only a single prospective study was identified to have examined muscle activity pattern as an isolated risk factor for non-contact ACL injury, in which 55 adult female elite team handball and football players (mean age of 24 years) without previous history of ACL injury were investigated (Zebis et al., 2009). No prospective studies investigating muscle activation deficits and ACL injury risk could be identified in adolescent or young female athletes. In the study by Zebis et al. (2009), it was reported that reduced medial hamstring activity during sidecutting as well as an elevated difference in normalized EMG activity between lateral quadriceps muscle (i.e., m.vastus lateralis) and medial hamstring muscle group [i.e., m.semitendinosus (ST)] were factors that predicted future episodes of non-contact ACL injury (Zebis et al., 2009). As such, these observations underline the importance of medial hamstring muscle activation for providing protection against non-contact ACL injury in female football and team handball athletes.

EFFECTS OF PREVENTIVE EXERCISE TRAINING ON MUSCLE ACTIVATION PATTERNS (Table 3)

Specific modes of training have been reported to result in altered neuromuscular coordination patterns during landing, jumping, and sidecutting (Zebis et al., 2008, 2016; Nagano

TABLE 3 | Studies examining effect of training on muscle activation in female athletes.

Study	Intervention/control	Age [years (SD)]	Outcome parameters	Results
Lephart et al., 2005	Plyometric (n = 14)/resistance training (n = 13)	I: 14.5 (1.3) C: 14.2 (1.3)	Jump-landing 3D biomechanics and hip and thigh EMG	Both training groups increased gluteus medius activity before and during landing
Letafatkar et al., 2015	Pertubation training (n = 15)/control (n = 14)	I and C: 24.3 (3.5)	Single leg drop landing EMG of quadriceps and hamstrings	Increased level of co-contraction between quadriceps and hamstrings in the intervention group after intervention
Nagano et al., 2011	Jump and balance training (n = 8)/no control group	I: 19.4 (0.7)	Single leg drop landing 3D biomechanics and quadriceps and hamstrings EMG	Intervention increased pre activity hamstring activation, but not H/Q-ratio
Wilderman et al., 2009	Agility training (n = 15)/control group (n = 15)	I: 21.1 (3.6) C: 21.1 (1.8)	Sidecutting 3D kinematics and quadriceps and hamstrings EMG	Intervention group increased medial hamstring activation during ground contact
Zebis et al., 2008	Balance+jump+landing (n = 20), compare control season vs. intervention season	I: 26 (3)	Sidecutting EMG of hip thigh and shank muscles	No change during control season but reduction in gluteus medialis pre activity and increase in medial hamstring activity following the intervention protocol
Zebis et al., 2016	Balance+jump+landing (n = 20)/control (n = 20)	I: 15.9 (0.4) C: 15.6 (0.5)	Sidecutting 3D biomechanics and EMG of quadriceps and hamstring	After intervention reduced VL-ST EMG difference was showed during the pre-landing phase for the intervention group

Only muscle activation study data are summarized.
VM, m.vastus medialis; VL, m.vastus lateralis; ST, m.semitendinosus.

et al., 2011; Letafatkar et al., 2015). Thus, a recent study using postural balance exercises and verbal instructions to land softly reported improved EMG H/Q-ratios prior to and after initial contact in single-leg drop landings in response to a 6-week intervention protocol in female university athletes (Letafatkar et al., 2015). An uncontrolled study in eight young female athletes employed a 5 weeks intervention protocol consisting of plyometric jump and landing exercises that were implemented in selected basketball exercises, which resulted in elevated hamstring muscle activation in the 50 ms time interval prior to landing indicating a more protective recruitment pattern after the period of training (Nagano et al., 2011). Likewise, Zebis et al. (2008) showed that a training program, previously documented to reduce the incidence of non-contact ACL-injury in female team handball players (Myklebust et al., 2003) and consisting of standing balance exercises, landing exercises and game specific jumping exercises, led to increased pre-activity in the medial hamstrings (i.e., m.semitendinosus) during standardized sidecutting maneuvers performed in adult female elite football and handball players (Zebis et al., 2008). Later, the same training protocol was repeated in a group of adolescent female football and team handball players, which resulted in increased medial hamstring-to-lateral quadriceps muscle activation levels compared to matched controls (Zebis et al., 2016). Using another type of intervention protocol, Wilderman et al. (2009) carried out a RCT (n = 30) investigating the effect of an agility training program lasting 6 weeks (Wilderman et al., 2009). In accordance with the above studies by Zebis et al. (2008, 2016) and Wilderman et al. (2009) also reported increased medial hamstring activity during sidecutting in young female basketball players, however, the increase was apparent during the contact phase of the sidecutting maneuver and not in the pre activity period immediately prior to contact as reported by the previous studies by Zebis et al. (2008, 2016), Nagano et al. (2011), and Letafatkar et al. (2015). The difference in neuromuscular effect might reflect differences in the specific exercises used, as the agility exercises applied by Wilderman et al. (2009) primarily consisted of exercises emphasizing speed in shuffling the feet and changing directions, while the aforementioned studies focused more on standing balance exercises, balance in landing exercises and joint control during sports-specific exercises.

The above studies suggest that increased medial hamstring muscle activity during high injury risk movements represents an important neuromuscular adaptation to ACL injury prevention training, and that uniform adaptive responses can be achieved in both adult and adolescent female athletes. As discussed in detail above, the protective role of a high medial hamstring activity may be to limit the risk of excessive dynamic valgus and external rotation of the knee joint and thereby reduce stress forces and strain in the ACL. Since no studies so far have performed long term follow-up, it remains unknown for how long the observed adaptation in motor program execution (elevated ST activation) can be sustained in the absence if training or when performing a reduced frequency of training. Also no studies exist on the effect

of age or maturation on the sustainability of the improved motor programs.

Most of the included studies investigated young female adults and only few (n = 6) comprised adolescent female athletes (age: 10–19 years). Given that the highest risk of non-contact ACL injury appears to exist during the adolescent years (Renstrom et al., 2008) and that patterns of muscular activation have been shown to represent a significant risk factor for ACL injury (Zebis et al., 2009), it seems striking that only a few experimental studies have been performed in this age group. No clear explanation for this lack of studies on muscle activation in adolescent athletes is evident, except that studies using EMG analysis generally are highly time consuming to conduct, and that elaborate efforts of obtaining ethical approval typically are required when studying adolescent athlete populations. However, in the light of the relatively drastic changes in landing biomechanics and lower limb muscle strength as a result of maturation, experiments to study muscle activation patterns in adolescent female athletes seem highly warranted.

SUMMARY AND PERSPECTIVES

Collectively, the available data suggests that selected biomechanical risk factors such as anterior shear forces, external knee abduction moments and internal/external knee joint rotation (**Figure 1**) – all factors known to stress the ACL during injury risk situations like landings and sidecutting – may be significantly counteracted by internal joint forces generated by the hamstring muscles. Furthermore, increased hamstring muscle activation and reduced quadriceps activation both would be expected to counteract the magnitude of anterior tibial shear forces, and elevated activation of the medial hamstring muscles (ST in particular) without or in combination with reduced activity in the lateral quadriceps muscle (VL) is expected to counteract external knee abduction (valgus) moments in the frontal plane that are known to represent a strong risk factor for non-contact ACL injury. When landings or cutting maneuvers are performed with extended knee joint angles, also a well-known high risk situation, increased medial hamstring activity would also be expected to protect the knee joint against excessive external rotation moments. Consequently, increased focus on avoiding (or even de-programming) non-optimal patterns of muscle activation seems highly important for reducing the incidence of non-contact ACL injury in young female athletes.

In conclusion, this review shows that young and adult female athletes, in comparison with male athletes, often demonstrate muscle activation patterns during high risk situations in sports that put the athletes at increased risk of sustaining non-contact ACL injury. Specifically, young as well as adult female athletes tend to have higher levels of quadriceps muscle activation, which may contribute to increase the magnitude of anterior tibial shear forces to cause significant ACL strain. In addition (and conjunction), female athletes tend to demonstrate reduced levels of hamstring muscle activation during high-risk movement conditions (sidecutting and stop landing), which further provides less protective capacity for ACL unloading. In the frontal plane, the importance of increased activity in the medial hamstring muscles have been demonstrated, while the balance of medial hamstring muscle activity in relation (proportion) to lateral quadriceps activity appears to particularly influence the magnitude of dynamic stabilization in the knee joint during sports specific high-risk situations. However, considering the fact that adolescent female athletes are at particular high risk of sustaining non-contact ACL injury, there is a striking lack of cross-sectional as well as prospective data on the influence of specific muscle activation patterns on the risk of ACL-injury in this age and gender group. In addition, almost no knowledge exists on the adaptive change in hamstring vs. quadriceps muscle activation patterns during high risk movements evoked by prophylactic neuromuscular exercise training. Consequently, further research is warranted to (1) investigate how certain patterns of lower limb muscle activation may represent a significant risk factor in relation to non-contact ACL injury, and (2) to develop more effective preventive intervention programs targeting adolescent and young female athletes.

AUTHOR CONTRIBUTIONS

JB took part in decision on structure and content of the review, performing literature, search, and writing the review. PA and MZ took part in decision on structure and content of the review, contributed to writting the review and gave thorough feedback throughout the process, and accepting the final version.

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Neuromuscular Training Improves Lower Extremity Biomechanics Associated with Knee Injury during Landing in 11–13 Year Old Female Netball Athletes: A Randomized Control Study

*Amanda J. Hopper[1], Erin E. Haff[1], Christopher Joyce[2], Rhodri S. Lloyd[3,4,5] and G. Gregory Haff[1]**

[1] Centre for Exercise and Sports Science Research, Edith Cowan University, Joondalup, WA, Australia, [2] School of Health Sciences, The University of Notre Dame Australia, Fremantle, WA, Australia, [3] Youth Physical Development Centre, Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, United Kingdom, [4] Sport Performance Research Institute New Zealand, Aukland University of Technology, Aukland, New Zealand, [5] Centre of Sport Science and Human Performance, Waikato Institute of Technlogy, Hamilton, New Zealand

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***Correspondence:**
G. Gregory Haff
g.haff@ecu.edu.au

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The purpose of this study was to examine the effects of a neuromuscular training (NMT) program on lower-extremity biomechanics in youth female netball athletes. The hypothesis was that significant improvements would be found in landing biomechanics of the lower-extremities, commonly associated with anterior cruciate ligament (ACL) injury, following NMT. Twenty-three athletes (age = 12.2 ± 0.9 years; height = 1.63 ± 0.08 m; mass = 51.8 ± 8.5 kg) completed two testing sessions separated by 7-weeks and were randomly assigned to either a experimental or control group. Thirteen athletes underwent 6-weeks of NMT, while the remaining 10 served as controls and continued their regular netball training. Three-dimensional lower-extremity kinematics and vertical ground reaction force (VGRF) were measured during two landing tasks, a drop vertical jump and a double leg broad jump with a single leg landing. The experimental group significantly increased bilateral knee marker distance during the bilateral landing task at maximum knee-flexion range of motion. Knee internal rotation angle during the unilateral landing task at maximum knee flexion-extension range of motion was significantly reduced ($p \leq 0.05$, $g > 1.00$). The experimental group showed large, significant decreases in peak vertical ground reaction force in both landing tasks ($p \leq 0.05$, $g > -1.30$). Control participants did not demonstrate any significant pre-to-post-test changes in response to the 6-week study period. Results of the study affirm the hypothesis that a 6-week NMT program can enhance landing biomechanics associated with ACL injury in 11–13 year old female netball athletes.

Keywords: female, injury prevention, landing mechanics, strength training, youth

INTRODUCTION

Adolescent female athletes experience non-contact anterior cruciate ligament (ACL) injuries at a 4–6 times higher rate than males participating in the same sports (Hewett et al., 1999, 2006). One possible explanation related to this observation is the absence of the neuromuscular spurt following maturation in female athletes, which results in neuromuscular imbalances in muscle strength and activation patterns (Myer et al., 2004). These imbalances increase loading on the joint consequently increasing non-contact ACL injury risk. Appropriately designed and implemented neuromuscular training (NMT) programs have been shown to decrease ACL injury risk in adolescent female athletes by improving their neuromuscular control and dynamic knee stability (Myer et al., 2005; Chappell and Limpisvasti, 2008). It appears that NMT programs inclusive of both resistance and plyometric training are most effective at reducing non-contact ACL injury risk in female athletes under the age of 18 (Yoo et al., 2010). These programs focus on improving neuromuscular strength and control, proprioception, motor control, fundamental movement patterns and functional biomechanics, with the aim of decreasing ACL injury risk (Myer et al., 2005).

The effectiveness of NMT programs to decrease ACL injury risk and improve lower extremity biomechanics has been studied within adolescent soccer, basketball and volleyball athletes (Myer et al., 2005; Chappell and Limpisvasti, 2008) as these sports exhibit high ACL injury rates (Boden et al., 2000). One sport that has not received a lot of attention in the scientific literature examining NMT and knee injury risk management is the sport of netball. Netball also displays high lower extremity injury incidence rates, with ACL rupture being the most commonly occurring injury in the sport (McManus et al., 2006). In non-professional netball athletes, over a 2 year period ligament sprains or tears accounted for 61.2% of total sports related injuries (Finch et al., 2002). Similarly, over a 3-day state netball competition there were 139.4 injuries per 1,000 players, with the knee and ankle being the most frequently injured body part, and ligament sprains being the most common injury (Hume and Steele, 2000). Furthermore, 65% of these injuries came from the under 17's squad which was the youngest division in the competition. Based upon these statistics it is apparent that there is a need for the implementation of effective NMT programs that specifically target the prevention of ACL injuries in netball athletes of all ages.

It has been suggested that the primary cause of lower limb injury in netball is incorrect landing technique (Hopper et al., 1995), combined with rapid deceleration or an abrupt landing (Cowling and Steele, 2001). In netball, a key rule requires players to only take a maximum of one and half steps whilst in possession of the ball, therefore the player must rapidly decelerate and stop after receiving the ball in order not to violate this rule (Steele, 1990). Jumping, landing, leaping and lunging movements are commonly performed during both netball practice and competition. For example, Lavipour (2011) found that on average netball players will perform one jump per minute during a game with athletes landing unilaterally 67% of the time, due to most of their jumps requiring them to jump to receive the ball. The impact of the frequency of jump landings on overall injury risk is clearly seen in the work of Stuelcken et al. (2015), where out of 16 ACL injuries in elite netball players, 13 of these occurred with the player landing from a jump.

Mechanisms of ACL injury in female athletes have been extensively studied and reported in scientific literature (Boden et al., 2000, 2010; Hewett et al., 2004, 2006; Hewett, 2005). Anterior cruciate ligament injury occurs during dynamic lower extremity valgus, which typically involves a combination of hip adduction and internal rotation, knee abduction, tibial external rotation and anterior translation, and ankle eversion (Hewett et al., 2006). The governing mechanisms for ACL injuries in young female athletes is generally associated with poor neuromuscular control leading to altered lower limb biomechanics such as; increased knee valgus and foot pronation angles, and decreased hip and knee flexion, and hip abduction during cutting and landing (Hewett et al., 2006). In particular, these risk factors are exacerbated as they mature and peak following the post-pubertal stage of development (Myer et al., 2009). Prior to puberty there is no difference in lower limb biomechanics during landing between males and females (Jackson et al., 2010). However, following puberty, females demonstrate changes in hip and knee biomechanics that predispose them to ACL injury (Hewett et al., 2004). In elite netball, Stuelcken et al. (2015) reported valgus knee collapse in 12 of 13 ACL injuries. One possible explanation for this occurrence may be related to an increase in joint laxity and reduction in lower extremity control that maturing athletes commonly experience. The consequence of this occurrence is a decrease in passive joint stability that may increase the tendency toward valgus knee motions (Quatman et al., 2008; Myer et al., 2009).

Previous studies have shown that with maturity (pre-pubertal to post-pubertal) female athletes land with greater knee extension, and greater extension moments and powers (Decker et al., 2003; Hass et al., 2003) thereby increasing the amount of force directly placed upon the ACL (Renström et al., 1986). Boden et al. (2000) found of athletes who had sustained an ACL injury the majority of them reported the knee being close to full extension at the time of injury. Another possible factor that can exacerbate this problem is weakness of the hip musculature (Powers, 2010). If the hip musculature is weak the hip can move into adduction during loading, which can place the knee into a valgus position (Jacobs et al., 2007; Powers, 2010) increasing the overall risk of sustaining an ACL injury. This problem is particularly evident in female athletes who demonstrate significantly more hip adduction and hip internal rotation during weight bearing activities than their male counterparts (Jacobs et al., 2007).

Neuromuscular training has been shown to decrease potential for ACL injury by improving biomechanical deficiencies typically associated with injury (Hewett et al., 1999; Myer et al., 2005). Myer et al. (2013) indicated that there is a potential window of opportunity to decrease ACL injury risk in young female athletes if NMT is implemented prior to the onset of puberty. A meta-analysis by Yoo et al. (2010) found NMT incorporating both plyometric and strength training were most effective in preventing ACL injuries in female soccer, handball and basketball

athletes, specifically those under the age of 18. In support of this contention Myer et al. (2005) found following a 6-week NMT intervention inclusive of strength training, plyometric and balance training, 14–16 year old female basketball, volleyball and soccer athletes were able to significantly increase their knee flexion angle and decrease internal knee valgus in response to a drop vertical jump task (DVJ). The effects of NMT to prevent incidence of ACL injury has been extensively studied in adolescent basketball, soccer and volleyball athletes (Hewett et al., 1999; Myer et al., 2005; Pfile et al., 2013). Hewett et al. (1999) found untrained high school female athletes presented a significantly higher incidence of sports related knee injury then the male control group, however female athletes who had participated in a NMT program showed no significant difference in injury incidence in contrast to the male control group. However, the effects of a 6-week NMT intervention in preventing factors associated with ACL injury is yet to be quantified with netball athletes.

Therefore, the aim of this study is to determine the effects of a 6-week NMT program on lower extremity biomechanics in youth female netball athletes. The hypothesis is that significant improvements will be seen in the biomechanical measures commonly related to ACL injury in female athletes (increased range of motion [ROM] in flexion-extension, decreased abduction-adduction and internal-external rotation, and decreased ground reaction force) following the training intervention.

MATERIALS AND METHODS

Twenty-three youth female netball athletes (age = 12.2 ± 0.9 yrs; height = 1.63 ± 0.08 m; mass = 51.8 ± 8.5 kg) were recruited from local netball clubs to participate in the study. The sample size was chosen based upon a power analysis ($\beta = 0.829$) indicating a minimum of 16 athletes are needed for the study. Further, samples size was considered based on similar multiple training group studies involving youth participants (Faigenbaum et al., 2007; Chaouachi et al., 2014; Meylan et al., 2014) who used sizes of $n \leq 12$, $n \leq 14$, and $n \leq 17$ respectively. Participants verbally reported no previous history of lower limb injury and no previous experience partaking in NMT. All participants were instructed to maintain their normal netball training regime. Participants were recruited for participation in this randomized control trial study and divided into either an experimental (EG; $n = 13$) or control group (CG; $n = 10$) in a blinded fashion following the first battery of testing (**Figure 1**). Control participants were instructed not to partake in any resistance training activity during the course of the study. No significant differences in age, height and mass were found between the EG and CG in either the pre- (Height: EG = 1.64 ± 0.07 m; CG = 1.64 ± 0.10 m; Mass: EG = 50.7 ± 8.8 kg; CG = 53.3 ± 8.2 kg) or post-testing (Height: EG = 1.63 ± 0.07 m; CG = 1.63 ± 0.10 m; Mass: EG = 52.0 ± 8.9 kg; CG = 53.9 ± 8.4 kg) sessions ($p \geq 0.05$). All participants had participated in competitive netball for more than 4 years. The Human Research Ethics Committee at Edith Cowan University approved all test procedures and written informed parental consent and participant assent was obtained prior to commencement of the study in accordance with the Declaration of Helsinki. Participants completed the Physical Activity Readiness Questionnaire (PAR-Q) prior to beginning of the study and a modified Pubertal Maturation Observational Scale (PMOS) (Davies and Rose, 2000) was used to classify participants into maturational categories: pre-pubertal mid-pubertal and post-pubertal. There was no significant difference in maturational categories ($p = 0.051$) found between the experimental (2.2 ± 0.9) and control groups (2.8 ± 0.4) indicating that both groups are primarily made up of pubertal athletes.

The present investigation explored the addition of NMT to traditional youth netball training (i.e., ∼1–2 court based netball training sessions and ∼1–2 netball games per week) on landing biomechanics in youth netball athletes. All participants completed a 1-week familiarization program during 3 × 60 min training sessions comprised of back squats, push ups, static lunges, horizontal pull ups and glute bridges prior to the initiation of any testing. Baseline testing occurred following the familiarization program, 1 week before the initial NMT session. Post-testing was performed approximately 7 weeks after baseline testing on the EG and CG. The 6-week NMT intervention involved 3 × 60 min training sessions per week performed on non-consecutive days, for a total of 18 training sessions. A minimum of 48 h separated each resistance training session to allow for sufficient recovery. The CG participated in both baseline- and post-testing sessions however did not receive any NMT during the study period.

A 10 camera MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics Ltd., Oxford, UK) operating at 250 Hz was used to capture hip and knee kinematics using the validated Vicon Plug-In Gait model, with each participant fitted with 37 retro-reflective markers 14 mm in diameter. A static trial was collected to align the joint coordinate system to the laboratory. Vertical ground reaction force data were collected using a 600 × 900 mm triaxial force platform (Kistler, Type 9287CA, Switzerland) recorded at 1,000 Hz with Vicon Nexus Software (ver. 1.6.1, Oxford Metrics Ltd., Oxford, UK).

Participants were instructed to perform a drop vertical jump (DVJ) task and a broad jump with a single leg landing (SL). The DVJ trials commenced with each participant standing on a box 31 cm in height with their feet positioned 35 cm apart. Each participant was instructed to step off the box onto the force platform with their dominant leg and immediately perform a maximal vertical jump (Markwick et al., 2015). During the SL task, participants were instructed to perform a maximal forward jump from two legs and land on the force plate with their dominant leg, which was determined by asking them which leg they would use to kick a ball (Ford et al., 2003). Participants were given three practice trials of each jump prior to data collection to ensure the markers were secure, and to confirm they understood the movement pattern.

The training program utilized in the present study was a synthesis of previously published ACL injury prevention studies (Myer et al., 2005, 2013; Yoo et al., 2010). The components of the integrated NMT program employed in this study included a combination of plyometric and strength training. All sessions were conducted by accredited strength and conditioning coaches (Australian Strength and Conditioning Association) and a

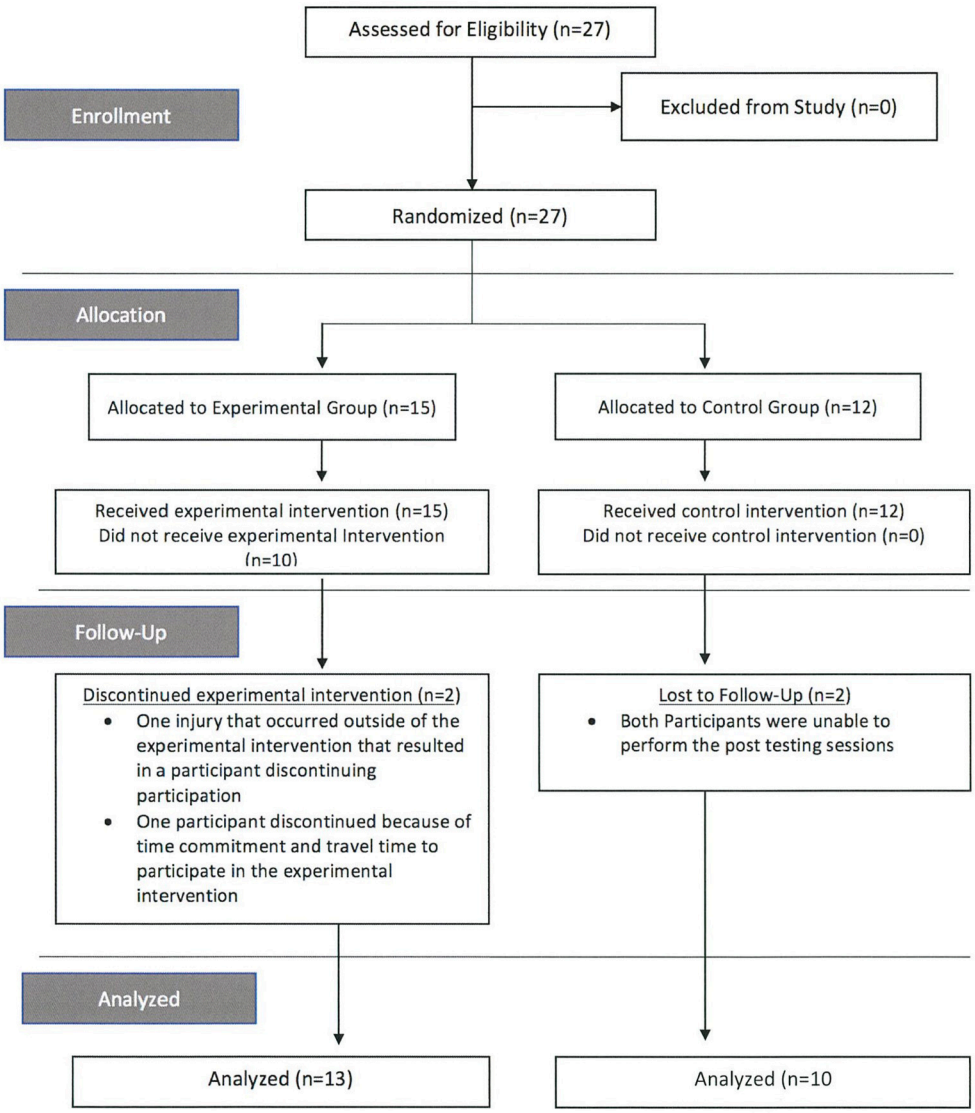


FIGURE 1 | Subject Recruitment and Randomization Process.

certified strength and conditioning specialist (National Strength and Conditioning Assosiation). The dynamic warm-up remained consistent throughout all sessions over the 6-week training period, whilst the plyometric and strength exercises were split into two 3-week blocks (**Tables 1**, **2**). Training intensity, volume and complexity of exercise increased in the second training block, with movement quality and technical competency being prioritized at all times. Participants recorded load lifted on each exercise for each set throughout the training intervention. This was then used to determine load for following week in combination with the OMNI Rate of Perceived Exhaustion (RPE) scale (Robertson et al., 2008) which was used to set a goal RPE for the session. All participants were familiarized with the use of the RPE scale prior to the first session and instructed to use the pictures and the words to provide a rating. The RPE goal incrementally increased each week with the first week being relatively easy (3–4 rating), second week being somewhat hard (5–6 rating) and the third week being hard (7–8 rating). This RPE guide was repeated for the second training block. Participants were also asked after each set to rate their RPE to determine if load could be increased, in conjunction with the opinion of the strength and conditioning coach to ensure technical efficiency and safety at all times.

Knee and Hip Kinematics

The Vicon plug-in gait model was used to obtain hip and knee kinematics. Coordinate data from each of the three-dimensional marker trajectories were filtered using a low-pass Butterworth

TABLE 1 | Neuromuscular Training Program for Weeks 1 through 3 for the experimental group.

Exercises	Sets	Reps	Rest
Dynamic Warm-up Sessions #1, #2, and #3			
High Knee March	2	10	60
Sumo Squat Arms MB Overhead	2	10	60
Arm Swing and Lunge	2	10	60
Backward Hip Flexion Walk	2	10	60
Superman	2	10	60
Knee Grab to Lunge and Twist	2	10	60
Carioca	2	10	60
Rocket Jump	2	10	60
Plyometric Training Sessions #1, #2, and #3			
½ Squat Jump	3	5	90
Lateral Bound with Stick	3	5	90
Single Leg Push Off	3	5	90
90° Spin Jump	3	5	90

Strength Training

Sessions #1 and #3				Session #2			
Exercises	**Sets**	**Reps**	**Rest**	**Exercises**	**Sets**	**Reps**	**Rest**
Back Squat	3	5	90	Front Squat	3	5	90
Bench Press	3	5	60	Incline Press	3	5	60
Medicine Ball Static Lunge (bent arms)	3	5	60	Medicine Ball Static Lunge (straight arms)	3	5	60
Military Press	3	5	60	Behind Neck Press	3	5	60
Horizontal Pull Up	3	5	60	Horizontal Pull Up	3	5	60

Ratings of perceived exertion was used to guide intensity.

filter at a cut off frequency of 12 Hz. Knee joint biomechanics; flexion-extension, abduction-adduction, and external-internal rotation angles, and hip joint biomechanics; flexion-extension, abduction-adduction and external-internal rotation angles at initial contact (i.e., intitial contact after stepping of the box) and maximum knee flexion-extension ROM were calculated from the embedded joint coordinate system. Three successful trials were collected for the DVJ task and the SL task and an average of the three trials for each landing task was used for data analysis. Positive values indicated knee flexion, knee abduction, knee external rotation, hip flexion, hip abduction and hip external rotation. Negative values represented knee adduction, knee internal rotation, hip adduction and hip internal rotation.

Bi-lateral Knee Valgus

Bi-lateral knee valgus (abduction) was calculated from the frontal plane by exporting the coordinate data as a text file in Microsoft Excel and calculating the distance (meters) between the right and left lateral knee markers at the point before initial contact (PIC) and maximum knee flexion-extension ROM as described in Ford et al. (2003).

Ground Reaction Force and Flight Time

Vertical ground reaction force (VGRF) data were derived from the embedded force platform through Vicon Nexus software. During the DVJ task, peak VGRF was recorded immediately following the box drop and immediately following the vertical jump. Peak VGRF was recorded following the jump in the SL landing task. Flight time was determined from the Kistler force plate system.

All results are represented as means ± SD. To compare differences between the pre- and post-test values for the experimental and control groups a 2 × 2 (group × time) repeated measures ANOVA was used. A significance level of $p \leq 0.05$ was set for all statistical analyses. If significant *F*-values were found, paired comparisons were used to determine differences in conjunction with a Holm's sequential Bonferonni correction to account for Type I errors. Homogeneity of variance was tested with the use of a Kolmogorov-Smirnov test and liliefors correction. If homogeneity of variance was violated the Kruskal-Wallis H test was used to determine statistical significance. One-way ANOVAs were performed on all variables to determine raw difference scores (post-pre) between groups. Effect sizes were calculated as Hedges *g* and were interpreted as the following: trivial, <0.2; small, 0.2–0.5; medium, 0.5–0.8;

TABLE 2 | Neuromuscular Training Program for Weeks 4 through 6 for the experimental group.

Exercises	Sets	Reps	Rest
Dynamic Warm-up Sessions #1, #2, and #3			
High Knee March	2	10	60
Sumo Squat Arms MB Overhead	2	10	60
Arm Swing and Lunge	2	10	60
Backward Hip Flexion Walk	2	10	60
Superman	2	10	60
Knee Grab to Lunge and Twist	2	10	60
Carioca	2	10	60
Rocket Jump	2	10	60
Plyometric Training Sessions #1, #2, and #3			
Medicine Ball ½ Squat Jump	3	5	90
Medicine Ball Lateral Bound	3	5	90
Single Leg Push off (Med Box)	3	5	90
180° Spin Jump	3	5	90

Strength Training

Sessions #1 and #3				Session #2			
Exercises	**Sets**	**Reps**	**Rest**	**Exercises**	**Sets**	**Reps**	**Rest**
Back Squat	3	8	90	Front Squat	3	8	90
Incline Bench Press	3	8	60	Bench Press	3	8	60
Split Squat –(Back foot elevated)	3	8	60	Split Squat –(Front foot elevated)	3	8	60
Chin-up*	3	8	60	Bent Over Row	3	8	60
Romanian Deadlift	3	8	60	Backward Alternating Lunge	3	8	60

Ratings of perceived exertion was used to guide intensity.
**If athletes could not perform a chin-up, resistance bands were used to assist them. In this case the resistance bands were modified to reduce reliance on the band across the training period.*

large, 0.8–1.3; and very large, >1.3 (Hopkins, 2010). Intra-class correlation coefficients (ICCα) were calculated for all variables to determine within-trial reliability. Analysis of scores in the present study demonstrated high reliability across all variables for the DVJ and SL landing tasks as indicated by $ICC\alpha \geq 0.80$ (Atkinson and Nevill, 1998). All statistical analyses were conducted using SPSS (SPSS 23.0.0.0, SPSS Inc., Chicago, IL).

RESULTS

Hip and Knee Kinematics

Significant group x time interactions were noted when examining the knee flexion-extension angle ($p = 0.009$; $g = 1.20$) and knee external rotation ($p = 0.043$, $g = 0.91$) at intitial contact during the DVJ task. Additionally, a group × time interaction was noted for hip abduction angle at maximum knee flexion-extension ROM ($p = 0.020$; $g = 1.05$). Baseline and post-testing lower extremity kinematics for the DVJ task are presented in **Table 3**.

Follow-up comparisions revealed no significant differences between groups at baseline testing for knee flexion-extension ROM ($p = 0.373$, $g = -0.39$) and knee external rotation ($p = 0.408$, $g = -0.35$) at initial contact. Additionally, there were no significant differences noted between the groups for hip abduction ($p = 0.308$, $g = -0.44$) and hip flexion ROM ($p = 0.289$, g $= -0.45$) at baseline testing. When examining the between group differences at post-testing there was a significant difference between the EG and the CG for knee-extension flexion ROM ($p = 0.002$; $g = 1.20$) and knee external rotation ($p = 0.044$, $g = 0.90$) at initial contact. There was a significant difference noted between the EG and CG when examining the hip abduction at maximum knee flexion-extension ROM ($p = 0.002$; $g = 1.05$).

When examining the SL broad jump landing task there was a significant group × time interaction for knee flexion ($p = 0.001$, $g = 1.69$) and external rotation ($p = 0.009$, $g = 0.99$) at initial contact were noted between the EG and CG. Additionally, there was a significant group x time interaction for knee external rotation ($p = 0.023$, $g = 0.73$) at maximum knee flexion-extension ROM. When examining the change score between pre and post testing the EG demonstrated a significantly greater knee flexion angle at initial contact ($p = 0.001$; $g = 2.84$) when compared to the CG. Additionally, the EG demonstrated a significantly greater ($p = 0.009$; $g = 1.21$) external rotation of the knee at initial contact. At maximum knee flexion-extension ROM

TABLE 3 | Drop vertical jump task biomechanics during pre- and post-intervention testing.

Variable			Initial contact		Maximum knee flexion angle	
			Experimental Mean ± SD	Control Mean ± SD	Experimental Mean ± SD	Control Mean ± SD
Knee Flexion	Pre	(°)	34.4 ± 5.3	36.2 ± 3.3	106.9 ± 8.9	103.7 ± 3.2
	Post	(°)	37.1 ± 4.8*	31.3 ± 6.5	114.8 ± 10.1	102.5 ± 7.2
	Δ (Post-Pre)	(°)	2.7 ± 5.4*	−4.9 ± 5.9	7.9 ± 12.2	−1.3 ± 9.2
Knee Abduction	Pre	(°)	−4.1 ± 5.8	−10.0 ± 5.5	−13.1 ± 4.5	−20.7 ± 3.4
	Post	(°)	2.6 ± 5.4	−2.6 ± 8.8	0.66 ± 9.3	−13.4 ± 2.2
	Δ (Post-Pre)	(°)	6.7 ± 6.3	7.4 ± 11.8	13.7 ± 9.6	7.2 ± 5.2
Knee External Rotation	Pre	(°)	−17.6 ± 10.4	−13.4 ± 12.8	2.3 ± 16.7	−4.8 ± 2.0
	Post	(°)	−9.9 ± 14.2*	−21.5 ± 8.7	8.1 ± 13.3	−10.2 ± 15.7
	Δ (Post-Pre)	(°)	7.6 ± 15.3*	−8.1 ± 18.7	5.8 ± 19.3	−5.4 ± 16.1
Hip Flexion	Pre	(°)	41.1 ± 4.5	43.7 ± 6.7	94.7 ± 4.9	87.2 ± 11.3
	Post	(°)	46.2 ± 2.7	44.1 ± 10.7	99.2 ± 7.5	88.7 ± 13.3
	Δ (Post-Pre)	(°)	5.0 ± 5.3	0.4 ± 7.8	4.5 ± 8.3	1.5 ± 5.7
Hip Abduction	Pre	(°)	10.4 ± 4.6	8.5 ± 3.4	6.7 ± 5.9	4.4 ± 6.7
	Post	(°)	10.7 ± 4.4	8.7 ± 3.9	13.9 ± 3.1*	5.5 ± 7.6
	Δ (Post-Pre)	(°)	0.3 ± 10.7	0.2 ± 3.5	7.3 ± 6.2	1.1 ± 4.5
Hip External Rotation	Pre	(°)	−10.6 ± 11.2	−19.5 ± 5.5	−7.3 ± 12.2	−19.4 ± 8.9
	Post	(°)	−6.3 ± 9.2	−8.5 ± 11.2	2.0 ± 12.4	−14.4 ± 3.8
	Δ (Post-Pre)	(°)	4.4 ± 11.2	11.0 ± 14.8	9.4 ± 13.0	4.9 ± 8.7

*Indicates statistical significance $p \leq 0.05$.

the EG demonstrated a significantly greater ($p = 0.023$; $g = 1.0$) external rotation of the knee when compared to the control group (**Table 4**).

When examining the baseline data there were no significant differences between the EG and CG for knee flexion ($p = 0.051$, $g = -0.89$) or external rotation ($p = 0.606$, $g = -0.22$) at initial contact or maximum knee flexion angles ($p = 0.590$, $g = -0.23$) during the SL landing task. However, at the post-testing time point the EG demonstrated significantly greater knee flexion angles at initial contact ($p = 0.04$; $g = 2.84$). Additionally, external rotation of the knee for the EG displayed significantly less external rotation at initial contact ($p = 0.03$; $g = 1.21$) and maximal knee flexion ($p = 0.003$; $g = 1.02$; **Figure 2**).

Bilateral Knee Marker Distance

There was a significant group x time interaction ($p = 0.045$; $g = 0.92$) when examining the distance between the right and left lateral knee markers before initial contact (PIC). Additionally, there was a significant group × time interaction ($p = 0.003$; $g = 1.45$) when examining the distance between the right and left lateral knee markers at maximum knee flexion. Follow-up tests revealed that there were no significant differences between the PIC at pre-testing at the initial contact ($p = 0.78$; $g = 0.12$) and max knee flexion ($p = 0.800$; $g = 0.02$). There was however a significant difference ($p = 0.004$; $g = 1.43$) between the PIC at maximum knee flexion with the experimental group displaying a significantly decreased knee abduction in comparison to CG (**Figure 3**).

Ground Reaction Force and Flight Time

Ground reaction force (GRF) mean ± SD and effect sizes for the experimental and control conditions for both the DVJ and SL jump tasks during the pre- and post-testing sessions are presented in **Table 5**. There were no differences between the groups for peak GRF prior to the training intervention in both landing tasks (DVJ: $p = 0.433$, $g = -0.35$; SL: $p = 0.737$, $g = 0.15$). When examining the post-testing DVJ performance the EG demonstrated a significantly ($p = 0.005$, $g = -1.92$) lower peak GRF when compared to the CG. Similarly the EG demonstrated a significantly ($p = 0.03$, $g = -1.05$) GRF during the landing phase following the vertical jump. Furthermore, the EG also showed very large statistically significant decreases in peak GRF during the SL landing task ($p = 0.001$; $g = -1.74$; **Figure 4**).

Flight time during the DVJ revealed no significant group × time interaction ($p > 0.05$). When raw-difference scores were examined the EG displayed an increase in their flight time (+0.03 ± 0.05 s) whilst the CG displayed a decrease in their flight time (−0.03 ± 0.07 s) however although these differences were not statistically significant ($p > 0.05$) they did display a large effect size ($g = 0.98$).

TABLE 4 | Single leg landing task biomechanics during pre- and post-intervention testing.

Variable			Initial contact		Maximum knee flexion angle	
			Experimental	Control	Experimental	Control
			Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Knee Flexion	Pre	(°)	20.3 ± 3.2	23.3 ± 3.0	58.8 ± 6.4	60.2 ± 5.6
	Post	(°)	24.3 ± 2.9*	18.5 ± 9.0	65.3 ± 11.7	60.0 ± 12.0
	Δ (Post-Pre)	(°)	4.1 ± 2.8*	−4.5 ± 6.8	6.6 ± 7.9	−0.3 ± 10.4
Knee Abduction	Pre	(°)	−5.66 ± 4.14	−8.46 ± 3.85	−7.39 ± 5.63	−12.15 ± 2.97
	Post	(°)	−1.71 ± 3.96	−4.67 ± 6.03	0.35 ± 8.80	−8.94 ± 5.04
	Δ (Post-Pre)	(°)	3.95 ± 4.16	3.79 ± 5.95	7.74 ± 7.42	3.21 ± 5.66
Knee External Rotation	Pre	(°)	−22.95 ± 4.15	−22.80 ± 1.85	−3.96 ± 11.60	−8.19 ± 5.70
	Post	(°)	−7.56 ± 11.47*	−21.39 ± 8.76	5.11 ± 14.11*	−12.29 ± 6.77
	Δ (Post-Pre)	(°)	15.39 ± 12.42*	1.40 ± 8.85	9.08 ± 14.89*	−4.09 ± 7.09
Hip Flexion	Pre	(°)	45.72 ± 8.61	53.10 ± 11.99	62.39 ± 8.79	63.21 ± 4.52
	Post	(°)	49.78 ± 7.90	50.17 ± 7.15	69.31 ± 6.59	62.94 ± 11.71
	Δ (Post-Pre)	(°)	4.05 ± 6.69	−2.94 ± 9.72	6.92 ± 7.97	−0.28 ± 12.50
Hip Abduction	Pre	(°)	9.53 ± 4.12	8.76 ± 2.00	1.42 ± 2.73	−1.75 ± 2.50
	Post	(°)	9.86 ± 3.5	9.25 ± 2.59	2.65 ± 5.28	0.54 ± 2.71
	Δ (Post-Pre)	(°)	0.32 ± 4.86	0.07 ± 1.96	1.23 ± 5.40	2.28 ± 4.48
Hip External Rotation	Pre	(°)	−14.24 ± 11.68	−24.15 ± 12.98	−7.72 ± 8.84	−15.39 ± 4.20
	Post	(°)	−7.01 ± 7.53	−13.74 ± 15.64	−3.15 ± 9.46	−12.59 ± 6.01
	Δ (Post-Pre)	(°)	7.23 ± 12.15	10.41 ± 19.53	4.57 ± 10.79	3.59 ± 7.30

**Indicates statistical significance $p \leq 0.05$.*

DISCUSSION

The objective of the current study was to determine if a comprehensive NMT program inclusive of plyometric and strength training could improve lower extremity biomechanics in 11–13 year old netball athletes. Results of the current study indicated EG demonstrated significant improvements in knee- and hip-joint biomechanics and decreases in peak GRF in both a DVJ and SL landing tasks in comparison to the CG.

The results of the current study support the work of Myer et al. (2005) who used a NMT program comprised of resistance training, plyometric and balance training to improve dynamic knee stability in comparison to an untrained control group. They demonstrated that 14–16 year old female athletes who underwent a NMT intervention were able to significantly improve their knee flexion angle during the landing phase of a box drop. These results are similar to those found in the current study with trained youth netball athletes. However, it should be noted that the current study used a slightly younger population aged 11–13 years. Results indicated that the strength trained youth netball athletes were able to significantly increase their knee flexion angle at initial contact in the DVJ task and SL landing task whilst the control group showed a decrease in knee flexion angle following the intervention. While the EG increases in knee flexion-extension ROM at maximal knee angle during the DVJ were not statistically different from the CG a medium effect size was determined suggesting a potential meaningful effect. Thus, practitioners should realize the biomechanical adaptations that NMT programs can elicit, which may enhance lower limb landing mechanics in young female athletes. The training program used in the current study focused on correction of movement patterns and muscular imbalances with resistance and plyometric training. It is assumed in the literature that NMT improves motor skills of athletes, which can decrease injury risk (Chappell and Limpisvasti, 2008). Myer et al. (2005) found NMT emphasizing deep knee flexion during plyometric and strength exercises significantly improves knee flexion angle during landing, which may decrease injury risk. This is similar to the results found in the current study, whereby the NMT program utilized also placed a large emphasis on deep knee flexion during both the plyometric and strength components of the program, resulting in improved lower extremity biomechanics.

Following maturation it has been reported that post-pubertal female athletes land with greater knee extension than pre-pubertal female athletes (Yu et al., 2002; Hass et al., 2003). This may be partly due to decreased neuromuscular control when landing from a jump commonly seen following maturation in female athletes (Hewett et al., 2004). Additionally, this may also be due to the increase in limb length following maturation providing a greater moment arm length for females to handle,

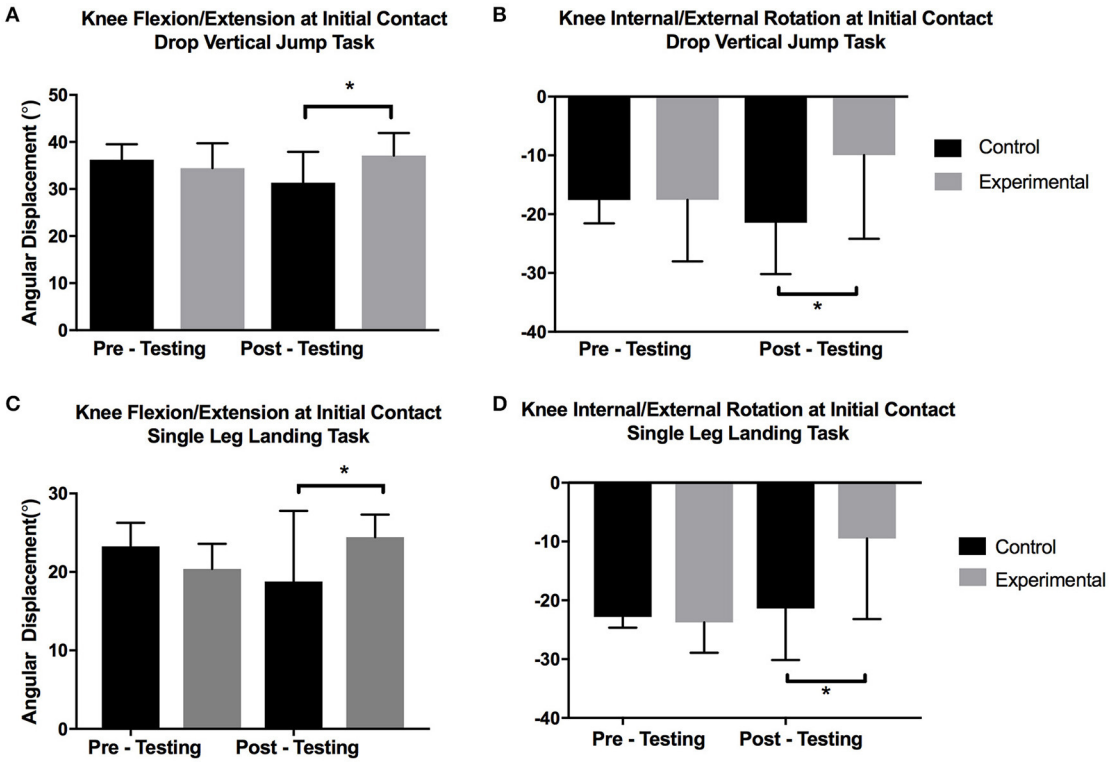


FIGURE 2 | Knee Flexion/Extension and Internal/External Rotations During Jumping Tasks. *Significant difference $p < 0.05$.

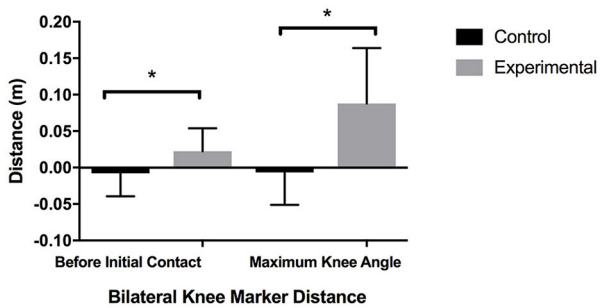


FIGURE 3 | Bilateral Knee Marker Distance. *Significant difference $p < 0.05$.

which in the absence of concomitant strength influences them to compensate by landing with the knee in a more extended position. Landing with an extended knee is likely to result in greater ground reaction forces, due to a rapid change in kinetic energy the muscles are in a disadvantageous position to safely absorb landing forces (Podraza and White, 2010). Quatman et al. (2006) showed that as female athletes matured they did not demonstrate any changes in landing forces despite their body mass increasing, thus exposing them to higher relative landing forces. Trained youth netball athletes in the present study were able to significantly decrease peak landing forces following the training intervention, in conjunction with increased knee flexion angle upon landing.

Steele and Milburn (1987) reported average landing forces generated by netball athletes ranged from 3.9 to 4.3 × bodyweight during a typical netball attacking movement pattern which required players to run forward, "break" to a specified side, catch a ball landing on one leg, pivot and throw the ball to a catcher. Landing forces in the present study prior to the training intervention showed youth netball athletes landed with 2.3 × bodyweight in a DVJ task and 1.9 × bodyweight in a SL landing task. These findings are a lot less than the 3.53–5.74 × bodyweight landing forces reported by Otago (2004) for a series of landing patterns more specific to netball. These tasks were more specific netball movement patterns commonly executed in a game which included change of direction and catching or passing a ball. This may indicate landing forces are much greater during the netball attacking movement pattern than in the DVJ or SL landing tasks used in this study. Moreover, it is important to note the EG in the present study were able to largely and significantly decrease their landing force by 1.2 × bodyweight during the box drop and 1.3 × body weight in the vertical jump portion of the DVJ task after completion of the training intervention. Support for these findings can be seen in the work of Hewett et al. (1996) who found that following a plyometric program adolescent female athletes were able to significantly decrease their landing forces by 1.2 × bodyweight following a vertical jump. The ability to reduce landing forces is particularly important for the maturing female athlete due to the relationship between high landing forces and knee injury (Hewett et al., 2006).

Therefore, a decrease in landing force may translate to reduced force absorption onto the connective and skeletal structures, decreasing load on the ACL and subsequently ACL injury risk (Myer et al., 2009). The results of the present study show both the combined resistance and plyometric training program were able to produce reductions in landing force in young netball athletes. The current training program emphasized landing with deep knee flexion and to softly absorb landing forces, which may explain the large decrease in GRF following the training intervention.

Knee internal rotation appears to be present in ACL injury situations and usually occurs in combination with valgus knee motion (Koga et al., 2010). Therefore, NMT interventions that are capable of increasing external rotation of the knee have the potential to reduce the amount of stress on the ACL during landing tasks, which may result in a minimisation of knee injury risk (Pfile et al., 2013). The present study found trained participants were able to significantly decrease their knee internal rotation angle following the training intervention. These findings are in agreement with Pfile et al. (2013) who found following a plyometric and core stability program, high school aged female athletes were able to significantly reduce their knee internal rotation angles. The core stability program utilized by Pfile et al. (2013) primarily focused on abdominal exercises, although they did incorporate specific lower body strengthening exercises such as; squats, lunges, hamstring bridges and lumbar extension exercises. Similarly, the strength training component of the present study also included specific lower body resistance exercises executed under load such as; back squats, lunges, split squats and Romanian deadlifts. A meta-analysis by Lesinski et al. (2016) revealed youth athletes respond better to high intensity (80–89% of 1RM) resistance training for improving muscular strength in comparison to lower training intensities (<79% of 1RM). Therefore, NMT programs that incorporate loaded exercises appear to be important in improving lower extremity biomechanics in youth female athletes. Nevertheless, in order to maintain subsequent strength and performance adaptations, athletes in the current study would ultimately need to extend to higher loads. However, it is important to note that technical competency must be upheld at all times and developed prior to executing high loads. Further, to decrease the imbalance between the hamstring and quadriceps musculature incorporation of exercises that promote hamstring activation and strengthening, such as the Romanian Deadlift as used in the present study are important in protecting and stabilizing the knee joint (Hewett et al., 1999).

The effect of the training program on frontal plane knee abduction motion during landing in the DVJ task demonstrated a large and significant increase in the distance between the two lateral knee markers in the trained participants indicating decreased frontal plane knee abduction motion following the 6-week study period. In contrast, the CG showed a decrease in the distance between the two lateral knee markers during landing. The observed increase in the distance between the right and left lateral knee markers designates that the trained participants were able to decrease their knee abduction motion in the frontal plane after completing the 6 week NMT intervention. This may be due to improved landing mechanics as a result of the NMT intervention. It is widely agreed in the literature that female athletes land with increased knee abduction motion in comparison to males (Ford et al., 2003), this increased knee abduction motion has been shown to be a primary predictor of ACL injury risk due to increased ACL loading (Hewett, 2005). Stuelcken et al. (2012) also found increased knee abduction motion in high performance adolescent netball athletes during a SL landing task. As SL landings are commonly performed in practice and competition with netball athletes landing on one leg approximately 67% of the time (Lavipour, 2011) and the primary cause of lower limb injury being incorrect landing technique combined with rapid deceleration and abrupt landing, the need for NMT programs that reduce abduction knee motion are vital to prevent knee injury in netball athletes. Especially during pre-adolescence (Myer et al., 2009). The present study revealed reductions in abduction knee motion in the sagittal plane during the SL landing task following the intervention in both groups. Although not statistically significant, trained participants made a 2.4 times higher reduction in knee abduction motion then the CG at maximum knee flexion-extension ROM, this change revealed a medium effect size. Therefore, in accordance with previous literature, implementation of NMT programs that alter knee biomechanics and reduce abduction knee motion during the landing phase of a jump appear particularly important in reducing ACL injury risk in youth netball athletes.

Implementation of NMT to reduce ACL injury incidence has been shown to be more effective for athletes under the age of 18 (Yoo et al., 2010; Myer et al., 2013). The findings of Myer et al. (2013) supports the rationale for the current study highlighting the need for effective NMT programs in younger athletes. Following puberty, female athletes demonstrate decreased neuromuscular control of the knee in comparison to males, with this loss of neuromuscular control creating altered landing mechanics placing the knee in a disadvantageous position and thus increasing ACL injury risk (Hewett et al., 2004). Knee extensor strength relative to body mass continues to increase through puberty, while knee flexor strength plateaus. This magnifies the imbalance in ham:quad ratio, which increases quadriceps dominance, thereby placing them at increased risk of ACL injury. Therefore, the NMT interventions are critical with a particular emphasis on posterior chain strength development (Quatman-Yates et al., 2013). A meta-analysis by Myer et al. (2013) demonstrated NMT programs would be best implemented during pre- or early-adolescence prior to the period of altered joint mechanics to decrease knee injury risk. They found that NMT may increase measures evidential of the neuromuscular spurt in females. Although plyometric training is important for injury prevention in young female athletes, a sound resistance training component is also imperative for youth athletes as they show the greatest strength adaptations in response to higher intensities (Lesinski et al., 2016), they also require adequate volume to provide an appropriate adaptive stimulus (Behringer et al., 2010). A meta-analysis by Sugimoto et al. (2014) found greater preventative effects with higher NMT volume inclusive of 2 or more sessions per week, exceeding 30 min, providing a higher benefit for ACL injury risk reduction in high school female

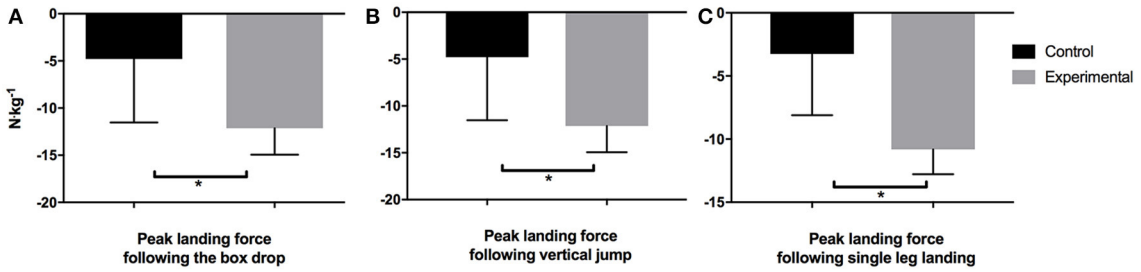


FIGURE 4 | Peak landing forces after a **(A)** Box Drop, **(B)** Vertical Jump, and **(C)** Single Leg Landing. *Significant difference $p < 0.05$.

TABLE 5 | Ground reaction force data for both landing tasks during pre- and post-intervention testing.

Variable			Experimental Mean ± SD	Control Mean ± SD
Drop Vertical Jump Following Drop	Pre	(N)	1,162.8 ± 197.3	1,257.8 ± 278.2
	Post	(N)	546.8 ± 107.5*	934.8 ± 277.5
	Δ (Post-Pre)	(N)	−616.1 ± 131.5*	−313.0 ± 482.6
Following Vertical Jump	Pre	(N)	1,221.5 ± 331.7	1,344.4 ± 234.2
	Post	(N)	611.1 ± 131.5*	1,064.2 ± 364.0
	Δ (Post-Pre)	(N)	−610.6 ± 221.7*	−280.2 ± 393.5
Single Leg Landing Task	Pre	(N)	1,082.3 ± 107.2	1,061.9 ± 167.7
	Post	(N)	556.8 ± 42.1*	877.45 ± 272.2
	Δ (Post-Pre)	(N)	−525.5 ± 95.5*	−184.5 ± 266.6

*Indicates statistical significance $p \leq 0.05$.

athletes. Therefore, it appears that NMT programs which utilize progressive overload as presented in the current study are most beneficial in reducing ACL injury risk factors in youth female athletes in comparison to completing netball training alone.

It should be noted that there are potential limitations with the current study. The inability to control the volume and frequency of netball training between each group may have impacted the results of the study. One of the main goals of the present study was to add resistance training to the netball practice of youth athletes in accordance with best practice recommendations for youth resistance training (Faigenbaum et al., 2016). While it is possible that adding more netball specific training in lieu of strength training might have resulted in improvements in injury risk factors it is important to note that youth sport practice and games may not enable the young athlete to accumulate the recommended amount of moderate-to-vigorous physical activity, as a large proportion of time in practice (and even competition) can be spent in sedentary or low-intensity physical activities (Leek et al., 2011; Guagliano et al., 2013). While the design of the current study is in-line with previous NMT interventions in young athletes (Sander et al., 2013; Keiner et al., 2014), it would be prudent to examine the effects of combined NMT and netball training vs. equated volumes of solely netball training. Although the present study was not designed to answer this specific question it is important to contextualize the fact that the present data suggests that simply adding a NMT program to regular netball training activities of youth netball players does in fact result in significant training benefits. These benefits are noted in the two landing tasks presented in the present study. It is however possible that more complex landing tasks that incorporate landing as well as sport specific skill such as catching and throwing need to be evaluated to develop a more comprehensive understanding of the impact of a NMT program in youth athletes. Even though the present study was not designed to specifically determine the neuromuscular factors that underpin the noted differences in landing mechanics, it does suggest that a NMT confers benefits to the youth netball player. Future research is warranted in order to understand the neuromuscular factors as well as to determine the long-term impact of integrating a NMT program in the preparation of youth Netball Players.

CONCLUSION

Netball has a reputation for a high incidence of knee injuries, with most injuries occurring during abrupt landings from a jump combined with incorrect landing technique. Therefore, it appears important that implementation of NMT programs that teach youth netball athletes proper landing technique and to safely absorb landing forces are important in the prevention of ACL injuries. The results of this study provide evidence that NMT programs encompassing progressive

resistance and plyometric training decrease associated risk factors for non-contact ACL injuryincluding poor knee-joint biomechanics and increased landing forces in youth female netball athletes. Much of the benefit of the program appeared to be through improved knee flexion-extension ROM, increased knee external rotation angle, decreased frontal plane knee abduction motion, and decreased landing forces. It is important to note that the current study used athletes who had no history of strength training prior to participating in the present study. As such for ongoing strength and performance adaptations to occur this program should be contextualized as part of a long-term athlete development program which when appropriately applied results in long term physical adaptations that are above and beyond that of growth and maturation.

AUTHOR CONTRIBUTIONS

AH: worked on study design, data collection, data analysis, and manuscript preparation. EH: assisted with training intervention design, delivery of training, data collection, and manuscript preparation. CJ: assisted with study design, worked on all biomechanical analyses, and assisted with manuscript preparation. RL: assisted with study design, data analysis and manuscript preparation. GH: assisted with study design, data collection, data analysis, and manuscript preparation.

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Trunk Muscle Activity during Drop Jump Performance in Adolescent Athletes with Back Pain

Steffen Mueller, Josefine Stoll, Juliane Mueller, Michael Cassel and Frank Mayer*

University Outpatient Clinic, Sports Medicine and Sports Orthopaedics, University of Potsdam, Potsdam, Germany

In the context of back pain, great emphasis has been placed on the importance of trunk stability, especially in situations requiring compensation of repetitive, intense loading induced during high-performance activities, e.g., jumping or landing. This study aims to evaluate trunk muscle activity during drop jump in adolescent athletes with back pain (BP) compared to athletes without back pain (NBP). Eleven adolescent athletes suffering back pain (BP: m/f: $n = 4/7$; 15.9 ± 1.3 y; 176 ± 11 cm; 68 ± 11 kg; 12.4 ± 10.5 h/we training) and 11 matched athletes without back pain (NBP: m/f: $n = 4/7$; 15.5 ± 1.3 y; 174 ± 7 cm; 67 ± 8 kg; 14.9 ± 9.5 h/we training) were evaluated. Subjects conducted 3 drop jumps onto a force plate (ground reaction force). Bilateral 12-lead SEMG (surface Electromyography) was applied to assess trunk muscle activity. Ground contact time [ms], maximum vertical jump force [N], jump time [ms] and the jump performance index [m/s] were calculated for drop jumps. SEMG amplitudes (RMS: root mean square [%]) for all 12 single muscles were normalized to MIVC (maximum isometric voluntary contraction) and analyzed in 4 time windows (100 ms pre- and 200 ms post-initial ground contact, 100 ms pre- and 200 ms post-landing) as outcome variables. In addition, muscles were grouped and analyzed in ventral and dorsal muscles, as well as straight and transverse trunk muscles. Drop jump ground reaction force variables did not differ between NBP and BP ($p > 0.05$). Mm obliquus externus and internus abdominis presented higher SEMG amplitudes (1.3–1.9-fold) for BP ($p < 0.05$). Mm rectus abdominis, erector spinae thoracic/lumbar and latissimus dorsi did not differ ($p > 0.05$). The muscle group analysis over the whole jumping cycle showed statistically significantly higher SEMG amplitudes for BP in the ventral ($p = 0.031$) and transverse muscles ($p = 0.020$) compared to NBP. Higher activity of transverse, but not straight, trunk muscles might indicate a specific compensation strategy to support trunk stability in athletes with back pain during drop jumps. Therefore, exercises favoring the transverse trunk muscles could be recommended for back pain treatment.

Keywords: SEMG-pattern, back pain, pre-activity, drop jump, neuromuscular, trunk, performance, young athletes

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****Correspondence:***
Steffen Mueller
stefmue@uni-potsdam.de

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INTRODUCTION

Back pain (point) prevalence in adolescent athletes is reported at a rate of 8–20%, with a relevant increase beginning around age 14 and featuring sport-specific differences (Schmidt et al., 2014; Müller et al., 2017). Consequently, back pain can be considered a relevant risk factor in the careers of young elite athletes.

In the context of back pain, great emphasis has been placed on the importance of trunk stability, especially in situations requiring compensation of repetitive, intense loading induced during high-performance activities, e.g., jumping or landing (Cholewicki et al., 2000; Borghuis et al., 2008; Simons and Bradshaw, 2016). In etiology, repetitive micro-trauma and insufficiency of the muscle-tendon complex based on an inadequate neuromuscular and postural control, and a reduced maximum strength capacity in addition to trunk muscle fatigue during dynamic loading are discussed as an explanatory model (George and Delitto, 2002; Sassmannshausen and Smith, 2002; Standaert, 2002, 2008; Trainor and Wiesel, 2002; Bono, 2004; Trainor and Trainor, 2004; Lawrence et al., 2006). In particular, trunk muscle forces providing stability are considered meaningful in counteracting high-impact loading during high-intensity activities (Kibler et al., 2006; Borghuis et al., 2008; Larivière et al., 2015; Prieske et al., 2016). When compensating high loading, a reduced trunk strength capacity as well as delayed muscle onset, increased co-contractions, and increased SEMG variability has been shown in back pain patients (Cholewicki et al., 2000; Radebold et al., 2000, 2001; Marras et al., 2005). In a recent systematic review, Abboud et al. could moreover show evidence for back pain related decreased erector spinae and increased external obliquus muscle reflex amplitudes (Abboud et al., 2016). In addition, trunk strength capacity is considered essential for the compensation of external forces and loads in young and adult athletes (Kibler et al., 2006; Zazulak et al., 2006, 2007; Wirth et al., 2016).

As reported in previous studies, different types of sports reveal specific demands on core stability (Helge and Kanstrup, 2002; McGregor et al., 2004; Iwai et al., 2008; Baur et al., 2010; Mueller et al., 2012). Nevertheless, Kibler et al. (2006) described the role of core stability for all types of sports, whether running, throwing or jumping tasks. High-impact forces acting on the trunk are reported in judo, rowing, weight lifting, (rhythmic) gymnastics, and jumping (Liemohn et al., 2005; Peate et al., 2007; Hibbs et al., 2008; Ripamonti et al., 2008). Repetitive loading with large components of translation, rotation and reclination movements are believed to result in stress of the structures involved (Hutchinson, 1999; Sassmannshausen and Smith, 2002; Adirim and Cheng, 2003; Jones et al., 2005). It could be shown that athletic tasks like running, hopping, jumping and landing increase the impact forces that need to be compensated (Dufek and Bates, 1990; Keller et al., 1996; Simons and Bradshaw, 2016). Simons and Bradshaw (2016) reported an additional loading of the trunk with up to eight times the body weight during repetitive hopping or drop landing. The importance of trunk strength capacity was recently reported as beneficial not only for compensating loading and stabilizing the trunk, but also for enhancing athletic performance (Kibler et al., 2006; Zazulak et al., 2006, 2007). Furthermore, Zazulak et al. (2007) reported an association between trunk muscle activity and lower limb kinematics during landing tasks. Decreased neuromuscular activity is attributed to higher knee valgus, increasing injury risk at the knee. Hence, an inadequate (neuromuscular) compensation strategy is discussed as a common cause of overloading and injury. As a possible consequence, there is a need to identify relevant trunk muscles that must necessarily be addressed in injury and overload prevention. Nevertheless, the role of back pain as one factor influencing neuromuscular activity of the trunk-encompassing muscles has not been clarified.

Therefore, this study aims to evaluate trunk muscle activity during drop jump (DJ) in adolescent athletes with back pain compared to their healthy counterparts. An altered neuromuscular activity strategy driven by higher ventral and reduced dorsal muscle SEMG amplitudes in athletes suffering from back pain while performing and compensating high-impact loading during drop jumps is expected compared to healthy athletes.

MATERIALS AND METHODS

Subjects

Twenty-two adolescent athletes ($n = 11$ with back pain, BP; $n = 11$ gender and age matched athletes without back pain, NBP) were enrolled in the study from different sports (BP: $n = 8$ canoeing/rowing, $n = 2$ triathlon, $n = 1$ wrestling; NBP: $n = 9$ canoeing/rowing, $n = 2$ triathlon). Age below 18 years and affiliation with the organized training system for elite athletes served for inclusion criteria, and acute infection, contraindications for exercise or pain other than BP served as exclusion criteria. BP was defined as current back pain intensity assessed with a visual analog scale (VAS: 0–10 cm; 0 = no pain, 10 = maximum imaginable back pain). All athletes reporting VAS $\geq$ 2.0 cm were assigned to BP (Nelson-Wong et al., 2012). This type of questionnaire is described as valid for the use of subjective pain assessment in adolescents (Kropp, 2004; Merati et al., 2004). Anthropometrics for BP and NBP are detailed in **Table 1**. This study was carried out in accordance with the recommendations of the European Community Good Clinical Practice (EC-GCP), approved by the University Potsdam Ethical Committee. All participants and their legal guardians were informed of the study and the specific testing procedures in a personal conversation with the principle investigator and through written study information during their stay at the University Outpatient Clinic. Before voluntary participation in the study, the legal guardian and the adolescent participant provided written informed consent in accordance with the Declaration of Helsinki.

Procedures

A cross-sectional study design was used to evaluate drop jump performance in young athletes with and without back pain. The test protocol started with a medical check-up to

TABLE 1 | Characteristics of adolescent athletes (anthropometric and training data) with (BP) and without (NBP) back pain.

Group	*n* (f/m)	Age [years]	Height [cm]	Weight [kg]	tr. volume [h/week]	Back pain VAS [cm]
BP	7/4	15.9 ± 1.3	176 ± 11	68 ± 11	12.4 ± 10.7	3.2 ± 1.4
NBP	7/4	15.5 ± 1.3	174 ± 7	67 ± 8	14.9 ± 9.5	0 ± 0

ensure that all participants were suitable for the upcoming jumping tests. In addition, anthropometric data, training history and subjective back pain intensity (visual analog scale VAS) were assessed. Afterwards, all participants were prepared for SEMG analysis of the trunk muscles. Following this, all athletes underwent a general physical warm-up of at least 5 min prior testing. For SEMG normalization, the maximum isometric voluntary contraction (MIVC) of trunk flexion and extension was measured using an isokinetic dynamometer (Contrex MJ/TP, Physiomed AG, Schnaittach, Germany). After 1 min. of trunk extension/flexion warm-up and a practice trial for maximum isometric trunk flexion and for trunk extension on the dynamometer, the test was executed for 5 s each time. Participants were fixed to the dynamometer in a standing position at the lower leg and the knee, and then additionally with 2 non-stretching belts at the hip and upper body. Measurement position was defined in a middle position at 17.5° trunk flexion. Further details for the positioning could be seen elsewhere (Mueller et al., 2014). Then, complex motor performance was assessed with drop jumps (DJ). Initial instruction was followed by a demonstration and one practice trial before jump measurements were performed. Three repetitions were always captured for DJ.

Ground Reaction Force

Drop jumps were performed from a 20 cm-high box onto a ground reaction force (GRF) plate (Amti OR6-6, Advanced Mechanical Technology, Inc., Watertown USA). Participants were instructed to drop onto the plate and jump as fast and high as possible from the plate, finally landing stably on the plate. No restrictions on arm movement were given. Ground contact time (Ct: [ms]), jump time (Jt: [ms]), peak force at take-off (Fz: [N]) and the performance index (Pi: [m/s]; formula: performance index = jump height/contact time) were calculated as the mean of 3 drop jumps GRF and act as secondary variables (Prieske et al., 2013).

Trunk Muscle Activity

Muscular activity of the trunk was assessed using a bilateral 12-lead SEMG (Radebold et al., 2000) (**Figure 1A**): Mm. rec. abd. (RA), obl. ext. abd. (EO), obl. int. abd (IO); Mm. erec. spinae thoracic (T9; UES)/lumbar (L3; LES), latis. dorsi (LD). The location of the electrodes was carefully determined according to Radebold et al. (2000). Before electrodes (AMBU Medicotest, Denmark, Type N-00-S, interelectrode distance: 2 cm) were applied, the skin was shaved and slightly roughened to remove surface epithelial layers and control skin resistance (<5 kΩ). The longitudinal axes of the electrodes were placed in line with the underlying muscle fibers and checked for minimum cross-talk by inspection during the initial muscle tests.

For SEMG data analysis, muscular activity was analyzed using a bilateral and bipolar surface telemetric SEMG (band-pass filter: 5–500 Hz, gain: 5.0, overall gain: 2,500, sampling frequency: 4,000 Hz, RFTD32, myon AG, Baar, CH). No additional filter was applied post processing. The signal was rectified and averaged before calculation of the outcome measures. SEMG amplitudes (rout mean square RMS: [%]) were normalized to the isometric maximum voluntary contractions (MIVC). Mean amplitudes for the left and right side were calculated separately and both sides were averaged for each muscle and analyzed in 4 time windows [100 ms pre- (Pre_i), 200 ms post- (Post_i) initial ground contact; 100 ms pre- (Pre_l), 200 ms post- (Post_l) drop jump landing], triggered manually by an experienced investigator using the ground reaction force signal, as SEMG measurements (**Figure 1B**). Jumping trials showing artifacts (movement) were not considered for further analysis (Software: IMAGO process master, LabView®-based, pfitec, biomedical systems, Endingen, Germany).

As SEMG outcome variables, the SEMG-RMS measurements [%] for all 12 muscles were computed (secondary outcomes). After calculation of the mean across all 4 time windows, muscles were grouped and analyzed in ventral (grouping of RA, IO, EO) and dorsal (grouping of LD, UES, LES) muscles, as well as straight (grouping of RA, UES, LES) and transverse (grouping of IO, EO, LD) trunk muscles. The SEMG-RMS for the grouped ventral muscles was defined as primary outcome all other variables as secondary outcomes.

Statistical Analysis

All non-digital data were documented in a handwritten case report form and transferred to a database for further statistical analysis (JMP Statistical Software Package 9, SAS Institute®). For all data, a plausibility check was performed. Implausible values (range check) were compared with the raw data and corrected/recalculated (<1%), if necessary. After data was tested for normality (Shapiro-Wilk-Test) descriptive statistics (mean ± SD) was followed by un-paired *t*-test to account for differences between groups (BP/NBP) ($\alpha = 0.05$).

RESULTS

Ground Reaction Force

The GRF measurements did not differ between NBP and BP ($p > 0.05$). Overall, athletes showed a ground contact time of 290 ± 71 ms, a mean jump time of 434 ± 49 ms, a peak force during take-off phase of 2,756 ± 539 N and a performance index of 0.83 ± 0.21 m/s. Group results (NBP/BP) for jump performance are detailed in **Table 2**.

Trunk Muscle Activity

In the pre-activity phase, 100 ms pre-initial ground contact, SEMG-RMS ranged from 15 ± 13 to 110 ± 54% in NBP and 11 ± 5 to 128 ± 74% in BP without significant group differences. SEMG-RMS for the 200 ms post-initial ground contact ranged from 28 ± 23 to 149 ± 52% in NBP and 34 ± 22 to 188 ± 73% in BP. BP revealed higher SEMG activity compared to NBP, except for LES, and was statistically significant for EO and IO ($p = 0.033/0.027$; $t = 2.29/2.39$) (**Figures 2**, **3**). In the second pre-activity phase, 100 ms before drop jump landing, LD showed the highest activity (NBP: 95 ± 182%; BP: 120 ± 62%) in both groups. Nevertheless, statistically significant differences between groups were not present. After landing, 200 ms post-drop jump landing, SEMG-RMS ranged from 12 ± 5% to 99 ± 64% in NBP and 17 ± 9% to 118 ± 44%. Group differences were only present for EO, with BP showing higher values compared to NBP ($p = 0.041$;

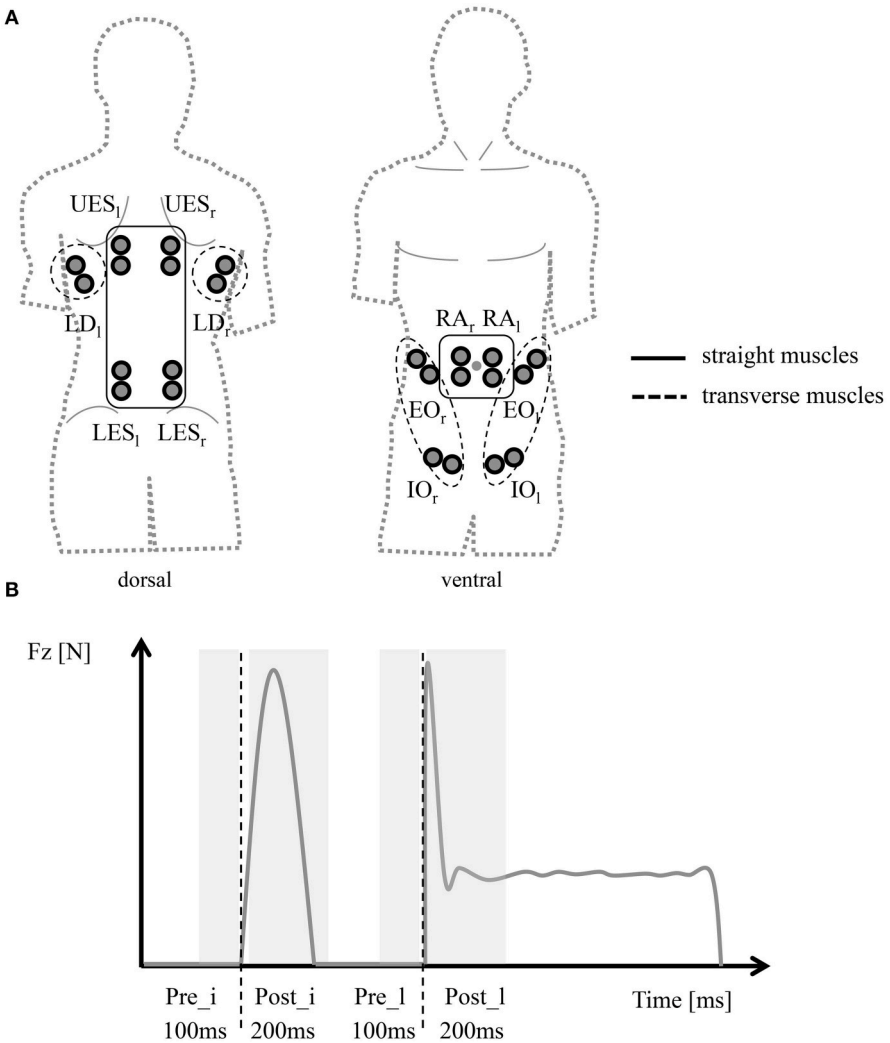


FIGURE 1 | Methodological SEMG setup. (A) Bilateral 12-lead SEMG setup framing groups of transverse and straight trunk muscles. **(B)** Time windows for SEMG-RMS analysis [100 ms pre- (Pre_i), 200 ms post- (Post_i) initial ground contact; 100 ms pre- (Pre_l), 200 ms post- (Post_l) drop jump landing] triggered by ground reaction force (Fz) signal.

TABLE 2 | Drop jump performance [ground contact time (Ct; ms); jump time (Jt; ms); peak force at take-off (Fz; N); performance index (Pi; m/s)] in athletes with (BP) and without (NBP) back pain (mean ± SD).

Group	Contact time (Ct, [ms])	Jump time (Jt, [ms])	Peak force (Fz, [N])	Performance index (Pi, [m/s])
BP	279 ± 60	427 ± 51	2677 ± 333	0.827 ± 0.188
NBP	302 ± 82	441 ± 49	2835 ± 697	0.837 ± 0.232

$t = 2.20$) (**Figure 4**). Overall, EO and IO presented a 1.26- to 1.93-fold higher SEMG-RMS in BP compared to NBP for all time windows analyzed. SEMG-RMS for RA, UES, LES, and LD did not differ between groups in the four time windows analyzed. For groups, all muscles and analyzed time phases normalized SEMG-RMS values are shown in **Table 3**.

The muscle group analysis over all 4 time window showed statistically significantly higher SEMG-RMS for BP in the ventral ($p = 0.031$; $t = 2.34$; power = 0.6021) and transverse muscles ($p = 0.020$; $t = 2.55$), with BP showing higher amplitudes compared to NBP (**Figure 5**).

DISCUSSION

Altered neuromuscular activity in back pain patients compared to healthy subjects is known (Radebold et al., 2001; Maaswinkel et al., 2016). This study aimed to evaluate neuromuscular activity of the trunk muscles during high-impact loading represented by drop jump performance in adolescent athletes with back pain compared to healthy counterparts. The main findings of the investigation are an altered neuromuscular activation pattern in adolescent athletes with back pain,

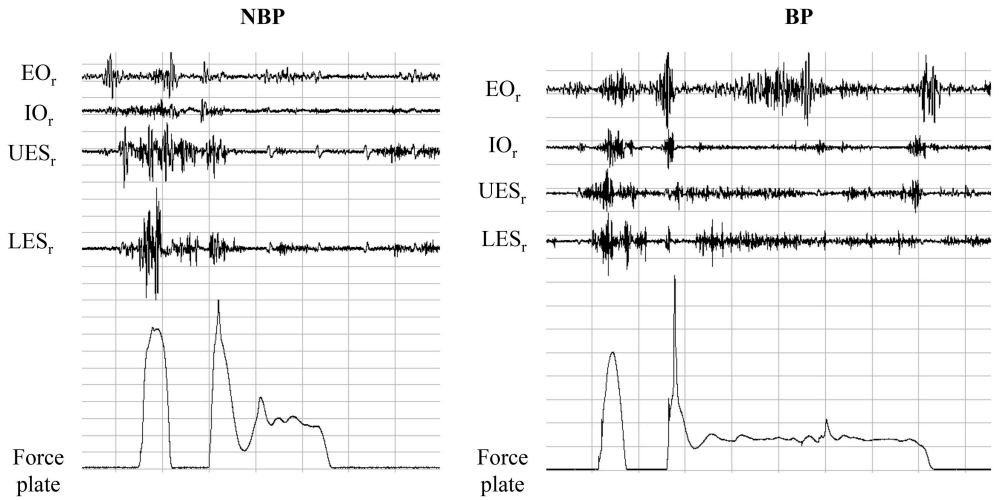


FIGURE 2 | In an exemplary way SEMG raw signals, for Mm. obl. ext. abd. (EO), obl. int. abd (IO); Mm. erec. spinae thoracic (T9; UES)/lumbar (L3; LES), and for ground reaction force signal (Fz) for one subject with (BP) and without (NBP) back pain, are shown.

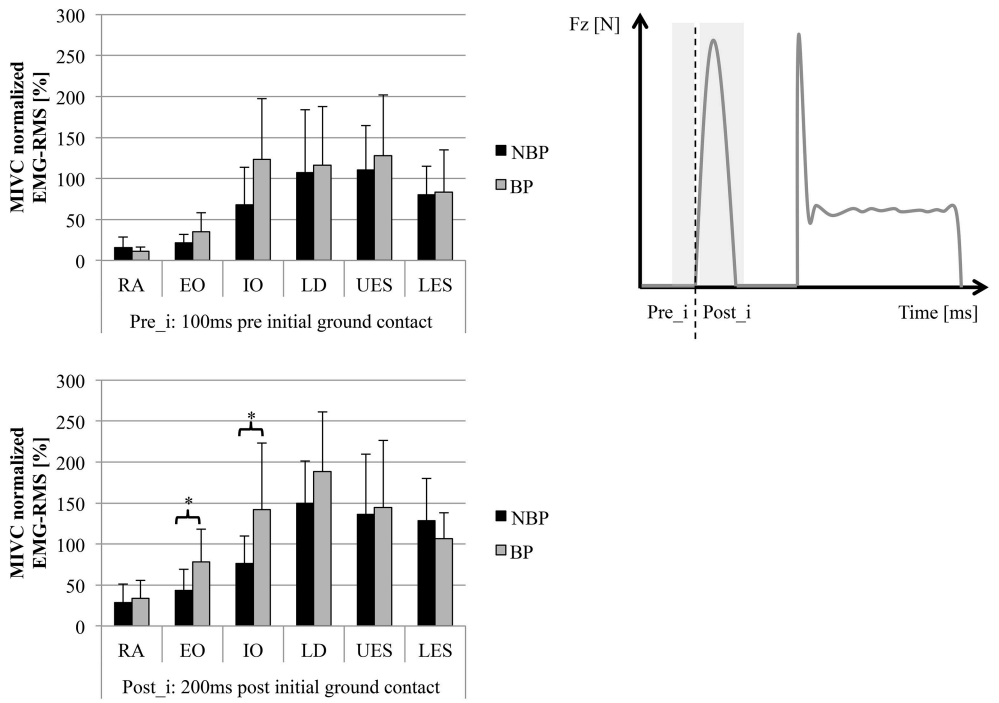


FIGURE 3 | SEMG-RMS (normalized MIVC [%]) for 6 trunk muscles (average of left/right sides) for pre- (Pre_i) and post- (Post_i) initial ground contact phase (mean ± SD; *$p < 0.05$). Muscles: Mm. rec. abd. (RA), obl. ext. abd. (EO), obl. int. abd (IO); Mm. erec. spinae thoracic (T9; UES)/lumbar (L3; LES), latis. dorsi (LD).

with increased SEMG amplitudes for the M. obl. ext. abd (EO) and M. obl. int. abd (IO) especially during reactive ground contact (Post_i). Regarding the total jumping cycle the abdominal and transverse muscle groups showed increased SEMG amplitudes with similar absolute drop jump performance measurements.

There is existing evidence that athletic performance and function is an outcome of the appropriate (neuromuscular and kinetic) coordination of body segments (Kibler et al., 2006). Back pain is often discussed as an influencing factor, but, despite the existence of back pain, the adolescent BP athletes do not show a reduction in (drop) jump performance capacity. Jump

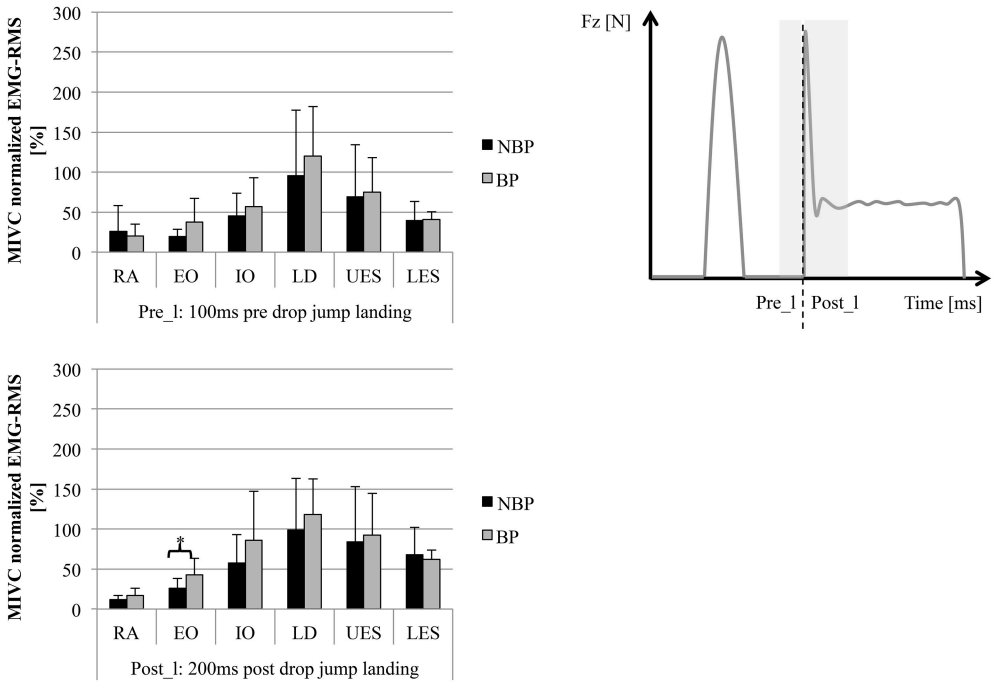


FIGURE 4 | SEMG-RMS (normalized MIVC [%]) for 6 trunk muscles (average of left/right sides) for pre- (Pre_l) and post- (Post_l) initial drop jump landing (mean ± SD; *$p < 0.05$). Muscles: Mm. rec. abd. (RA), obl. ext. abd. (EO), obl. int. abd (IO); Mm. erec. spinae thoracic (T9; UES)/lumbar (L3; LES), latis. dorsi (LD).

TABLE 3 | SEMG-RMS (normalized MIVC [%]) for 6 trunk muscles (average of left/right sides) for pre- (Pre_i) and post- (Post_i) initial ground contact phase and for pre- (Pre_l) and post- (Post_l) initial drop jump landing (mean ± SD).

Group	Phase	RA	EO	IO	LD	UES	LES
BP	Pre_i	11 ± 5	35 ± 23	124 ± 74	116 ± 71	128 ± 74	84 ± 51
NBP	Pre_i	15 ± 13	21 ± 11	68 ± 45	108 ± 76	110 ± 54	80 ± 35
BP	Post_i	34 ± 22	78 ± 40	142 ± 81	188 ± 73	144 ± 82	106 ± 31
NBP	Post_i	28 ± 23	44 ± 26	76 ± 34	149 ± 52	136 ± 73	128 ± 51
BP	Pre_l	20 ± 15	38 ± 30	57 ± 36	120 ± 62	75 ± 43	41 ± 10
NBP	Pre_l	26 ± 32	20 ± 9	45 ± 29	95 ± 82	69 ± 65	40 ± 24
BP	Post_l	17 ± 9	43 ± 21	86 ± 61	118 ± 44	93 ± 52	62 ± 12
NBP	Post_l	12 ± 5	26 ± 12	57 ± 36	99 ± 64	84 ± 69	68 ± 34

Muscles: Mm. rec. abd. (RA), obl. ext. abd. (EO), obl. int. abd (IO); Mm. erec. spinae thoracic (T9; UES)/lumbar (L3; LES), latis. dorsi (LD).

performance alone might therefore not serve as a valid indicator for deficits in adolescent athletes with back pain. In this context, the level of back pain and chronification might play a relevant role. It could also be speculated that high pain levels compared to our cohort might show reduced performance as described in other papers (Balagué et al., 2012; Bauer et al., 2015).

However, in terms of trunk muscle activity, BP is associated with an altered neuromuscular activity level as reported previously (Radebold et al., 2001; Nelson-Wong and Callaghan, 2010; Abboud et al., 2016; Maaswinkel et al., 2016). A decreased muscle activity for the dorsal muscle group (e.g., erector spinae), as reported by Ramprasad et al., and Shenoy et al., for patients with back pain, could not be supported by our data (Ramprasad et al., 2010; Shenoy et al., 2013). But, increased muscle activity in the abdominal and transverse muscle groups correspond to higher co-contractions, already presented in other trunk loading experiments (Radebold et al., 2001; Nelson-Wong and Callaghan, 2010). Furthermore, Liebetrau et al. could present in their musculoskeletal model that delayed abdominal muscle reflex lead to a reduced trunk stability. Information's about detailed association for pain and function (higher pain—higher functional deficits) are rare since experimental studies mainly remain to the dichotomous comparisons of pain to identify functional differences (Liebetrau et al., 2013; Schinkel-Ivy et al., 2013; Abboud et al., 2016). To compensate delayed reflex activity, higher activation amplitudes of the abdominal

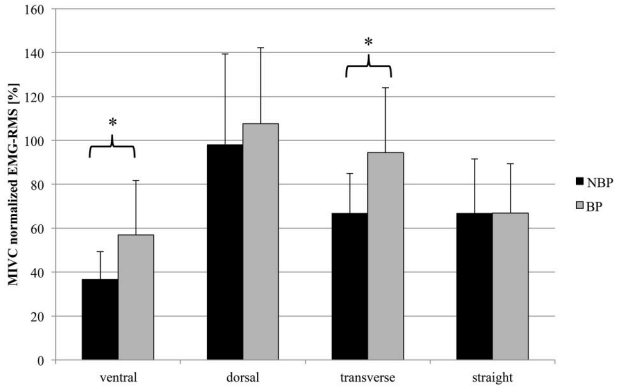


FIGURE 5 | Mean SEMG-RMS (normalized MIVC [%]) for muscle groups (ventral vs. dorsal; transverse vs. straight) across total drop jump performance (mean ± SD; *$p < 0.05$). Muscles: Mm. rec. abd. (RA), obl. ext. abd. (EO), obl. int. abd (IO); Mm. erec. spinae thoracic (T9; UES)/lumbar (L3; LES), latis. dorsi (LD).

muscles are valid (Liebetrau et al., 2013). Transferring this to drop jumps, it could be speculated that the shown increased muscle activity (Mm obl. abd. intern./extern.) serves as a compensation strategy to enhance core stability and protect the trunk from further negative loading (Kibler et al., 2006; Hibbs et al., 2008; Prieske et al., 2015; Wirth et al., 2016). It is also known that the stability provided by the trunk muscles is meaningful in counteracting single and repetitive loading during high-intensity performance (Kibler et al., 2006).

The combination of a similar (jump) performance and yet increased neuromuscular trunk activity level in adolescent BP athletes compared to NBP athletes still appears controversial. It could be speculated that BP athletes present a less efficient jump performance execution. Otherwise, the additional muscle activation might show the functional adaptive response in athletes supporting an appropriate protection from overloading (Maaswinkel et al., 2016). Therefore, drop jumps could serve as a suitable test situation to analyze alterations in the neuromuscular trunk activity of athletes with and without back pain. Additionally, SEMG activity might reflect the compensation capacity for repetitive high loading. It remains to be seen whether this might not only serve to identify athletes suffering from back pain, but also athletes at risk for developing it. In addition, this analysis might allow a valid evaluation of athletes in order for them to return to sports after a period of back pain. Nevertheless, these points of discussion need further verification.

Consequently, optimizing neuromuscular core stability is considered beneficial for protection against repetitive and excessive overloading of the trunk (Kibler et al., 2006; Borghuis et al., 2008; Saragiotto et al., 2016; Wirth et al., 2016). In line with the results presented here, core stability exercises (with additional repetitive loading) addressing the complex interaction of transverse, straight, ventral and dorsal muscles in adolescent athletes with back pain should be preferred (Pedersen et al., 2004; Saragiotto et al., 2016).

Certain limitations have to be considered when interpreting the results. Acute but no average pain was assessed and association of pain with outcome variables is not presented since correlation analysis would not be valid for the existing skewed pain distribution (no subjects with pain intensity between 0 and 2 VAS). SEMG normalization is often used to acquire comparable values between different individuals and groups, but contains some crucial points. The pain might influence the MIVC measurement used, since the intended 100% activation might not be reached. This could lead to reduced strength values and a systematic overestimation of the normalized SEMG amplitudes during the jumps for the patients (Marras et al., 2005). Our data showed for the MIVC measurement in extension and flexion (18/23%) lower strength values for BP. But, the higher (BP) activity during jumping was only for the flexor muscles, but not for the others present. Therefore, considering this limitation, the SEMG method and normalization procedure used seem valid. Furthermore, the highly standardized dynamometer-based MIVC extension and flexion test might not challenge all ventral/dorsal or straight/transverse muscles identically (Iida et al., 2011). This should be noted to put the normalized SEMG values (e.g., LD > 100%) into perspective. The SEMG setup used has been shown as valid in previous studies, but the possibility of a bit of cross-talk between muscles cannot be totally denied (Radebold et al., 2001). Concerning the investigated athletes performing mainly rowing, the applicability to other sports needs to be proven in future investigations. Finally, only the current, but not the average back pain intensity across days or weeks was assessed and might have influenced the results.

In conclusion, adolescent athletes with moderate back pain intensity are capable of presenting (jump) performance comparable to that of their healthy counterparts. Higher activity of the transverse, but not the straight, trunk muscles indicates a specific compensation strategy to support trunk stability in athletes with back pain during drop jumps. For prevention and therapy, specific sensorimotor exercises addressing the transverse trunk muscles with e.g., 3-dimensional loading situations might be beneficial.

AUTHOR CONTRIBUTIONS

The author contributions are distributed as followed: conception or design of the work (SM, JM, FM), data acquisition (SM, JS, JM, MC), data analysis (SM, JM) and interpretation (SM, JM, FM); drafting (SM) or revising (JS, JM, MC, FM) the work; final approval of the version to be published (SM, JS, JM, MC, FM); agreement to be accountable for all aspects of the work (SM, JS, JM, MC, FM).

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REVIEW
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Imbalances in the Development of Muscle and Tendon as Risk Factor for Tendinopathies in Youth Athletes: A Review of Current Evidence and Concepts of Prevention

Falk Mersmann[1,2], *Sebastian Bohm*[1,2] *and Adamantios Arampatzis*[1,2*]

[1] Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany, [2] Berlin School of Movement Science, Berlin, Germany

Tendons feature the crucial role to transmit the forces exerted by the muscles to the skeleton. Thus, an increase of the force generating capacity of a muscle needs to go in line with a corresponding modulation of the mechanical properties of the associated tendon to avoid potential harm to the integrity of the tendinous tissue. However, as summarized in the present narrative review, muscle and tendon differ with regard to both the time course of adaptation to mechanical loading as well as the responsiveness to certain types of mechanical stimulation. Plyometric loading, for example, seems to be a more potent stimulus for muscle compared to tendon adaptation. In growing athletes, the increased levels of circulating sex hormones might additionally augment an imbalanced development of muscle strength and tendon mechanical properties, which could potentially relate to the increasing incidence of tendon overload injuries that has been indicated for adolescence. In fact, increased tendon stress and strain due to a non-uniform musculotendinous development has been observed recently in adolescent volleyball athletes, a high-risk group for tendinopathy. These findings highlight the importance to deepen the current understanding of the interaction of loading and maturation and demonstrate the need for the development of preventive strategies. Therefore, this review concludes with an evidence-based concept for a specific loading program for increasing tendon stiffness, which could be implemented in the training regimen of young athletes at risk for tendinopathy. This program incorporates five sets of four contractions with an intensity of 85–90% of the isometric voluntary maximum and a movement/contraction duration that provides 3 s of high magnitude tendon strain.

Keywords: muscle, tendon, adaptation, athletes, adolescence, tendinopathy, imbalance

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****Correspondence:***
Adamantios Arampatzis
a.arampatzis@hu-berlin.de

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INTRODUCTION

Tendinopathy is a clinical condition that is associated with pathological processes within the tendon and pain (Fredberg and Stengaard-Pedersen, 2008). In specific sport disciplines (i.e., jump disciplines) about every second athlete develops a tendinopathy during the athletic career and most individuals suffer from chronic symptoms (Lian et al., 2005). Until recently, only few information was available on the prevalence of tendinopathy in children and adolescents. However, the available literature indicates that tendon overload injury is a common issue in youth sports and that the

prevalence increases during maturation (Simpson et al., 2016). Some reports indicate that tendinopathy is the most frequent overuse injury in adolescent athletes (Le Gall et al., 2006). The present narrative review explores the hypothesis that an imbalanced adaptation of muscle and tendon might contribute to the etiology of tendinopathies in youth sports.

In the production of movement, muscles and tendons work as a unit, in which the tendon transmits the forces generated by the muscle to the skeleton (Józsa and Kannus, 1997; Nigg and Herzog, 2007). The resultant stress that is applied to the tendon (i.e., force normalized to tendon cross-sectional area) is a measure of absolute load on the tissue irrespective of its dimensions. Yet, ultimate stress (i.e., stress at tendon failure) varies markedly across different tendons and species (LaCroix et al., 2013). In contrast, the ultimate strain of tendons is remarkably constant (Abrahams, 1967; Loitz et al., 1989; LaCroix et al., 2013; Shepherd and Screen, 2013). This means that, from a mechanobiological perspective, tendon strain is the most adequate indicator of the mechanical demand for the tendon as a result of loading. Though it has been argued that an increase of stress might still contribute to either physiological adaptation (Wiesinger et al., 2015) or pathological changes (Couppé et al., 2013), experimental evidence clearly highlights habitual tendon strain as the most crucial parameter for the risk of injury (Wren et al., 2003; LaCroix et al., 2013; Veres et al., 2013). Therefore, an increase of the strength-generating capacity of a muscle needs to go in line with a corresponding modulation of the mechanical properties of the respective tendon. The increase of tendon stiffness (i.e., the slope of the force-elongation relationship) serves as a protective mechanism for integrity of the tendinous tissue and has been frequently observed in humans to accompany strength gains due to both mechanical loading (Kubo et al., 2001a; Arampatzis et al., 2007; Kongsgaard et al., 2007) as well as maturation (Kubo et al., 2001b, 2014; O'Brien et al., 2010b; Waugh et al., 2012; Mersmann et al., 2016). Yet, there is now growing evidence that the adaptation of muscle and tendon does not necessarily proceed in a uniform manner during a training process. In young athletes, maturation acts as an additional stimulus on the development of the muscle-tendon unit, which could potentially further challenge the uniformity of muscle strength and tendon stiffness changes. In the following chapters, we will summarize potentially influential factors for an imbalanced musculotendinous development during training and maturation. We discuss evidence of non-uniform muscle and tendon adaptation in adults and adolescent athletes and the potential implications. The review concludes with proposing a concept for prevention, which targets the increase of tendon stiffness and is based on recent advancements in our understanding of tendon adaptation.

INFLUENTIAL FACTORS OF IMBALANCED MUSCLE-TENDON ADAPTATION AND DEVELOPMENT

The following sections will briefly review the basic mechanisms of muscle and tendon adaptation and mechanotransduction. We will emphasize differences in the temporal dynamics of adaptive changes and the mechanical stimuli that effectively elicit changes of the respective tissue properties, structure and morphology. For a more comprehensive overview on muscle or tendon adaptation the reader is referred, for instance, to the reviews by Toigo and Boutellier (2006), Folland and Williams (2007), and Gonzalez et al. (2016), or Wang (2006), Magnusson et al. (2007), and Bohm et al. (2015), respectively.

Differences in the Temporal Dynamics of Muscle and Tendon Adaptation

Muscle and tendon tissue both adapt to increased mechanical loading from the subcellular to the macroscopic level. Here we give a synopsis about the changes that can be observed in the musculotendinous system that are most relevant for strength and power production. With regard to the scope of this review, we will specifically address the time course of these changes and the features of muscles and tendons that might be responsible for differences in the temporal dynamics of adaptation.

Basic Mechanisms of Muscle Adaptation

The adaptive changes that affect the strength generating capacity of a muscle can be categorized into (a) radial adaptation, (b) longitudinal adaptation and (c) adaptation of specific tension (Goldspink, 1985; Bottinelli, 2001). Radial adaptation describes the modulation of the number of sarcomeres in parallel and is best reflected by changes of the physiological cross-sectional area (PCSA) of a muscle (Haxton, 1944), which is the area of the muscle cross-section perpendicular to the orientation of the fibers. In humans, an increase in muscle PCSA following strength training has been demonstrated for the elbow flexors (Kawakami et al., 1995) and knee extensors (Kawakami et al., 1995; Seynnes et al., 2009; Erskine et al., 2010). Moreover, several authors reported an increase of pennation angle after applying interventions that promote muscle strength (Aagaard et al., 2001; Blazevich et al., 2007; Seynnes et al., 2007; Farup et al., 2012). An increase of pennation angle is considered to be a modulating factor of the PCSA (Alexander and Vernon, 1975) that enables fiber hypertrophy and hence radial muscle growth to exceed the changes of the whole muscle anatomical cross-sectional area (ACSA; Häkkinen et al., 1998; Aagaard et al., 2001). The increase in single muscle fiber cross-sectional area that governs the radial muscle adaptation is the main contributor to the increasing force generating potential of the muscle (Johnson and Klueber, 1991; Aagaard et al., 2001; Farup et al., 2012) and is in turn attributed to increased myofibrillar growth (McDougall et al., 1980) and proliferation (Goldspink, 1970). Longitudinal muscle adaptation refers to the modulation of the number of sarcomeres in series, which is positively associated with the maximum shortening velocity and mechanical power of muscle fibers (Goldspink, 1985). Animal models (Lynn and Morgan, 1994; Butterfield et al., 2005) and indirect evidence from human *in vivo* studies (Blazevich et al., 2007; Duclay et al., 2009; Potier et al., 2009; Reeves et al., 2009; Franchi et al., 2014; Sharifnezhad et al., 2014) both support the notion that eccentric loading can induce longitudinal muscle plasticity. Specific tension (or force) refers to the intrinsic strength generating capacity of the muscle tissue (i.e., active force normalized to PCSA upon maximum

activation). However, in light of the conflicting results on loading-induced changes of single-fiber specific tension (Widrick et al., 2002; D'Antona et al., 2006; Pansarasa et al., 2009) it is still unclear if the modulation of specific tension is a relevant contributor to strength gains in response to exercise (Folland and Williams, 2007).

Basic Mechanisms of Tendon Adaptation

The early work of Ingelmark (1945, 1948) already suggested that tendons adapt to their mechanical environment. When a muscle-tendon unit is repeatedly exposed to increased mechanical loading, for instance by means of resistance exercise, it is commonly observed that the associated gains of muscle strength are accompanied by an increase of tendon stiffness (Kubo et al., 2001a; Arampatzis et al., 2007; Kongsgaard et al., 2007). When a shortening of the tendon is ruled out as a potential contributor, two candidate mechanisms can account for exercise-induced increases of tendon stiffness: (a) changes of the material properties (i.e., elastic modulus) and (b) radial tendon hypertrophy. Exercise intervention studies on human adults that reported an increase of tendon stiffness almost exclusively (with the exception of Kongsgaard et al., 2007) also found the tendon elastic modulus increasing by 17–77% (Kubo et al., 2001a; Arampatzis et al., 2007, 2010; Seynnes et al., 2009; Carroll et al., 2011; Malliaras et al., 2013b; Bohm et al., 2014). In comparison, indications of tendon hypertrophy were documented less consistently, with some evidence of moderate increases of tendon cross-sectional area (CSA; 4–10%) in response to increased mechanical loading (Arampatzis et al., 2007; Kongsgaard et al., 2007; Seynnes et al., 2009; Bohm et al., 2014), and several reports of increased tendon stiffness without concomitant radial tendon growth (Kubo et al., 2001a, 2002, 2007, 2010a; Arampatzis et al., 2010; Carroll et al., 2011; Malliaras et al., 2013b). However, cross-sectional comparisons between athletes and untrained adults suggest that tendon hypertrophy of 20–35% is well possible (Rosager et al., 2002; Magnusson and Kjaer, 2003; Kongsgaard et al., 2005; Seynnes et al., 2013). Negating potential selection bias and intersubject variations by comparing the dominant with the nondominant leg of badminton players and fencers, Couppé et al. (2008) found habitually increased loading to result in an average increase of tendon CSA of about 20%. Therefore, tendon hypertrophy is currently considered to contribute to increased tendon stiffness following long-term mechanical loading.

Temporal Dynamics of Adaptation

It is evident that both muscle and tendon are responsive to mechanical loading. However, the metabolism of tendons is designed to meet the functional demand of bearing loads over long durations and, thus, tendon tissue needs to tolerate low oxygen tension (Józsa and Kannus, 1997). Therefore, tendon tissue is characterized by a lower cell to overall dry mass ratio, vascularization, and metabolism compared to muscle tissue (Peacock, 1959; Smith, 1965; Laitinen, 1967; Ippolito et al., 1980). The half-life of tendon collagen is estimated to be almost tenfold higher compared to the muscle proteins actin and myosin (Lundholm et al., 1981; Thorpe et al., 2010). A recent study that investigated tissue renewal by means of comparing nuclear bomb ^{14}C residues in forensic muscle and tendon samples provided strong support for the hypothesis of a lower rate of tissue remodeling in tendon, especially following the formation of the tendon core tissue during adolescence (Heinemeier et al., 2013). Though similar to muscle proteins, collagen synthesis increases rapidly following exercise (Miller et al., 2005), effective tissue turnover is markedly lower, leading to the suggestion that a considerable amount of the synthesized collagen molecules is not permanently incorporated in the tissue structure but broken down relatively quickly (Heinemeier et al., 2013). In accordance with this notion, it has been demonstrated in adults that changes of muscle morphology and architecture can occur as early as after 3 to 4 weeks in a heavy resistance training intervention (Seynnes et al., 2007; DeFreitas et al., 2011), while there are no reports of such rapid adaptations of tendon morphological or mechanical properties. Moreover, neuronal adaptation enables muscle strength to increase markedly even before major morphological changes occur (Folland and Williams, 2007). An increase of tendon stiffness on the other hand relies on a modulation of tissue metabolism and subsequent adaptive changes of tissue structure and tendon morphology.

Kubo and colleagues investigated the time course of muscle and tendon adaptation in two separate 3-month exercise intervention studies on the patellar (Kubo et al., 2010b) and the Achilles tendon (Kubo et al., 2012), respectively. In both studies, a marked increase of muscle strength preceded significant changes of tendon stiffness by 1–2 month and morphological (CSA) changes occurred at the muscle level only. In contrast, Urlando and Hawkins (2007) reported no significant changes of Achilles tendon strain during maximum voluntary contractions despite an increase of tendon force determined at six time-points over an 8-week strength training intervention. This finding indicates a uniform adaptation of muscle strength and tendon stiffness. However, it is interesting to note that the individual tendon strain values showed great fluctuations between the measurement sessions. The highest single values of tendon strain measured in each session, for example, ranged from 8.6 to 13.5%. This substantial variation indicates that the time course of muscle and tendon adaptation might show an individual development and that imbalances of muscle strength and tendon stiffness might have remained undetected in the study by Urlando and Hawkins (2007) due to the analysis of group mean values only.

In conclusion, both muscle and tendon are able to adapt to a change of their mechanical environment. Though information on the time course of muscle and tendon adaptation *in vivo* is still rare, the metabolic features and adaptive mechanisms differ between muscle and tendon. Muscle seems to be characterized by a greater rate of effective tissue renewal compared to tendon, and neural adaptation further increases the plasticity of the force generating capacity of the neuromuscular system. Thus, it is possible that imbalances of muscle strength and tendon stiffness can develop during a training process.

Differences of Muscle and Tendon in the Responsiveness to Certain Mechanical Stimuli

Besides the potentially different time course of adaptive changes reviewed above, substantial evidence suggest that muscle and tendon feature significant differences regarding the mechanical stimuli that effectively elicit adaptive changes. This section gives a short overview about the processes of mechanotransduction and the stimuli that seem to successfully activate the respective signaling pathways for both muscle and tendon, and then closes with a comparative discussion.

Mechanotransduction in Muscle

It is now well known that both mechanical and metabolic stress are important, separate but interacting stimuli that trigger muscle adaptation and growth (Goldberg et al., 1975; Vandenburgh and Kaufman, 1979; Rooney et al., 1994; Schott et al., 1995; Smith and Rutherford, 1995). Briefly, mechanical stress subjected to muscle tissue leads to the activation of mechanosensitive calcium channels (Kameyama and Etlinger, 1979), intracellular enzymes and second messengers (Hornberger et al., 2006) and stimulates insulin-like growth factor I (IGF-I) release from the muscle cells (Perrone et al., 1995). These events trigger a signaling cascade via autocrine and direct intracellular pathways that results in an increase of protein synthesis (Tidball, 2005; Toigo and Boutellier, 2006; Gonzalez et al., 2016). It has been demonstrated that the increase of muscle protein synthesis following an acute bout of resistance exercise exceeds the increase of protein breakdown, given a sufficient amino acid availability provided by appropriate feeding (Rennie et al., 1982; Biolo et al., 1995; Phillips et al., 1997). The positive net muscle protein balance remains elevated for several days and contributes to the remodeling of the contractile machinery and, subsequently, to hypertrophy (Kumar et al., 2009; McGlory et al., 2017 for reviews). The increase of protein synthetic capability is mediated by an increase of myonuclear number (Allen et al., 1999). Satellite cells are activated by nitric oxide efflux of stressed myofibers (Anderson, 2000) and proliferate under the regulatory influence of IGF-I (Barton-Davis et al., 1999). The proliferated satellite cells then fuse with existing myofibers as new myonuclei (Allen et al., 1999).

Metabolic stress refers to the exercise-related accumulation of metabolites (specifically lactate and hydrogen ions). The role of metabolic stress for muscle growth in response to exercise has been attributed to the associated systemic growth-related hormone and local myokine up-regulation and/or the increased fiber recruitment with muscle fatigue (Schoenfeld, 2013; Ozaki et al., 2016). Muscle hypertrophy was consequently suggested to be driven by the interaction of mechanical and metabolic stress, and that the degree of contribution depends on the exercise modality (i.e., greater mechanical stress at high intensities and greater metabolic stress at moderate intensities; Ozaki et al., 2016). It can be concluded from this assumption that, given a sufficient overall training volume, a wide range of exercise intensities effectively elicits muscle hypertrophy, which is convincingly supported by experimental evidence (Campos et al., 2002; Tanimoto and Ishii, 2006; Mitchell et al., 2012; Schoenfeld et al., 2015, 2016).

Mechanotransduction in Tendon

In tendon tissue, the load-induced strain of the extracellular matrix is transmitted to the cytoskeleton of the embedded fibroblast via specific transmembrane proteins (Wang, 2006; Heinemeier and Kjaer, 2011). The conformational changes of these transmembrane proteins upon load application and the activation of stretch-sensitive ion channels in the cell membrane activate intracellular signaling cascades of gene and growth factor expression for the up-regulation of collagen and matrix protein synthesis (Sackin, 1995; Chiquet, 1999; Wang, 2006; Lavagnino et al., 2015). Accordingly, studies demonstrate an increased concentration of both interstitial growth factors and binding proteins (Heinemeier et al., 2003; Olesen et al., 2006; Jones et al., 2013) as well as elevated collagen synthesis (Langberg et al., 1999, 2001; Miller et al., 2005) in mechanically loaded tendon tissue. The load-induced proliferation and collagen synthesis of tendon stem cells seems to contribute to this anabolic response of tendons to mechanical loading as well (Bi et al., 2007; Zhang et al., 2010). Further, it has been demonstrated in a rat model that mechanical loading leads to an increased production of enzymes that mediate collagen cross-linking (Heinemeier et al., 2007a), which is thought to be involved in the modulation of collagen cross-link profile in humans following resistance exercise (Kongsgaard et al., 2009).

From a mechanobiological point of view, fibroblast cell deformation and fluid flow-induced shear stress are important determinants of mechanotransduction and, thus, the adaptive response of tendons (Lavagnino et al., 2008). *In vitro* testing on the effects of cyclic load-application demonstrated that high-level magnitude strains are associated with greater tenocyte cell deformation (Arnoczky et al., 2002), collagen fiber recruitment (Kastelic et al., 1980; Hansen et al., 2002), and greater inhibition of catabolic activity (Lavagnino et al., 2003; Arnoczky et al., 2004) in comparison to lower levels of cyclic strain. These results correspond well to observations from human *in vivo* exercise intervention studies. Arampatzis et al. (2007, 2010) compared the effects of two equivolume loading regimen and found significant changes of tendon stiffness and elastic modulus of the Achilles tendon only in response to the high-strain protocols [i.e., 90% isometric maximum voluntary contraction (iMVC), corresponding to 4.6% of tendon strain], while no significant changes were induced by moderate-strain training (i.e., 55% iMVC, 2.9% tendon strain). Similar results from experimental studies on the patellar tendon (Kongsgaard et al., 2007; Malliaras et al., 2013b) and two recent meta-analyses (Bohm et al., 2015; Wiesinger et al., 2015) strengthened the conclusion that high-intensity loading is a crucial stimulus for *in vivo* tendon adaptation. The muscle contraction type (i.e., isometric, concentric, eccentric) for load application does on the other hand not seem to be of particular relevance for the adaptive response (Kjaer and Heinemeier, 2014; Bohm et al., 2015).

Interestingly, against the assumptions of finite-element modeling (Lavagnino et al., 2008), the main body of experimental *in vivo* evidence suggests that the induction of high strain

rates and associated increased fluid flow-related shear stress by means of plyometric exercise fails to elicit significant adaptive changes of human tendons (Kubo et al., 2007; Fouré et al., 2009, 2010; Houghton et al., 2013), even at high-intensity loading magnitudes (Bohm et al., 2014). Though it needs to be acknowledged that there are also reports of an increase of tendon stiffness in response to plyometric loading (Burgess et al., 2007; Wu et al., 2010; Hirayama et al., 2017), some of these findings might have been biased by the lack of consideration of the contribution of antagonistic activity in the calculation of tendon forces (Wu et al., 2010; Hirayama et al., 2017), which leads to an overestimation of the increase of tendon stiffness upon a training-induced reduction of antagonistic coactivation. Yet, more importantly, the few existing studies directly comparing the effects of plyometric training to low-strain-rate loading regimen consistently show lower adaptive responses in the plyometric training groups (Burgess et al., 2007; Kubo et al., 2007; Bohm et al., 2014). It has been argued that a short duration of strain-application (e.g., high-frequency load-relaxation cycles or plyometric loading) might reduce the effectiveness of mechanotransduction processes (Arampatzis et al., 2010; Bohm et al., 2014). In a systematic experimental modulation of strain duration at high strain magnitude *in vivo*, an increase by up to 3 s facilitated tendon adaptation (Arampatzis et al., 2010; Bohm et al., 2014). However, a further increase of strain duration to 12 s per cycle did not further promote adaptive effects. It seems possible that longer sustained tendon strains become less effective if the strain duration is increased at the expense of the number of loading cycles (Bohm et al., 2014).

Collectively, current *in vivo* evidence on human tendon adaptation suggests that tendons can be most effectively strengthened if loading regimen incorporate slow repetitive high-magnitude tendon strain application. High strain rate and frequency modes of loading as, for instance, plyometric exercise, do not seem to consistently stimulate tendon adaptation.

Comparison of Muscle and Tendon Mechanical Stimulation

Comparing the types of mechanical stimulation that effectively elicit muscle compared to tendon adaptation, it seems that fatiguing training with moderate loads can trigger increases of muscle strength and size (Moss et al., 1997; Wernbom et al., 2007; Mitchell et al., 2012; Schoenfeld et al., 2016), but do not provide a sufficient stimulus for tendon adaptation (Arampatzis et al., 2007, 2010; Kongsgaard et al., 2007). This way, an increase of muscle strength without a concomitant modulation of tendon stiffness following moderate intensity loading can result in higher tendon strain during maximal voluntary contractions, which implies an increase of the mechanical demand placed upon the tendon by the working muscle (Arampatzis et al., 2007, 2010; **Figure 1**). Furthermore, numerous studies demonstrated that plyometric loading effectively promotes muscle strength development, also in trained athletes (Sáez-Sáez de Villarreal et al., 2010 for review), while evidence suggests that plyometric loading does not consistently increase tendon stiffness (Kubo et al., 2007; Fouré et al., 2009, 2010; Houghton et al., 2013). Accordingly, Kubo et al. (2007) reported increased tendon elongation (and, thus, tendon strain, given that the rest length did not change) during maximum muscle contractions following their plyometric training intervention. Such differences in the responsiveness of muscles and tendons to plyometric loading and its mechanical implications could be of particular significance in light of the high prevalence of tendon overuse injuries in sports with a plyometric loading profile like volleyball, basketball or athletic jump disciplines (Lian et al., 2005). Studies on growth factor transcription following loading also support the idea of differently graded responses of muscle and tendon to specific types of loading. For example, Heinemeier et al. (2007a,b) found a contraction type-specific expression of growth factors in muscle but not tendon tissue using a rat model. More recently, it was also demonstrated in humans that following a fatiguing one-leg kicking exercise with moderate loads the expression of tissue-specific growth factors increased only at the muscle but not tendon level (Heinemeier et al., 2011). This observation led the authors to conclude that an imbalanced adaptation of muscle and tendon might develop under specific loading conditions (Heinemeier et al., 2007a, 2011).

In summary, muscle responds well to a wide range of exercise modalities with an increase of strength. Tendon tissue on the other hand seems only to be responsive to high magnitude loading and repetitive loading cycles featuring long tendon strain durations show greater effects compared to modes of loading where single-cycle strain duration is short. Those differences in the responsiveness to certain stimuli might promote the development of imbalances of muscle strength and tendon stiffness in the training process in specific sport disciplines (e.g., jump disciplines).

The Effects of Maturation on Muscle and Tendon Development and Plasticity

Aside from mechanical loading, maturation induces profound changes of the skeletal, neuromuscular and tendinous system in young athletes. The following section briefly reviews muscle and tendon development from child to adulthood, then focuses on somatic and hormonal changes that might challenge the balance of the development of muscle and tendon properties. The section closes with a synopsis of recent experimental evidence of an imbalanced muscle and tendon development in adolescent athletes.

Maturation and Muscle Development

Whole body muscle mass increases progressively from childhood to adulthood, with a pronounced rise during adolescence, especially in boys (Malina et al., 2004; McCarthy et al., 2014; Kim et al., 2016). Even when normalized to body mass, these changes are still marked in boys yet modest in girls (McCarthy et al., 2014; Kim et al., 2016). Studies investigating single muscle development consequently reported an increase in length, ACSA and volume (Kanehisa et al., 1995a,b; Kubo et al., 2001b; Neu et al., 2002; Tonson et al., 2008; O'Brien et al., 2010c). It seems that the gain of muscle volume is governed by both an increase in PCSA and fascicle length, yet the gains in PCSA exceed those of fascicle length in pennate muscles, which is an indication of a remodeling in favor of force production

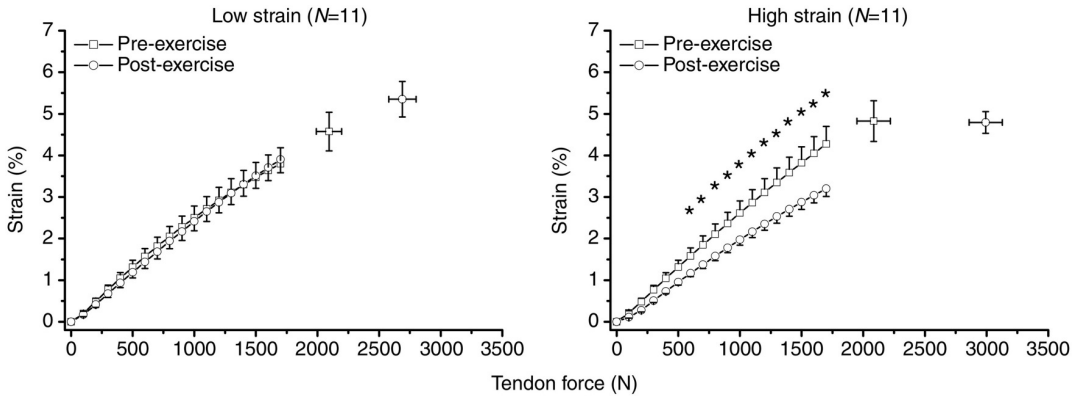


FIGURE 1 | Achilles tendon-aponeurosis force-strain relationship before and after two isometric exercise protocols. The two legs of eleven adults were subjected to either moderate [i.e., 55% maximum voluntary contraction (MVC); low strain] or high loading (90% MVC; high strain) for 14 weeks, respectively. Both protocols induced an increase of tendon force. However, following moderate loading (i.e., low strain protocol) tendon stiffness did not change significantly and, thus, there was a significant increase of tendon strain during maximum muscle contractions. This implies an increase of the mechanical demand placed upon the tendon. No change was observed in a control group (data not shown). *Significant difference between pre- and post-exercise values (Arampatzis et al., 2007, adapted with permission from The Company of Biologists Limited).

(Morse et al., 2008; O'Brien et al., 2010c; Bénard et al., 2011). Together with an increase of moment arm lengths (O'Brien et al., 2009; Waugh et al., 2012) and muscle activation (Dotan et al., 2012), this leads to a disproportionate increase of muscle strength (O'Brien et al., 2010a). The development of muscle PCSA from childhood to adulthood is most likely based on single fiber hypertrophy and not hyperplasia (Bowden and Goyer, 1960; Aherne et al., 1971; Oertel, 1988; Lexell et al., 1992). The growth hormone-IGF-I axis, which is markedly activated during adolescence for the regulation of overall body growth, stimulates fiber hypertrophy and protein synthesis (Grohmann et al., 2005). For example, myoblast proliferation and fusion with myotubes—a prerequisite for radial and longitudinal fiber growth—depends on growth hormone and IGF-I secretion (Cheek et al., 1971; Allen et al., 1999; Grohmann et al., 2005). Consequently, there is a close association between single fiber CSA and body height (Aherne et al., 1971). The alteration of the endocrine environment during adolescence, specifically the increasing systemic levels of sex steroid hormones, further initiate the development of the muscle functional, morphological and structural differences between boys and girls (Oertel, 1988; Round et al., 1999).

Maturation and Tendon Development

First information on the development of the mechanical properties of human tendinous tissue *in vivo* was provided by Kubo et al. (2001b). Their comparison of vastus lateralis tendon-aponeurosis compliance between children, adolescents and adults indicated a progressive increase of tendinous stiffness (i.e., the inverse of compliance) from childhood to adulthood, despite the longitudinal growth of the muscle-tendon unit. Theoretically, an increase in length of the series elastic elements would reduce their stiffness (given similar material properties and CSA; Butler et al., 1978). However, O'Brien et al. (2010b) found greater stiffness of the patellar tendon in adults compared to pre-pubertal children as well, and Mersmann et al. (2016) recently demonstrated an increase of patellar tendon stiffness in a longitudinal study over 1 year throughout adolescence. More detailed information on the time course of human tendon development *in vivo* is strongly limited. Kubo et al. (2014) compared the mechanical and morphological properties of the patellar tendon of elementary and high school boys to adult men. The results indicated that the major developmental increase of tendon elastic modulus from childhood to adulthood occurs until early-adolescence. This corresponds to the observations on the Achilles tendon by Waugh et al. (2012), who found that the differences in Achilles tendon material properties between younger (5–7 years) and older pre-pubertal children (aged 8–10 years) were of similar order as the differences between the latter group and the notably older adults (∼26 years). Thus, the material properties of tendons might demonstrate their most pronounced development early in youth (i.e., before the growth spurt at the onset of adolescence), while it seems that tendon hypertrophy progresses further throughout adolescence (Kubo et al., 2014). This assumption also parallels observations in rodent models (Ansorge et al., 2011; Miller et al., 2012). The development can probably be attributed to a great extent to the increase of mechanical loading due to gains in body mass and muscle strength, as predicted by Waugh et al. (2012) using a stepwise multiple regression model and data of the Achilles tendon properties of children and adults. Interestingly, age was shown to be an additional significant predictor of elastic modulus in the regression model, independent of body mass and tendon stress, explaining 31 and 52% of the variance of the elastic modulus in children and both age groups combined, respectively. Thus, it seems very likely that maturation is a separate factor for tendon development, besides the effects of increased mechanical loading. Indeed, several hormones and growth factors that are involved in the regulation of somatic growth (see Murray and Clayton, 2013 for review) have been shown to mediate tendon metabolism as well. For instance, growth hormone and IGF-I stimulate gene expression, collagen synthesis and cross-linking (Abrahamsson et al., 1991; Choy et al., 2005; Doessing et al., 2010; Nielsen et al., 2014) and thyroid hormones are involved

in the regulation of tenocyte proliferation, growth and collagen synthesis (Oliva et al., 2013; Berardi et al., 2014).

Challenges to the Musculotendinous System Induced by Maturation

Neugebauer and Hawkins (2012) reported that the longitudinal growth of the muscle-tendon unit during adolescence can go in line with a temporary reduction of tendon CSA. At given tendon material properties, the resultant increase of tendon stress would lead to higher tendon strain. However, as Neugebauer and Hawkins (2012) found both elastic modulus and maximum tendon strain to increase only in tendency, the implications of the observed morphological development of tendons during the adolescent growth spurt still need to be elucidated. Similarly, little information is available on the effects of the rapid increase of circulating sex hormones (i.e., testosterone in boys and estrogens in girls) during puberty on the muscle-tendon unit. Yet, it seems possible that the change of the endocrine milieu could affect the uniformity of the development of muscle strength and tendon stiffness. It is well established that testosterone is one of the most potent hormones promoting muscle hypertrophy and thus increasing muscle strength (see Vingren et al., 2010 for review). Its role in the development of tendinous tissue on the other hand is basically unknown to date (Hansen and Kjaer, 2014). In adults it has been shown that anabolic-androgenic steroid supplementation stimulates collagen synthesis (Pärssinen et al., 2000) and increases tendon stiffness (Inhofe et al., 1995; Marqueti et al., 2011; Seynnes et al., 2013), but impairs tissue remodeling (Marqueti et al., 2006) and reduces ultimate stress and strain (Inhofe et al., 1995; Marqueti et al., 2011; Tsitsilonis et al., 2014). Though it seems likely that steroid supplementation is not necessarily representative of the physiological mechanisms of testosterone action, it can at least be concluded that the anabolic and strength-promoting effects of testosterone are more clearly established for muscle than tendon tissue. The effects of estrogens on muscle and tendon metabolism have been studied more extensively. In a recent review, Hansen and Kjaer (2014) concluded that current scientific evidence from studies on humans renders estrogens as muscle-anabolic, since they decrease protein turnover and increase the responsiveness to mechanical loading. Conversely, estrogens seem to reduce tendon collagen synthesis and the plasticity of tendon mechanical properties in response to exercise (Miller et al., 2007; Hansen et al., 2009). While it must be stated clearly that our current understanding of the effects of sex hormones on the muscle-tendon unit is based primarily on studies administering exogenous hormones to adults, these findings allow the hypothesis that the change of endogenous sex hormone levels in child to adulthood development could contribute to an imbalanced adaptation of muscle and tendon in youth athletes.

Evidence of Imbalanced Muscle and Tendon Development in Adolescent Athletes

A first series of studies that explicitly investigated the uniformity of muscle and tendon development and adaptation during adolescence supports the idea that the two-fold stimulus of (a) maturation and (b) a predominantly plyometric loading profile can lead to a musculotendinous imbalance that increases the load (i.e., stress) and internal demand (i.e., strain) for the tendon. Mersmann et al. (2014) compared mid-adolescent to middle-aged elite volleyball athletes, which were subjected to many years of sport-specific loading. While there were no significant differences in vastus lateralis PCSA and in the force applied to the patellar tendon during maximum isometric knee extension contractions, the adolescents had a deficit with regard to patellar tendon CSA compared to the adult counterparts and, as a consequence, were subjected to increased levels of tendon stress and strain. The conclusion that the morphological plasticity of the tendon unfolds at later stages during development was supported by the results of a subsequent 2-year longitudinal study. The observations suggested that the muscular development was already far progressed in the mid-adolescent athletes, demonstrating only minor changes until the end of adolescence, while the tendon still showed remarkable radial growth and an associated increase of stiffness (Mersmann et al., 2017a). Finally, the time course of muscle and tendon development in mid-adolescent athletes was investigated in five measurement sessions over 1 year in more detail and the effects of maturation and mechanical loading were differentiated by including a similar-aged control group of non-athletes (Mersmann et al., 2016). It was found that the development in elite volleyball athletes was characterized by significantly greater fluctuations in muscle strength and a non-uniformity of muscle and tendon adaptation. Consequently, tendon strain during maximum contractions was not only increased chronically in comparison to controls, but also demonstrated significantly greater fluctuations during the period of investigation (**Figure 2**). In addition to the discordant changes of muscle strength and tendon stiffness that occur during a training process, results of a very recent study indicate that also the adaptive potential, at least in response to predominantly plyometric long-term loading, is lower with regard to tendon stiffness compared to muscle strength in both adolescent boys and girls (Mersmann et al., 2017b). Though from this study it still remains an assumption that maturation contributed to the development musculotendinous imbalance in addition to the unfavorable type of loading, the increased stress and strain observed in the earlier study (Mersmann et al., 2014) in adolescent athletes compared to the adults, which were habitually subjected to intense plyometric loading as well, carefully suggest that the risk might be increased during adolescence.

Summary

Collectively, the evidence reviewed in this chapter strongly suggests that muscle and tendon show differences in the time course of adaptation to mechanical loading and in the types of mechanical stimulation that effectively elicits adaptive processes. Maturation acts as an additional stimulus on the muscle-tendon unit of young athletes and could further contribute to a development of an imbalance of muscle strength and tendon stiffness. Adolescence could

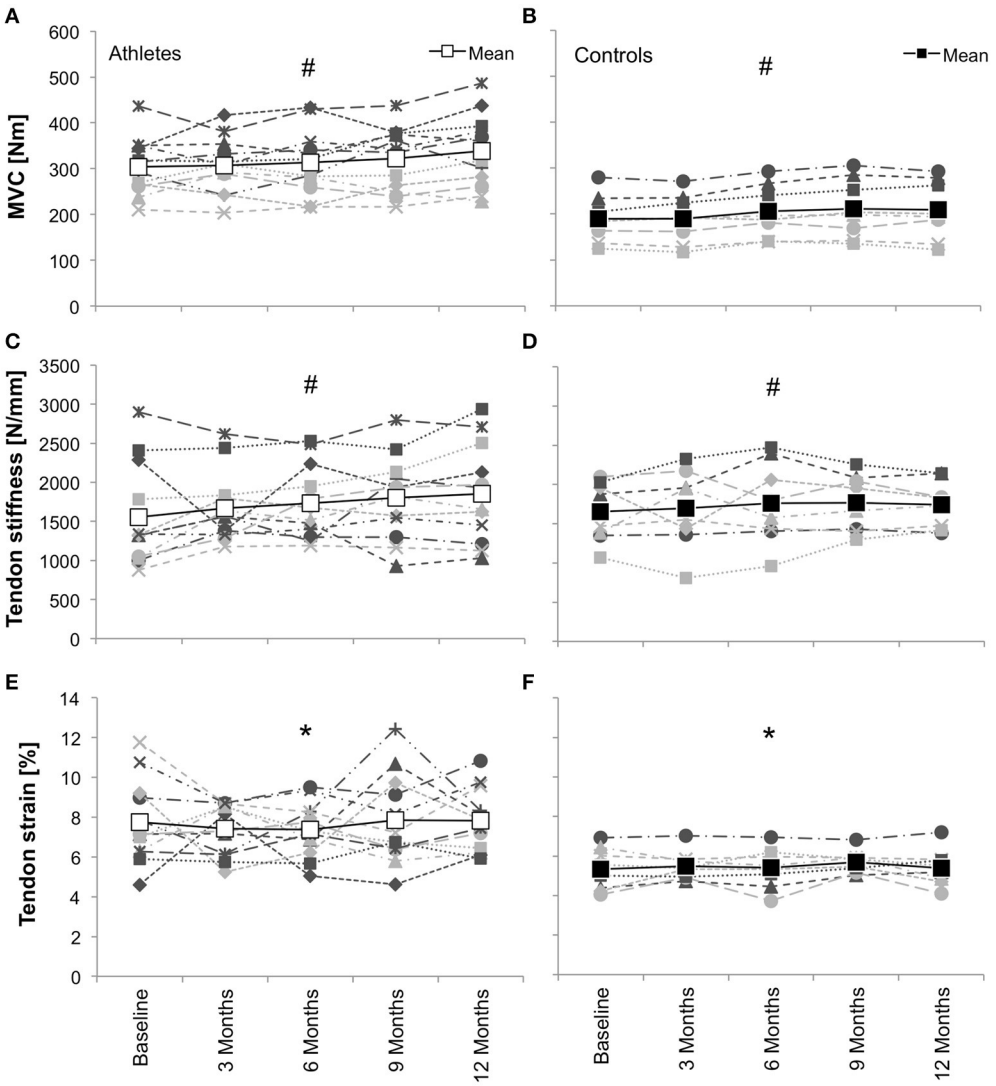


FIGURE 2 | On-year development (in 3-month intervals) of knee extensor muscle strength (MVC; **A,B**), patellar tendon stiffness **(C,D)** and tendon strain during maximum contractions **(E,F)** in adolescent volleyball athletes ($n = 12$; **A,C,E**; white symbols show mean values) and controls ($n = 8$; **B,D,F**; black symbols show mean values), including individual data of female (light gray) and male participants (dark gray) in both groups. *Significant difference between groups (i.e., intercept; $p < 0.05$); #significant change over time (i.e., slope; $p < 0.05$). Note that differences between groups were not tested for MVC and stiffness. The data shows greater fluctuations of muscle strength in the athletes and, as a result of an imbalanced adaptation of muscle and tendon, both greater average tendon strain during maximum contractions as well as greater fluctuations of strain over time (Mersmann et al., 2016, with permission from American Physiological Society).

be a critical phase in that context due to the associated increase of sex hormones. However, the interplay of mechanical loading and changes of the hormonal milieu on muscle and tendon plasticity in general, and with regard to adolescence in particular, is still largely unknown. Similarly, though recent evidence demonstrated that an imbalanced musculotendinous adaptation can occur during adolescence (Mersmann et al., 2014, 2016, 2017a,b), it is yet unclear how the likelihood of an imbalanced adaptation develops as a function of maturation and how it relates to specific types of loading.

IMPLICATIONS AND CONCEPTS FOR PREVENTION

It has been described above that muscle and tendon properties might not develop homogeneously during a training process. The following chapter provides an overview about the potential implications for the risk of tendon injury based on experimental and epidemiological observations. Finally, we give recommendations for the design of preventive interventions and critically discuss the current lack of knowledge with regard to the efficacy and timing of such preventive measures.

Potential Implications for the Risk of Tendinopathy

Experimental Observations

An imbalanced adaptation of muscle and tendon—when the development of the force generating capacity of a muscle is not paralleled by an adequate change of the properties of the associated tendon—increases the mechanical demand placed upon the tendon at a given activation of the muscle and, therefore, might impose a challenge for the integrity of the tendinous tissue (especially during maximum efforts). Though tendinopathy has certainly a multifactorial etiology, the mechanical strain theory is currently considered the most probable injury mechanism and attributes the histological, molecular and functional changes of the affected tissue to mechanical overload (Archambault et al., 1995; Fredberg and Stengaard-Pedersen, 2008; Magnusson et al., 2010; Legerlotz, 2013). There is convincing evidence that repetitive loading of tendon tissue at high strain magnitudes (Butler et al., 1978; Lavagnino et al., 2006; Legerlotz et al., 2013) leads to cumulative damage in the extracellular matrix by successive collagen denaturation and fibril tears (Woo, 1982; Veres et al., 2013). The subsequent load redistribution among intact fibrils probably increases the risk of damage upon further loading cycles (Neviaser et al., 2012) and might explain the associated decrease of stiffness and ultimate stress (Schechtman and Bader, 2002; Fung et al., 2009, 2010; Legerlotz et al., 2013). The manifestation of tendinopathy is commonly ascribed to the progression of cumulative microtrauma to higher structural levels of the tissue and successive matrix breakdown (Kannus, 1997; Cook and Purdam, 2009). The degenerative cascade might also be related to the discontinued mechanotransduction of ruptured fibrils (Knörzer et al., 1986) and the associated catabolic responses of under-stimulated fibroblasts (Arnoczky et al., 2007). As both scenarios (i.e., mechanical over- or understimulation) are based on initial strain-induced damage, it seems plausible that an imbalanced adaptation of muscle and tendon could increase the risk of overload-induced tendinopathy. Wren et al. (2003) performed static and cyclic loading experiments on human Achilles tendons and demonstrated that the initial level of strain induced by a given load was inversely correlated with time or loading cycles until failure (**Figure 3**). This suggests that if tendon strain increases during muscle contractions due to an imbalanced musculotendinous adaptation, repetitive loading could induce significant sub-rupture fatigue and trigger pathological processes. Indeed, there are *in vivo* studies on patients and athletes with tendinopathy, which report increased levels of tendon strain during maximum voluntary contractions (Arya and Kulig, 2010; Child et al., 2010). Though other studies did not identify increased levels of strain—which might be a methodological issue as pain reduces the level of muscle activation (Hart et al., 2010; Palmieri-Smith et al., 2013) and, thus, the tendon strain measured during voluntary contraction—they found other indications of a mechanical weakening of the tendon, like a decrease of stiffness (Helland et al., 2013) or increase of tendon stress (Couppé et al., 2013).

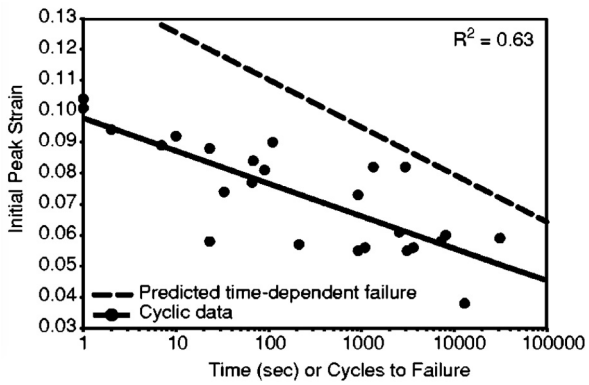


FIGURE 3 | Cyclic loading lifetime results of human oder AT specimen Achilles tendons as a function of initial (peak) tendon strain during loading and associated coefficients of determination (R^2). These data demonstrate that the tendon strain magnitude determines the challenge for the tissue integrity. Greater tendon strain at a given load reduces the lifetime of the tendon during cyclic loading (Wren et al., 2003, with permission from Springer).

Epidemiological Observations

The assumption that an imbalanced adaptation of the muscle-tendon unit could contribute to the development of overuse injuries with increasing risk during adolescence also finds support from several epidemiological observations. First, it is interesting to note that the probability of non-contact soft-tissue injury rises when training loads are increased rapidly (Gabbett, 2016). Though this increase clearly could also have different origins, it still indicates that the differing time course of muscle and tendon adaption (i.e., delayed tendon adaptation compared to the increase of muscle strength) might potentially be of clinical relevance. Second, the prevalence of tendinopathy in both elite and recreational athletes is particularly high in sports with predominantly plyometric loading (Lian et al., 2005; Zwerver et al., 2011). In adolescent volleyball players, it was found that jumping ability and the weekly hours of volleyball training (and not strength training) increase the risk of tendinopathy (Visnes et al., 2013). It seems that especially the frequency of jumps during training and competition could be a major determinant of the risk of tendon overload (Bahr and Bahr, 2014). These observations could well be related to the different responsiveness of muscle and tendon to plyometric loading and increased risk of tendon fatigue damage upon repetitive loading with high magnitude strains. Third, a recent epidemiological meta-analysis on tendinopathy in children and adolescents regularly participating in sports indicated an increasing risk with age (Simpson et al., 2016), which corresponds to the incidence of general soft-tissue overuse injuries reported earlier (Stracciolini et al., 2014). These findings underline the potential influence of maturation on the balance of muscle and tendon adaptation and the necessity to deepen our understanding of the interaction of maturation and loading.

Summary

In summary, the pathogenesis and epidemiology of tendinopathy provides a solid theoretical background for the hypothesis that an imbalanced adaptation of muscle and tendon could have consequences for the risk of tendon injury as (a) the resultant increased mechanical demand is a candidate mechanism to induce overload, (b) the prevalence of soft-tissue overuse injuries is high at time-points in the training process (i.e., sudden increase of loading) and in sport disciplines that favor the development of a muscle-tendon imbalance from a mechanobiological point of view, and (c) maturation seems to be a potential risk factor for the development of both tendinopathy and musculotendinous imbalances in young athletes. There certainly is a need to provide more direct support for an association between imbalanced muscle and tendon adaptation and overuse. Yet, it appears that the interaction of maturation with mechanical loading could potentially increase the likelihood of the occurrence of such imbalances, which in turn might be related to the increasing risk of tendon overuse in adolescence. However, these assumptions need to be supported by further research.

Concepts for Prevention

Following the hypothesis that an imbalanced development of muscle strength and tendon stiffness could increase the risk for tendon overuse injury, it might be promising to target the increase of tendon stiffness in groups at risk (e.g., athletes of jump disciplines, adolescents commencing with resistance exercise). The following chapter provides evidence-based suggestions for an effective tendon training and comments on open issues. The chapter concludes with a critical discussion of the current evidence on the effects of preventive interventions outlines the anticipated effects of an intervention-induced increase of tendon stiffness on athletic performance.

Effective Tendon Training

Current evidence on human tendon adaptation *in vivo* (see section Mechanotransduction in Tendon) suggests that both contraction intensity and contraction duration need to exceed a certain threshold to provide an efficient training stimulus. The training intensity is considered to be optimal around 85–90% of iMVC and the contraction duration around 3 s (Arampatzis et al., 2010; Bohm et al., 2014, 2015; Wiesinger et al., 2015). The contraction mode (i.e., isometric, concentric, eccentric) does not seem to be relevant (Kjaer and Heinemeier, 2014; Bohm et al., 2015), however, it needs to be considered that during classic dynamic training (i.e., eccentric-concentric exercises) the necessary high tendon forces occur only in specific ranges of joint angles due to the change of gear ratios during movement (e.g., between 60° and 100° of knee flexion in a parallel squat; 0° = full extension) (Flanagan et al., 2003; Peñailillo et al., 2015). Therefore, it is recommendable to increase the movement duration (e.g., to ∼6 s) when a large range of motion is used during the exercise. Isometric training should be performed in joint angles close to the optimum for force generation (i.e., ∼60° knee flexion for patellar tendon training or ∼10° ankle dorsiflexion and extended knee for the training the Achilles tendon) and has the advantage that the training stimulus in terms of intensity and duration can be controlled quite easily. Moreover, it does not require the complex technical skills of free weight training for a safe execution and can be performed without expensive equipment (e.g., using non-elastic slings). **Figure 4** illustrates a training stimulus for increasing tendon stiffness based on the most effective training protocol of a series investigations that systematically modulated mechanical strain parameters (Arampatzis et al., 2007, 2010; Bohm et al., 2014). We suggest to apply the training protocol three times a week for at least 12 weeks. These recommendations also correspond to the conclusions of two recent meta-analyses on tendon adaptation (Bohm et al., 2015; Wiesinger et al., 2015). Suggestions for specific exercises are provided as Supplementary Material to this review.

There are several important, but currently open issues that need to be elucidated with regard to the stimulation of tendon adaptation in general, its implementation in elite athletic training as a preventive measure in particular and with regard to its application in youth sports. There have been experimental investigations systematically modulating strain magnitude, rate, duration and frequency (Arampatzis et al., 2007, 2010; Kongsgaard et al., 2007; Bohm et al., 2014), however, the effects of overall training volume, number of sessions per week or rest between sets are basically unexplored thus far, and meta-analyses are limited in their potential to improve our understanding in this regard (Gentil et al., 2017) due to the heterogeneity of intervention studies (Bohm et al., 2015). In a recent study, Waugh et al. (2017) modulated inter-cycle rest duration (i.e., 3 and 10 s) between two equivolume isometric loading protocols. While the improvements of stiffness and material properties were similar between protocols, some potentially unfavorable structural changes were detected by means of ultrasound tissue characterization (UTC) following the short rest loading. It should be noted that it is still unclear if such changes of UTC-parameters indicate overload and the overall loading volume in the study by Waugh and colleagues was 2.5 times the volume of the program that we recommend based on our experience. Nevertheless, these findings highlight the necessity to deepen our understanding of tendon tissue recovery

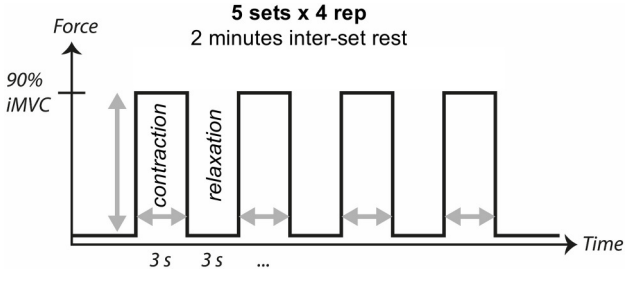


FIGURE 4 | Evidence-based recommendations for an effective stimulus for tendon adaptation. High intensity loading to the tendon (85–90% iMVC) should be applied in five sets of four repetitions with a contraction and relaxation duration of 3 s each, and an inter-set rest of 2 min. We suggest the training to be applied three times a week for at least 12 weeks.

during cyclic loading, especially with regard to injury prevention and rehabilitation.

It is currently a matter of speculation when to implement the preventive intervention during the course of athletic training, if the training stimulus should be applied continuously or in periods, and how a specific tendon training interferes with training regimen that target other determinants of athletic performance. Given the moderate overall loading volume of the program recommended in this review, it seems realistic to implement the tendon exercises without any major reductions of other training contents. It can be considered that the program increases muscle strength as well (Arampatzis et al., 2007, 2010) and, therefore, could complement or replace some routines used for muscle strength development. We are currently applying a preventive tendon training in adolescent athletes to investigate its efficacy. The overall duration of exercises implemented in the regular training schedule that target the increase of tendon stiffness is around 15 min. Considering this low time-effort and the uncertainty if training at specific time-points during a season would be equally effective, we are applying this intervention over the whole season. Future research might help to further develop this approach and investigate if scheduling tendon training in advance of marked increases of loading that is assumed to provide a more potent stimulus for muscle strength compared to tendon stiffness development (i.e., plyometric loading or fatiguing moderate intensity loading) yields similar results.

The recommendations given in this chapter are based on our current knowledge on tendon adaptation, which is derived from studies on adults. Though it is known that the tendons of pre-pubertal children and adolescents are able to adapt to mechanical loading (Waugh et al., 2014; Mersmann et al., 2017b), dose-response relationships specific for the immature tendinous system still need to be established in the future. However, as we are convinced that the basic mechanisms of mechanotransduction should not be profoundly different in children and adults, we can argue that it is likely that the characteristics of an effective stimulus for tendon adaptation (i.e., high strain magnitude and ∼3 s strain duration applied with low frequency) is widely independent of age. Nevertheless, there might be restrictions with regard to overall mechanical loading and intensity control. The number of sets and repetitions could then be used to adjust the overall training volume to the loading capacity of the young athletes. Moreover, in age groups where maximum strength testing is contraindicated, perceived exertion scales can be used to estimate training intensity (Waugh et al., 2014).

In conclusion, adult tendons, and likely immature tendons as well, receive effective mechanical stimulation upon high strain magnitude loading with an appropriate strain duration. Though the role of recovery is widely unexplored, the recommendations outlined above could have the potential to decrease the likelihood of an imbalanced muscle and tendon development in a training process. However, it needs to be stated clearly that specific considerations for the implementation in athletic training schedules of different sports and for the application in youth athletes need to be elucidated in future research.

Potential Effects on Risk of Injury and Athletic Performance

The prevention or reduction of musculotendinous imbalances could, in our view, have beneficial effects on (a) the risk of tendon injury and (b) athletic performance. A recent systematic review on the effects of preventive interventions for tendinopathy concluded that evidence for their efficacy is only limited (Peters et al., 2016). However, the exercise interventions examined were either not targeting the improvement of the mechanical properties of the tendon (e.g., balance training, stretching) or did not apply training stimuli that are in accordance with the current view on the mechanobiological basis of human tendon adaptation *in vivo* (e.g., Alfredson eccentric training or Silbernagel's combined concentric-eccentric exercise; Malliaras et al., 2013a for a discussion). Conventional eccentric training approaches, for example, are characterized by high training volume but only moderate load intensity (i.e., body weight), which might even increase discrepancies between muscle strength and tendon stiffness (Arampatzis et al., 2007, 2010). Though conventional eccentric training is associated with pain relief in patients with tendinopathy, its application as a preventive measure can also increase injury risk of tendons that already feature structural abnormalities (Fredberg et al., 2008). A load-based intervention with scientific evidence supporting its efficacy on promoting tendon stiffness is likely to be a more effective preventive strategy following the hypothesis that an imbalance of muscle and tendon predispose for tendinopathy. An increase of stiffness that parallels the increase of the force generating capacity of the neuromuscular system would serve as a protective mechanism against increased strain during maximum muscle contractions. Moreover, if the increase of stiffness is governed by radial hypertrophy upon long-term training, this would also reduce tendon stress.

Aside from the potentially beneficial effects for the health of young athletes, tendon stiffness and the interaction of muscle and tendon during movement are important contributors to movement performance. For example, increased tendon stiffness is associated with a lower electromechanical delay, a greater rate of force development and jump height (Bojsen-Møller et al., 2005; Waugh et al., 2013). Certainly, the elasticity of the tendon and the associated storage and release of mechanical strain energy are important contributors to sportive performance as well (Roberts, 1997; Kawakami et al., 2002). Greater elongation at a given force allows more energy to be stored in the tendon and has been positively associated, for example, with sprint performance (Stafilidis and Arampatzis, 2007; Kubo et al., 2011). However, a greater muscle force output combined with higher tendon stiffness increases the potential exchange of mechanical energy between muscle and tendon as well (Wu et al., 2010). Moreover, if the force production during a movement task increases due to an increase of the muscular capacity, an increase of stiffness of the series elastic elements is necessary to maintain fascicle kinetics within an optimal working range (Lichtwark and Wilson, 2007). For example, it has been recently shown that vastus lateralis fascicles operate around optimum length and close to optimum velocity for power production (Nikolaidou et al., 2017) during

vertical jumping. A change of the balance of muscle strength and series elastic stiffness could lead to a distortion of the musculotendinous interaction and in turn increase the demand for neuromuscular control (i.e., due to a change of fascicle kinetics), which could reduce the extent to which the increased muscular capacity can be exploited. Therefore, it is likely that a facilitation of tendon stiffness in line with muscle strength would lead to greater improvements of movement performance as opposed to a sole increase of muscle strength.

CONCLUSIONS AND FUTURE DIRECTIONS

Current scientific evidence strongly supports the idea that the development of muscle strength during a training process is not necessarily accompanied by an adequate modulation of tendon stiffness. The differences in the time course of adaptation and in the mechanical stimuli that trigger adaptive processes provide two mechanisms that can account for a dissociation of the muscular and tendinous development. Though the additional influence of maturation is still a heavily under-investigated topic, it is likely that an imbalanced development of muscle strength and tendon stiffness is a relevant issue for youth sports and it seems that the risk might even be increased compared to adults. Adolescence, with its associated somatic and endocrine processes, could be a critical phase in that regard. Due to the mechanical loading profile, musculotendinous imbalances especially concern athletes from jump disciplines and the high prevalence of tendinopathy in those sports as well as the increasing incidence during adolescence support the hypothesis that imbalances of muscle strength and tendon stiffness could have implications for the health of young athletes. The implementation of interventions targeting the improvement of tendon mechanical properties could be a promising approach to prevent such imbalances, promote athletic performance and reduce the risk of tendon injury. However, there is still a clear lack of information on the time course of changes of the musculotendinous system during premature development and the interaction of maturation and mechanical loading. The effects of changing sex hormone levels on tendon properties and plasticity is also widely unknown. Similarly, the association of musculotendinous imbalances with tendon overuse injury as well as the preventive value of interventions that promote the development of tendon mechanical properties has not been established thus far. The effects of recovery for tendon adaptation in general are largely unexplored and a future challenge with regard to the application of preventive tendon training in youth sports is the determination of age-specific dose-response relationships and the implementation in the training schedule in elite sports. The increasing prevalence of tendinopathy in athletic adolescents certainly calls for further research on these issues.

AUTHOR CONTRIBUTIONS

All authors substantially contributed to the interpretation of the literature addressed in this review. FM drafted and finalized the manuscript. SB and AA made important intellectual contributions in revision of all sections of the manuscript. AA supervised the preparation of the manuscript. All authors approved the final version of the manuscript and agree to be accountable for the content of the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2017.00987/full#supplementary-material

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Muscle and Tendon Adaptation in Adolescence: Elite Volleyball Athletes Compared to Untrained Boys and Girls

Falk Mersmann[1,2], *Georgios Charcharis*[1,2], *Sebastian Bohm*[1,2] *and Adamantios Arampatzis*[1,2]*

[1] Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany, [2] Berlin School of Movement Science, Berlin, Germany

Though the plasticity of human tendons is well explored in adults, it is still unknown how superimposed mechanical loading by means of athletic training affects the properties of tendons during maturation. Due to the increased responsiveness of muscle to mechanical loading, adolescence is an important phase to investigate the effects of training on the mechanical properties of tendons. Hence, in the present study we compared vastus lateralis (VL) architecture, muscle strength of the knee extensor muscles and patellar tendon mechanical properties of male and female adolescent elite athletes to untrained boys and girls. Twenty-one adolescent volleyball athletes (A; 16.7 ± 1 years; 12 boys, 9 girls) and 24 similar-aged controls (C; 16.7 ± 1 years; 12 boys and girls, respectively) performed maximum isometric contractions on a dynamometer for the assessment of muscle strength and, by integrating ultrasound imaging, patellar tendon mechanical properties. Respective joint moments were calculated using an inverse dynamics approach and an electromyography-based estimation of antagonistic contribution. Additionally, the VL pennation angle, fascicle length and muscle-thickness were determined in the inactive state by means of ultrasound. Adolescent athletes produced significantly greater knee extension moments (normalized to body mass) compared to controls (A: 4.23 ± 0.80 Nm/kg, C: 3.57 ± 0.67 Nm/kg; $p = 0.004$), and showed greater VL thickness and pennation angle (+38% and +27%; $p < 0.001$). Tendon stiffness (normalized to rest length) was also significantly higher in athletes (A: 86.0 ± 27.1 kN/strain, C: 70.2 ± 18.8 kN/strain; $p = 0.04$), yet less pronounced compared to tendon force (A: 5785 ± 1146 N, C: 4335 ± 1015 N; $p < 0.001$), which resulted in higher levels of tendon strain during maximum contractions in athletes (A: 8.0 ± 1.9%, C: 6.4 ± 1.8%; $p = 0.008$). We conclude that athletic volleyball training provides a more efficient stimulus for muscle compared to tendon adaptation, which results in an increased demand placed upon the tendon by the working muscle in adolescent volleyball athletes. Besides implications for sport performance, these findings might have important consequences for the risk of tendon overuse injury.

Keywords: muscle, tendon, adaptation, athletes, adolescence, tendinopathy, imbalance

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***Correspondence:**
Adamantios Arampatzis
a.arampatzis@hu-berlin.de

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INTRODUCTION

Tendons transmit the forces generated by the muscle to the skeleton and, thus, feature a crucial role in the production of torques around joints for movement. The viscoelastic properties of tendons importantly contribute to the force- and power-generating capacity of the muscle-tendon unit by optimizing the operating range with regard to the force-velocity and force-length relationship and storage and release of mechanical strain energy (Hof et al., 1983; Ettema et al., 1990; Roberts, 1997; Kawakami and Fukunaga, 2006). Thus, there is a clear relationship between the properties of tendons and human movement performance, for example for running (Arampatzis et al., 2006; Fletcher et al., 2010; Albracht and Arampatzis, 2013), sprinting (Stafilidis and Arampatzis, 2007; Kubo et al., 2011b), jumping (Bojsen-Møller et al., 2005), rapid force production (Waugh et al., 2013) or balance recovery performance (Karamanidis et al., 2008).

On the other hand, the tissue deformation during loading makes the tendon susceptible for injury. Cyclic (or constant) high-magnitude strains applied to a tendon can cause fatigue damage and even rupture (Woo, 1982; Wren et al., 2003; Lavagnino et al., 2006; Legerlotz et al., 2013; Veres et al., 2013). Therefore, tendons are able to adapt to changes in their mechanical environment and, for example, respond to an increase in muscle force potential with a modulation of its mechanical properties. The increase of tendon stiffness in response to biologically effective repetitive mechanical stimulation over a certain time is mediated by changes of the material properties (Kubo et al., 2001; Arampatzis et al., 2007, 2010; Malliaras et al., 2013; Bohm et al., 2014) and, following long-term loading, radial tendon growth (Rosager et al., 2002; Magnusson and Kjaer, 2003; Kongsgaard et al., 2005; Couppé et al., 2013).

The plasticity of tendons is well explored in human adults (Bohm et al., 2015; Wiesinger et al., 2015). In contrast, there is basically no information on the adaptation of human tendons in response to mechanical loading during childhood and adolescence. Waugh et al. (2014) were the first to investigate the effects of mechanical loading on Achilles tendon adaptation in pre-pubertal children in a longitudinal study and found a significant increase of muscle strength and a concomitant increase of tendon stiffness following a resistance exercise intervention. However, puberty is associated with profound changes of the musculoskeletal and endocrine system, which affect the plasticity of muscle and likely tendon as well. Estrogen and particularly testosterone increase the anabolic responsiveness of muscle to mechanical loading (Vingren et al., 2010; Hansen and Kjaer, 2014) and a recent meta-analysis provided evidence for an increase of muscle strength plasticity during and after peak height velocity (Moran et al., 2016). Youth athletes feature markedly greater muscle size compared to untrained adolescents, as demonstrated by Kanehisa et al. (1995b, 2003) as well as Hoshikawa et al. (2011), and, though it has not been demonstrated thus far experimentally, it is likely that changes in muscle architecture also contribute to training-induced gains in strength in adolescents (Aagaard et al., 2001). How the change in the hormonal environment affects tendon adaptation is on the other hand virtually unknown and, thus, the findings of Waugh et al. (2014) on pre-pubertal children are not necessarily representative for pubertal children or adolescents. Second, the mechanical stimulus provided by Waugh and colleagues in their machine-based resistance training intervention (i.e., high magnitude loading, long contraction durations) is known to facilitate tendon mechanical properties (Bohm et al., 2015), yet the dominant type of loading for young athletes is sport-specific and might not automatically provide an efficient stimulus for both muscle and tendon adaptation.

As the incidence of tendon overuse injuries seems to increase during adolescence (Stracciolini et al., 2014; Simpson et al., 2016) and pose a major threat to athletes from jump disciplines (Lian et al., 2005), it is crucial (a) to deepen our understanding of the adaptive processes of muscle and tendon in adolescents and (b) to detect potential factors that could promote tendon overuse pathology. Therefore, the present study investigated the properties of the knee extensor muscle-tendon unit of male and female adolescent elite volleyball athletes compared to untrained boys and girls. With regard to the seemingly lower responsiveness of the tendon to plyometric loading compared to muscle (Kubo et al., 2007; Sáez-Sáez de Villarreal et al., 2010; Bohm et al., 2014) and our recent findings of a deficient modulation of tendon stiffness in relation to muscle strength development in adolescent athletes (Mersmann et al., 2016), we hypothesized to find markedly greater muscle strength in volleyball athletes compared with untrained adolescents, mediated by greater muscle thickness and fascicle pennation angles but only moderately higher tendon stiffness. The resultant higher mechanical demand (i.e., strain) placed upon the tendon during maximum effort muscle contractions could have important implications for the risk of tendon overload injury in adolescent volleyball athletes.

MATERIALS AND METHODS

Participants and Experimental Design

Twenty-four recreationally active adolescents [12 males, 12 females; $\leq$4 h of training per week, including school sports over the last 12 month (average values were 2.6 $\pm$ 0.9 h); henceforth referred to as *controls*] and 21 similar-aged elite volleyball athletes (12 male and 9 female athletes of the junior national team; $\geq$16 h of sport-specific training per week) participated in the present study. At the time of data acquisition the athletes had participated in national elite training for 9 $\pm$ 5 month, which comprised $\sim$3 h of strength training, $\sim$4 h of athletic training (i.e., jump and sprint drills, and core stability training) and $\geq$9 h of ball practice per week. As the effects of oral contraceptives (OC) on *in vivo* patellar tendon properties are most likely negligible (Hansen et al., 2013), we decided to include girls using OC in the present study (Athletes: $n = 1/9$; controls: $n = 2/12$; none of which were long-term OC users, i.e., <1 year of use).

The study was carried out in accordance with the recommendations of the university ethics committee with written informed consent from all subjects. All subjects (and the respective legal guardians when necessary) gave written informed consent in accordance with the Declaration of Helsinki. The

protocol was approved by the university ethics committee. The measurements of muscle strength (i.e., knee extension moments), vastus lateralis architecture and patellar tendon mechanical properties were carried out on the dominant leg (i.e., leading leg in the spike jump in athletes or leg used for kicking a ball in controls) following a standardized warm-up including 5 min of ergometer cycling, 10 submaximal jumps and 10 submaximal isometric knee extension contractions as accustoming and preconditioning.

Measurement of Maximum Knee Joint Moment

For the assessment of knee extensor muscle strength, the participants performed three maximum voluntary isometric knee extension contractions (MVC) on a dynamometer (Biodex Medical System 3, Shirley, NY, USA) at resting knee joint angles of 65°, 70°, and 75° (neutral full knee extension = 0°, values refer to the joint angle determined via the dynamometer). The resting angles were chosen based on our experience that participants reach their approximate optimum angle during contractions from these starting positions. The trunk angle was set to 85° (neutral full hip extension = 0°) and the hip as fixed to the dynamometer seat using a non-elastic strap (**Figure 1**). Kinematic data were recorded using a Vicon motion capture system (version 1.7.1; Vicon Motion Systems, Oxford, UK) integrating eight cameras operating at 250 Hz. Five reflective markers were fixed to the following anatomical landmarks: greater trochanter, lateral, and medial femoral epicondyles, and malleoli. The electromyographic (EMG) activity of the lateral head of the biceps femoris was recorded using two bipolar surface electrodes (Blue Sensor N, Ambu GmbH, Bad Nauheim, Germany) fixed over the mid-portion of the muscle belly with an inter-electrode distance of 2 cm after shaving and cleaning the skin. EMG data was captured at 1,000 Hz (Myon m320RX; Myon, Baar, Switzerland) and transmitted to the Vicon system via a 16-channel A-D converter.

Due to the non-rigidity of the human-dynamometer system (Arampatzis et al., 2004), the knee joint angle that was reached in the trails where the maximum knee extension moments were generated was 54 ± 4°, calculated in post-processing from the kinematic model. The resultant knee joint moments were calculated based on the inverse dynamics approach proposed by Arampatzis et al. (2004), which takes into account the inevitable axes misalignments of the knee joint and dynamometer during the course of the contraction as well as moments due to gravity. To account for the latter, an additional trial was recorded, where a passive knee extension was driven by the dynamometer at 5°/s with the shank of the participants fixed to the dynamometer lever pad. The contribution of the antagonistic muscles during the isometric contractions was estimated in the calculation of the maximum knee extension moments using the approach described by Mademli et al. (2004). In short, an EMG-activity knee flexion moment relationship was established on the basis of two additional knee flexion trials featuring an EMG-activity that was slightly lower and higher compared to the activity registered during the maximum knee extension trials, respectively.

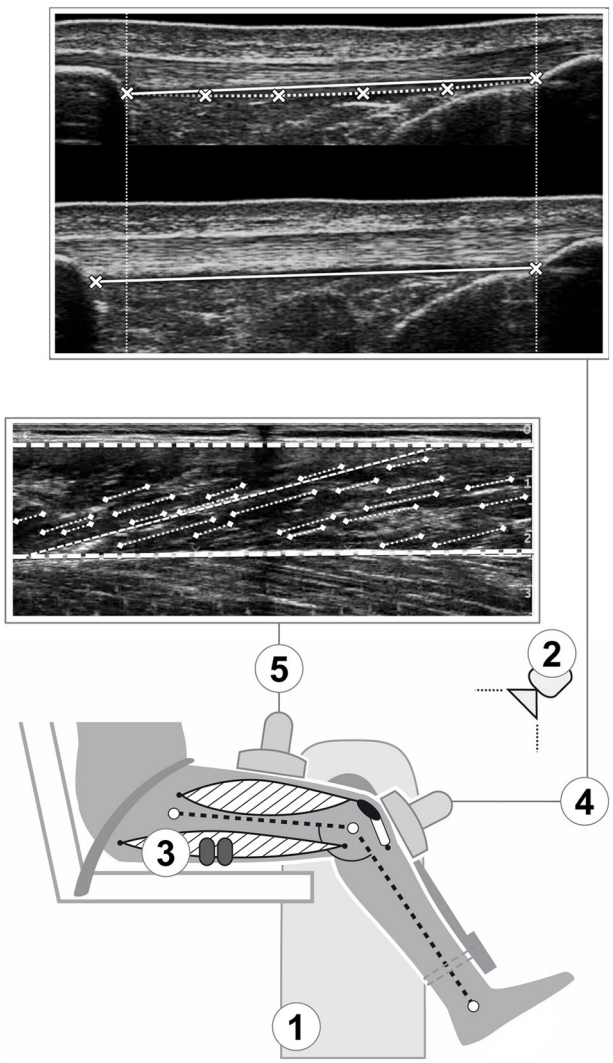


FIGURE 1 | Schematic representation of the experimental setup. A dynamometer (1) was used to measure knee joint moments, while kinematic recordings (2) were used for inverse dynamics and electromyography (3) for the consideration of antagonist coactivation. Ultrasound imaging was integrated to assess patellar tendon elongation (4; the crosses indicate the reference points at the deep insertion sites and lower border of the tendon used for measuring elongation and rest length respectively; see methods section for details) and vastus lateralis architecture (5; the digitalization of the aponeuroses and the fascicle portions, indicated by the thick dashed line and pointed lines respectively, and the calculated reference fascicle, represented by the thin dashed line, are overlayed over the ultrasound image).

Measurement of Vastus Lateralis Muscle Architecture

Vastus lateralis architecture was assessed at a knee joint angle of 60°, which has been reported earlier to be the approximate optimum knee angle for force production of the knee extensors (Herzog et al., 1990). A 10-cm linear ultrasound probe (7.5 MHz; My Lab60; Esaote, Genova, Italy; probe: linear array (LA923), depth: 7.4 cm, focal point: 0.9 and 1.9, no image filter) was

placed over the belly of the inactive muscle in its longitudinal axis at ∼60% thigh length (average location of the maximum anatomical cross-sectional area; Mersmann et al., 2015). The ultrasound images were analyzed offline using a custom written MATLAB interface (version R2012a; MathWorks, Natick, MA, USA). The upper and deeper aponeuroses were defined by setting reference points along the aponeuroses that were approximated by a linear least squares fitting. Subsequently, we digitized the visible features of multiple fascicles (on average 22 ± 5) and calculated a reference fascicle based on the average inclination of the fascicle portions and the distance of the aponeuroses (**Figure 1**; Mersmann et al., 2014). The pennation angle refers to the angle between the reference fascicle and the deeper aponeurosis and fascicle length is reported normalized to femur length (average value of two measurements from the greater trochanter to the lateral epicondyle, identified by palpation, by means of a measuring tape).

Measurement of Patellar Tendon Mechanical Properties

To establish the force-elongation behavior of the patellar tendon, the ultrasound probe was fixed overlying the patellar tendon in the sagittal plane using a modified knee brace (i.e., similar probe and settings as described above). The elongation of the tendon was captured at 25 Hz during five trials of isometric ramp contractions (i.e., steadily increasing effort from rest to maximum in ∼5 s). The resting knee joint angle for the ramp contractions was chosen for each participant according to the MVC trial in which the highest moments were achieved.

The knee extension moments were calculated using the same considerations as described above for the MVC measurement (i.e., experimental setup, inverse dynamics approach, and correction for antagonistic contribution; see 2.2). The tendon force was then calculated by dividing the knee extension moment by the tendon moment arm. In 19 athletes it was possible to assess the moment arm directly from magnetic resonance images as described earlier (Mersmann et al., 2014). In all other participants, the moment arms were predicted based on sex, body height and mass, using the regression equation reported by Mersmann et al. (2016). The moment arms were adjusted to the respective knee joint angle position using the data of Herzog and Read (1993).

The ultrasound images were synchronized offline with the data recorded with the Vicon system using an externally induced voltage peak, which could be identified in both the ultrasound images and the analog data stream. Patellar tendon elongation during the contractions (**Figure 1**) was determined manually by tracking the deep insertion of the tendon at the patellar apex and the tibial tuberosity frame-by-frame using a custom-written MATLAB interface. To account for tendon slackness at rest, elongation was measured when the distance between the deep insertion points exceeded tendon rest length, which in turn was measured using a spline fit through the deep insertion marks and four additional points along the lower border of the slack tendon. The tracking was done by two experienced observers (F.M. and G.C.) and the force-elongation relationship of the five trials of each participant was averaged, using the highest common force value as peak force. This approach provides excellent reliability (≥0.95) and observer-independence (Schulze et al., 2012). The resultant force-elongation curve was fitted using a second-order polynomial, and tendon stiffness was calculated between 50 and 100% of the peak tendon force. As the length of a tendon has significant effects on its stiffness (Butler et al., 1978), we accounted for the anthropometric differences between the groups by also calculating *normalized tendon stiffness* (i.e., the product of stiffness and rest length). In one participant (male, control group), it was not possible to analyze patellar tendon elongation due to ultrasound image artifacts during the contraction.

Statistics

The statistical analysis was conducted in SPSS (version 20.0; IBM, Armonk, NY, USA). We performed a two-way analysis of variances with the fixed factors training (i.e., controls, athletes) and sex (i.e., male, female). Normality of the standardized residuals was tested using the Kolmogorov–Smirnov test with Lilliefors correction (Lilliefors, 1967) and Levene's test was applied to test homoscedasticity. If normality or homoscedasticity was violated, we separately tested differences between athletes and controls, and males and females respectively, using the Mann-Whitney-Wilcoxon test and Bonferroni adjustment (adjusted p-values, denominated p_{adj}, will be reported). The alpha level for all tests was set to 0.05. The effect size f for significant observations were calculated in G*Power (Version 3.1.6; HHU, Düsseldorf, Germany; Faul et al., 2007), based on either the partial eta squared or the group means and pooled standard deviation (for non-parametrically tested parameters). The subscript *Training* or *Sex* indicates if the effect size refers to differences between controls and athletes or males and females, respectively. Effect sizes of $0.1 \leq f < 0.25$ will be referred to as small, $0.25 \leq f < 0.5$ as medium and $f \geq 0.5$ as large (Cohen, 2013).

RESULTS

There was no significant difference of age between the four groups ($p = 0.9$), but athletes compared to controls as well as males compared to females had significantly greater body height ($f_{\text{Training}} = 1.91, p < 0.001; f_{\text{Sex}} = 1.27, p < 0.001$), mass ($f_{\text{Training}} = 0.50$, $p_{\text{adj}} = 0.004$; $f_{\text{Sex}} = 0.46$, $p_{\text{adj}} = 0.008$) and femur lengths ($f_{\text{Training}} = 1.60$, $p < 0.001$; $f_{\text{Sex}} = 0.56$, $p = 0.001$; **Table 1**, respectively). There were no significant training-by-sex interactions on the anthropometric parameters ($p > 0.05$).

Absolute ($f_{\text{Training}} = 1.07$, $p < 0.001$; $f_{\text{Sex}} = 1.11$, $p < 0.001$) and normalized knee extensor muscle strength ($f_{\text{Training}} = 0.48$, $p = 0.004$; $f_{\text{Sex}} = 0.51$, $p = 0.002$), and absolute ($f_{\text{Training}} = 1.18$, $p < 0.001$; $f_{\text{Sex}} = 1.09$, $p < 0.001$) and normalized resultant knee joint moments ($f_{\text{Training}} = 0.56, p = 0.001; f_{\text{Sex}} = 0.45, p = 0.006$) were significantly greater in athletes and males, respectively (**Table 2**), without significant training-by-sex interactions ($p > 0.05$). Further, there was a tendency toward lower coactivation in athletes ($f_{\text{Training}} = 0.32$, $p_{\text{adj}} = 0.056$), yet no significant differences between males and females ($p_{\text{adj}} = 1.0$; **Table 2**).

TABLE 1 | Antrhopometric data of the adolescent controls and volleyball athletes.

	Controls		Athletes	
	Male ($n = 12$)	Female ($n = 12$)	Male ($n = 12$)	Female ($n = 9$)
Age [years]	16.8 ± 1.1	16.6 ± 0.9	16.8 ± 1.0	16.7 ± 0.9
Height [cm]*#	175.0 ± 4.4	162.1 ± 8.1	195.2 ± 4.0	181.6 ± 3.4
Mass [kg]*#	67.9 ± 11.5	61.9 ± 17.7	86.1 ± 7.2	68.0 ± 5.8
Femur length [cm]*#	41.5 ± 2.3	38.1 ± 3.6	48.4 ± 1.5	46.4 ± 1.9

*Values are means ± standard deviation. *Significant difference between athletes and controls, #significant difference between males and females, $p < 0.05$.*

TABLE 2 | Knee joint moments and antagonistic coactivation of adolescent controls and volleyball athletes.

	Controls		Athletes	
	Male ($n = 12$)	Female ($n = 12$)	Male ($n = 12$)	Female ($n = 9$)
MVC [Nm]*#	264.2 ± 57.2	192.8 ± 25.5	385.6 ± 48.3	260.6 ± 48.0
Normalized MVC [Nm/kg]*#	3.89 ± 0.52	3.25 ± 0.67	4.52 ± 0.74	3.86 ± 0.74
Resultant moment [Nm]*#	237.9 ± 54.2	174.7 ± 22.2	355.2 ± 38.7	245.2 ± 45.2
Normalized resultant moment [Nm/kg]*#	3.50 ± 0.54	2.96 ± 0.66	4.15 ± 0.58	3.63 ± 0.68
Antagonistic coactivation [%](*)	13.0 ± 7.9	11.3 ± 6.4	9.1 ± 6.0	7.0 ± 3.4

*Values are means ± standard deviation. Moments were normalized to body mass. Antagonistic coactivation is the antagonistic moment normalized to the resultant knee joint moment. MVC, Maximum voluntary contraction. *Significant difference between athletes and controls, #Significant difference between males and females, $p < 0.05$; (*) tendency toward a difference between controls and athletes, $p_{adj} = 0.056$.*

We found significantly greater vastus lateralis muscle thickness in athletes compared to controls ($f_{\text{Training}} = 1.12$, $p < 0.001$) as well as in males compared to females ($f_{\text{Sex}} = 0.37$, $p = 0.023$), without significant training-by-sex interactions ($p = 0.29$; **Figure 2A**). Further, athletes featured greater pennation angles compared to controls ($f_{\text{Training}} = 0.75$, $p < 0.001$), while there were no significant differences between males and females ($p = 0.72$) or training-by-sex interactions ($p = 0.3$; **Figure 2B**). No significant effects or interactions were found on normalized fascicle length ($p > 0.05$; **Figure 2C**).

In athletes compared to controls, we found greater maximum patellar tendon force ($f_{\text{Training}} = 0.82$, $p < 0.001$; **Figure 3A**), normalized tendon stiffness ($f_{\text{Training}} = 0.34$, $p = 0.04$; **Figure 3B**), tendon strain ($f_{\text{Training}} = 0.42$, $p_{\text{adj}} = 0.016$; **Figure 3C**) and elongation during maximum contractions ($f_{\text{Training}} = 0.55$, $p = 0.001$; **Table 3**), tendon moment arm ($f_{\text{Training}} = 1.58$, $p < 0.001$; **Table 3**), and rest length ($f_{\text{Training}} = 0.57$, $p = 0.001$; **Table 3**), but no significant difference in absolute tendon stiffness ($p = 0.26$; **Table 3**). Tendon force ($f_{\text{Sex}} = 0.83$, $p < 0.001$), moment arm ($f_{\text{Sex}} = 1.55$, $p < 0.001$) and rest length ($f_{\text{Sex}} = 0.48$, $p = 0.004$) were higher in males compared to females. However, there were no significant differences between sexes with regard to absolute ($p = 0.57$) or normalized tendon stiffness ($p = 0.17$), strain ($p = 0.49$) and elongation ($p = 0.12$) or training-by-sex interactions in general ($p > 0.05$).

DISCUSSION

The present study investigated the effects of mechanical loading in terms of athletic volleyball training on the properties of the knee extensor muscle-tendon unit in male and female adolescents. The results demonstrate that, irrespective of sex and anthropometric differences, both muscle and tendon show clear differences between trained and untrained boys and girls. We found a significantly greater muscle strength capacity in the athletes compared to the control group and corresponding differences in vastus lateralis muscle thickness and pennation angle. Similarly, athletes demonstrated greater normalized patellar tendon stiffness, indicating that the tendon adapts to mechanical loading before full maturation of the musculoskeletal system. However, the only medium effects of training status on normalized tendon stiffness compared to the large effects on tendon force ($f = 0.34$ and 0.84, respectively) suggest an imbalance in the adaptation of muscle and tendon, subjecting the tendons of athletes to higher levels of strain during maximum contractions compared to controls. Therefore, our hypotheses were confirmed.

It is well established that physical training increases muscle strength even in childhood (Falk and Eliakim, 2003; Matos and Winsley, 2007; Legerlotz et al., 2016) and, thus, our findings of greater knee extensor strength in trained compared to untrained adolescents were not surprising. Similarly, our findings of greater vastus lateralis thickness, pennation angle, and, in tendency, reduced antagonistic coactivation in athletes are in line with earlier reports of muscle morphological (Fukunaga et al., 1992; Kanehisa et al., 1995a, 2003; Daly et al., 2004; Mersmann et al., 2016) and neuronal adaptations (Ramsay et al., 1990; Ozmun et al., 1994) as potential contributors to training-induced increases of strength in young athletes. However, this is, to our knowledge, the first study to report differences in patellar tendon mechanical properties between an athletic and untrained adolescent population. Waugh et al. (2014) investigated the effects of a strength training intervention on the mechanical properties of the Achilles tendon in pre-pubertal children and reported a significant increase of tendon stiffness. More recently, a cross-sectional comparison of tendon thickness between 500 adolescent athletes from different sports provided an indication of tendon plasticity in response to increased loading for the patellar tendon as well (Cassel et al., 2016). Earlier work of our group already suggested that the patellar tendon is responsive to mechanical stimulation, but it was not possible to differentiate the effects of mechanical loading and maturation (Mersmann et al., 2017) or to directly compare the mechanical properties of the patellar tendon between athletes and controls due to inhomogeneous sample composition with regard to sex (Mersmann et al., 2016). The different normalized patellar tendon stiffness between athletes and controls in the present study provide evidence that also the patellar tendon adapts to mechanical loading before adulthood. With regard to

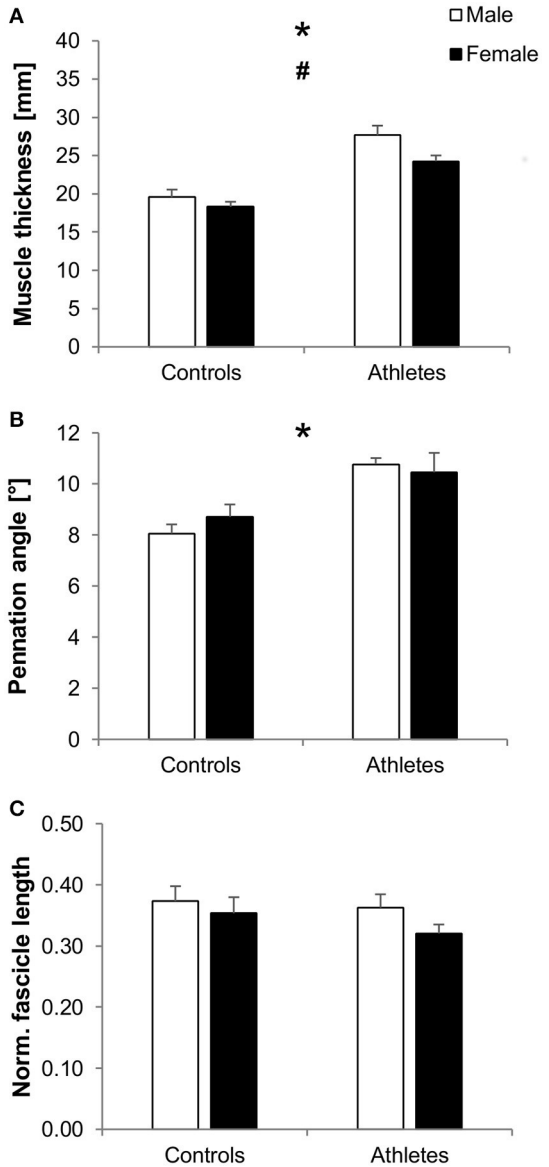


FIGURE 2 | Mean values and standard error (error bars) of vastus lateralis muscle thickness **(A)**, pennation angle **(B)**, and normalized fascicle length (**C**; normalized to femur length) of male (white) and female (black) adolescent controls and volleyball athletes. *Significant difference between athletes and controls, #significant difference between males and females, $p < 0.05$.

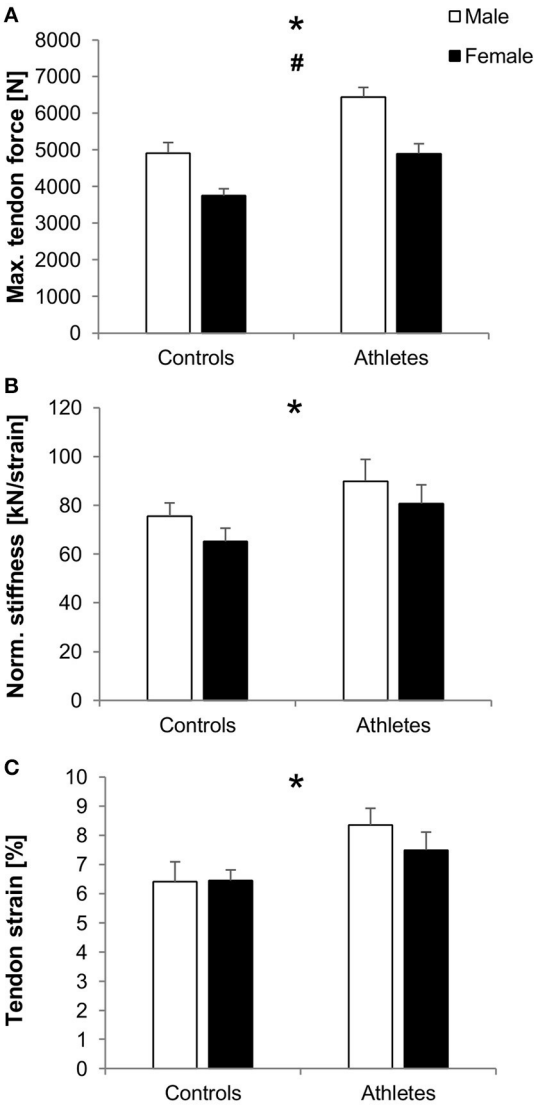


FIGURE 3 | Mean values and standard error (error bars) of patellar tendon force **(A)**, normalized stiffness **(B)** and strain during maximum isometric contractions **(C)** of male (white) and female (black) adolescent controls and volleyball athletes. *Significant difference between athletes and controls, #significant difference between males and females, $p < 0.05$.

the marked effect of athletic training on muscle strength, the increase of tendon stiffness serves two important mechanical functions. First, it improves the performance capacity of the muscle-tendon unit. Higher tendon stiffness is associated with a reduction of electromechanical delay (Waugh et al., 2014), increased rate of torque development (Bojsen-Møller et al., 2005; Waugh et al., 2013) and jump performance (Bojsen-Møller et al., 2005; Burgess et al., 2007), and it maintains muscle fascicle kinetics within an optimal operating range when the force production during a movement task (e.g., jumping) increases due to training (Lichtwark and Wilson,

TABLE 3 | Patellar tendon properties of adolescent controls and volleyball athletes.

	Controls		Athletes	
	Male ($n = 11$)	**Female ($n = 12$)**	**Male ($n = 12$)**	**Female ($n = 9$)**
Moment arm [mm]*#	53.6 ± 1.3	49.2 ± 2.0	59.8 ± 3.2	53.5 ± 3.0
Rest length [mm]*#	51.6 ± 4.5	46.6 ± 4.5	56.0 ± 5.8	52.5 ± 3.4
Stiffness [N/mm]	1474 ± 375	1392 ± 352	1650 ± 670	1560 ± 518
Maximum elongation [mm]*	3.30 ± 1.26	2.98 ± 0.64	4.71 ± 1.37	3.94 ± 1.05

*Values are means ± standard deviation. *Significant difference between athletes and controls, #Significant difference between males and females, $p < 0.05$.*

2007). Second, the modulation of stiffness may serve as a protective mechanism against unphysiological levels of strain induced by the increased force-generating capacity of the trained muscle, since the ultimate strain of tendons is considered to be relatively constant (Abrahams, 1967; Loitz et al., 1989; LaCroix et al., 2013; Shepherd and Screen, 2013). However, besides increased normalized stiffness, the athletes in the present study featured increased levels of tendon strain during maximum muscle contractions as well, which is in accordance with earlier findings of our group (Mersmann et al., 2016) and indicates an imbalanced adaptation of muscle and tendon. Tendon strain during maximum contractions is an indicator of how the integrity of the tissue is challenged by the working muscle. Wren et al. (2003) demonstrated that the initial strain induced in the tendon by a given load predicts the lifetime of the tendinous tissue during static and cyclic loading. The increased demand placed upon the tendon by the working muscle we observed in athletes could increase the risk of accumulating microdamage and predispose for tendon injury (Butler et al., 1978; Fung et al., 2009; Legerlotz et al., 2013), especially in athletes that are subjected to high frequencies of maximum jumping in their sportive activity (Bahr and Bahr, 2014). The high prevalence of tendinopathy in volleyball athletes (Lian et al., 2005) and *in vivo* reports of increased levels of tendon strain in patients with tendinopathy (Arya and Kulig, 2010; Child et al., 2010) further support the idea that an imbalanced adaptation of muscle and tendon in athletes might increase the risk to develop tendinopathy, though certainly more direct evidence is needed to support this assumption.

The higher normalized stiffness compared to untrained adolescents as well as the imbalance between muscle strength and tendon stiffness are most likely related to the type of mechanical loading the athletes are subjected to. Systematic investigations on the specific effects of different modes of mechanical stimulation on human tendons *in vivo* demonstrated that high magnitude loading (in terms of tendon force and corresponding strain) effectively promote tendon stiffness (Arampatzis et al., 2007, 2010; Kongsgaard et al., 2007; Malliaras et al., 2013). High-level strain application has been associated with greater tendon cell deformation (Arnoczky et al., 2002) and collagen fiber recruitment (Kastelic et al., 1980; Hansen et al., 2002), which are considered important factors for the transmission of extracellular matrix strains into cellular responses (Lavagnino et al., 2008). Direct measurements (Finni et al., 2000) and estimations of patellar tendon forces (Janssen et al., 2013) suggest tendon loads to exceed five times body weight during jumping and landing, which makes it reasonable to assume that athletic volleyball training provides sufficient loading in terms of load magnitude to induce tendon adaptation. High tendon strain rates during plyometric loading and the associated fluid-flow dependent shear stress on tendon cells might additionally stimulate tendon metabolism (Haut and Haut, 1997; Archambault et al., 2002; Lavagnino et al., 2008). Interestingly though, most longitudinal intervention-studies that applied plyometric exercise (over 8–14 weeks) failed to elicit significant adaptive changes of human tendons (Kubo et al., 2007; Fouré et al., 2009, 2010; Houghton et al., 2013), even at high loading magnitudes (Bohm et al., 2014). In consequence, an increase of muscle strength without an adequate modulation of stiffness induced by plyometric loading can result in increased levels of tendon deformation (Kubo et al., 2007), which is commonly not observed following high-intensity loading with long contraction durations (e.g., Kongsgaard et al., 2007; Arampatzis et al., 2007, 2010; Malliaras et al., 2013). It has been argued that short strain durations of plyometric regimen or high-frequency load-relaxation cycles might compromise the effectiveness of the mechanotransduction at the tendon level (Arampatzis et al., 2010; Bohm et al., 2014). Therefore, it seems well possible that only long-term habitual plyometric loading results in a notable modulation of tendon stiffness, but that the effects are still less pronounced compared to the associated and more clearly established increases of muscle strength (Sáez-Sáez de Villarreal et al., 2010). With regard to the greater body mass of the athletes in our study, it cannot be excluded, of course, that increased habitual loading during everyday activities partly contributed to the greater tendon stiffness compared to the control group. However, body mass was not correlated to normalized tendon stiffness in the present study ($r = 0.013$, $p = 0.94$) and data by Waugh et al. (2011) sugests that, at least in the Achilles tendon, a clear association between body mass and tendon stiffness only exists during pre-pubertal growth and not in adulthood. Thus, it is reasonable to conclude that the sport-specific loading was the main determinant for both the greater normalized tendon stiffness as well as the imbalance between muscle strength and tendon mechanical properties.

An alternative or additional explanation for the imbalance between muscle strength and tendon stiffness, indicated by the increased levels of tendon strain during maximum contractions in athletes compared to controls, could be differences in the plasticity of muscle and tendon as a function of maturation. Earlier work of our group already provided evidence that under the influence of maturation and superimposed mechanical loading the development of muscle morphology and function might precede adaptive and developmental processes at the tendon level in adolescent volleyball athletes (Mersmann et al., 2014, 2017). The results of a recent meta-analysis indicate an increase in the responsiveness of the neuromuscular system to mechanical loading early in adolescence (Moran et al., 2016), which is likely in part related to the muscle-anabolic effects of sex hormones (Vingren et al., 2010; Hansen and Kjaer, 2014). The effects of the rapid increase of circulating sex hormones on tendon plasticity during growth on the other hand are basically unknown (Hansen and Kjaer, 2014). Evidence on human adults suggest that estrogens reduce collagen synthesis in response to exercise, indicating a reduced adaptability of the tendinous system in women compared to men (Hansen and Kjaer, 2014; for reviews see Magnusson et al., 2007). In the present study, however, the differences between athletic and untrained adolescents of both patellar tendon mechanical properties and tendon strain (as an indicator of musculotendious imbalances) were similar in boys and girls (i.e., no significant training-by-sex interaction: $p = 0.94$ and 0.44, respectively). Therefore, it is well possible that sex-related differences in the responsiveness of tendinous tissue to mechanical loading unfold with the formation of the tendon core tissue at the end of adolescence (Heinemeier et al., 2013) and long-term exposure

to elevated levels of circulating estrogens (Bryant et al., 2008; Hansen and Kjaer, 2014). However, due to a lack of comparable data on adult volleyball athletes with a similar training history compared to the adolescents of the present study, the additional influence of maturation on the balance of musculotendinous adaptations to loading still remains an assumption. Clinical evidence shows that the probability of non-contact soft-tissue injury in adults rises when training loads are increased rapidly (Gabbett, 2016) and differences between muscle and tendon in the responsiveness to distinct mechanical stimuli (Arampatzis et al., 2007, 2010; Kubo et al., 2007) as well as in the time course of adaptation (Kubo et al., 2010, 2011a) are issues that affect the balance of muscle and tendon adaptation in adult athletes as well. Nevertheless, it is evident that there is a need to increase our understanding of the complex interaction of mechanical loading and changes of the hormonal milieu on tendon plasticity in general, and with regard to adolescence in particular.

The World Health Organization defines adolescence as a period ranging roughly from 10 to 19 years of age (World health organization: department of child adolescent health development, 2001), yet a distinction between early adolescence (i.e., 10–14 years) and late adolescence (i.e., 15–19 years) has become common more recently (Sawyer et al., 2012) to partly account for the drastic physical, cognitive and socio-emotional development during the overall period of adolescence. Since it is barely possible to adequately control for biological age with non-invasive measures (Malina et al., 2015), this study investigated late adolescent cohorts following the assumption that the differences in biological and chronological age are most pronounced in early adolescence. Therefore, it is unclear if the observations of the present study are representative for other stages of development. Considering the observations of increased tendon stress during the longitudinal growth of the muscle-tendon unit in early adolescence (Neugebauer and Hawkins, 2012), this could be important maturational phase to address with future experimental designs.

Due to the cross-sectional design of the study, the time course of muscle and tendon adaptation in relation to training history (i.e., 6 $\pm$ 3 years of volleyball practice, 9 $\pm$ 5 month of elite-level training) and/or maturation also remains unclear. The fluctuations of both muscle and tendon properties during a competitive season, which was observed in a recent study of our group (Mersmann et al., 2016), suggests that also the time point of data acquisition could be important for a comparison to untrained individuals. In the present study, it was not possible to adjust the scheduling of the measurements to a specific time point in the competitive season of the athletes. However, since the fluctuations over time reported earlier (e.g., MVC: 5%, stiffness: 8%, strain: 14%; Mersmann et al., 2016) were markedly lower as the differences observed between the athletes and controls of the present study (MVC: 45%, normalized stiffness: 23%, strain: 24%) it is unlikely that this limitation affected our main findings and conclusions.

The selection of elite volleyball athletes as trained group was based on the sport-specific loading profile (i.e., high intensity plyometric loading) and the urgent need for a better understanding of muscle and tendon adaptation due to the high incidence of tendinopathy in that group (Lian et al., 2005). The generalizability of our findings to other athletic populations is speculative. It seems well possible that differentially graded adaptations of muscle and tendon might occur in other sports that incorporate types of loading that lead to rapid strength gains (i.e., high intensity muscle contractions; Seynnes et al., 2007; DeFreitas et al., 2011) or more effectively stimulate muscle compared to tendon adaptation (i.e., moderate intensity loading, plyometric loading; Arampatzis et al., 2007, 2010; Kubo et al., 2007; Bohm et al., 2014). Our findings might therefore be relevant for the design of training programs in sports such as Basketball, Soccer or athletic jumping disciplines as well. However, this assumption warrants verification in future studies.

In conclusion, the present study provides evidence that, irrespective of sex, adolescent volleyball athletes feature markedly greater muscle strength, mediated by greater muscle thickness and pennation angle as well as reduced antagonistic coactivation, and greater normalized tendon stiffness compared to untrained adolescents. However, increased levels of tendon strain during maximum contractions in athletes indicate an imbalance in the development of muscle strength and tendon stiffness that might be partly due to (a) suboptimal tendon mechanical stimulation by sport-specific loading and (b) deviations in the temporal dynamics of muscle and tendon adaptation during adolescence. The potential contribution of musculotendinous imbalances to the increasing risk of tendon overload injury during adolescence (Stracciolini et al., 2014; Simpson et al., 2016) highlight the importance to further increase our understanding of muscle and tendon plasticity during growth and maturation as well as to evaluate the potential of implementing loading regimen that effectively facilitate tendon mechanical properties (Bohm et al., 2015) into the athletic training of adolescents for injury prevention.

AUTHOR CONTRIBUTIONS

FM and AA conceived the experiment; FM, GC, and SB performed the experiments; all authors substantially contributed to data analysis; FM and AA interpreted the data; FM drafted the manuscript and GC, SB, and AA made important intellectual contributions during revision. All authors approved the final version of the manuscript and agree to be accountable for the content of the work.

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Physiological Tendon Thickness Adaptation in Adolescent Elite Athletes: A Longitudinal Study

Michael Cassel, Konstantina Intziegianni, Lucie Risch, Steffen Müller, Tilman Engel and Frank Mayer*

Department of Sports Medicine, University Outpatient Clinic, University of Potsdam, Brandenburg, Germany

Increased Achilles (AT) and Patellar tendon (PT) thickness in adolescent athletes compared to non-athletes could be shown. However, it is unclear, if changes are of pathological or physiological origin due to training. The aim of this study was to determine physiological AT and PT thickness adaptation in adolescent elite athletes compared to non-athletes, considering sex and sport. In a longitudinal study design with two measurement days (M1/M2) within an interval of 3.2 ± 0.8 years, 131 healthy adolescent elite athletes (m/f: 90/41) out of 13 different sports and 24 recreationally active controls (m/f: 6/18) were included. Both ATs and PTs were measured at standardized reference points. Athletes were divided into 4 sport categories [ball (B), combat (C), endurance (E) and explosive strength sports (S)]. Descriptive analysis (mean ± SD) and statistical testing for group differences was performed ($\alpha = 0.05$). AT thickness did not differ significantly between measurement days, neither in athletes (5.6 ± 0.7 mm/5.6 ± 0.7 mm) nor in controls (4.8 ± 0.4 mm/4.9 ± 0.5 mm, $p > 0.05$). For PTs, athletes presented increased thickness at M2 (M1: 3.5 ± 0.5 mm, M2: 3.8 ± 0.5 mm, $p < 0.001$). In general, males had thicker ATs and PTs than females ($p < 0.05$). Considering sex and sports, only male athletes from B, C, and S showed significant higher PT-thickness at M2 compared to controls ($p \leq 0.01$). Sport-specific adaptation regarding tendon thickness in adolescent elite athletes can be detected in PTs among male athletes participating in certain sports with high repetitive jumping and strength components. Sonographic microstructural analysis might provide an enhanced insight into tendon material properties enabling the differentiation of sex and influence of different sports.

Keywords: Achilles and patellar tendon, training adaptation, sonography, young athletes, non-athletes

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****Correspondence:***
Michael Cassel
mcassel@uni-potsdam.de

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INTRODUCTION

Achilles and patellar tendinopathy was shown to be present already in adolescent athletes (Cook et al., 2000; Cassel et al., 2015). An increasing prevalence for patellar tendinopathy of 33% with increasing age up to 18 years could be identified (Simpson et al., 2016). In contrast, the Achilles tendon (AT) is less often affected during adolescence. Data among adolescent athletes from 16 different sports identified prevalence of Achilles and patellar tendinopathy with 1.8 and 5.8% at an average age of 13 years (Cassel et al., 2015). Athletes having patellar tendinopathy showed higher patellar tendon (PT) thickness compared to asymptomatic athletes in cross-sectional analysis (Cassel et al., 2015). Furthermore, a higher prevalence of intratendinous abnormalities

(hypoechoic regions and higher grades of vascularization in ultrasound) was associated with patellar tendinopathy (Cassel et al., 2015). This supports the hypothesis of a continuum model of pathological tendon changes already at a young age (Cook and Purdam, 2009; Malliaras and Cook, 2011).

Besides a pathological increase in tendon diameter a physiological tendon adaptation due to repetitive and higher loading in sports is discussed (Kjaer et al., 2009; Malliaras and Cook, 2011; Cassel et al., 2016). ATs of healthy adult runners were shown to have higher cross-sectional area (CSA) compared to controls (Kongsgaard et al., 2005). Moreover, a correlation between body mass and AT-thickness was reported (Hirschmüller et al., 2010). For PTs, 12 weeks of strength training led to an increased CSA in Magnetic Resonance Imaging (MRI) scans of the proximal and distal tendon region by 4–7% in 12 untrained healthy males aged 25 years (Kongsgaard et al., 2007). Higher PT-CSA was also detected in the leading leg of seven elite fencers and badminton players with an average age of 23 years (Couppé et al., 2008). In a recent cross-sectional study on 500 adolescent athletes and 40 recreationally active controls with a mean age of 13 years, higher AT and PT thickness of ball and water sport athletes compared to controls could be detected (Cassel et al., 2016). However, statistically significant differences in AT and PT diameter for younger compared to older adolescent athletes could not be found (Cassel et al., 2016).

For the early detection of initial pathological changes normative values of physiological tendon thickness in athletes are required. Physiological AT diameter in adults has been reported to be 4–6 mm, while values of the patellar tendon thickness were observed between 3 and 5 mm, depending on measurement location (Schmidt et al., 2004; Fredberg et al., 2008; Hirschmüller et al., 2010; Cassel et al., 2012). Cross-sectional data among young adolescent athletes and non-athletes showed AT and PT thickness to be already on adult elite athletes' level (Cassel et al., 2016). Whether the higher tendon diameter in some types of sports has to be interpreted as a physiological adaptation due to loading or if it might represent the first sign of a pathological degeneration remains unclear (Malliaras and Cook, 2011; Cassel et al., 2016). None of the studies among asymptomatic adolescent athletes examined tendon dimensions as well as the presence of structural intratendinous abnormalities (i.e., echoic irregularities) potentially indicating initial tissue pathologies, in a longitudinal setting. In addition, the long-term effect of sex, training as well as anthropometric prerequisites on tendon thickness has to be determined.

The purpose of this study was to determine the longitudinal AT and PT thickness adaptation in healthy adolescent elite athletes compared to non-athletes during growth. In addition, the influence of sex, sport-specific loading, anthropometric data as well as intratendinous abnormalities were analyzed.

MATERIALS AND METHODS

Subjects

A total of 168 adolescent athletes were recruited in the context of a preparticipation examination before entrance to a federal elite school of sports (Mayer et al., 2012). In addition, 28 recreationally active control subjects were recruited from a local secondary school. Exclusion criteria were the presence of Achilles or patellar tendinopathy, rupture or surgery, rheumatic disease, dyslipidemia as well as acute injury of the knee or ankle. Due to the clinical presence of AT or PT tendinopathy at inclusion (first measurement day: M1) in 11 athletes and 3 controls, 14 subjects had to be excluded. In consequence, 157 healthy adolescent athletes out of 14 different sports and 25 healthy control subjects were included at M1 (**Figure 1**). Follow-up-examination (M2) took place after 3.2 ± 0.8 years for athletes and after 3.0 ± 0.1 years for controls. At M2 26 athletes and one control subject had to be excluded due to a newly developed diagnosis of tendinopathy in the AT or PT region (**Figure 1**). Parents of all adolescent athletes signed written informed consent before data acquisition. The study was approved by the Ethics Committee of the local University.

Measurement Procedure

Athlete's examination was conducted during preparticipation and annual health examinations at the university outpatient clinic, Olympic center, responsible for athletes' health in the federal state. For recreational subjects investigations took place at a secondary school by use of the same portable ultrasound equipment. Each examination composed of history, local tendon examination and a brief status of the adjacent joints. In addition to anthropometric data, age and sex, specific training-related data (sport-type, training duration and frequency) were documented in a standardized case report form.

Ultrasound scans were conducted to measure tendon diameter and to detect intratendinous abnormalities (intratendinous blood flow, hypo- and hyperechoic regions). Investigations of both ATs and PTs were performed using high-resolution ultrasonography (Viamo SSA-640A; Toshiba, Tokyo, Japan) with a multi-frequency linear transducer (PLT-704SY) and standardized transducer settings (11 MHz, gain = 93, DR = 50, penetration depth = 3 cm, focus at 0.5 cm). Ultrasound investigations were performed by three trained examiners. Examinations of ATs were investigated in a prone position with feet hanging over the examination table and ankle passively dorsi-flexed to a neutral position. PT examinations were carried out in a supine position with 30° knee flexion, controlled by use of a soft pad. As previously described, both ATs and PTs were longitudinally examined to determine tendon diameters at a reference point 2 cm proximal to the calcaneal insertion (AT 2 cm) and 2 cm distal the Patella (PT 2 cm), respectively (Cassel et al., 2012, 2016). Tendon thickness was reported to be reliably measureable at these standardized locations (Schmidt et al., 2004; Fredberg et al., 2008). Moreover, the diameter at the thickest part of the AT "mid-portion" was measured (AT max) (Cassel et al., 2012, 2016). Longitudinal scans were performed by a strict orthogonal placement of the transducer on ATs and PTs in order to measure "true tendon thickness", excluding epitenon and paratenon.

For Doppler ultrasound (DU) detection of intratendinous blood flow (IBF) subjects were requested to relax their muscles leading to a slight plantar-flexion ankle angle, while the knee angle stayed at 30° flexion. IBF was measured using power

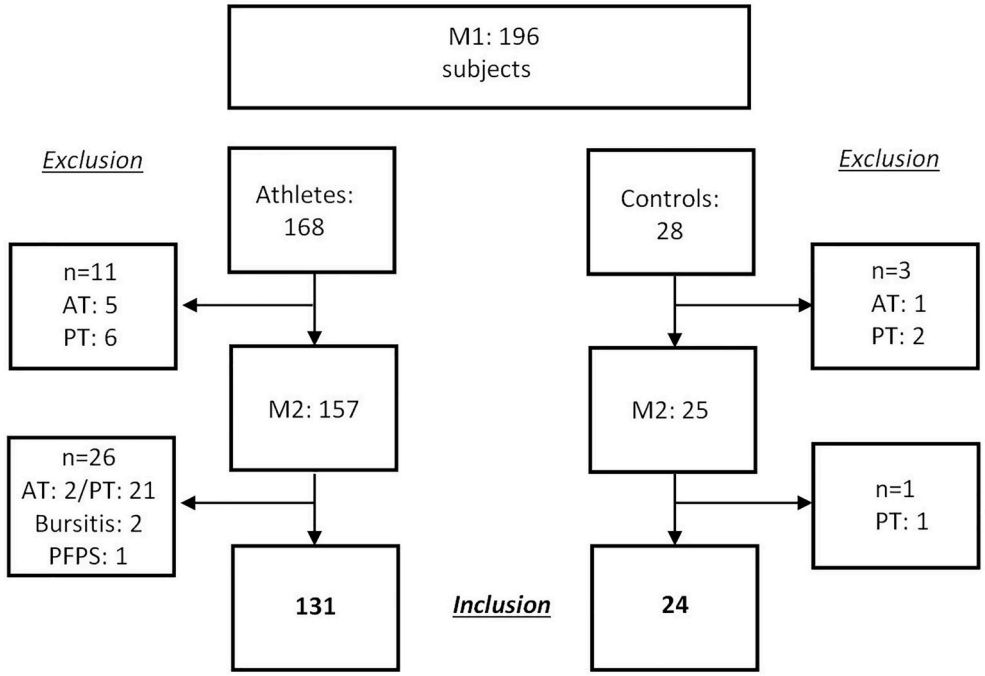


FIGURE 1 | Study flow chart: recruitment at M1, exclusion of subjects due to diagnoses (Atp, Achilles tendinopathy; Ptp, patellar tendinopathy; PFPS, patellofemoral pain syndrome) in the region of Achilles and patellar tendons.

Doppler ultrasonography (Advanced dynamic flow mode) with standardized DU settings (frequency = 4.5 MHz, pulse repetition frequency = 0.5 kHz, color velocity = 4.39 cm/s, color intensity just below the artifact threshold, size of the color box (region of interest, ROI = 3 cm^2) (Cassel et al., 2015; Risch et al., 2016). IBF was graded according to a modified "Ohberg score" from 0 to 5 (0 = no vessels, 1 = 1–2 vessels, 2 = 3–5 vessels, 3 = vessels in up to 30%, 4 = vessels in 30–50% and 5 = vessels in >50% within the ROI) (Ohberg and Alfredson, 2002; Hirschmüller et al., 2010). Three examiners with experience in DU examinations performed the investigations.

Data Categorization and Data Analysis

Adolescent elite athletes were allocated into 4 categories according to their sports (ball sports (B, $n = 40$), combat sports (C, $n = 39$), endurance sports (E, $n = 20$) and explosive strength sports (S, $n = 32$); **Table 2**) (Müller et al., 2017). Data was analyzed descriptively by mean and standard deviation of anthropometrics, training and tendon parameters within all athletes (A), sports categories (B, C, E, S) and controls (Co). All tendon data is shown as means of both sides for each thickness parameter. Depending on data distribution (Kolmogorov-Smirnov-Test), differences were tested either by unpaired *t*-test, one-way and two-way ANOVA (*post-hoc* Tukey-Kramer-Test/Fishers least significant differences test) or Kruskal-Wallis-ANOVA (*post-hoc* Wilcoxon test) for non-normally distributed data. To identify potential influencing factors (age, sex, BMI, training amount and years, intratendinous abnormalities) on tendon thickness development a multiple logistic regression analysis was performed (Jmp 9.0 and SPSS Statistics 20). Results with a $p < 0.05$ were considered significant.

RESULTS

A total of 131 athletes as well as 24 controls were analyzed (**Table 1**). Anthropometric and training data of athletes, controls and sports categories are presented in **Table 2**. Athletes showed higher height, weight, BMI and training amount at M2 compared to M1 ($p < 0.001$). Controls presented higher anthropometric data at M2 ($p < 0.003$), but did not show statistically significant differences for training data ($p > 0.05$). At both measurement days, athletes were younger and had higher training volume than controls ($p < 0.001$; **Table 2**).

Tendon Parameters at M1 and M2 (Cross-Sectional Analysis)

Athletes had higher AT thickness than controls at M1 and M2 ($p < 0.001$) as well as PT thickness at M2 ($p \leq 0.04$; **Table 3**). Sports categories showed highest AT thickness of B (AT 2 cm at M1, AT max at M1/2) and highest PT thickness of E at M1 ($p < 0.04$), while there were no statistically significant differences of PT-thickness at M2 ($p > 0.05$). Male subjects had higher AT and PT thickness compared to females at both measurement days among athletes and controls ($p < 0.05$; **Table 4**). Intratendinous abnormalities were present at both measurement days. In M1 IBF (grade 1 and 2) was visible in 5% of PTs, hypoechogenicities in 1.5% of ATs and 2% of PTs. In M2 IBF (grade 1 and 2) was visible

TABLE 1 | Number of athletes [n] as well as sex distribution [n] per sport categories (ball sports [B], combat (C), endurance [E] and explosive strength sports [S]), controls (Co), and group/sport at M2.

Category	n	n (m/f)	Group/Sport	n	n (m/f)
Co	24	6/18	Controls	24	6/18
B	40	33/7	Handball	10	9/1
			Soccer	27	24/3
			Volleyball	3	0/3
C	39	30/9	Boxing	5	4/1
			Judo	19	13/6
			Wrestling	15	13/2
E	20	13/7	Canoeing	8	6/2
			Cycling	2	2/0
			Rowing	3	2/1
			Swimming	7	3/4
S	32	14/18	Modern Pentathlon	5	3/2
			Shooting	2	2/0
			Track and field	25	9/16

in 3% of ATs and 4% of PTs, hypoechogenicities in 2.5% of ATs and 8% of PTs, hyperechogenicities in 1% of ATs as well as PTs.

Tendon Adaptation (Longitudinal Analysis)

For ATs, thickness did not differ statistically significant between M1 and M2, neither for athletes or controls, nor between different sport categories ($p > 0.05$; **Table 3**). For PTs, athletes presented higher thickness at M2 compared to M1 ($p < 0.001$). In contrast, controls did not show statistically significant differences between measurement days ($p > 0.05$; **Table 3**). Differences (M2-1) of AT- and PT-thicknesses between sports categories and controls ranged from −0.3 mm to 0.4 mm (**Figure 2**). Male athletes had higher PT thickness at M2 ($p < 0.001$). Sex-specific analysis of sport categories identified male subjects from B, C and S having higher PT-thickness at M2 ($p \leq 0.01$; **Figure 3**). Regression analysis showed an influence of sex on all tendon thickness parameters at both measurement days in athletes and controls, with males having higher thicknesses than females ($p < 0.05$). Increased PT thickness was associated with higher BMI in athletes. In contrast, factors age, training amount (h/week and years) and presence of intratendinous abnormalities did not lead to a higher AT or PT thickness ($p > 0.05$).

DISCUSSION

The study aimed to determine the physiological AT and PT thickness adaptation in healthy adolescent elite athletes in comparison to non-athletes during growth. Furthermore, the influences of sex, sport-specific loading, anthropometric data as well as intratendinous abnormalities were analyzed.

AT-thickness did not differ significantly between measurement days, neither for athletes nor for controls. In addition, AT-thickness was shown to be on adult athletes' level (Hirschmüller et al., 2010; Cassel et al., 2016), indicating that maximum AT thickness is already determined by the age of 12 years. It was previously argued that an increased tendon thickness results from an adaptation to increased force generation capacity, i.e., due to higher body/muscle mass, leading also to increased stiffness of its structure (Intziegianni et al., 2016; Kulig et al., 2016). Taking results of the present study into account it can be hypothesized that tendons might adapt to higher forces by changes on micro-morphological level (Kulig et al., 2016), leading to higher fiber density, which was not analyzed in the present study. Further investigations by use of tendon tissue characterization methods (i.e., spatial frequency parameters) might clarify this possible relationship (Bashford et al., 2008; van Schie et al., 2010).

In contrast, an increase in PT-thickness could be detected with up to 10% differences in athletes but not in controls. This supports the hypothesis of a physiological tendon adaptation by thickness due to loading. However, thickness adaptation seems to be dependent on sports categories as well as sex, as an increase was shown to be solely present in males from ball, combat and explosive strength sports. In the same line, a cross-sectional study including 500 adolescent athletes and 40 non-athletes previously did not show a general physiological AT and PT adaptation related to tendon loading (Cassel et al., 2016). Comparable to present longitudinal data, cross-sectional results identified small differences (up to 10% change) in PT thickness among athletes of certain sport categories (i.e., ball sports) compared to controls (Cassel et al., 2016). Further data analyzing the physiological thickness adaptation in young adolescent athletes is recently not available. During late adolescence (16–18 years of age), an increase up to 27% in PT-CSA has been reported in the leading leg among 18 Volleyball players (Mersmann et al., 2017). However, presence or absence of structural intratendinous abnormalities have not been considered in this study (Mersmann et al., 2017). In adult athletes, sports-specific PT adaptation by thickness has also been postulated (Kongsgaard et al., 2007; Couppé et al., 2008; Seynnes et al., 2009). Couppé et al. found higher PT-CSA in leading leg of 7 pain-free fencing and badminton elite athletes compared to the contralateral side using MRI (Couppé et al., 2008). Seynnes et al. examined PT-CSA in 15 young men (mean age 20 years) before and after 9 weeks of resistance training and reported an increase in CSA of approximately 4% (Seynnes et al., 2009). Kongsgaard et al. investigated PT-CSA in 12 untrained male participants before and after a 12 weeks strength training program. Participants presented a 4–7% higher tendon CSA at the distal and proximal tendon insertion (Kongsgaard et al., 2007). In contrast, Kubo and Yata did not see a change in patellar tendon CSA in 9 healthy males (mean age 21 years) following 3 month of resistance training (Kubo and Yata, 2017). Changes in CSA as well as sample sizes of these investigations are very small and should therefore be interpreted with caution. However, data are in line with results of the present study since detected changes are small and only visible in PTs among athletes of specific sports categories.

TABLE 2 | Anthropometric and training data among all athletes (A), controls (Co) and sport categories (ball sports [B], combat (C), endurance [E], and explosive strength sports [S]) at M1/2.

Category	M	N (m/f)	Age [years]	Height [cm]	Weight [kg]	BMI [kg/m^2]	Training [h/week]	Training years	M1/M2 [*p*-value]
A	M1	131 (90/41)	12.1 ± 0.7	157 ± 9	45 ± 9	18.1 ± 2.5	5.8 ± 3.0*	4.3 ± 2.3*	<0.001
	M2	131 (90/41)	15.2 ± 0.7	174 ± 9*	63 ± 11	20.8 ± 2.4	14.4 ± 4.4*	7.5 ± 2.5*	
Co	M1	24 (6/18)	13.3 ± 0.6*	160 ± 8*	48 ± 12	18.8 ± 3.4	1.9 ± 1.3	2.5 ± 2.8	$^+$≤0.003
	M2	24 (6/18)	16.2 ± 0.6*$^+$	169 ± 9$^+$	60 ± 14$^+$	21.0 ± 3.3$^+$	2.4 ± 2.2	3.9 ± 3.3	
B	M1	40 (33/7)	12.0 ± 0.5	157 ± 8	45 ± 7	18.0 ± 1.6	5.2 ± 1.8	5.7 ± 2.0	<0.001
	M2	40 (33/7)	15.1 ± 0.6	175 ± 8	64 ± 10	20.7 ± 2.2	12.2 ± 3.2	8.8 ± 2.0	
C	M1	39 (30/9)	12.1 ± 0.9	154 ± 10	47 ± 12	19.3 ± 3.2	6.1 ± 2.7	4.2 ± 2.3	<0.001
	M2	39 (30/9)	15.2 ± 0.8	170 ± 9	62 ± 12	21.5 ± 2.8	15.2 ± 4.3	7.1 ± 2.6	
E	M1	21 (14/7)	12.0 ± 0.8	160 ± 8	46 ± 8	17.6 ± 1.8	7.7 ± 3.9	4.1 ± 2.2	<0.001
	M2	20 (13/7)	15.2 ± 1.0	180 ± 10	68 ± 11	20.9 ± 2.2	17.1 ± 3.2	7.5 ± 2.3	
S	M1	31 (13/18)	12.2 ± 0.6	158 ± 8	43 ± 9	17.0 ± 2.3	4.9 ± 3.3	3.0 ± 2.0	<0.001
	M2	32 (14/18)	15.3 ± 0.5	174 ± 7	61 ± 9	20.2 ± 2.3	14.5 ± 5.3	6.3 ± 2.3	
p-value$^\#$	M1	131 (90/41)	n. s.	n. s.	n. s.	≤0.001	≤0.002	<0.001	
	M2	131 (90/41)	n. s.	<0.001	n. s.	n. s.	<0.001	<0.001	

**Represents statistically significant higher value in comparison of A against Co at M1/2 ($p < 0.05$ for height; $p < 0.001$ for age, training h/week and years)*

$^+$Represents statistically significant higher values of Co-subjects at M2.

$^\#$Data of p-value for ANOVA of differences between sports categories at M1 and M2 (n. s.: not significant). Post-hoc tests: Height: $p \leq 0.04$: B/E/S higher C and E higher S at M2; BMI: $p \leq 0.006$ for B/C higher S at M1; training h/week: $p < 0.008$ for E higher B/S and C higher S at M1, $p \leq 0.03$ for C/E/S higher B and E higher S at M2; training years: $p \leq 0.03$ for B higher C/E/S and C higher S at M1, $p < 0.03$ for B higher C/E/S at M2.

Influence of Pathology

Existence of intratendinous abnormalities (i.e., hypoechogenicities) usually goes along with enlarged tendon diameter (Docking et al., 2015) and has been reported to predict patellar tendinopathy in athletes (Gisslén et al., 2007; Comin et al., 2013; Visnes et al., 2015). Malliaras and Cook stated that mild patellar tendon thickening (>4.2 mm among men, >4.0 mm among women) may already indicate pathology among active athletes (Malliaras and Cook, 2011). The present study is the first differentiating between tendons with and without structural irregularities when looking at tendon thickness development. However, regression analysis did not show a statistically significant influence of intratendinous abnormalities on tendon thickness, neither in athletes nor in controls. Furthermore, within subgroups of sport categories mean PT thickness values were reported to be below the thickening threshold, postulated by Malliaras and Cook (2011).

In a recently published longitudinal study Visnes et al. followed 141 initially asymptomatic young elite volleyball players (in mean 17 years of age at inclusion) for an average of 1.7 years (Visnes et al., 2015). A total of 22 players developed tendinopathy. The remaining 119 athletes did not show a statistically significant change in PT diameter (differences 0.0–0.1 mm) at follow-up. However, mid-tendon PT-thickness was already on a high level (males: 4.3 mm, females: 3.7 mm). Furthermore, 50% of asymptomatic volleyball players already had intratendinous abnormalities at baseline (Visnes et al., 2015). These findings support data of the present study showing that PT thickness is already determined in earlier stages of adolescence. Moreover, changes in thickness or physiological adaptation by thickness are small and structural changes have to be considered when interpreting physiological adaptations.

Influence of Sex

Present longitudinal data show higher PT-thickness in follow-up exclusively in males from ball, combat and explosive strength sports suggesting a sex-specific adaptation of PTs due to loading. Sex-influence on absolute thickness values was also detected for AT tendon thickness parameters at both measurement days, irrespective of activity level in athletes as well as in controls. This is in line with data from Visnes et al. who found PT and quadriceps tendon thickness to be statistically significantly higher in 16–20 year old male compared to female volleyball players (Visnes et al., 2015). This fact might be explained by hormonal levels or genetic prerequisites. Increased estrogen levels were seen to be responsible for inhibition of the acute exercise-related collagen synthesis (Magnusson et al., 2007; Kjaer et al., 2009; Hansen and Kjaer, 2016). However, in the present study, lower AT and PT thickness of females were already detected at baseline (mean age of 12 years), where hormonal influences are assumed to be less relevant. Furthermore, differences were visible irrespective of activity level in athletes as well as controls.

Limitations

When interpreting the results, some limitations have to be considered. Sample size of the longitudinal study was relatively

TABLE 3 | Mean Achilles and patella tendon thickness values [mm] of all athletes [A], controls [Co] and different sport categories (ball sports [B], combat (C), endurance [E], and explosive strength sports [S]) at M1/2 (Tendon values for Achilles tendon 2 cm proximal to the insertion [AT 2 cm] and maximum midportion value [AT max] and for Patella tendon 2 cm distal to the tendon insertion [PT 2 cm]).

Location	M	A	Co	B	C	E	S	B/C/E/S
	n	[*n* = 131]	[24]	[40]	[39]	[21/20]	[31/32]	*p*-value[#]
AT 2 cm	M1	5.1 ± 0.6[+]	4.6 ± 0.6	5.2 ± 0.6	5.0 ± 0.7	5.3 ± 0.7	5.1 ± 0.5	n. s.
	M2	5.1 ± 0.6[+]	4.6 ± 0.4	5.3 ± 0.5[#]	5.0 ± 0.7	5.0 ± 0.6	5.0 ± 0.6	<0.04
AT max	M1	5.6 ± 0.7[+]	4.8 ± 0.4	5.8 ± 0.6[#]	5.4 ± 0.6	5.7 ± 0.9	5.5 ± 0.5	=0.057
	M2	5.6 ± 0.7[+]	4.9 ± 0.5	5.9 ± 0.6[#]	5.6 ± 0.9	5.5 ± 0.6	5.4 ± 0.6	≤0.03
PT 2 cm	M1	3.5 ± 0.5	3.4 ± 0.5	3.5 ± 0.4	3.6 ± 0.5	3.8 ± 0.5[#]	3.3 ± 0.4	≤0.01
	M2	3.8 ± 0.5*[+]	3.5 ± 0.5	3.9 ± 0.5*	3.9 ± 0.6*	3.7 ± 0.4	3.6 ± 0.4*	n. s.
M1/M2 [*p*-value]*		<0.001	n. s.	<0.001	<0.02	n. s.	<0.02	

*Data of t-test (statistical significant differences M1 vs. M2) for values of each parameter (location) in different categories (n. s.: not significant).

[+]Represents statistically significant differences of A vs. Co at both measurement days for AT 2 cm and AT max ($p < 0.001$) and for PT 2 cm at M2 ($p \leq 0.04$).

[#]ANOVA p-value for sports categories at M1 as well as at M2. Post-hoc tests: AT 2 cm: $p < 0.04$ for B higher C/E/S at M2; AT max: $p \leq 0.01$ for B higher C at M1; $p < 0.03$ for B higher S at M2; PS 2 cm: $p < 0.01$ for E higher S at M1.

TABLE 4 | Mean Achilles (AT 2 cm, AT max) and patella tendon thickness (PT 2 cm) values [mm] for sex [m/f] among all athletes [A] and controls [Co] at M1/2.

Category	M	AT 2 cm		AT max		PT 2 cm		M1-M2 [*p*-value[#]]
	Sex	*m*	*f*	*m*	*f*	*m*	*f*	
A	M1	5.2 ± 0.5[+]	4.9 ± 0.7*	5.7 ± 0.7[+]	5.3 ± 0.7*	3.6 ± 0.5[+]	3.3 ± 0.4	<0.001
	M2	5.2 ± 0.6[+]	4.7 ± 0.6	5.8 ± 0.7[+]	5.2 ± 0.6*	4.0 ± 0.5[+#]	3.4 ± 0.3	
Co	M1	5.2 ± 0.6[+]	4.4 ± 0.4	5.4 ± 0.7[+]	4.6 ± 0.3	3.8 ± 0.6[+]	3.2 ± 0.4	n. s.
	M2	4.9 ± 0.7[+]	4.5 ± 0.4	5.4 ± 0.5[+]	4.7 ± 0.4	4.0 ± 0.5[+]	3.4 ± 0.4	
p-value*	M1	n. s.	≤0.002	n. s.	<0.001	n. s.	n. s.	
	M2	n. s.	n. s.	n. s.	≤0.01	n. s.	n. s.	

*Represents statistically significant higher value in comparison of A against Co at M1 and M2.

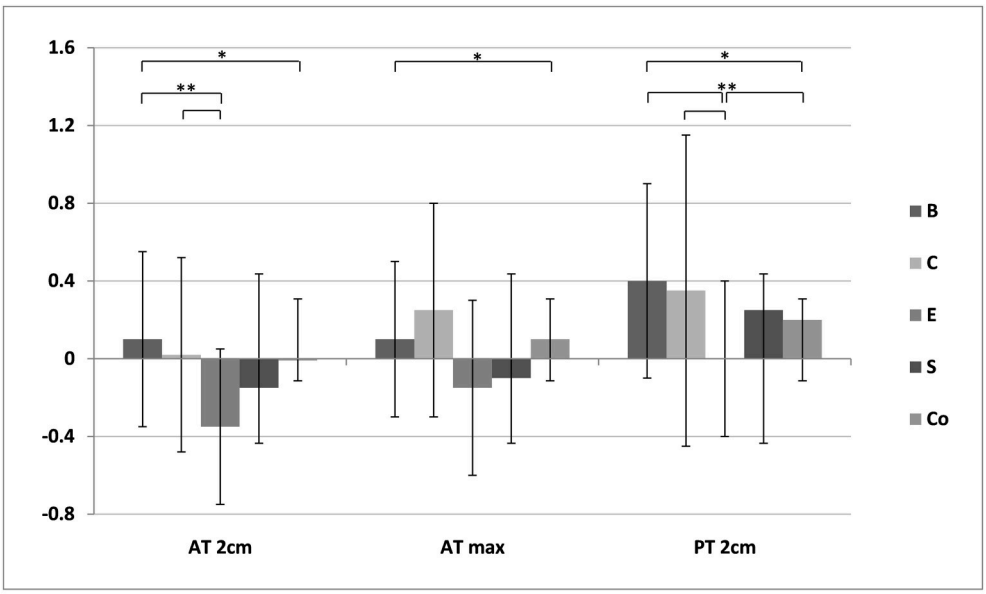
[+]Represents statistically significant sex differences within groups (A or Co) at M1 and M2 for AT 2 cm (A: $p \leq 0.02$; Co: $p < 0.05$) and AT max (A: $p < 0.001$; Co: <0.01) and for PT 2 cm (A: $p < 0.001$; Co: <0.01).

[#]Represents statistically significant higher value of PT 2 cm in male athletes at M2 compared to M1 ($p < 0.001$). All other tendon parameters of A or Co between M1 and M2 were not statistically significant ($p > 0.05$).

low, especially for the differentiation of several sports disciplines. Furthermore, measurement location of thickness parameters is assumed to be of high relevance when interpreting physiological tendon adaptation by thickness, especially during maturation. According to prior sonographic reliability studies thickness parameters were used at presented sites instead of width or CSA-measurements (Fredberg et al., 2008; Cassel et al., 2012). For ATs, a second measurement location (thickest part in midportion) was chosen to consider possible length changes due to maturation. For PTs, it was decided to take only one standardized parameter in the "mid-tendon" since tendinopathic tissue abnormalities in adolescent athletes usually are visible in the proximal or distal portion of the tendon (Cassel et al., 2015). However, since some studies reported on an increased thickness or CSA in proximal and/or distal PT region following training (Kongsgaard et al., 2007; Couppé et al., 2008; Kulig et al., 2013) future investigations should also consider the insertional regions. Additionally, in order to take length changes due to maturation into account, future investigations might also include measurement of thickest mid-tendon part. Overall, three trained examiners were responsible for the ultrasound measurements, which might have influenced the results. However, investigations on intra- and inter-observer reliability of AT and PT thickness measurements as well as IBF assessment using the 'modified Ohberg Score' showed good to high reliability (Fredberg et al., 2008; Risch et al., 2016).

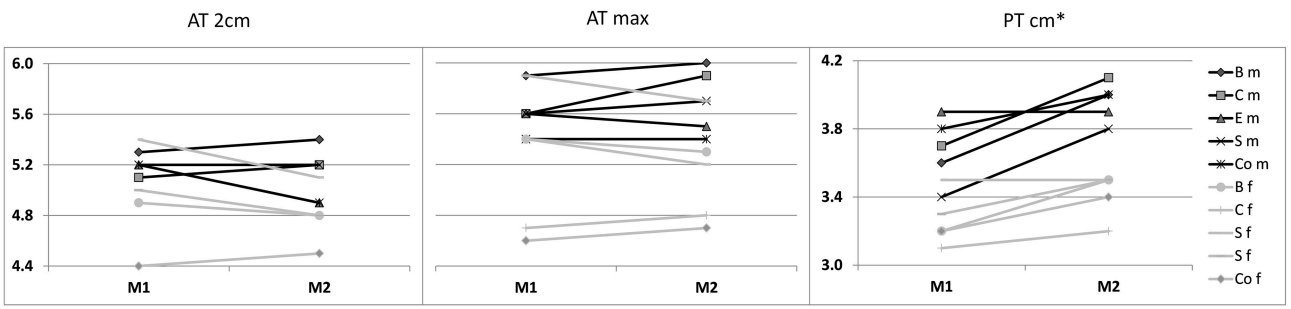
CONCLUSION

In between 12 and 15 years of age AT-thickness did not increase due to loading. In contrast, PT-thickness was increased in male athletes among ball, combat and explosive strength sports, indicating a sports- and sex-specific tendon adaptation by thickness. However, changes seem to be small. Controversial adaptability of ATs and PTs



* Statistically significant group differences in ANOVA of AT- and PT-thickness changes (p≤0.04).
** Statistically significant post-hoc differences of AT- and PT-thickness changes between sports categories and controls (post-hoc: p≤0.04).

FIGURE 2 | Differences of mean Achilles (AT 2 cm, AT max) and patellar tendon thickness (mean ± SD [mm]) of M2-1 between sport categories (ball sports [B], combat [C], endurance [E] and explosive strength sports [S]), and controls (Co).



* Statistically significant higher PT-thickness of males compared to females from ball sports [B m], combat sports [C m] and explosive strength sports [S m] at follow-up (p≤0.01).

FIGURE 3 | Sex-specific (m/f) mean Achilles (AT 2 cm, AT max) and patellar tendon thickness [mm] from M1 to M2 between sport categories (ball sports [B], combat [C], endurance [E] and explosive strength sports [S]), and controls (Co).

could explain the higher sustainability of young athletes in the development of patellar tendinopathy (Mersmann et al., 2016). Influence of sex is obvious in all parameters measured at both measurement days. Implementation of sonographic microstructural analysis might provide an enhanced insight into tendon material properties enabling the differentiation of sex and influence of different sports.

AUTHOR CONTRIBUTIONS

The author contributions are distributed as followed: conception or design of the work (MC, SM, FM), data acquisition (MC, LR), data analysis (MC, KI) and interpretation (MC, KI, LR, TE, FM); drafting (MC) or revising (MC, KI, LR, SM, TE, FM) the work; final approval of the version to be published (MC, KI, LR, SM, TE, FM); agreement to be accountable for all aspects of the work (MC, KI, LR, SM, TE, FM).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Training Load, Immune Status, and Clinical Outcomes in Young Athletes: A Controlled, Prospective, Longitudinal Study

Katharina Blume[1], Nina Körber[2], Dieter Hoffmann[2] and Bernd Wolfarth[1]*

[1] Department of Sports Medicine, Humboldt-University, Charité University Medicine, Berlin, Germany, [2] Institute of Virology, Technische Universität München, Helmholtz Zentrum München, Munich, Germany

Introduction: Beside positive effects on athlete's health, competitive sport can be linked with an increased risk of illness and injury. Because of high relative increases in training, additional physical and psychological strains, and an earlier specialization and professionalization, adolescent athletes needs an increased attention. Training can alter the immune system by inducing a temporary immunosuppression, finally developing infection symptoms. Previous studies identified Epstein Barr Virus (EBV) as potential indicator for the immune status. In addition to the identification of triggering risk factors for recurrent infections, the aim was to determine the interaction between training load, stress sense, immunological parameters, and clinical symptoms.

Methods: A controlled, prospective, longitudinal study on young athletes ($n = 274$, mean age: 13.8 ± 1.5 yrs) was conducted between 2010 and 2014. Also 285 controls (students, who did not perform competitive sports, mean age: 14.5 ± 1.9 yrs) were recruited. Athletes were examined 3 times each year to determine the effects of stress factors (training load: training hours per week [Th/w]) on selected outcome parameters (clinical [susceptibility to infection, WURSS-21: 21-item *Wisconsin Upper Respiratory Symptom Survey*], immunological, psychological end points). As part of each visit, EBV serostatus and EBV-specific IgG tiers were studied longitudinally as potential immune markers.

Results: Athletes (A) trained 14.9 ± 5.6 h weekly. Controls (C) showed no lower stress levels compared to athletes ($p = 0.387$). Twelve percent of athletes reported recurrent infections (C: 8.5%, $p = 0.153$), the presence of an upper respiratory tract infection (URTI) was achieved in 30.7%. EBV seroprevalence of athletes was 60.3% (C: 56.6%, $p = 0.339$). Mean EBV-specific IgG titer of athletes was 166 ± 115 U/ml (C: 137 ± 112 U/ml, $p = 0.030$). With increasing Th/w, higher stress levels were observed ($p < 0.001$). Analyzes of WURSS-21 data revealed no relationship to training load ($p = 0.323$). Also, training load had no relation to EBV serostatus ($p = 0.057$) or the level of EBV-specific IgG titers ($p = 0.364$).

Discussion: Young elite athletes showed no increased sense of stress, no higher prevalence of recurrent infections, and no different EBV-specific serological parameters

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Adamantios Arampatzis, Humboldt-Universität zu Berlin, Germany

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Giovanni Messina, University of Foggia, Italy
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****Correspondence:***
Katharina Blume
katharina.blume@charite.de

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compared to controls. Also, no direct relationship between training loads, clinical complaints, and EBV-specific immune responses was found. With increasing training loads athletes felt more stressed, but significant associations to EBV-specific serological parameters were absent. In summary, EBV serostatus and EBV-specific IgG titers do not allow risk stratification for impaired health. Further investigations are needed to identify additional risk factors and immune markers, with the aim to avoid inappropriate strains by early detection and following intervention.

Keywords: EBV, URTI, athlete, training load, infection, susceptibility, stress, immune system

INTRODUCTION

Competitive sport is associated with various physical and psychological strains (Sabato et al., 2016; Schwellnus et al., 2016a,b). Beside positive effects on athlete's health and well-being, including cardiovascular and muscular fitness, bone health, weight control, psychosocial outcomes, cognitive and brain health, and reduced morbidity and premature death (Wartburton and Bredin, 2016, 2017; Chieffi et al., 2017), acute prolonged exercise can be linked with an increased risk of illness and injury (Armstrong and Mc Manus, 2011; Hastmann-Walsh and Caine, 2015). Success requires numerous years of training, starting already in adolescence, with presumed health and less lack of practice to achieve sports specific skills and necessary overall capacity (Mårtensson et al., 2014). The trend of recent years shows an increased duration, intensity, and difficulty of training, a high-frequency participation in sports events, and an earlier specialization and professionalization (Mountjoy et al., 2008; Caine, 2010; Armstrong and Mc Manus, 2011). Such conditions can negatively affect the risk of physical and psychological illness and injury (Armstrong and Mc Manus, 2011; Sabato et al., 2016). Therefore, to ensure resilience in young athletes, age-based additional endo- and exogenous risk factors, which can negatively influence the ability to withstand stress, should be known and considered: e.g., physical development, high training load (DiFiori and Mandelbaum, 1996; Dennis et al., 2005; Dun et al., 2005; Loud et al., 2005; Fleisig et al., 2011; Hjelm et al., 2012), early specialization (Barynina and Vaitsekhovskii, 1992; Bompa, 1995; Jayanthi et al., 2013), performance capacity, previous illnesses, environmental factors, and negative stressors such as school, parental conflicts, pressure to perform, and competition failure (Cohn, 1990; Scanlan et al., 1991; Puffer and McShane, 1992; Gould et al., 1993; Puente-Diaz and Anshel, 2005). Ignoring the multifactorial interactions of various triggers can lead to a diminished immune competence affecting health, training and ability for regeneration (Borresen and Lambert, 2009; Dhabhar, 2014). Light clinical symptoms over one episode usually result in short training breaks. In contrast, recurrent infections, mild or severe, can cause frequent interruptions, lack or stagnation of performance, retirement from competitive sports, furthermore, influencing long-term everyday life (Maffulli et al., 2010; Whittaker et al., 2015).

Upper respiratory tract infections (URTI) belong to the most common diseases in athletes (Gleeson and Pyne, 2016; Schwellnus et al., 2016a). Beside musculoskeletal injuries (Schwellnus et al., 2016b), they are the main cause responsible for training failures, suboptimal performances, and competition cancellations (Fricker, 1997; Alonso et al., 2010; Engebretsen et al., 2010, 2013; Mountjoy et al., 2010; Schwellnus et al., 2011, 2016a; Soligard et al., 2014). During the Winter Olympics 2014 in Sotschi, 8.9% of athletes had an illness, 64% of them an URTI as reason (Soligard et al., 2014). While the prevalence of URTI is comparable to the general population, an increased rate of susceptibility was found in athletes (Gleeson et al., 1995; Fricker et al., 2000). Studies have shown that moderate exercise reduces the incidence of infections compared to physical inactivity (Matthews et al., 2002). In contrast, high-intensity or rather extensive training loads are associated with an increased susceptibility to infections due to a diminished transient immune competence (Peters and Bateman, 1983; Fricker et al., 1999; Gleeson et al., 2000; Spence et al., 2007). The duration of this mentioned immunosuppression takes several hours, called as >open window< (Walsh and Oliver, 2016). Training, particularly high intensities, and marked load increases, can induce this temporary immunosuppression causing recurrent infections (Gleeson et al., 2000; Konig et al., 2000; Tiollier et al., 2005; Tsai et al., 2011; Walsh et al., 2011a; Hellard et al., 2015). Nevertheless, other potentially triggers and promotive risk factors must also be considered, such as previous illnesses (e.g., bronchial asthma; Reid et al., 2004; Spence et al., 2007; Cox et al., 2008), female gender (Himmelstein et al., 1998; Konig et al., 2000; He et al., 2014), age (Monto, 2002), genetic predispositions (Cox et al., 2010; Zehsaz et al., 2014), low IgA secretion rates (Gleeson et al., 1995, 1999; Putlur et al., 2004; Fahlman and Engels, 2005; Nieman et al., 2006), air travel (Svendsen et al., 2016), cold (Walsh and Oliver, 2016), heat (Walsh and Oliver, 2016), hypoxia (Walsh and Oliver, 2016), stress (Novas et al., 2002; Putlur et al., 2004; Main et al., 2010), lack of sleep (Cohen et al., 2009; Main et al., 2010), malnutrition (Zapico et al., 2007; Walsh et al., 2011b; Calder et al., 2014), and weight loss (Umeda et al., 2004; Shimizu et al., 2011). So far, it remains still controversial which factors, degree (e.g., duration, intensity, frequency), and attendant circumstances must be present for affecting immune system and finally developing clinical complaints (Fricker et al., 2000; Konig et al., 2000).

In addition to the question which factors lead to an impaired health and performance, it is necessary to quantify immunological parameters that potentially indicate a risk early. The clinical relevance of such immunological changes remains controversial. So far, no direct association between

immune responses and increased infection rates could be clearly demonstrated (Reid et al., 2004; Fricker et al., 2005; Helenius et al., 2005; Tiollier et al., 2005; Cox et al., 2008). Consistently, physical stress activates the immune system more or less, depending on amount, intensity and frequency, resulting in weakness or stabilization. An association between low saliva IgA concentrations or rather reduced secretion rates and URTI symptoms has been demonstrated (Gleeson et al., 1995, 1999; Putlur et al., 2004; Fahlman and Engels, 2005; Nieman et al., 2006). Nevertheless, the results are inconsistent and the quantitation requires complex and time-consuming demands (Gleeson, 2000; Walsh et al., 2011a). A limitation that makes it difficult to use in practice. Therefore, simple, non-invasive and feasible tools should be developed including parameters that influence and reflect the immunological aspect of the individual capacity and resilience.

Diminished performance and fatigue with concurrent unspecific flu-like symptoms are often associated with an Epstein Barr Virus (EBV) infection in competitive athletes (Gleeson et al., 2002; Balfour et al., 2015). This herpes virus persists lifelong in the organism and is controlled by the adaptive immune system. The detection of antibodies to specific EBV antigens by immunoblot allows to determine the infection stage (De Paschale and Clerici, 2012). In contrast to other viruses (e.g., varicella-zoster virus, cytomegalovirus), replication of EBV occurs frequently by reactivation, intermittently or even continuously. Thus, in addition to EBV-specific antibodies, the viral genome is also well accessible for polymerase chain reaction (PCR, viral load), allowing the detection of a systemically increased EBV activity in whole blood or saliva (Yamauchi et al., 2011). The lifelong persistence in the organism after primary infection and a prevalence of more than 90% in adults, and between 55 and 80% in adolescent (Karrer and Nadal, 2014; Lee, 2016), make EBV-specific immune responses suitable as interesting surrogate markers for the immune function of the host (Karrer and Nadal, 2014).

EBV and accordingly the immunological reactions to the virus can be used as indicator of the current immune status (Gleeson et al., 2002; Pottgiesser et al., 2012). Thus, EBV and accordingly the immunological reactions to the virus could help to identify athletes with an increased susceptibility to infections (Bakker et al., 2007; Hoffmann et al., 2010). Despite immunological changes, obvious clinical symptoms, and further potential impairments of performance, do not necessarily occur. Lower EBV-specific IgG titers were detected in winter sports athletes compared to controls suggesting a weaker immune function in competitive athletes with lower control of EBV (Hoffmann et al., 2010), in addition, observed slightly elevated EBV-specific IgG titers over the competition season were interpreted as a reaction to increased EBV activity accompanying stress-induced diminished T-cell function (Hoffmann et al., 2010). However, similar results from other studies were missed (He et al., 2013). Furthermore, there has been an ongoing controversy whether EBV infections among elite athletes occur at a higher incidence than in the general population (Pottgiesser et al., 2006). Thus, the clinical relevance of EBV infections remains unclear, especially in competitive sports, because a clear relationship between training, EBV-specific parameters, clinical symptoms and performance could not be demonstrated consistently.

The challenge is to objectify individual resilience in order to control future burdens and thus to be able to counteract overloading at all levels. With a proven relationship, the training could be adjusted to prevent clinical complaints. First of all, it is necessary to identify a dependent cascade between physical, psychological, and environmental stress factors, their effects on immunological parameters and their association to performance and clinical symptoms. So far, only isolated aspects have been examined with different results (Fricker et al., 1999, 2005; Gleeson et al., 2000; Konig et al., 2000; Reid et al., 2004; Pyne et al., 2005; Walsh et al., 2011a,b; Hellard et al., 2015). Furthermore, past studies were mostly undertaken on heterogeneous collectives with a small number of cases and selection of inconsistent outcomes (Cox et al., 2008; Alonso et al., 2010; Mountjoy et al., 2010; Dvorak et al., 2011; Schwellnus et al., 2012; Theron et al., 2013).

To date, the relationship between stress parameters, immune status and clinical outcomes, and the characterization of each aspect, have not been sufficiently addressed, especially in young elite athletes. Due to this lack, a prospective study was initiated, in which selected parameters in detail and their relationships to each other were examined. The study involved young elite athletes who were monitored longitudinal and included a clinical assessment for known causes of impaired health and performance, the determination of immune reactions and a standardized collection of illness parameters. The following hypotheses should be investigated: (1) Due to the high training loads, already at a young age, the athletes show a higher susceptibility to infections and prevalence of URTI, and indicate an increased sense of stress compared to controls; (2) EBV-specific immune responses can be used as a potential biomarker of the overall immune status due to the high EBV seroprevalence in adolescence; (3) Differences in EBV-specific IgG titers will be detected in the young athlete collective compared to controls; (4) High training loads lead to an impaired stress sense and increase the incidence of clinical complaints; (5) Training load and stress affect the immune system; (6) The prevalence of upper respiratory tract infections (URTI) is associated with EBV serostatus and EBV-specific IgG titers.

Comprehensive data were collected to characterize the collective of young elite athletes. For the present analysis the following parameters were selected: training hours per week (training load), self-reported stress level, EBV serostatus and EBV-specific IgG titers (immune status), upper respiratory tract infection symptoms and susceptibility to infections (clinical outcome).

MATERIALS AND METHODS

Study Design

A controlled, prospective, longitudinal study was conducted between 2010 and 2014 with several regenerations, training and competitive seasons. Each year, the athletes were examined three times to determine the effects of certain stress factors (e.g., training load), plus their dynamics, on selected outcome

measures (e.g., clinical, immunological, psychological end points). The study design included up to 13 visits per athlete. The timeline for the prospective surveillance study is shown in **Figure 1**. Comprehensive parameters for characterization of each athlete were determined once a year at one of three sports medicine centers (*Munich*, *Leipzig*, *Dresden*) to detect underlying conditions including case history, physical examination, anthropometry, clinical chemistry, ECG (electrocardiogram), echocardiography, and stress test. Additional baseline data and contained questionnaires that assessed e.g., training history, training loads, the WURSS-21 (21-item *Wisconsin Upper Respiratory Symptom Survey*), and health-related demands (self-reported health/stress sense, fatigue) were collected. As part of each visit, EBV serostatus and EBV-specific IgG titers were determined longitudinally.

Participants

The athletes were recruited from different sport disciplines. Participation in the examinations (Munich, Leipzig or Dresden) was required. A total of 274 national class adolescent athletes (national junior top-level or comparable training level, age: 13.8 ± 1.5 years [yrs], male [m]: $n = 175$, female [f]: $n = 99$) from ten different sports (cross-country skiing [$n = 43$], cycling [$n = 64$], figure skating [$n = 6$], gymnastics [$n = 4$], high diving [$n = 6$], soccer [$n = 72$], speed skating [$n = 11$], swimming [$n = 30$], tennis [$n = 7$], volleyball [$n = 31$]) were enrolled in the study. The sports were categorized into three groups depending on the dynamic load (*low*: gymnastics, high diving; *medium*: figure skating, volleyball; *high*: speed skating, cycling, swimming, cross-country skiing, soccer, tennis; Mitchell and Haskell, 2005). The athletes were located in 18 training groups at seven locations. Prior to commencement of the investigations each athlete underwent a comprehensive clinical examination and was checked to assess inclusion (at V1 age ≤18 years; competing successfully at international or national level competitions for at least 2 years; belonging to one of the 18 training groups to ensure systematic training; future perspective of the athlete; written informed consent from parents and athletes) and exclusion criteria (chronic pathology or use of drugs that affected immune function; long-lasting injury or illness at V1). Athletes were prospectively followed for 2.2 ± 1.1 yrs. The maximum time between initial examination (V1) and the last visit (mean age: 16.1 ± 1.9 yrs) was 4 years. In addition, 285 control subjects (students, who did not perform competitive sports, age: 14.5 ± 1.9 yrs, m: $n = 122$, f: $n = 163$) were recruited. Athletes were tested up to ten times while controls had a maximum of two tests. In both groups, not all subjects could be tested at each time points resulting in some missing values. In total, 2.600 study days (athletes: 2.259, controls: 341) were collected. Depending on the analysis, data with inadequate detail in the recording were excluded. All athletes and controls were fully informed about the rationale for the study and of all procedures to be undertaken. Before baseline visit (V1) participants and their parents signed a written informed consent form. The study was approved by the medical research ethics committee (TU München) and it conforms to the principles outlined in the Declaration of Helsinki.

Outcome and End Point Definitions

EBV Serology

Blood samples were collected at each visit and peripheral blood was taken by puncture of the antecubital vein. EBV-specific IgG and IgM antibodies were measured by ELISA (Enzygnost®, Siemens Healthcare Diagnostics GmbH, Germany) according to the manufacturer's instructions. The assay detects antibodies directed against early EBV antigens (EA), viral capsid EBV antigens (VCA), and EBV nuclear antigen 1 (EBNA-1) in equal proportions. EBV-specific IgG and IgM antibodies were reported in units per milliliter (U/ml). The lower limit of detection was 25 U/ml. *Recom*Line® EBV IgG immunoblot assay (Mikrogen GmbH, Germany) detects antibodies against various EBV antigens (EBNA-1 [p72]), VCA [p18 and p23]), immediate-early antigen (BZLF-1), and EA [p138 and p54]). EBV-specific antibodies present in the cohort sample bound to these recombinant antigens and were detected by secondary antibodies directed against human IgG and coupled with horseradish peroxidase. Band signals were evaluated and stages of EBV infection (EBV serostatus) were differentiated according to the manufacturer's instructions in the following categories:

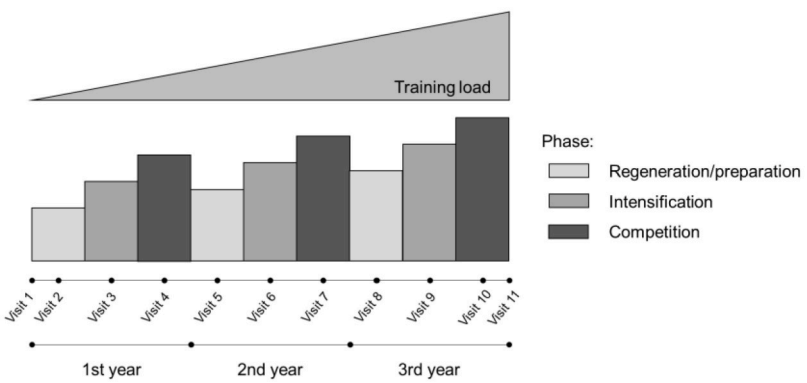


FIGURE 1 | Timeline for the prospective study.

EBV-seronegative (EBV–), EBV-seropositive (EBV+), suspicion of EBV reactivation (sRA), and suspected EBV infection (sNI).

Upper Respiratory Tract Infection (URTI)

The WURSS-21 (21-item *Wisconsin Upper Respiratory Symptom Survey*) was used to compute symptoms of URTI (Barrett et al., 2005). This questionnaire is a responsive, reliable and valid instrument including 21 items (10 items: symptoms, 9 items: functional impairments, 1 item: global severity and global change over the last 24 h). All the items are responded to using a Likert scale of severity, ranging from 0 to 7. Symptoms not experienced were recorded as 0. An overall score (WTS) was calculated by adding the severity scores from the items 2–20 with high severity scores indicating high symptom load. An URTI episode was deemed present when total symptom score was greater seven, representing either one severe symptom or impairment or seven mild symptoms/impairments presented simultaneously. The occurrence of URTI symptoms were recorded at each visit every third day in an observation period of 2 weeks (5 times per visit). For representing the whole time span, all available scores were averaged.

Self-Reported Stress Level, Susceptibility to Infection, Training Load

Each subject was asked to complete a questionnaire prior each examination among (1) stress level (%), (2) susceptibility to infection, and (3) training load (Th/w).

(1) To estimate the individual level of stress a visual analog scale (VAS) was used, with a range from 0 to 100 percent. A higher score indicated greater stress sense (0: "no stress," 100: "highest stress level"). (2) In addition, athletes were asked if they felt sick more often (compared to the past/to others). The question could be answered with *"yes", "no", "I don't know."* If the question was answered with *"yes,"* there was a subjective tendency to recurrent infections (susceptibility to infection). (3) For every visit, training loads were recorded after completing questionnaire and interview. In addition, the average number of training hours per week (Th/w) of the last 4 weeks was reported.

Statistical Analyses

The data were compiled using Microsoft Excel® and evaluated using the SPSS® software (version 23.0; SPSS Lead Technologies Inc, Chicago, IL). Frequency distributions of all continuous variables were examined to detect outlying values, and the Kolmogorov-Smirnov test was used to check the normal distribution of variables. All results, assuming normal distribution, were presented as mean ± standard deviation (SD). Differences between groups were analyzed using an independent samples *t*-test. To determine the differences in the group analysis (e.g., WURSS-21), ANOVA was used. The chi-square test was performed to verify possible differences between nominal scaled variables. Significance was accepted at the $P < 0.05$ level. Depending on the analysis, data were stratified by sex and age, were presented by percentiles (using 10th and 90th percentile), and variables were categorized in ordinal gradation.

RESULTS

Characterization (Training Load, Stress Level, Susceptibility to Infection, URTI) and Comparison of the Collectives (Athletes vs. Controls)

Training Load

During the study period, the athletes (age: 15.1 ± 1.9 yrs) trained, on average, 14.9 ± 5.6 h weekly (>80% specific training for each sports discipline). Increasing training loads were significantly associated with a higher age (<10 h: 13.6 ± 1.8 yrs vs. ≥10 h: 15.4 ± 1.7 yrs, $p < 0.001$). A 16-year-old female figure skater achieved the maximum of 31.5 h. 22.3% of all, in particular 40.2% of the female athletes (m: 11.6%), completed at least 20 h of training per week, mostly belonging to gymnastics (25.9 ± 1.9 h), high diving (23.5 ± 4.6 h), or figure skating (22.8 ± 4.9 h). Remarkable, athletes of these three kind of sports were significantly younger compared to the others (13.7 ± 1.8 yrs vs. 15.2 ± 1.8 yrs, $p = 0.002$). Female volleyball players offered, despite younger age (f: 14.9 ± 1.5 yrs vs. m: 16.1 ± 1.0 yrs, $p = 0.008$), higher training loads compared to the male team (f: 20.4 h vs. m: 11.7 h, $p < 0.001$).

Stress Level

Taking all athletes' data sets into account, a mean stress level of 45.3 ± 18.0% (MIN 0%, MAX 88.0%) was reported. Unlike the male participants, female athletes felt more stressed (f: 50.0 ± 15.7% vs. m: 42.5 ± 18.6%, $p = 0.001$). Similar results were found in the control group (f: 50.8 ± 25.9 % vs. m: 41.4 ± 23.9%, $p = 0.005$), who had in comparison to the athletes no lower stress levels (47.0 ± 25.5%, $p = 0.387$), in both sexes (f: $p = 0.789$, m: $p = 0.668$). The control subjects indicated a maximum stress level of 90.0%.

Susceptibility to Infection

At baseline visit 12.0% of competitive athletes (A) reported a subjective susceptibility to infection with no significant difference compared to the control (C) group (A: 12.0% vs. C: 8.5%, $p = 0.153$), in female (A: 18.2% vs. C: 12.3%, $p = 0.188$) as well as in male subjects (A: 8.6% vs. C: 3.3%, $p = 0.064$). Female athletes and female controls reported more often recurrent infections than males (A: f: 18.2% vs. m: 8.6%, $p = 0.019$; C: f: 12.3% vs. m: 3.3%, $p = 0.006$). Exemplary, no male volleyball player was anamnestic susceptible to infections, compared to 33.3% of the female players. While 11-year-old athletes had a prevalence of 7.7% for recurrent infections, this increased to 13.0% at the age of 14, and to 44% among 17-year-old participants (**Figure 2**). Athletes with recurrent infections (I+) were older compared to clinically unremarkable (I−) subjects (I−: 13.7 ± 1.5 yrs vs. I+: 14.4 ± 1.6 yrs, $p = 0.016$). During the total study process, while an observation period of 2.2 ± 1.1 yrs, 32.8% of all athletes reported recurrent illnesses, again with a significantly higher occurrence in the female group (f: 51.5% vs. m: 22.3%, $p < 0.001$).

URTI

The mean total WURSS-21 score (WTS) was 6.98 ± 10.25, with a highest value of 62.40. Gender differences did not occur (f:

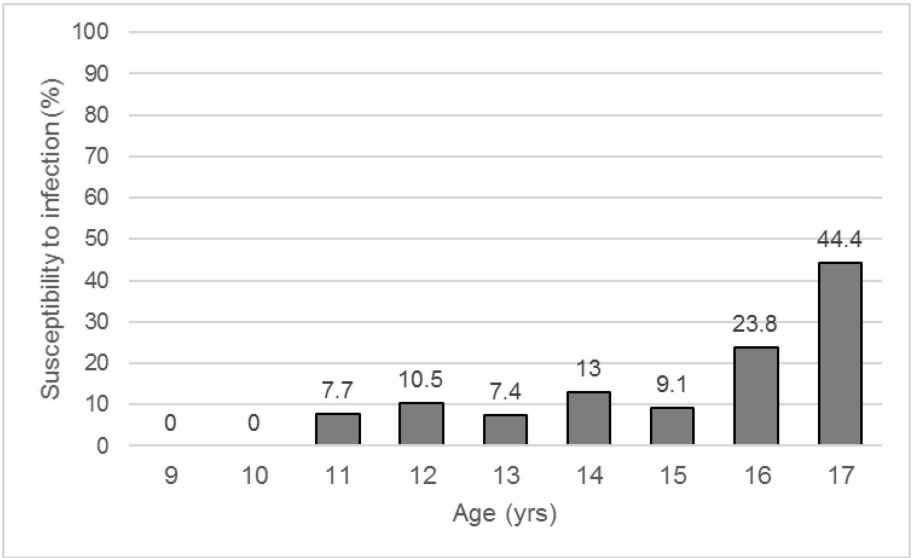


FIGURE 2 | Prevalence of susceptibility to infection in athletes depending on age. Values are expressed as means.

7.28 ± 10.39 vs. m: 6.67 ± 10.12, $p = 0.430$). A total score greater seven (WTS > 7 at least in one of five surveys within one visit), and thus the presence of an URTI, was achieved in 30.7% of cases (f: 30%, m: 31.5%). Among these, the gender proportion was similar (f: 48.4%, m: 51.6 %, $p = 0.674$). No age dependencies could be shown, neither of WTS ($p = 0.829$), nor in terms of URTI prevalence ($p = 0.957$).

EBV Serostatus

At V1, 60.3% of the athletes (mean age: 13.8 ± 1.5 yrs) were EBV-seropositive, including 6.1% of the athletes with a serological suspected EBV reactivation (sRA), and 0.6% with a primary EBV infection (sNI). The proportion of EBV-seropositive subjects did not differ significantly between male and female athletes (m: 58.6% vs. f: 63.3%, $p = 0.452$). Male subjects were significantly younger (m: 13.6 ± 1.5 yrs vs. f: 14.0 ± 1.6 yrs, $p = 0.041$), but no significant differences regarding the percentage of EBV-seropositive female and male athletes were detected. Furthermore, EBV-seropositive (EBV+) athletes showed a similar age compared to EBV-seronegative (EBV–) subjects (EBV+: 13.8 ± 1.6 yrs vs. EBV–: 13.6 ± 1.4 yrs, $p = 0.351$), both in male ($p = 0.166$) and female participants ($p = 0.695$). 56.6% of the controls (mean age: 14.5 ± 1.9 yrs) were EBV-seropositive, resulting in no significant differences of the EBV serostatus compared to the athletes at baseline visit ($p = 0.376$). In line with the athlete group, no significant gender difference was observed within the control group (EBV+: m: 53.7% vs. f: 58.8%, $p = 0.339$). Age-depending analyzes between the athlete and control group revealed comparable numbers of EBV-seropositive subjects (e.g., age 13 yrs: A ($n = 54$): 42.6% vs. C ($n = 36$): 44.4%, $p = 0.862$; age 14 yrs: A ($n = 77$): 67.5 % vs. C ($n = 64$): 62.5%, $p = 0.532$; age 15 yrs: A ($n = 54$): 63% vs. C ($n = 52$): 61.5%, $p = 0.880$).

EBV-Specific Antibody Levels

In 145 athletes (m: $n = 91$, f: $n = 54$; age: 13.8 ± 1.6 yrs) EBV-specific IgG-titers (mean 166 ± 115 U/ml; range 30–810 U/ml) were detectable at baseline visit (V1). Female athletes showed significantly higher EBV-specific IgG titers compared to male athletes (f: 197 ± 145 U/ml vs. m: 147 ± 89 U/ml, $p = 0.012$), an age dependency was not proven ($p = 0.365$). Endurance athletes (high dynamic kind of sports) had the lowest EBV-specific IgG titers, compared to athletes of low and medium dynamic kind of sports (high: 153 ± 104 U/ml vs. medium: 225 ± 148 U/ml vs. low: 189 ± 138 U/ml, $p = 0.025$). The mean detectable EBV-specific IgG titers of the control group were 137 ± 112 U/ml (range: 26–878 U/ml), resulting in significant lower levels of EBV-specific IgG titers compared to the athletes at V1 ($p = 0.030$). This difference was confirmed in sub-analyzes of the male subjects ($p = 0.026$), but not in females ($p = 0.055$) (**Figure 3**). Similar to the athlete group, female control subjects showed higher EBV-specific IgG titers (C: m: 113 ± 90 U/ml vs. f: 152 ± 122 U/ml, $p = 0.038$), without any apparent age dependency ($p = 0.839$). The highest detectable EBV-specific IgG titer was measured in the collectives of the control subjects (C: 878 U/ml vs. A: 810 U/ml).

It Was Investigated Whether the Subjective Stress Level, an Increased Susceptibility to Infections, and the Occurrence of URTI Are Related to the Extent of Training Loads

Training Load∼Stress Level

With increasing training loads, defined as hours per week (Th/w), according to ordinal categorization (6 groups), a higher stress level was observed (<5 h: 42.2 ± 26.1%, 5 – ≤9.9 h: 41.8 ± 25.7%, 10 – ≤14.9 h: 47.2 ± 24.3%, 15 – ≤19.9 h: 52.9 ± 21.9%, 20–≤24.9 h: 54.4 ± 23.6%, ≥25 h: 61.4 ± 17.9%, $p < 0.001$), both in female ($p = 0.007$) and male athletes ($p = 0.029$). The 90th percentile of training load was 20 h per week, the 10th percentile was 6 h per

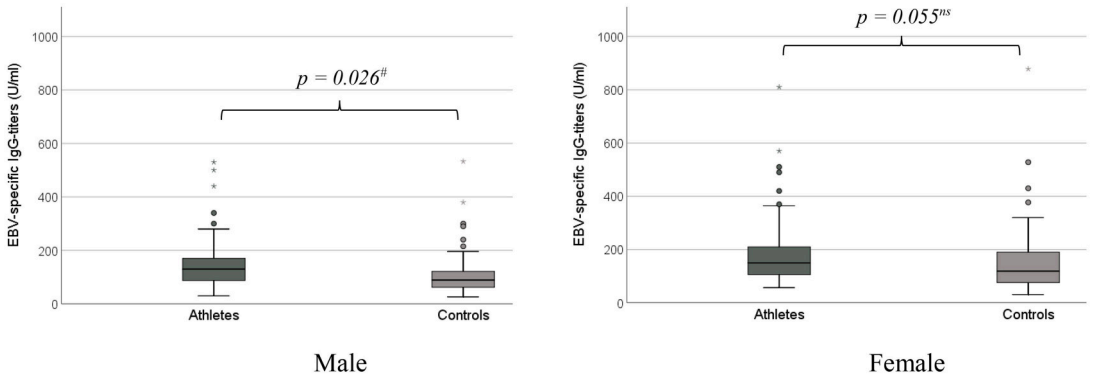


FIGURE 3 | EBV-specific IgG-titers (U/ml) in comparison between athletes and controls. **(A)** male subjects. **(B)** female subjects. $^{\#}p < 0.05$. *Extreme value (defined as a value that is smaller (or larger) than 3 box-lengths).

week. Significant differences in stress sensation were identified between the three groups (≤6 h: 40%, >6–<20 h: 48.3%, ≥20 h: 55.6%, $p < 0.001$). This counted for both sexes, female ($p = 0.007$) and male athletes ($p = 0.029$).

Training Load∼Susceptibility to Infection

Based on the ordinal categorization, athletes with less than 5 h training load per week (Th/w) showed the highest prevalence of susceptibility to infections (20%). Overall, no significant differences between the groups were observed (<5 h: 20%, 5–≤9.9 h: 11.4%, 10–≤14.9 h: 11.1%, 15–≤19.9 h: 13.4%, 20–≤24.9 h: 12.8%, ≥25 h: 11.5%, $p = 0.436$), in both sexes (f: $p = 0.113$, m: $p = 0.843$). Athletes with a training load of at least 20 h per week (90th percentile), reported not more often recurrent infections compared to athletes with less strains (≤6 h: 13%, >6–<20 h: 12.4%, ≥20 h: 12.6%, $p = 0.982$).

Training Load∼URTI

Analyzes of WURSS-21 data revealed no ordinal relationships between training loads and WTS (<5 h: 8.74 ± 13.42, 5–≤9.9 h: 6.60 ± 9.16, 10–≤14.9 h: 7.36 ± 11.52, 15–≤19.9 h: 4.92 ± 7.21, 20–≤24.9 h: 6.21 ± 9.33, ≥25 h: 13.74 ± 16.81, $p = 0.016$), or rather URTI prevalence (<5 h: 30.8%, 5–≤9.9 h: 29.9%, 10–≤14.9 h: 30.8%, 15–≤19.9 h: 22.4%, 20–≤24.9 h: 31.3%, ≥25 h: 46.7%, $p = 0.323$). But, an obvious higher score (WTS) and URTI prevalence were seen at trainings loads of at least 25 Th/w. Taking into account the categorization according to percentiles, significant associations were also missing (URTI: ≤6 h: 25.8%, >6–<20 h: 28.2%, ≥20 h: 34.2%, $p = 0.479$), both, in female ($p = 0.702$) and male group ($p = 0.146$).

In Order to Show a Possible Influence of Training and Stress on the Immune System, Training Hours per Week and Subjective Stress Levels Were Compared With EBV-Specific Parameters

Training Load∼EBV Serology

Training loads (Th/w) had no relation to EBV-serostatus (EBV–: 12.3 ± 5.3 h vs. EBV+: 13.0 ± 5.7 h, $p = 0.057$). After ordinal categorization of the training load (six groups), the relating mean EBV-specific IgG-titers were determined. No significant correlations between training hours per week and the extent of EBV-specific IgG-titers was observed (<5 h: 111 ± 75 U/ml, 5–≤9.9 h: 138 ± 99 U/ml, 10–≤14.9 h: 146 ± 110 U/ml, 15–≤19.9 h: 149 ± 113 U/ml, 20–≤24.9 h: 148 ± 113 U/ml, ≥25 h: 127 ± 45 U/ml, $p = 0.364$). Sub-analyzes of different training loads in female ($p = 0.791$), and male athletes ($p = 0.380$) revealed no gender-specific significant differences. Also after comparing the EBV-specific IgG-titers between the percentile groups, no significant differences were recognizable (≤6 h: 144 ± 104 U/ml, >6–<20 h: 147 ± 109 U/ml, ≥20 h: 117 ± 80 U/ml, $p = 0.087$). However, subgroup analyzes illustrated obvious lower EBV-specific IgG titers for athletes who trained at least 20 h per week (≥20 h: 117 ± 80 U/ml vs. >6–<20 h: 147 ± 109 U/ml, $p = 0.028$; ≥20 h; 117 ± 80 U/ml vs. ≤6 h: 144 ± 104 U/ml, $p = 0.072$).

Stress Level∼EBV Serology

EBV-seropositive athletes reported significantly higher stress levels compared to EBV-seronegative subjects (EBV–: 44.8 ± 24.4% vs. EBV+: 49.1 ± 25.0%, $p = 0.004$). This difference was confirmed in female athletes ($p = 0.002$), but not in the male collective ($p = 0.393$). After subdividing the subjects in different age groups, no significant differences regarding the stress level of EBV-seronegative and EBV-seropositive athletes were observed. Exemplary, in the subgroup of 18-year-old subjects, EBV-seronegative athletes showed stress levels of 54.0 ± 5.5%, in contrast to 46.1 ± 22.9% of EBV-seropositive athletes ($p = 0.450$). After further serological differentiation, athletes with suspected EBV reactivation (sRA) or primary EBV infection (sNI) offered the highest levels of stress sense (EBV–: 44.8 ± 24.4%, EBV+: 48.5 ± 24.9%, sRA: 58.8 ± 24.0%, sNI: 57.1 ± 25.8%, $p = 0.004$). Based on ordinal categorization of the stress levels (five groups), relative EBV-specific IgG-titer were assessed and compared with each other. Differences between the groups were not found, neither in the overall cohort (≤10%: 129 ± 83 U/ml, >10–≤30%: 128 ± 83 U/ml, >30–≤50%: 143 ± 106 U/ml, >50–≤70%: 150 ± 117 U/ml, >70%: 142 ± 127 U/ml, $p = 0.279$), nor in the female ($p = 0.303$) or male

group ($p = 0.186$). Analyzes based on the percentiles yielded comparable results (≤10%: 129 ± 83 U/ml, >10–80%: 141 ± 105 U/ml, ≥80%: 143 ± 133 U/ml, $p < 0.601$).

Finally, the Relations Between EBV-Specific Parameters and Clinical Outcomes Were Investigated

EBV Serology~Susceptibility to Infection

12.4% of EBV-seronegative and 11.8% of EBV-seropositive athletes reported recurrent infections. The difference was not significant, both in female ($p = 0.178$) and male sub-collectives ($p = 0.575$). Exemplary, 25.0% of EBV-seronegative athletes above 18 years declared susceptibility to infections, in contrast to 16.7% of EBV-seropositive subjects ($p = 0.681$). Closer examination of clinically conspicuous athletes showed a prevalence rate of 63.7% compared to a prevalence rate of 64.9% in healthy athletes ($p = 0.769$). These results were confirmed regardless of age- and gender-based sub-analyzes. Athletes with recurrent infections had no significant different levels of EBV-specific IgG-titers compared to clinically healthy subjects (I–: 139 ± 102 U/ml vs. I+: 160 ± 120 U/ml, $p = 0.078$), in both genders (f: I–: 151 ± 121 U/ml vs. I+: 179 ± 135 U/ml, $p = 0.118$; m: I–: 129 ± 84 U/ml vs. I+: 120 ± 63 U/ml, $p = 0.580$). The highest rates of susceptibility to infections were found in athletes within the 90th percentile group of EBV-specific IgG-titers, but with no significance (≤51 U/ml: 9.6% vs. >51–<268 U/ml: 10.3% vs. >268 U/ml: 15.3%, $p = 0.415$).

EBV Serology~URTI

There was no relation between EBV serostatus and extent of WTS (EBV–: 6.59 ± 9.40 vs. EBV+: 7.14 ± 10.48, $p = 0.470$), in both genders (f: $p = 0.128$, m: $p = 0.529$). Also, the URTI prevalence (WTS >7) between the two groups did not differ (EBV–: 31.6% vs. EBV+: 30.2%, $p = 0.486$). This was confirmed in all age ranges (≤12 yrs: EBV–: 28.6% vs. EBV+: 31.8%, $p = 0.791$; 13–14 yrs: EBV–: 31.5% vs. EBV+: 28.8%, $p = 0.661$; 15–16 yrs: EBV–: 33.3% vs. EBV+: 31.7%, $p = 0.773$; 17–18 yrs: EBV–: 28.0% vs. EBV+: 26.3 %, $p = 0.874$; >18 yrs: EBV–: 100% vs. EBV+: 36.4%, $p = 0.460$). 62.8% of the athletes with reported URTI symptoms were EBV seropositive, 64.3% of athletes without an URTI ($p = 0.696$). Athletes with serological suspected EBV reactivation showed the highest WTS, but no significant difference in comparison to the other groups was found (EBV–: 6.56 ± 9.40, EBV+: 7.09 ± 10.57, sRA: 9.45 ± 8.70, sNI: 5.84 ± 8.07, $p = 0.641$; **Figure 4**). The same was shown for the URTI prevalence (EBV–: 31.6%, EBV+: 29.6%, sRA: 52.6%, sNI: 30.0%, $p = 0.183$). Subjects with conspicuous WTS (>7) did not differ in EBV-specific IgG-titers from the unremarkable participants (URTI–: 137 ± 101 U/ml vs. URTI+: 158 ± 114 U/ml, $p = 0.082$), neither in female (URTI–: 164 ± 122 U/ml vs. URTI+: 170 ± 127 U/ml, $p = 0.393$) nor in male subjects (URTI–: 121 ± 74 U/ml vs. URTI+: 143 ± 95 U/ml, $p = 0.100$). In further analyzes, the URTI prevalence was determined as a function of the percentiles. An ordinal increase in prevalence with higher EBV-specific IgG-titers was evident, but at no time with any significance (URTI: ≤51 U/ml: 17.9%, >51–<268 U/ml: 29.9%, ≥268 U/ml: 43.2%, $p = 0.064$l; **Figure 5**).

In addition, presentation of the results was made in tabular form (**Tables 1**–**3**).

DISCUSSION

The major aim of the study was to determine the interaction between training load, stress level, immune status, and clinical

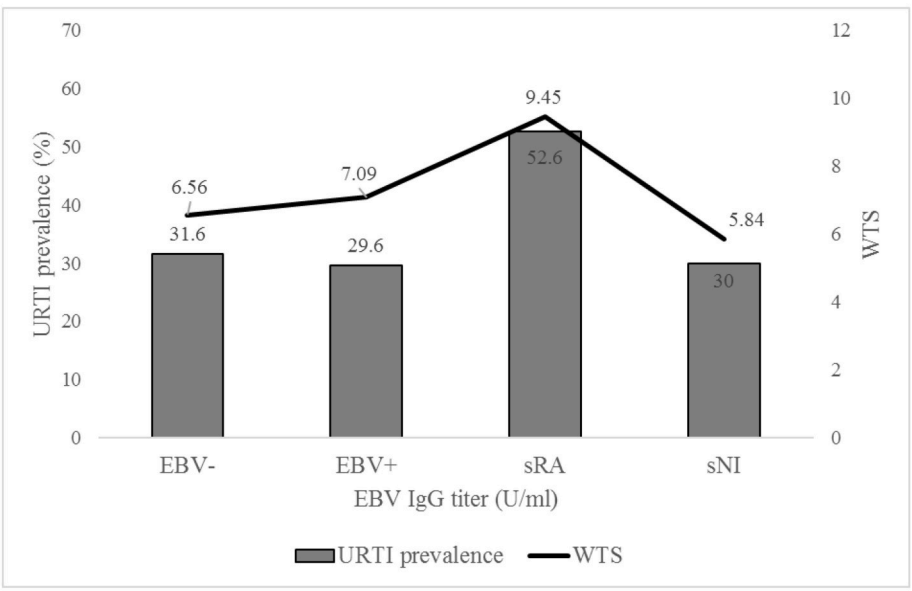


FIGURE 4 | URTI prevalence and WURSS-21 total score (WTS) depending on EBV serostatus (EBV–: EBV-seronegative [$n = 253$], EBV+: EBV-seropositive [$n = 392$], sRA: suspected reactivation [$n = 19$], sNI: suspected new infection [$n = 5$]). Values are expressed as means.

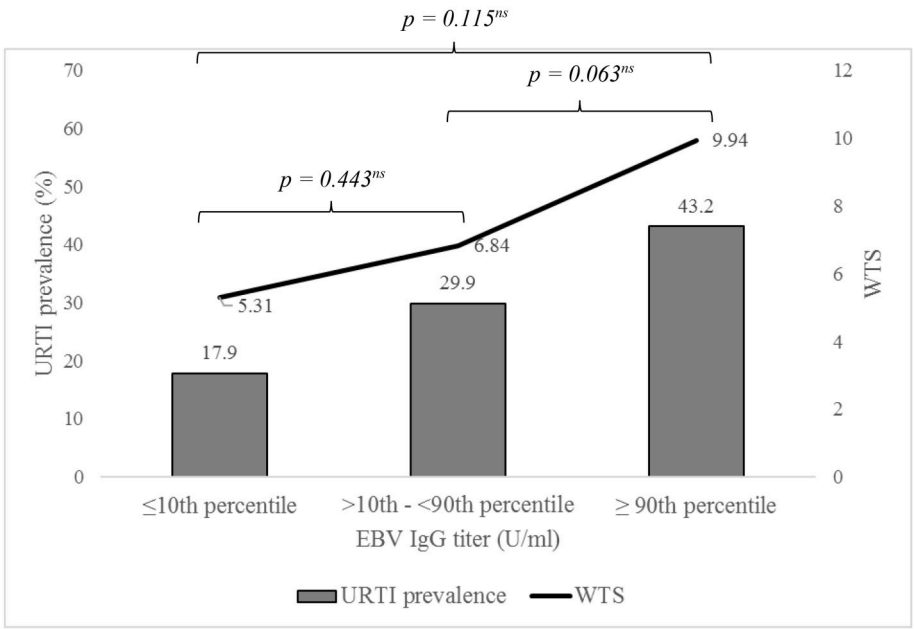


FIGURE 5 | URTI prevalence and WURSS-21 total score (WTS) depending on EBV-specific IgG titers categorized in different percentiles (≤10th percentile: ≤51 U/ml, >10th-<90th: >51-<268 U/ml, ≥90th: ≥268 U/ml). Values are expressed as means.

TABLE 1 | Clinical parameters of EBV-seronegative and -seropositive athletes.

	EBV-seronegative	EBV-seropositive	*P*
Age (yrs)	13.6 ± 1.4	13.8 ± 1.6	= 0.351
Stress level (%)	44.8 ± 24.4	49.1 ± 25.0	= 0.004*
Training load (Th/w)	12.3 ± 5.3	13.0 ± 5.7	= 0.057
Recurrent Infections (%)	12.4	11.8	= 0.769
WTS	6.59 ± 9.40	7.14 ± 10.48	= 0.470
URTI prevalence (%)	31.6	30.2	= 0.696

*WTS, WURSS-21 total score; URTI; Upper respiratory tract infection. Data are shown as mean ± SD and percentage values. *p < 0.01.*

endpoints. In advance, an independent evaluation of each parameter, with the relationships to each other, were necessary to characterize the cohort of young elite athletes. Therefore, a large prospective study was initiated involving young elite athletes who were monitored longitudinally in terms of clinical relevant parameters.

On the way becoming a top athlete, many barriers are to overcome. Success needs a high degree of health, because less lack of practice for exercising the physiological demands is necessary (Armstrong and Mc Manus, 2011; Hastmann-Walsh and Caine, 2015). In particular, adolescence needs an increased attention (Sabato et al., 2016). First, because of the high relative increase in training in this timeframe, on the other hand due to the consideration of additional factors influencing individual development, such as school, parental conflicts, puberty, or other physical and psychological strains (Cohn, 1990; Scanlan et al., 1991; Puffer and McShane, 1992; Gould et al., 1993; Puente-Diaz and Anshel, 2005). For the athlete, a safe passage through this phase with presumed health and continuous training must be ensured (Mårtensson et al., 2014). Therefore, knowledge of necessary conditions, at all levels (e.g., clinical, physical, psychological), are essential (Sabato et al., 2016). Although junior sports have become more and more the focus of science and public in recent years, large prospective studies characterizing young athletes in this regard are missing (Armstrong and Mc Manus, 2011). The knowledge of all influencing factors, including their weighting, makes it possible to regulate them in order to avoid negative consequences.

High-performance sport is associated with physical strains. To ensure an optimal development, systematic increases in training loads, from adolescence to adulthood, are necessary to avoid overtraining or negative health outcomes (Sabato et al., 2016). In certain kind of sports, high levels of training are mandatory even at a young age (Armstrong and Mc Manus, 2011). On the one hand, e.g., gymnastics need physical requirements, which are limited in adulthood, on the other hand, e.g., tennis players have to learn difficult skills already in the early age. So it is not uncommon from an age of 12–13 years to train 15–20 h per week (Armstrong and Mc Manus, 2011). Our study examined 274 junior athletes from ten different sports. Already at a mean age of 15 years, the average training load was nearly 15 h per week, with a maximum of over 30 h. One in five athletes (22.3%) trained at least 20 h a week. There were marked differences in training loads between the athletes, depending on age, gender, kind of sports, and localization. The results illustrated that young athletes offer high training loads, comparable to adults. In addition to the training, also school lessons are to complete resulting in over 60 h overall strain per week. Despite the same sport, age, and gender, the strains can vary clearly and, therefore, have to be

TABLE 2 | Clinical and immune parameters dependent on training load (training hours per week).

Training load (Th/w)	Stress level (%)	Recurrent infections (%)	WTS	URTI (%)	EBV-specific IgG (U/ml)
<5	42.2 ± 26.1	20	8.74 ± 13.42	30.8	111 ± 75
5 – ≤9.9	41.8 ± 25.7	11.4	6.60 ± 9.16	29.9	138 ± 99
10 – ≤14.9	47.2 ± 24.3	11.1	7.36 ± 11.52	30.8	146 ± 110
15 – ≤19.9	52.9 ± 21.9	13.4	4.92 ± 7.21	22.4	149 ± 113
20 – ≤24.9	54.4 ± 23.6	12.8	6.21 ± 9.33	31.3	148 ± 113
≥25.0	61.4 ± 17.9	11.5	13.74 ± 16.81	46.7	127 ± 45
	< 0.001**	= 0.436	= 0.016#	= 0.323	= 0.364

*WTS, WURSS-21 total score; URTI, Upper respiratory tract infection. Data are shown as mean ± SD and percentage values. #p < 0.05, **p < 0.001.*

TABLE 3 | Clinical parameters and training loads dependent on EBV-specific IgG titers categorized in different percentiles (≤10th percentile: ≤51 U/ml, >10th-<90th: >51-<268 U/ml, ≥90th: ≥268 U/ml).

	EBV-specific IgG (U/ml)			
	≤10th percentile	>10th-<90th percentile	≥90th percentile	*p*
Stress level (%)	52.8 ± 24.1	47.6 ± 25.1	52.0 ± 23.7	= 0.093
Training load (Th/w)	12.2 ± 5.5	13.1 ± 5.8	13.2 ± 5.2	= 0.429
Recurrent Infections (%)	9.6	10.3	15.3	= 0.415
WTS	5.31 ± 11.60	6.84 ± 9.94	9.94 ± 12.25	= 0.117
URTI prevalence (%)	17.9	29.9	43.2	= 0.064

WTS, WURSS-21 total score; URTI, Upper respiratory tract infection. Data are shown as mean ± SD and percentage values.

evaluated individually. Since young athletes show similar training loads as top-level adults, an adequate infrastructure (e.g., medical network) should already be available as early as possible.

Training can alter the immune system, by inducing a temporary immunosuppression (Reid et al., 2004; Fricker et al., 2005; Helenius et al., 2005; Tiollier et al., 2005; Cox et al., 2008), finally developing clinical complaints (Fricker et al., 2000; Konig et al., 2000). Competitive sport is associated with an increased risk for illness and injury (Armstrong and Mc Manus, 2011; Hastmann-Walsh and Caine, 2015). Here, upper respiratory tract infections belong to the most common reasons for impaired health and a diminished ability for regeneration (Schwellnus et al., 2016a). In certain circumstances, recurrent infections can result in frequent interruptions, lack of performance, and possibly retirement from competitive sports, furthermore, influencing long-term everyday life (Fricker, 1997; Alonso et al., 2010; Engebretsen et al., 2010, 2013; Mountjoy et al., 2010; Schwellnus et al., 2011, 2016a; Soligard et al., 2014). Based on the temporary immunosuppression, we assumed, that athletes show a higher susceptibility to infections, an increased prevalence of URTI, due to the high training loads already at a young age, and indicate an impaired sense of stress compared to controls (hypothesis 1). To prove these assumptions and to characterize each young elite athlete concerning this matter, following parameters were systematically examined and evaluated: (a) subjective stress level, (b) susceptibility to infections, (c) upper respiratory tract infection symptoms.

(a) Stress can negatively affect health (Novas et al., 2002; Putlur et al., 2004; Main et al., 2010). Therefore, the general aim is to minimize stress factors. In competitive sports, high training loads are inevitable, which can increase the subjective sense of stress and, thus, adversely affect the athletes' health. The cascade between extent of training, stress level, and health, respectively performance, is still unclear. Remarkable, our analyzes showed no increased sense of stress among the athletes compared to the control group, despite higher training loads and therefore increased strains. This illustrates the individual and multi-factorial etiology of stress. The counteracting positive effects of exercise on stress level can be assumed (e.g., increased vagotonus, structured everyday life, social environment, recognition, mental stability). In accordance to the literature, female subjects, in both cohorts, showed higher stress levels. In further analyzes, athletes with increased subjective stress levels have to been selected. After determining them, triggering risk factors can be avoided. Further investigations are needed to identify such triggering stress factors for developing appropriate interventions (Schwellnus et al., 2016a).

(b) Studies found an increased rate of recurrent infections in athletes due to a diminished transient immune competence after high-intensity or rather extensive training loads (Peters and Bateman, 1983; Fricker et al., 1999; Gleeson et al., 2000; Spence et al., 2007). In contrast, moderate exercise reduces the incidence of infections compared to physical inactivity (Matthews et al., 2002). This relation between extent of exercise and infection prevalence is described as J-shaped curve. To each visit, athletes and controls were asked how frequent they felt sick. At baseline visit a susceptibility to infections affirmed twelve percent of the athletes. There was no significant difference to the controls,

maybe justified by the young age, fewer years of training, and, therefore, less chronic effects on the immune system. However, a gender difference was detected with a higher prevalence of subjective recurrent infections in female subjects, both in athletes and controls. Recent studies have shown fewer episodes of infections in successful top-ranking athletes, mentioned as S-curve relationship (Mårtensson et al., 2014; Hellard et al., 2015). In the future, the question must be clarified whether a certain adaptation of the immune system is responsible for this, the results are based on a selection mechanism, or the outcome is compatible with a better lifestyle (Schwellnus et al., 2016a). It must be noted, that our results are based on self-reported data. The clinical relevance of such subjective susceptibility to infection remains to be investigated. An increased physical focus of the athlete compared to the general population is conceivable. However, in our analyzes no higher prevalence of recurrent infections between both collectives was found.

(c) In addition to the subjective susceptibility to infections, the WURSS-21 was used to compute symptoms of URTI as an objective and validated clinical endpoint (Barrett et al., 2005). After calculation of the WURSS-21 total scores (WTS), no differences depending on age and sex were observed. Overall, a maximum value of 133 could have been achieved. In contrast, during analyzed observation a mean WURSS-21 score of under seven was found, leading to the assumption of an investigated collective with less clinical complaints. Fewer chronical effects of long-lasting and intensive training loads on immune system are feasible reasons for the results. On the other hand, there might be a different perception of exercise in adolescence (e.g., less pressure to succeed, "playful" component), with the used questionnaire symptoms and functional impairments were recorded. Furthermore, the objectivization of influencing the performance in practice remains questionable and needs more investigation.

The persistence of EBV in the organism after primary infection, the lifetime prevalence of more than 90%, the simple measurement of infection stage after an antigen-antibody-reaction, the practicable detection of a systemically increased EBV activity in whole blood or saliva, and the known associations to clinical parameters, although with inconsistent results, make EBV and accordingly the immunological reactions to the virus as interesting markers of the overall immune function of the host (Gleeson et al., 2002; Pottgiesser et al., 2012; Karrer and Nadal, 2014). In our own preliminary work, we examined EBV-specific serological parameters in adult elite athletes (Pottgiesser et al., 2006, 2012; Hoffmann et al., 2010). To clarify the use of EBV-specific immune responses as a potential marker of the immune status (hypothesis 2), we investigated the EBV seroprevalence in our recruited adolescent subjects. The examined athletes showed, at a mean age of approximately 14 years, an EBV seroprevalence of already 60%. Serostatus differences did not depend on sex and age. Particularly, in controls a similar prevalence rate was found (56.6%). The missing difference confirmed previous data (Pottgiesser et al., 2006; Hoffmann et al., 2010). So, the incidence of primary infection, and thus seroconversion, does not depend on the level of physical training, and argue against an increased EBV seroprevalence in athletes (Hoffmann et al., 2010). The elicited EBV prevalence corresponds with the literature (Pottgiesser et al., 2012). Because of the already high rate of seroprevalence in adolescence, EBV-specific parameters can be used as potential immune markers for further analyzes.

Illness, impaired performance, and fatigue are often associated with EBV infection (Balfour et al., 2015). High-intensity or rather extensive training loads transiently diminish the immune competence (Peters and Bateman, 1983; Fricker et al., 1999; Gleeson et al., 2000; Spence et al., 2007). Encouraging this assumption, lower EBV-specific IgG tiers were detected in studies with competitive athletes compared to controls (Hoffmann et al., 2010). In this regard, the authors suggested a weaker immune function in competitive athletes. Therefore, we assumed lower EBV-specific IgG titers in young elite athletes compared to controls (hypothesis 3). However, we measured higher antibody titers in the samples of young athletes. These data suppose a necessary chronic influence of training loads on immune system for obvious alterations, e.g., lower antibody titers. Otherwise, the elevated EBV-specific IgG titers are a result of a reaction to increased EBV activity accompanying stress-induced diminished T-cell function (Hoffmann et al., 2010). So, a reduced T-cell function allows higher EBV loads, and in turn stimulating IgG production. To prove the effects, an additional determination of viral loads (EBV DNA) and EBV-specific T-cell responses, in a longitudinal study design, and the consideration of different seasonal time points are necessary. These was done in the present study. However, we refer to future publications regarding these results. Sub-analyzes proved the lowest IgG titers in endurance athletes in comparison to subjects of sports with a medium or low dynamic load. Possibly, the missing IgG titer differences to controls are due the high activity of the students in this age range. In summary, our results showed no differences in EBV serostatus and no lower EBV-specific IgG titers in athletes compared to controls in adolescent age.

Consistent data on the relationship between physical, psychological, and environmental stress factors, their effects on immunological parameters and their association to performance and clinical symptoms are missing. After analyzing parameters (training load, subjective stress level, EBV seroprevalence, EBV-specific IgG titers, susceptibility to infections, and upper respiratory tract infection symptoms) for themselves, the associations to each other have been addressed.

At first, we inspected if high training loads lead to an impaired stress sense and increase the incidence of clinical complaints (hypothesis 4). With increasing training loads, athletes felt more stressed, both in female and male athletes. The results were expected and can be justified with the higher time effort of training sessions. Contrariwise, controls showed no lower subjective stress levels compared to athletes despite more leisure time. Athletes offered an average training load of nearly 15 h per week corresponding with a mean stress level under 50 percent. In contrast, athletes with at least 25 h per week reported a level above 60%. So, a cut-off value of hours per week is to be assumed. The missing difference to the controls illustrated moreover the necessary consideration of further triggering factors, which cause conspicuous stress sense. Consequently, the positive and negative aspects of competitive sports should always be taken

into account. In addition to the presence of high strains, the individual handling of these should also be assessed. For further sub-analyzes athletes with high stress levels but low training loads will be selected. In addition, the influences of the extent of training load on infection-related parameters were examined. Neither the occurrence of subjective susceptibility to infection nor the presence of relevant clinical symptoms (URTI) were affected by the amount of exercise. Athletes with training loads of at least 25 h per week showed an obvious higher rate of an URTI (46.7%). However, an ordinal gradation of occurrence did not depend on training load. It is important to mention, that athletes with training loads under 5 h per week were mostly ill, resulting in high prevalences of clinical parameters in this group. In summary, no direct relationship between training loads and clinical outcomes were found. In further analyzes, ill and injured athletes should be excluded.

Published studies documented an altered immune system depending on strains (Dennis et al., 2005; Dun et al., 2005; Fleisig et al., 2011). We assumed an influence of training loads and stress sense on the immune system, hence, on EBV-specific parameters (hypothesis 5). In the examined young athlete collective, significant associations between training loads or rather stress levels and EBV-specific serological parameters, as potential immune markers, were absent. In our preliminary work we found lower EBV-specific IgG titers in competitive athletes compared to controls (Hoffmann et al., 2010). This could reflect weaker immune function because of high training loads. In the present study, EBV-specific IgG levels from young athletes do not correlate to training loads and subjective stress levels. Unique, athletes with a suspected EBV reactivation showed significantly higher stress levels compared to the others. For an adequate evaluation, further multivariate subgroup analyzes with the addition of other relevant parameters (e.g., EBV DNA, CRP, leucocytes) will be achieved.

Clinical relevant symptoms, such as recurrent infections and fatigue, are often associated with EBV (Balfour et al., 2015). So, studies with competitive athletes showed an association between viral load and the frequency of respiratory infections (Gleeson et al., 2002). Based on that, we assumed a relationship between the prevalence of upper respiratory tract infections (URTI) and EBV-serostatus or rather EBV-specific IgG titers. In the conducted analyzes, neither the prevalence of upper respiratory tract infections (WTS $>$ 7) nor the occurrence of susceptibility to infections are associated with EBV-serostatus or EBV-specific IgG titer levels. High IgG titers tended to show conspicuous clinical complaints, but at no time with a significance. Particularly, athletes with serological suspected EBV reactivation (sRA) presented the highest prevalence for URTI, even if there was no significant difference between the groups.

In summary, young elite athletes offered high training loads comparable to adults. Athletes showed no increased sense of stress, no higher prevalence of recurrent infections, and no different EBV-specific serological parameters compared to controls. With increasing training loads athletes felt more stressed, but significant associations to EBV-specific serological parameters were absent. Also no direct relationships between training loads and clinical outcomes with EBV-specific immune responses were found.

Due to the high strain variability, each athlete has to be evaluated individually, taking into account all influencing factors, and needs an adequate medical infrastructure to avoid negative long-term outcomes. After their objectification, inappropriate loads should be avoided by early detection and following interventions. In synopsis of the results, the occurrence of clinical symptoms cannot be established by training loads alone. Furthermore, EBV serostatus and the level of EBV-specific antibodies do not allow risk stratification for infections. Further investigations are needed, in particular subgroup-analyzes of athletes at risk and the addition, respectively the consideration, of other parameters (e.g., viral load, EBV-specific T-cell responses, performance data, CRP, leucocytes, psychological parameters). One strength of our study was that numerous parameters, in an interdisciplinary approach, were determined to characterize the collective of adolescent athletes compared to controls. In contrast to previous studies, upper respiratory tract infection symptoms were interrogated with a validated questionnaire (WURSS-21). In further analyzes other blood parameters for infection detection will be used. Otherwise, results of susceptibility to infections, training loads, and stress levels based on self-reported assessments. To our knowledge, we present the first prospective, controlled study of elite young athletes to examine the relationship between training load, stress parameters, immune status and clinical outcomes on such a large-scale cohort.

AUTHOR CONTRIBUTIONS

KB and BW conceived of the presented idea. KB and BW developed the theory and performed the computations. KB and BW verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

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Standardized Assessment of Resistance Training-Induced Subjective Symptoms and Objective Signs of Immunological Stress Responses in Young Athletes

Christian Puta[1†], Thomas Steidten[1†], Philipp Baumbach[2], Toni Wöhrl[1], Rico May[3], Michael Kellmann[4,5], Marco Herbsleb[1], Brunhild Gabriel[1], Stephanie Weber[1], Urs Granacher[6] and Holger H. W. Gabriel[1]*

[1] Department of Sports Medicine and Health Promotion, Friedrich-Schiller-University Jena, Jena, Germany, [2] Department of Anesthesiology and Intensive Care Medicine, University Hospital Jena, Jena, Germany, [3] Sportgymnasium Jena "Johann Chr. Fr. GutsMuths", Jena, Germany, [4] Faculty of Sport Science, Ruhr University, Bochum, Germany, [5] School of Human Movement and Nutrition Sciences, The University of Queensland, St Lucia, QLD, Australia, [6] Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany

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Brian Keith McFarlin,
University of North Texas,
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Leonardo Roever,
Federal University of Uberlândia, Brazil
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University Hospital Zurich, Switzerland

***Correspondence:**
Christian Puta
christian.puta@uni-jena.de

[†]Shared first authorship

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From a health and performance-related perspective, it is crucial to evaluate subjective symptoms and objective signs of acute training-induced immunological responses in young athletes. The limited number of available studies focused on immunological adaptations following aerobic training. Hardly any studies have been conducted on resistance-training induced stress responses. Therefore, the aim of this observational study was to investigate subjective symptoms and objective signs of immunological stress responses following resistance training in young athletes. Fourteen (7 females and 7 males) track and field athletes with a mean age of 16.4 years and without any symptoms of upper or lower respiratory tract infections participated in this study. Over a period of 7 days, subjective symptoms using the Acute Recovery and Stress Scale (ARSS) and objective signs of immunological responses using capillary blood markers were taken each morning and after the last training session. Differences between morning and evening sessions and associations between subjective and objective parameters were analyzed using generalized estimating equations (GEE). In *post hoc* analyses, daily change-scores of the ARSS dimensions were compared between participants and revealed specific changes in objective capillary blood samples. In the GEE models, recovery (ARSS) was characterized by a significant decrease while stress (ARSS) showed a significant increase between morning and evening-training sessions. A concomitant increase in white blood cell count (WBC), granulocytes (GRAN) and percentage shares of granulocytes ($GRAN_{\%}$) was found between morning and evening sessions. Of note, percentage shares of lymphocytes ($LYM_{\%}$) showed a significant decrease. Furthermore, using multivariate regression analyses, we identified that recovery was significantly associated with $LYM_{\%}$, while stress was significantly associated with WBC and $GRAN_{\%}$. *Post hoc* analyses revealed

significantly larger increases in participants' stress dimensions who showed increases in $GRAN_{\%}$. For recovery, significantly larger decreases were found in participants with decreases in $LYM_{\%}$ during recovery. More specifically, daily change-scores of the recovery and stress dimensions of the ARSS were associated with specific changes in objective immunological markers ($GRAN_{\%}$, $LYM_{\%}$) between morning and evening-training sessions. Our results indicate that changes of subjective symptoms of recovery and stress dimensions using the ARSS were associated with specific changes in objectively measured immunological markers.

Keywords: immune system, strength training, track and field, youth, Acute Recovery and Stress Scale (ARSS)

INTRODUCTION

According to Nieman (1994), high training volumes and intensities are associated with a higher risk of sustaining respiratory tract infections. This could be due to acute immunological responses which are often observed after intense training sessions (Northoff et al., 1998). From a health and performance-related perspective, it is important to detect and evaluate training-induced symptoms and signs of immunological responses in young athletes. Previous studies examined training-induced immunological responses in child and adolescent athletes (see **Table 1**). For instance, Freitas et al. (2016) monitored 26 young male soccer players (15.6 ± 1.1 years) and observed differences in immunological markers between official and simulated soccer matches. The evaluation of 15 mL salvia samples revealed a significant saliva immunoglobulin A (s-IgA) reduction after official matches. There is evidence that different s-IgA kinetics are associated with higher ratings of perceived exertion (RPE) in official matches which is indicative of a relation between intensity and immune response (Freitas et al., 2016; Owen et al., 2016). Interestingly, Moraes et al. (2017) demonstrated that an intensified training load followed by a tapering period negatively affected the mucosal immune function in young basketball players without causing significant changes in severity of upper respiratory tract infections. Of note, findings from Moraes et al. (2017) are in line with data from Gleeson et al. (2000) who evaluated markers of immune function over a 12-week training period in 22 elite swimmers aged 16–22 years. These authors did not detect significant associations between serum or salivary immunoglobulin levels, NK-cell numbers and symptoms of upper respiratory tract illness over the course of the 12-week training program (Gleeson et al., 2000). In addition, Moreira et al. (2013) did not find significant changes in objectively measured immunological parameters (s-IgA) after a 4-week training program in 12 male elite futsal players. In contrast, results from Mortatti et al. (2012) indicate that decrements in mucosal immunity (s-IgA) lead to a greater incidence of upper respiratory tract infections in elite young soccer players. Furthermore, these authors were able to establish a link between upper respiratory infections (URTI) and immunological responses (Mortatti et al., 2012) and between RPE and URTI (Moreira et al., 2013).

Training responses can also be monitored using self-reported questionnaires. Thereby, athletes' perceived internal load, mood and recovery-stress states can be examined. Previously, it has been shown that mood disturbances are associated with performance declines and biological changes such as immunosuppression (Fry et al., 1994).

Spence et al. (2007) reported that elite athletes suffer more often from URTI symptoms than recreational athletes. Notably,

TABLE 1 | Mini-Review of immunological responses in young athletes.

Publication	Subjects	Method	Main measures	Period	ISR?	Acute or chronic?
Freitas et al., 2016	*N* = 26 male youth soccer players (15.6 ± 1.1 years)	15 ml salvia samples	s-IgA	1 week (2 official and 2 simulated matches)	yes	acute
Moraes et al., 2017	*N* = 23 male youth basketball players (15.8 ± 0.8 years)	15 ml salvia samples, WURSS-21, Borg-Scale	s-IgA, URTI, RPE	8 weeks training (1 familiarization, 4 intensive training, 3 taper)	yes	chronic
Mortatti et al., 2012	*N* = 14 elite male youth soccer players (18.5 ± 0.4 years)	15 ml salvia samples, Borg-Scale	s-IgA, Cortisol, RPE	20 days (7 matches)	yes	chronic
Gleeson et al., 2000	*N* = 22 elite swimmers (16–22 years, 12 m/10f)	1 mL salvia, 2 mL blood samples	s-IgA, s-IgM, s-IgG, NK-Cells, Albumin	12 weeks training	yes	chronic
Moreira et al., 2013	*N* = 12 male elite futsal players (19.0 ± 1 years)	15 mL saliva samples, WURSS-21, Borg	s-IgA, URTI, RPE	4 weeks training	no	chronic

WURSS-21, Wisconsin Upper Respiratory Symptom Survey-21; s-IgA, secretory immunoglobuline A; s-IgM, secretory immunoglobuline M; s-IgG, secretory immunoglobuline G; NK-Cells, natural killer cells; URTI, upper respiratory infections; RPE, rating of perceived exertion; ISR, training-induced immunological responses.

URTI symptoms caused by infections were registered in 30% of all examined athlete. No causes of URTI symptoms were identified in the remaining 70% of athletes. Interestingly, both infected and unidentified athletes showed similar symptoms during the first 2 days (Spence et al., 2007). The results from Spence et al. (2007) imply the need to evaluate objective and subjective measures to distinguish between infect-based and exercise-induced immunological responses.

Walsh et al. (2011) in their position statement recommended that "we need to focus on the nature of exercise." Most studies in the field of "exercise and immune response" are related to cardiorespiratory exercises (e.g., endurance, aerobic training). In contrast, the effects of resistance training on pro- and anti-inflammatory processes remains poorly understood (Walsh et al., 2011) which is why this is an area for future investigations.

Therefore, the aim of this observational study was to examine resistance-training induced changes in subjective [i.e., Acute Recovery and Stress Scale (ARSS)] and objective measures (i.e., capillary blood) of immunological stress responses over a period of 7 days with daily morning and evening tests in young athletes. In addition, potential associations between subjective and objective markers of immunological stress responses were computed. Recently, Kellmann et al. (2016) developed ARSS to asses and monitor multidimensional recovery and stress states. ARSS represents a promising assessment tool that considers multidimensionality and sport specificity. Most importantly, the ARSS questionnaire is economically valid (Kellmann et al., 2016).

With reference to the relevant literature on ARSS (Kölling et al., 2015; Kellmann et al., 2016; Hitzschke et al., 2017), we expected that stress dimensions increase and recovery dimensions decrease from morning to evening training sessions. In accordance with findings from Ihalainen et al. (2014), we hypothesized that granulocytes would increase from morning to evening training sessions because young athletes are subject to endocrine, immunological, and metabolic stress due to school, training, and social demands. Given that subjective and objective measures are sensitive to strains of everyday life and training, we hypothesized that changes in subjective symptoms using ARSS between morning and evening training sessions are associated with changes in objective signs following resistance training-induced immunological responses in young track and field athletes.

MATERIALS AND METHODS

Participants

Our study sample was recruited with reference to the recently introduced conceptual model on how to implement resistance training during the stages of long-term athlete development (Granacher et al., 2016). According to this model, young athletes aged between 12 and 18 years (Granacher et al., 2016) who span the stages "Late Childhood" (pre-pubertal, Tanner Stage I-II) and "Adolescents" (pubertal, Tanner Stage III-IV) would participate in regular resistance training programs. Thus, 14 (7 females and 7 males) young track and field athletes with a mean age of 16.4 years and an age range of 15–18 years participated in this 7-day observational study. To be eligible for inclusion in this study, athletes had to be free from any signs and symptoms of upper or lower respiratory tract infections during the last 2 weeks prior to the start of this study. If any sign or symptoms (>48 h) occurred during the 7-day observational study, participants were excluded from our final statistical analyses (Spence et al. (2007). In addition, participating athletes had to be experienced with resistance training (minimum 2 years of experience) and conduct resistance training over the 7-day study period. Track and field athletes were recruited because the multidimensional demands of this sport afford resistance training for performance development and injury prevention. Our study sample was experienced with free weight training, core strength training, and plyometric training and performed these types of resistance training during their daily training routines. Prior to the start of the study, experimental procedures, risks and benefits of the study were explained to all participating athletes and their legal representatives and written informed consent was obtained from all involved parties. This study was carried out in accordance with the recommendations of the University Research Ethics Committee of the Friedrich-Schiller-University Jena, Germany and the latest version of the Declaration of Helsinki. The protocol was approved by the University Research Ethics Committee of the Friedrich-Schiller-University Jena (458510/15).

Contents of Training

Training was performed in small athletic groups (2–3) or even individually according to age of participants and sport discipline. Due to the multidimensional demands of track and field disciplines, resistance training sessions addressed neuromuscular adaptations using core strength training, plyometric training, and free weight training. In addition, technical aspects of resistance training to achieve sufficient movement quality was part of the program as well (see Supplementary Material for detailed information).

Procedures

Subjective and objective measures were taken each morning and after the last training session of the day. Subjective symptoms of immunological stress responses were assessed using ARSS. Objective markers were taken from capillary blood samples to evaluate immune cell distribution. In order to exclude *ad hoc* infectious cases from our analyses, a questionnaire was used to identify signs of upper and lower respiratory infections (ULI).

Subjective Measures

The German version of the ARSS (Kölling et al., 2015; Hitzschke et al., 2016; Kellmann et al., 2016) was used as an assessment tool to record recovery and stress states in our study sample. The English version of the ARSS was recently described and published elsewhere (Nässi et al., 2017). ARSS consists of 32 items and it assesses aspects of emotional, physiological, mental, and overall stress and recovery. Those items are equally arranged and distributed in four stress-related (i.e., muscular stress, lack of activation, negative emotional state, and overall stress) and four recovery-related (physical performance capability, mental performance capability, emotional balance, and overall recovery)

scales (Kellmann et al., 2016). Participants were asked to rate each item on a seven-point Likert-type scale from 0 (does not apply at all) to 6 (fully applies). Several recently published studies (Kölling et al., 2015; Kellmann et al., 2016; Hitzschke et al., 2017) indicated that the ARSS is a sensitive measure for the evaluation of recovery and stress states in athletes. All scales of the ARSS showed satisfactory internal consistency (range between $\alpha = 0.84$ and $\alpha = 0.96$) and a good model fit for both the recovery (RMSEA = 0.07, CFI = 0.97, SRMR = 0.04) and stress (RMSEA = 0.09, CFI = 0.94, SRMR = 0.05) items (Kellmann et al., 2016). These dimensions were used for further analysis.

Objective Measures

The capillary blood markers white blood cells (WBC), Lymphocytes (LYM), Lymphocytes % ($LYM_{\%}$), Monocytes (MID) Monocytes % ($MID_{\%}$), Granulocytes (GRAN), Granulocytes % ($GRAN_{\%}$), red blood cells (RBC), Hemoglobin (HGB), Hematocrit (HCT), mean corpuscular volume (MCV), mean corpuscular concentration (MCVC), red blood distribution width ($RDW_{\%}$), red blood cell distribution width absolute (RDWa), Platelets (PLT), platelet distribution width (PDW, fl), Large platelet (LPCR, %) were measured using a 20 µl capillary blood sample taken from the earlobe between 30 and 45 min after morning and evening training sessions. Analysis was performed using a medonic hematology system (Medonic M16M, Boule Medical AB, Spånga, Sweden). Intra-Assay Coefficients of Variability for Micro Pipette Adapters were recently provided by the manufacturer (WBC $\leq$ 2,5%, RBC $\leq$ 1,5%, MCV $\leq$ 0,5%, PLT $\leq$ 3,0%, HGB $\leq$ 1,3%; Medical AB, Spånga, Sweden). Our own measurements revealed acceptable Intra-Assay Coefficients of Variability for WBC $\leq$ 2,22%, GRAN $\leq$ 2,14%, $GRAN_{\%} \leq$ 1,42%, LYM $\leq$ 2,95%, $LYM_{\%} \leq$ 1,20%. Inter-Assay Coefficients of Variability were also acceptable with WBC $\leq$ 1,06%, GRAN $\leq$ 1,40%, $GRAN_{\%} \leq$ 1,39%, LYM $\leq$ 2,90%, $LYM_{\%} \leq$ 2,11%.

Statistical Analyses

Resistance Training and Immunological Response

Differences between time of day (morning vs. evening training session) in the ARSS dimensions and the capillary blood markers were tested using generalized estimating equations (GEE). This technique is appropriate for repeated measurements (i.e., 7 training days with two tests per day). It allows imputation of randomly missing data for different time points, and it produces robust parameter estimates and standard errors (Zeger and Liang, 1986; Burton et al., 1998). The recorded ARSS dimensions and capillary blood markers served as dependent variables. The factor *time of day* (dichotomous: morning vs. evening training session) was entered as independent variable in our statistical model. We used a Gaussian link function and within-subject dependencies were modeled as first-order autoregressive. Finally, to examine significant differences between *time of day*, we estimated pairwise contrasts of the marginal means. The reported marginal means and corresponding confidence intervals were collected for all training days.

Relation of the Acute Recovery and Stress Scale With Capillary Blood Markers

To assess associations between objectively tested capillary blood markers and subjectively recorded recovery and stress ratings, GEE was used as well. All variables were z-transformed before a regression analysis was computed. Here, ARSS dimensions served as dependent variables. In univariate analysis, the capillary blood markers (e.g., percent of lymphocytes) were entered separately as independent variables. In accordance with recommendations for logistic regression analyses (Bursac et al., 2008), all capillary blood markers with a p-value ≤ 0.2 in univariate analyses were entered in a multivariate model. In case of highly correlated blood markers (e.g., absolute values and percent of lymphocytes), the parameter with the better univariate model fit (Quasi Likelihood under Independence Model Criterion, QIC) was entered in the multivariate model. Finally linear stepwise regression analyses was used to remove predictors with p-values > 0.1 (starting with the highest p-value) from the model (Bursac et al., 2008). During each step, the model fit was evaluated by means of the QIC. In case of a worsening of the model-fit, the respective parameter was kept in the final model.

Daily Change-Scores of Acute Recovery and Stress Scale and Capillary Blood Samples

Using *post hoc* analyses, we aimed at comparing ARSS recovery and stress dimensions between subjects. For this purpose, participants were selected who showed an increase in $GRAN_{\%}$ (vs. none) or a decrease in $LYM_{\%}$ (vs. none). In a first step, change-scores were calculated from morning to evening training sessions for all ARSS dimensions and the blood markers. Next, participants were classified in groups who showed an increase in $GRAN_{\%}$ or a decrease in $LYM_{\%}$. Change-scores of ARSS dimensions were compared between the respective groups using Mann-Whitney-*U*-Tests. In addition, effect sizes were reported as Pearson correlation coefficients (r = 0.5; 0.3; 0.1 corresponding to large, medium, small effects; Fritz et al., 2012).

The significance level was set at $\alpha = 5\%$ and we reported two-sided p-values. In case of multiple comparisons, Bonferroni-Holm corrected p-values were used. Data analyses was computed using SPSS (Version 22, IBM, United States).

RESULTS

Our final analysis included 56 datasets with complete information for the morning and evening training sessions (112 observations from 13 athletes). In accordance with Spence et al. (2007), one participant (KS008) was excluded from our final data analysis because of showing ULI signs and symptoms for longer than 48 h.

Resistance Training and Subjective Symptoms

Table 2 contains marginal means and 95% confidence intervals for ARSS from GEE models. Pairwise comparisons revealed a highly significant decrease ($p < 0.001$) in the ARSS recovery dimension between morning and evening training sessions. In addition, a highly significant increase ($p < 0.001$) in the

TABLE 2 | Marginal means and confidence intervals (95%CI) resulting from the Generalized Estimating Equation models for the dimensions of the Acute Recovery and Stress Scale (ARSS) and capillary blood markers.

		Morning			Evening			p_{raw}	p_{adj}
		Mean	95% CI		Mean	95% CI			
ARSS: recovery	[0–5]	4.46	4.10	4.82	4.01	3.67	4.36	**<0.001**	**<0.001**
ARSS: stress	[0–5]	0.91	0.63	1.20	1.51	1.13	1.89	**<0.001**	**<0.001**
White blood cells	[10^9/l]	7.41	6.88	7.95	9.26	8.16	10.36	**<0.001**	**<0.001**
Lymphocytes	[10^9/l]	2.98	2.64	3.33	3.14	2.79	3.48	0.363	0.999
Lymphocytes	[%]	40.55	37.33	43.76	35.10	32.50	37.71	**<0.001**	**<0.001**
Monocytes	[10^9/l]	0.63	0.58	0.67	0.75	0.65	0.85	**0.006**	0.063
Monocytes	[%]	7.74	7.39	8.08	7.53	7.20	7.86	0.165	0.999
Granulocytes	[10^9/l]	3.79	3.43	4.15	5.36	4.59	6.14	**<0.001**	**<0.001**
Granulocytes	[%]	51.69	48.40	54.98	57.34	54.58	60.10	**<0.001**	**<0.001**
Red blood cells	[10^{12}/l]	4.66	4.45	4.87	4.52	4.34	4.69	**0.005**	0.062
Hemoglobin	[mmol/l]	8.70	8.34	9.05	8.46	8.15	8.76	**0.004**	0.052
Hematocrit	[%]	38.80	37.33	40.28	37.68	36.42	38.95	**0.003**	**0.049**
Mean corpuscular volume	[fl]	83.22	82.21	84.22	83.33	82.43	84.24	0.450	0.999
MCH	[fmol]	1.87	1.84	1.90	1.87	1.85	1.90	0.382	0.999
MCHC	[mmol/l]	22.47	22.32	22.63	22.49	22.31	22.66	0.661	0.999
Blood cell distribution width	[fl]	52.26	51.29	53.24	52.53	51.58	53.47	0.194	0.999
Red blood cell distribution width	[%]	13.94	13.74	14.14	13.99	13.77	14.21	0.083	0.834
Platelets	[10^9/l]	136.49	119.34	153.63	137.36	121.61	153.11	0.870	0.999
Platelet distribution width	[fl]	12.72	12.13	13.31	12.91	12.25	13.56	0.205	0.999
Large platelet	[%]	22.05	19.98	24.11	22.60	20.18	25.01	0.250	0.999

Significant differences between time of day (morning vs. evening training sessions) are marked with bold p-values. Raw (p_{raw}) and Bonferroni-Holm corrected p-values are reported (p_{adj}).

ARSS stress dimension was noted between morning and evening training sessions.

Resistance Training and Objective Signs

Results for capillary blood markers from GEE models are displayed in **Table 2** as well. Pairwise comparisons of capillary blood parameters revealed a highly significant increase ($p < 0.001$) in WBC, GRAN and $GRAN_{\%}$ between morning and evening training sessions. In addition, a significant decrease was found for $LYM_{\%}$ ($p < 0.001$) and HCT ($p = 0.049$) from morning to evening training sessions. Statistical trends in the form of an increase were found for MID ($p = 0.063$) and RBC ($p = 0.062$) and a decrease for HGB ($p = 0.052$). Of note, changes in WBC, GRAN, $GRAN_{\%}$, and $LYM_{\%}$ exceeded Intra-Assay and Inter-Assay Coefficients of Variability.

Associations of the Acute Recovery and Stress Scale With Capillary Blood Markers

Results of the univariate regression analyses for the ARSS dimensions are displayed in **Table 3**. In summary, ARSS recovery ratings were positively associated with LYM (standardized regression coefficient βz = 0.09, 95% CI: −0.03 to 0.22, $p = 0.127$), $LYM_{\%}$ (βz = 0.38, 95% CI: 0.18 to 0.59, $p < 0.001$), $MID_{\%}$ (βz = 0.17, 95% CI: −0.01 to 0.35, $p = 0.057$), RBC (βz = 0.15, 95% CI: −0.01 to 0.32, $p = 0.072$), HGB (βz = 0.13, 95% CI: −0.04 to 0.30, $p = 0.124$), HCT (βz = 0.12, 95% CI: −0.03 to 0.28, $p = 0.117$) and negatively associated with WBC (βz = −0.21, 95% CI: −0.39 to −0.03, $p < 0.05$), GRAN (βz = −0.29, 95% CI: −0.49 to −0.08, $p = 0.006$), $GRAN_{\%}$ (βz = −0.38, 95% CI: −0.58 to −0.18, $p < 0.001$) and RDWa (βz = −0.19, 95% CI: −0.41 to 0.04, $p = 0.106$). Stress ratings were positively associated with WBC (βz = 0.34, 95% CI: −0.14 to 0.55, $p = 0.001$), MID (βz = 0.20, 95% CI: −0.01 to 0.41, $p = 0.064$), GRAN (βz = 0.40, 95% CI: 0.19 to 0.62, $p < 0.001$), $GRAN_{\%}$ (βz = 0.40, 95% CI: 0.19 to 0.62, $p < 0.001$) and negatively associated with $LYM_{\%}$ (βz = −0.41, 95% CI: −0.62 to −0.19, $p < 0.001$) and $MID_{\%}$ (βz = −0.15, 95% CI: −0.34 to 0.04, $p = 0.123$).

Findings from multivariate regression analyses revealed that recovery ratings were positively associated with $LYM_{\%}$ (βz = 0.38, 95% CI: 0.18 to 0.59, $p < 0.001$) and negatively associated with $GRAN_{\%}$ (βz = −0.39, 95% CI: −0.59 to −0.19, $p < 0.001$) and RDWa (βz = −0.21, 95% CI: −0.43 to 0.02, $p = 0.073$). Stress ratings were positively associated with WBC (βz = 0.22, 95% CI: 0.06 to 0.38, $p = 0.006$) and $GRAN_{\%}$ (βz = 0.31, 95% CI: 0.12 to 0.50, $p = 0.001$) and negatively associated with $LYM_{\%}$ (βz = −0.21, 95% CI: −0.51 to −0.11, $p = 0.002$). Due to high multicollinearity, it was not possible to include $LYM_{\%}$ and $GRAN_{\%}$ in a joint model (see **Table 4**).

Post hoc analyses (see **Figure 1**) revealed that participants who showed a decrease in $LYM_{\%}$ ($n = 41/56$ datasets, vs. no change or increase) between morning and evening training sessions reported a significantly higher decrease ($p < 0.01$) in

TABLE 3 | Results of the univariate regression analysis using generalized estimating equations for the dimensions of the Acute Recovery and Stress Scale (ARSS).

		ARSS: stress				ARSS: recovery			
		β	95%CI		*p*	β	95%CI		*p*
White blood cells	*z*-score	0.34	0.14	0.55	**0.001**	−0.21	−0.39	−0.03	**0.020**
Lymphocytes	*z*-score	0.00	−0.11	0.12	0.985	0.09	−0.03	0.22	**0.127[a]**
Lymphocytes: percent	*z*-score	−0.41	−0.62	−0.19	**<0.001**	0.38	0.18	0.59	**0.000**
Monocytes	*z*-score	0.20	−0.01	0.41	**0.064[a]**	−0.09	−0.27	0.08	0.294
Monocytes: percent	*z*-score	−0.15	−0.34	0.04	**0.123**	0.17	−0.01	0.35	**0.057**
Granulocytes	*z*-score	0.40	0.19	0.62	**<0.001[a]**	−0.29	−0.49	−0.08	**0.006[a]**
Granulocytes: percent	*z*-score	0.40	0.19	0.62	**<0.001**	−0.38	−0.58	−0.18	**<0.001**
Red blood cells	*z*-score	−0.08	−0.30	0.15	0.493	0.15	−0.01	0.32	**0.072**
Hemoglobin	*z*-score	−0.08	−0.29	0.12	0.424	0.13	−0.04	0.30	**0.124**
Hematocrit	*z*-score	−0.07	−0.27	0.12	0.468	0.12	−0.03	0.28	**0.117**
Mean corpuscular volume	*z*-score	0.03	−0.25	0.31	0.840	−0.19	−0.50	0.12	0.230
MCH	*z*-score	0.02	−0.30	0.34	0.894	−0.17	−0.45	0.11	0.238
MCHC	*z*-score	−0.02	−0.18	0.15	0.829	0.01	−0.16	0.19	0.868
Blood cell distribution width: absolute	*z*-score	0.10	−0.07	0.27	0.260	−0.19	−0.41	0.04	**0.106**
Red blood cell distribution width: percent	*z*-score	0.10	−0.23	0.43	0.551	−0.09	−0.38	0.20	0.532
Platelets	*z*-score	0.08	−0.24	0.40	0.633	−0.19	−0.48	0.10	0.204
Platelet distribution width	*z*-score	0.00	−0.24	0.24	0.992	−0.08	−0.29	0.14	0.479
Large platelet: percent	*z*-score	−0.02	−0.27	0.23	0.885	−0.05	−0.26	0.17	0.651

[a]*Because of high multicollinearity between absolute and relative values and a better model fit only percent values were entered in the multivariate models. Standardized regression weights (β) and corresponding confidence intervals (95%CI) and p-values are presented. Bold p-values indicate variables used for multivariate modeling.*

TABLE 4 | Results of the multivariate regression analysis using Generalized Estimating Equations for the dimensions of the Acute Recovery and Stress Scale (ARSS).

	Unit	Model I				Model II			
		β	95%CI		*p*	β	95%CI		*p*
ARSS: recovery									
Intercept		*0.00*	*−0.36*	*0.37*	*0.998*	*0.00*	*−0.36*	*0.37*	*0.991*
Lymphocytes: percent	*z*-score	0.38	0.18	0.59	<0.001	was not entered because of high multicollinearity			
Granulocytes: percent	*z*-score	was not entered because of high multicollinearity				−0.39	−0.59	−0.19	<0.001
Blood cell distribution width: absolute	*z*-score	−0.20	−0.43	0.04	0.098	−0.21	−0.43	0.02	0.073
ARSS: stress									
Intercept		−0.07	−0.47	0.33	0.738	−0.07	−0.47	0.33	0.729
White blood cells	*z*-score	0.22	0.05	0.38	0.010	0.22	0.06	0.38	0.006
Lymphocytes: percent	*z*-score	−0.31	−0.51	−0.11	0.002	was not entered because of high multicollinearity			
Granulocytes: percent	*z*-score	was not entered because of high multicollinearity				0.31	0.12	0.50	0.001

Standardized regression weights (β) and corresponding confidence intervals (95%CI) and p-values are presented.

ARSS recovery dimensions ($r = 0.40$). In line with this finding, the aforementioned athletes also showed a significantly higher increase ($p < 0.01$) in the ARSS stress scale ($r = 0.36$). In addition, participants with an increase in $GRAN_{\%}$ ($n = 41/56$ datasets vs. no change or decrease) showed a significantly higher decrease ($p < 0.01$) in ARSS recovery dimensions ($r = 0.47$) and a significantly higher increase ($p < 0.01$) in ARSS stress dimensions ($r = 0.41$).

DISCUSSION

The main goal of this observational study was to examine resistance-training induced changes in subjective (i.e., ARSS) and objective measures (i.e., capillary blood) of immunological stress responses over a period of 7 days with daily morning and evening tests in young track and field athletes. Research on this topic is scarce because most studies examined immunological responses following endurance/aerobic training (Walsh et al., 2011). Our data demonstrated for the first time that resistance training evokes exercise-induced immunological responses in young track and field athletes. From a practitioners point of view, an important finding of this study is that training-induced changes in ARSS stress and recovery dimensions were associated with capillary blood markers. Thus, ARSS can be used as an easy-to-administer tool to detect signs of immunological stress responses.

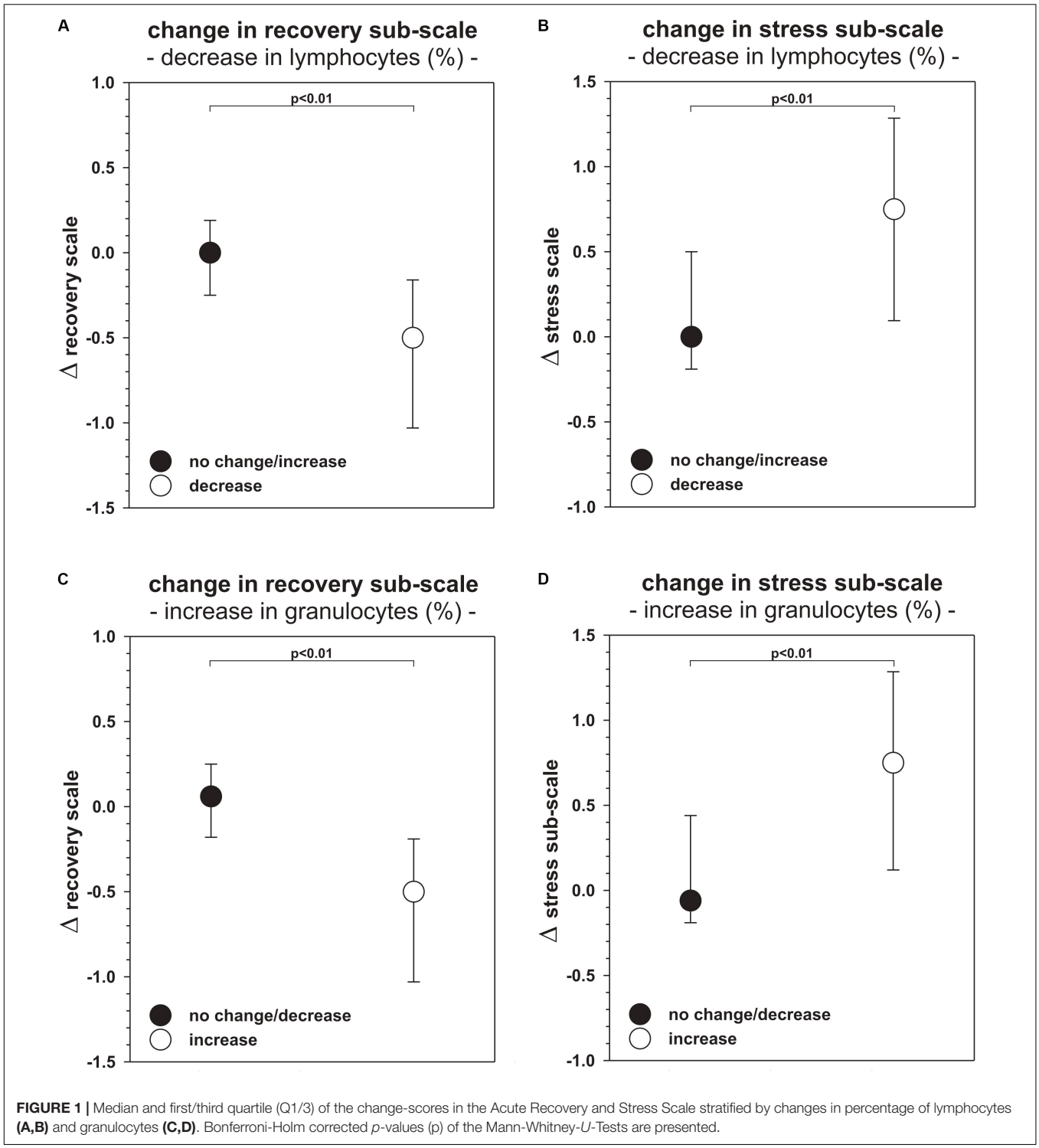


FIGURE 1 | Median and first/third quartile (Q1/3) of the change-scores in the Acute Recovery and Stress Scale stratified by changes in percentage of lymphocytes **(A,B)** and granulocytes **(C,D)**. Bonferroni-Holm corrected *p*-values (p) of the Mann-Whitney-*U*-Tests are presented.

Resistance Training and Subjective Symptoms

It has previously been reported that ARSS is an appropriate and well-established tool for monitoring of acute recovery-stress states in young athletes (Nässi et al., 2017). Our data showed that ARSS recovery dimensions significantly decreased from morning to evening training sessions while ARSS stress dimensions increased. Our results are in line with previous work from Kölling et al. (2015) and Hitzschke et al. (2016) who showed that ARSS is able to measure recovery and stress imbalances over numerous training days which is why our first research hypothesis can be accepted.

Resistance Training and Objective Signs

Our results demonstrate highly significant inverse shifts in GRAN% and LYM%, due to resistance training in young track and field athletes. These shifts are most likely related to highly significant GRAN ($p < 0.001$) and highly significant WBC ($p < 0.001$) increases from morning to evening training sessions. According to this finding, our second hypothesis can be accepted. Our findings on the acute effects of resistance training are in line with results from Gabriel and Kindermann (1997). These authors observed increases in WBC and GRAN and inverse shifts in GRAN% and LYM% 1–3 h after a single bout of aerobic cycling. In contrast, we were not able to detect decreases in lymphocytes after resistance training. Training type specific lymphocyte kinetics might be related to different metabolic, cardiorespiratory, and hormonal demands in resistance versus endurance training. Even though increases in GRAN are related to improved innate immune function, a reduced bacterial-induced oxidative burst (Robson et al., 1999; Peake and Suzuki, 2004; Nagatomi, 2006) might leave athletes vulnerable to infections (Walsh et al., 2011). We were able to detect changes in capillary blood markers following resistance training which is indicative of exercise-induced immunological responses following this type of training in young track and field athletes.

Previous studies already examined immunological responses following resistance training (Gabriel and Kindermann, 1998; Gleeson et al., 2000; Mayhew et al., 2005; Paulsen et al., 2010; Moreira et al., 2013; Ihalainen et al., 2014; Moraes et al., 2017). However, most studies did not assess immune cell kinetics by means of blood analyses (Paulsen et al., 2010; Moreira et al., 2013; Ihalainen et al., 2014; Moraes et al., 2017). Those few studies that examined immune cell kinetics scrutinized different cohorts and applied different types of resistance training (Mayhew et al., 2005; Ihalainen et al., 2014, 2017). Given that our study sample conducted training in small (relation of supervisor to coach) training groups (see Supplementary Material) with different emphasis, overall comparison of our findings with results from previous studies is hardly feasible.

Relation of the Acute Recovery and Stress Scale With Capillary Blood Markers

The univariate regression revealed that ARSS stress dimensions are either positively (WBC, MID, GRAN, GRAN%) or negatively (LYM% and MID%) related to immunological blood markers. The positive association of WBC, GRAN, and GRAN% is in line with the predicted cell kinetics of biphasic leukocytosis (Gabriel and Kindermann, 1997). During the first phase, exercise-induced stress causes migration of WBC (GRAN, LYM, and MID) from the marginal pool into the circulating blood (Gabriel and Kindermann, 1998). This reaction matches specific immune cell kinetics for infections (Northoff et al., 1998). Although our study focused on the investigation of post-training immune cell kinetics, this mechanism may still contribute and explain our findings. The second phase is characterized by further increases of GRAN caused by mobilization of GRAN from the bone marrow and their extended stay within blood circulation. In contrast, LYM is reduced by homing (Gabriel, 2006). Therefore, positive (GRAN, GRAN%, and WBC) and negative (LYM% and MID%) associations with ARSS stress dimensions may indicate the beginning of the second phase of biphasic leukocytosis. Furthermore, ARSS recovery dimensions showed positive (LYM, LYM%, MID%, RBC, HGB, HCT) and negative (WBC, GRAN, GRAN% and RDWa) associations with blood measures. Post training and during recovery, a restoring of the homeostasis takes place. Thus, inverse associations of immune parameters could be expected. Positive correlations of the blood markers RBC, HGB, and HCT could also be indicative of an ongoing regeneration process. To elucidate the main determinants responsible for changes during recovery, related blood measures were entered into our multivariate regression analyses. Notably, GRAN% and LYM% were not entered into a joint model due to high multicollinearity. Multivariate models revealed that LYM%, GRAN%, and WBC accounted for changes in the examined ARSS dimensions. Most importantly, immune measures were identified that are related to changes in the stress-recovery balance. The absolute immune measures were not entered in the joint models though.

As percentage shares of WBC seem to reflect changes in ARSS, *post hoc* analyses were applied to identify the specific directions in relative immune cell shifts in relation to ARSS changes (see **Figure 1**). Our findings emphasized the importance of GRAN% and LYM% for the observed changes in ARSS stress and recovery dimensions. As illustrated in **Figure 1A**, participants with a training-induced decrease in LYM% (41/56 datasets) showed significantly higher reductions in ARSS recovery dimensions and increases in ARSS stress dimensions (**Figure 1B**). In addition, subjects with training-induced increases in GRAN% (41/56 datasets) showed significantly lower ARSS recovery dimensions (**Figure 1C**) and significantly higher ARSS stress dimensions (**Figure 1D**). These findings are in line with the behavior of immune cell kinetics following endurance training. In other words, higher inverse shifts in WBC percentage shares are expressed through changes in the stress-recovery balance using ARSS dimensions. Having this in mind, we can accept our third research hypothesis. Thus, it can be postulated that subjectively measured symptoms (ARSS) of immunological responses following resistance training are associated with objectively tested blood markers (shift of GRAN% and LYM%) in young track and field athletes.

Limitations

Our study was carried out as an observational study that was conducted in the field. Therefore, this study comes with a few limitations that warrant discussion. The most notable limitation of the present study was the narrow post-training window in which capillary blood samples were taken and the subjective measures of acute recovery and stress. However, it has to be noted that the study was designed as an applied study in the field. In contrast to laboratory-based research, our post-training capillary blood samples were not obtained at distinct time points after the respective training sessions. In fact, we had to cope with a delay of 30–45 min post-training. In this regard, it has previously been purported that later measurements are associated

with ongoing shifts in $GRAN_{\%}$ and $LYM_{\%}$ as well as with a decrease in LYM (McCarthy and Dale, 1988; Gabriel and Kindermann, 1997; Gabriel, 2006). However, we would like to point out that the detection of peak immunological responses in WBC, GRAN, and LAM was not the primary goal of this study. Yet, we acknowledge that different post-training time intervals are a limitation of this study. There is evidence of further increases in $GRAN_{\%}$ and $LYM_{\%}$ shifts during later recovery stages (McCarthy and Dale, 1988; Gabriel and Kindermann, 1997; Gabriel, 2006). In our field setting with young athletes, it was not feasible to take measurements at later time points because this would have affected athletes' daily training program and schedule (school, social contacts, family). Data from this study do not allow to determine resistance training specific dose-response relationships in the context of training-induced changes in subjective symptoms and objective signs of immunological responses. Well controlled laboratory studies are needed to elucidate this research question.

It has to be acknowledged that ARSS is limited to rating biases. However, self-reported measures using questionnaires represent the most common form of athlete monitoring on an elite level, and are often favored over physiological and performance measures due to cost effectiveness and practical advantages (Taylor et al., 2012). Our study is the first study that investigated associations between changes in subjective symptoms and objectively measured signs of stress and recovery following resistance training. Therefore, when interpreting our findings, it has to be taken into account that research in elite athletes always comes with certain limitations that are specific to the field setting. Finally, we examined young track and field athletes with a mean age of 16.4 years. Caution is needed when translating these findings to other sports, training types, or cohorts.

Recommendations for the Assessment of Exercise-Induced Immunological Responses

We were able to show for the first time that demands during resistance training are related to immunological responses in young athletes. What practically relevant recommendations can be provided for practitioners working with young athletes? First, as was already shown for endurance training, resistance training is associated with training-induced immunological responses in adolescent young track and field athletes. Thus, daily monitoring (early in the morning and in the evening) of subjective and objective measures of immunological responses for at least 48 h (Spence et al., 2007) and up to 7 days (own data) is recommended during intense training periods. Second, with reference to the identified associations between ARSS and blood markers, ARSS is recommended to be implemented in daily training routines to monitor subjective signs of immunological responses. Third, clinical blood reference values should not be used to determine exercise-induced immunological responses. Even though we were able to show immunological responses following resistance training in young track and field athletes, capillary blood markers did not exceed the reported clinical ranges.

Future Implications

In order to detect resistance training-induced immunological stress responses in young athletes, the following aspects should be considered for future research:

First, $LYM_{\%}$, $GRAN_{\%}$ and WBC were related to changes in ARSS stress and recovery dimensions. It has to be noted that even though these blood markers changed significantly due to training, they did not exceed the clinically relevant range. However, to the best of our knowledge, our assessment of changes in subjective symptoms and objective signs during a 7-day resistance training period is a new approach that was not yet tested in a clinical setting. From this it follows that we cannot deduce clinical implications from our findings. Therefore, future research is needed to examine larger cohorts of young athletes and to extend our approach concerning infections (e.g., upper respiratory tract infections). To differ between training-induced and infection-induced immunological responses, cohort specific reference value studies have to be carried out. Clinically relevant immunological changes of subjective symptoms and objective signs concerning resistance training and how they are related to clinically relevant immunological changes (e.g., upper respiratory tract infection) should be addressed in further studies. Data from our study could be used as a first (preliminary) benchmark for the assessment of norm values concerning resistance training-induced immunological responses. Second, associations between ARSS recovery and stress dimensions and objectively measured capillary blood need further validation on larger sample sizes and in adolescent athlete populations. Based on our study findings, future research might concentrate on the detection of immunological responses to resistance training using the ARSS stress and recovery scales. Third, an assessment protocol needs to be established that is easy-to-administer and not time consuming. The practicability should be regarded as a main requirement for future application in young athletes.

CONCLUSION

Findings from this study suggest that resistance training is associated with exercise-induced immunological responses in young male and female track and field athletes. More specifically, results from capillary blood samples indicated an increase in WBC, GRAN, $GRAN_{\%}$ and a decrease in $LYM_{\%}$ from morning to evening training sessions. Daily change-scores of subjective symptoms of recovery and stress dimensions were assessed using ARSS. Accordingly, we observed a concomitant decrease in ARSS recovery dimensions together with an increase in ARSS stress dimensions from morning to evening training sessions over the 7-day study period. Moreover, ARSS scale findings were associated with specific changes in objectively measured immunological markers ($GRAN_{\%}$ and $LYM_{\%}$) It is noteworthy that participants with an increase in $GRAN_{\%}$ also showed a larger decrease in ARSS recovery dimensions and a larger increase in ARSS stress dimensions from morning to evening training sessions. Furthermore, young athletes who showed a decrease in $LYM_{\%}$ also demonstrated a larger decrease in ARSS recovery dimensions and a larger increase in ARSS stress dimensions

from morning to evening training sessions. Our findings indicate that subjective parameters of stress and recovery using ARSS are suitable to detect resistance-training induced immunological changes over a time period of 7 days. Future well-controlled studies are crucial to determine dose-response relationships following resistance training in young athletes in the context of training-induced immunological responses using subjective (e.g., ARSS) and objective (e.g., blood samples) testing tools.

AUTHOR CONTRIBUTIONS

CP, TS, RM, and UG designed the experiments. RM, SW, MH, and CP gathered the data. PB, TS, TW, and CP conducted the data analysis. CP, TS, MK, PB, UG, and HG wrote the manuscript. All authors discussed the results and its implications, commented and edited the manuscript at all stages, and approved the final version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2018.00698/full#supplementary-material

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ORIGINAL RESEARCH
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Symptoms of Anxiety and Depression in Young Athletes Using the Hospital Anxiety and Depression Scale

Stephanie Weber[1], Christian Puta[1], Melanie Lesinski[2], Brunhild Gabriel[1], Thomas Steidten[1], Karl-Jürgen Bär[3], Marco Herbsleb[1], Urs Granacher[2] and Holger H. W. Gabriel[1]*

[1] Department of Sports Medicine and Health Promotion, Friedrich Schiller University Jena, Jena, Germany, [2] Division of Training and Movement Sciences, Research Focus Cognition Sciences, University of Potsdam, Potsdam, Germany, [3] Department of Psychiatry and Psychotherapy, University Hospital Jena, Jena, Germany

Elite young athletes have to cope with multiple psychological demands such as training volume, mental and physical fatigue, spatial separation of family and friends or time management problems may lead to reduced mental and physical recovery. While normative data regarding symptoms of anxiety and depression for the general population is available (Hinz and Brähler, 2011), hardly any information exists for adolescents in general and young athletes in particular. Therefore, the aim of this study was to assess overall symptoms of anxiety and depression in young athletes as well as possible sex differences. The survey was carried out within the scope of the study "Resistance Training in Young Athletes" (KINGS-Study). Between August 2015 and September 2016, 326 young athletes aged (mean ± SD) 14.3 ± 1.6 years completed the Hospital Anxiety and Depression Scale (HAD Scale). Regarding the analysis of age on the anxiety and depression subscales, age groups were classified as follows: late childhood (12–14 years) and late adolescence (15–18 years). The participating young athletes were recruited from Olympic weight lifting, handball, judo, track and field athletics, boxing, soccer, gymnastics, ice speed skating, volleyball, and rowing. Anxiety and depression scores were (mean ± SD) 4.3 ± 3.0 and 2.8 ± 2.9, respectively. In the subscale anxiety, 22 cases (6.7%) showed subclinical scores and 11 cases (3.4%) showed clinical relevant score values. When analyzing the depression subscale, 31 cases (9.5%) showed subclinical score values and 12 cases (3.7%) showed clinically important values. No significant differences were found between male and female athletes ($p \geq 0.05$). No statistically significant differences in the HADS scores were found between male athletes of late childhood and late adolescents ($p \geq 0.05$). To the best of our knowledge, this is the first report describing questionnaire based indicators of symptoms of anxiety and depression in young athletes. Our data implies the need for sports medical as well as sports psychiatric support for young athletes. In addition, our results demonstrated that the chronological classification concerning age did not influence HAD Scale outcomes. Future research should focus on sports medical and sports psychiatric interventional approaches with the goal to prevent anxiety and depression as well as teaching coping strategies to young athletes.

Keywords: youth athletes, anxiety, depression, gender differences, late childhood, adolescents

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****Correspondence:***
Stephanie Weber
stephanie.weber@uni-jena.de

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INTRODUCTION

During stressful situations, the body is threatened by external or internal forces that may lead to an alteration of its homeostasis. The adaptive changes, which occur in the body during stress, can either be behavioral or physical. Physiologically, stress stimulates the activation of the sympathetic nervous system and the hypothalamic-pituitary-adrenal axis (Messina et al., 2016). Psychologically, increased stress may lead to the development of symptoms of anxiety and depression (Mineka and Zinbarg, 2006).

The development of psychological distress and the prevalence of anxiety and depression in the athletic population is of interest to athletes, coaches, parents, teachers, and the scientific community, and has recently gained increasing awareness by the public in general. Current research lacks a precise description of prevalence rates of anxiety disorder or major depressive disorder in high performance athletes. Most studies used questionnaires leading to both, over and under estimation of occurrence rates of anxiety or depressive symptoms (Storch et al., 2005; Yang et al., 2007; Gulliver et al., 2014; Gouttebarge et al., 2015; Junge and Feddermann-Demont, 2015). Thus, descriptions of anxiety symptoms in the adult athlete population range from 7.1 to 26% (Gulliver et al., 2014; Gouttebarge et al., 2015) and symptoms of depression from 10.3 to 27.2% (Gulliver et al., 2014; Junge and Feddermann-Demont, 2015). In contrast, intercollegiate student-athletes have higher anxiety symptom rates of up to 37% (Storch et al., 2005) but similar rates of depressive symptoms (21%) (Yang et al., 2007). These variabilities might be explained by methodological differences such as application of different questionnaire, or differences in time of testing during a training season for example training or competition phase. In addition, assessment time of the day, including before or after a training session could explain the differences (Hines, 2004; Moskowitz and Young, 2006). Further, it is important to stress, that the use of questionnaires is very susceptible to be biased by confounding covariates (Luppino et al., 2010) and is by no means sufficient to establish a clinical diagnosis. However, likely reasons for these high rates are the elevated risk of injuries, performance plateaus or decrements or an approaching retirement form elite sports (Rice et al., 2016). This could explain the 37% prevalence rate of anxiety symptoms in college student-athletes. Furthermore, it has been suggested that transition stages in the athletic career are accompanied by increased stress levels and emotional imbalances. All these factors contribute to the higher anxiety symptom rates described in college student-athletes.

With regards to the young athlete population, limited research regarding anxiety and depressive symptoms is available. For instance, Brand et al. (2013) investigated psychological symptoms in elite student athletes compared to non-athletes aged 12–15 years. Findings show higher anxiety and depressive symptom frequencies for female compared to male students regardless of their athletic status. In addition, anxiety and depressive symptom scores were higher in the student athletes compared with their non-athletic peers. However, this finding was only significant for the anxiety level in female participants. Further, Nixdorf et al. (2016) found higher levels of depressive symptoms in athletes (mean age: 14.96 ± 1.56) participating in individual sports compared to team sports.

For young athletes, the time of adolescence can be regarded as a transition stage. Transition stages in the athletic career are characterized by changes on a psychosocial, academic vocational, and psychological level (Wylleman et al., 2004). On a psychosocial level, the athlete changes from relying entirely on his/her parents, siblings, and peers, to peer to peer relationships and coach-athlete relationship. On an academic vocational level, young athletes are faced with the challenges of entering secondary education, whilst on a psychological level having to deal with the changes that occur in the body during adolescence. Finally, on an athletic level, young athletes are faced with the challenges of developing sport-specific skills and techniques, increased training volumes and intensities, and higher competition frequencies (Wylleman et al., 2004). These multiple demands might be associated with an increased occurrence rate of anxiety or depressive symptoms. However, there is far more research necessary.

Whilst the research of Brand et al. (2013) and Nixdorf et al. (2016) clearly show the presence of symptoms of anxiety and depression in young athletes, they do not indicate how severe these symptoms are. However, it is of high relevance for athletes, parents, coaches, and sport psychologists to elucidate the clinical relevance of these symptoms. One way to measure symptoms of anxiety and depression and their severity is the use of the Hospital Anxiety and Depression Scale (HAD Scale). The HAD Scale is a questionnaire, which has been developed to detect the overall state and severity of anxiety and depression (Zigmond and Snaith, 1983). Since its development, various international versions and reference values have been generated for a variety of patient groups in the adult population (Herrmann, 1997). In addition, the HAD Scale has been validated for the use in the adolescent population (White et al., 1999). However, limited data regarding normative values are available. Furthermore, to the best of our knowledge the athletic population has not been studied yet.

Therefore, the aim of this study was to provide an overview of symptoms of anxiety and depression in young athletes using the HAD Scale. The following research questions were specifically addressed:

1. How are the symptoms of anxiety and depression in young athletes distributed?
2. How severe are clinically relevant symptoms of anxiety and depression?
3. Are there any age and sex differences for symptoms of anxiety and depression in young athletes?

MATERIALS AND METHODS

Participants

The cross-sectional survey was carried out within the scope of the study "Resistance Training in Youth Athletes" (KINGS-Study). Between August 2015 and June 2017, 326 young athletes aged 12–18 years (mean ± SD 14.3 ± 1.6 years) were asked to complete the HAD Scale. Of these 155 were male and 171 female athletes. The participating young athletes were recruited from handball (80), volleyball (43), judo (41), canoeing (39), track and

field athletics (32), soccer (25), rowing (21), ski jumping (15), Olympic weight lifting (10), boxing (10), ice speed skating (8), and gymnastics (2).

The study was carried out in accordance with the Declaration of Helsinki and was approved by the Ethics committee of the Friedrich Schiller University Jena (4584-10/15), Germany. All subjects and their legal representatives gave their written informed consent after having been thoroughly informed about the nature and course of the experiment.

Schooling Background

Regarding the schooling background, all participating athletes except ski jumping athletes were from *Eliteschulen des Sports* (elite sport schools). Elite sport schools are facilities in which highly gifted and/or talented athletes are given an opportunity to develop and maximize their sporting talent, whilst maintaining school education (Emrich et al., 2009). The ski jumping athletes were partly from elite sport schools and partly from a general Gymnasium (high-school).

The Hospital Anxiety and Depression Scale

The HAD Scale was originally developed and validated by Zigmond and Snaith (1983) with the intention to detect states of depression and anxiety in adults aged 16–65 years. It contains an anxiety (HADS-A) and a depression (HADS-D) subscale each consisting of 7 items, rated on a four point Likert scale (0–3), therefore a maximum count of 21 points per subscale is possible. The questions are designed to focus solely on psychiatric symptoms by excluding questions related to physical illness such as dizziness or headaches, thereby excluding somatic components (Zigmond and Snaith, 1983). The questionnaire is designed to assess the participants' state over the past 2 weeks. In the studies on the adult population, the HAD Scale shows good internal consistency, good diagnostic qualities and case-finding properties (Bjelland et al., 2002; Brennan et al., 2010).

Original cut-offs for anxiety and depression have been defined as 0–7 no case, 8–10 doubtful case, and 11–21 case (**Table 1**). White et al. (1999) validated the HAD Scale for the use in the adolescent population (12–16 years) and suggested different cut-offs for the interpretation of severity. For HADS-A 0–8: no case, 9–11 possible case, 11–21 probable case and for HADS-D: 0–6 no case, 7–9 possible case, 10–21 probable case. It was argued that a higher threshold value for depression (10+) and anxiety (12+) would minimize false positive diagnostics, whereas a lower cut-off for depression (7) and anxiety (9) would minimize false negative diagnostics. Research on the adolescent population showed sufficient validity, psychometric properties and internal consistency of the HAD Scale (White et al., 1999; Chan et al., 2010). Since the HAD Scale is a questionnaire developed to detect clinical forms of anxiety and depression, the cut-off scores could equally be named as subclinical and clinical values.

Data Processing and Statistical Analysis

Originally, 376 athletes were asked to complete the HAD Scale. Thirty-six athletes were excluded from the analysis because of missing values in the questionnaire. In addition, 14 athletes were excluded because they were not within the age range of 12–18 years or they did not provide their chronological age on the questionnaire (**Figure 1**).

For the distribution analysis, percentiles ranging from 50 to 98% were calculated and contrasted with cut-offs reported in the literature (Zigmond and Snaith, 1983; White et al., 1999). Furthermore, we z-transformed HAD Scale-data for anxiety and depression using the following equation:

$$Z - \text{Score} = (\text{single}_{\text{young athlete}} - \text{mean}_{\text{young athletes}})/\text{SD}_{\text{young athletes}}.$$

Z-scores above "0" indicate higher values on the HAD Scale-subscale compared to the sample mean. Z-score values below "0" indicate lower values on the HAD Scale-subscale compared to the sample mean (Dancey and Reidy, 2014). After having completed Z-transformation, it is legitimate to compare a single athlete with the group mean of all investigated athletes because the 95% confidence interval (CI) of a standard normal distribution is defined as follows: 95% CI $= \text{mean}_{\text{youngathletes}} \pm 1.96\text{SD}_{\text{youngathletes}}$ (Dancey and Reidy, 2014). *Z*-values above +1.96 were considered as relevant for diagnostic purposes (Magerl et al., 2010; Puta et al., 2013).

To detect age effects on the anxiety and depression subscales, age groups were classified based on Granacher et al. (2016) as follows: late childhood (12–14 years) and late adolescents (15–18 years). Spearman's rho correlation coefficient was used for the assessment of the relationship between HADS-A and HADS-D. All statistical analyses were carried out using SPSS Statistics Version 23. In general, graphics were made using R Software 3.3.2 with the packages ggplot2 and grid amongst other things (The R Foundation for Statistical Computing). The line of best fit for

TABLE 1 | Anxiety and depression cut-offs for the adult and adolescent population.

	No cases	Doubtful cases	cases
Zigmond and Snaith, 1983		**Anxiety and depression**	
	0–7	8–10	11–21
White et al., 1999		**Anxiety**	
	0–8	9–11	>11
		Depression	
	0–6	7–9	>9

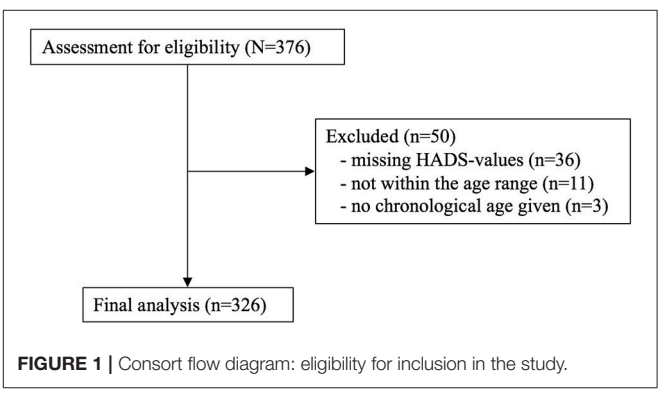


FIGURE 1 | Consort flow diagram: eligibility for inclusion in the study.

the Z-score was computed using the Local Polynomial Regression Fitting (Cleveland et al., 1992).

RESULTS

Distribution of Symptoms of Anxiety and Depression in Young Athletes

Both HAD Scales were not normally distributed. As indicated in **Figure 2A**, the anxiety scores are positively skewed (0.74) with a shift of the distribution curve to the left. The curve has a steep incline and peaks at score 3 after which it falls again. The curve declines until score 15 on the anxiety scale. Overall the minimum and maximum score for anxiety are 0 and 14, respectively (mean ± SD: 4.3 ± 3.0, **Table 2**). Fifty percent of the young athletes are at or below an anxiety score of 4. Furthermore, 70% of the young athletes are within a score range of 6, 80% are at or below a score of 7, 90% of athletes are at or below a score of 8.5, 95% are at or below a score of 10, and 98% of the athletes are at or below a score of 12 on the anxiety scale.

The distribution of the depression scores is positively skewed as well (1.36). The depression curve (**Figure 2B**) displays a sharp incline until point 1 on the depression scale where it peaks. This is followed by a similar sharp decline until point 6 on the depression scale. After a small rise in density at point 7, the distribution of the depression scores levels off until score 16. Overall, the depression scores range from 0 to 15 (mean ± SD: 2.8 ± 2.9, **Table 2**). Of these, 50% of the young athletes score 2 or lower on the depression scale. Seventy percent are within a score of 3, 80% reach a score of 5, 90% a score of 7, 95% a score of 9, and 98% a score of 10.5 on the depression scale.

Regarding the relationship between anxiety and depression, the graphical presentation of the z-scores (**Figure 3**) indicates that with an increase in anxiety scores there is a concomitant increase in depression scores. However, this is not linear as can be seen from the percentiles of the distribution. For example, whilst 50% of the anxiety scores are at 4 on the anxiety scale, 50% of the depression scores are at 2 on the depression scale. This is equal to a z-score below 0 for both HAD Scales. Further, 70% of the athletes are at score 6 on the anxiety scale and 3 on the depression scale. This pattern continues until 98% of the distribution of scores (anxiety at score 12, depression at score 10.5). Furthermore, the illustration of the z-scores shows that the highest anxiety score (14) is 3 standard deviations above the mean HADS-A and the highest depression score (15) 4 standard deviations above the mean HADS-D, which highlights the spread of the data.

The combination of Z-score data together with percentiles of distribution enables a descriptive evaluation of our data, especially of the abnormal values. This is particularly useful because cut-off values vary between studies. However, when looking at the 95th percentile on the anxiety scale, it corresponds to a Z-score just below two. This however, is not the case for the

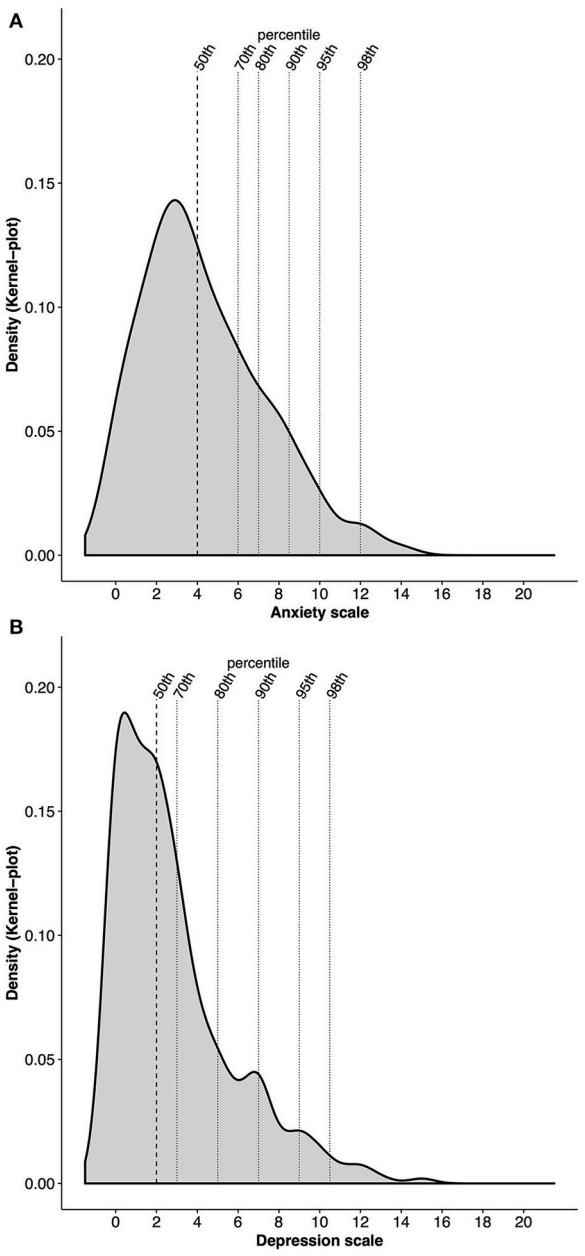


FIGURE 2 | (A,B) Density of the distribution of anxiety **(A)** and depression **(B)** with percentiles (50th, 70th, 80th, 90th, 95th, and 98th) in alignment with the HAD Scale scores.

TABLE 2 | Overall results (mean±SD, 95% Confidence interval of the mean) of anxiety (HADS-A) and depression (HADS-D) as well as comparison between age groups (12–14: late childhood; 15–18: late adolescents) and sex.

	Male/Female	HADS-A (95% CI)	HADS-D (95% CI)
Overall	326 (171/155)	4.3 ± 3.0 (4.01–4.67)	2.8 ± 2.9 (2.52–3.15)
Age-group			
12–14	88/92	4.2 ± 3.2 (3.71–4.65)	2.8 ± 3.0 (2.40–3.29)
15–18	83/63	4.5 ± 2.8 (4.08–5.00)	2.8 ± 2.7 (2.82–3.26)
Sex	Male: 171	4.1 ± 2.9 (3.65–4.53)	3.0 ± 2.9 (2.51–3.38)
	Female:155	4.6 ± 3.1 (4.13–5.11)	2.7 ± 2.9 (2.25–3.16)

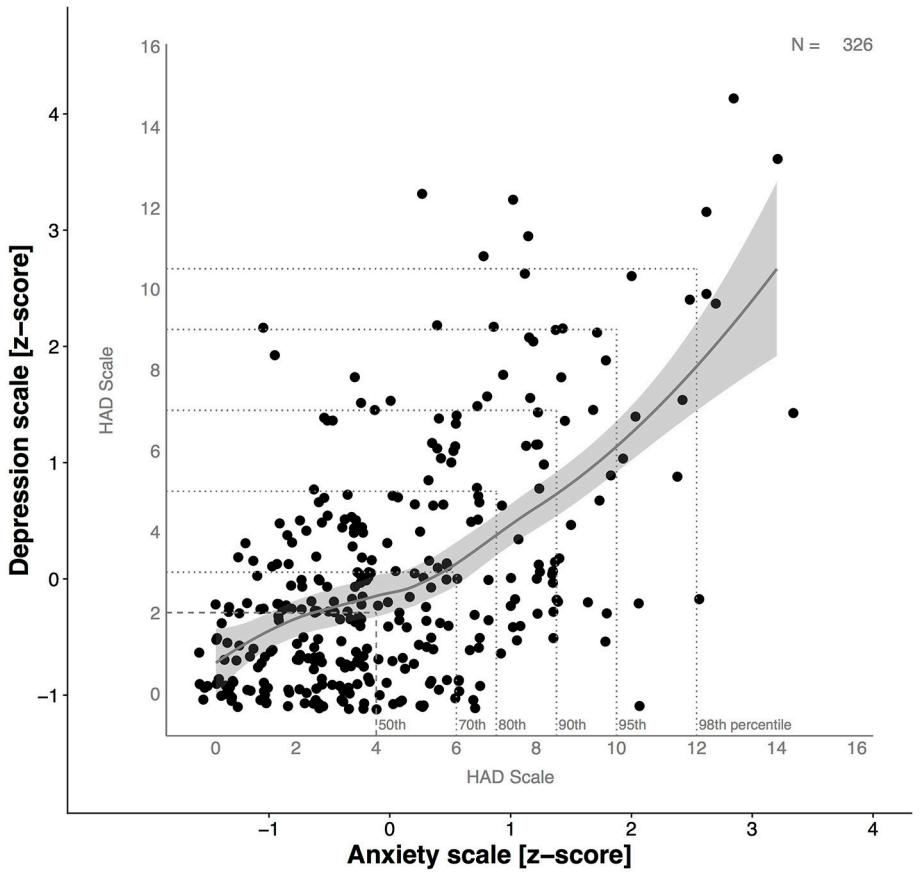


FIGURE 3 | Relationship between anxiety and depression and expression as Z-scores. Line of best fit with 95% CI as highlighted in gray. Z-scores above "0" indicate higher values on the HAD Scale-subscale compared to the sample mean. Z-score values below "0" indicate lower values on the HAD Scale-subscale compared to the sample mean. *Z*-values above +1.96 were considered as relevant for diagnostic purposes. Please note: the graphic shows a slightly greater increase in anxiety than depression.

depression scale where the 95th percentile is just above a Z-score of 2.

Combining the relationship of the percentiles with the scores for HADS-A and HADS-D and the distribution of the data, the Spearman rho correlation coefficient between anxiety and depression amounted to $r_s = 0.48$ ($p < 0.01$).

Severity of Symptoms of Anxiety and Depression in Young Athletes

When looking at the severity of symptoms of anxiety and depression, different methods can be used for categorization purposes. If original cut-off scores are applied, 43 (13.2%) and 11 (3.4%) of the young athletes are to be classified as doubtful cases and cases for anxiety, respectively. For depression, 18 (5.5%) and 7 (2.1%) young athletes can be classified as doubtful cases and cases, respectively (**Table 3**). However, when cut-off scores, as validated for the adolescent population are used, the classifications are slightly different. For HADS-A 23 (7.1%) and 10 (3.1%) young athletes can be categorized as possible and probable cases, respectively. In addition, on the depression scale 31 (9.5%) and 12 (3.7%) would be classified as possible and probable cases, respectively. Of these, 8 athletes showed subclinical values on both subscales and 6 athletes reported clinically relevant values for symptoms of anxiety and depression.

Age and Sex Differences Regarding the Severity of Symptoms of Anxiety and Depression in Young Athletes

Age: Overall, our findings revealed that by trend (Mann-Whitney-U Test, $p = 0.07$), late childhood athletes had a slightly lower mean anxiety score (4.2 ± 3.2) than late adolescent athletes (4.5 ± 2.8). The mean of HADS-D for both age groups were the same (**Table 2**) with no significant between-group differences (Mann-Whitney-U Test, $p = 0.55$). In addition, both HAD Scales showed a positive skewness with regards to late childhood (HADS-A:0.9; HADS-D:1.3) and late adolescents (HADS-A:0.6; HADS-D:1.4), with a shift of the distribution curve to the left. This is illustrated when examining the distribution of scores for anxiety and depression (**Figures 4**, **5**). For late childhood, 50% of all athletes had an anxiety score of 4 and a depression score of 2. Both distribution curves are similar, with a sharp increase in distribution and a smaller, steadier decrease (**Figures 4G**, **5G**).

TABLE 3 | Identified cases as well as percentage for anxiety (HADS-A) and depression (HADS-D) depending on cut-off levels as reported by the literature.

	Zigmond and Snaith, 1983			White et al., 1999		
HADS-D	**No case (0–7)**	**Doubtful case (8–10)**	**Case (11–21)**	**No case (0–6)**	**Possible case (7–9)**	**Probable case (10–21)**
12–14	164 (91.1%)	12 (6.7%)	4 (2.2%)	155 (86.1%)	17 (9.4%)	8 (4.4%)
15–18	137 (93.8%)	6 (4.1%)	3 (2.1%)	128 (87.7%)	14 (9.6%)	4 (2.7%)
Overall	301 (92.3%)	18 (5.5%)	7 (2.1%)	283 (86.8%)	31 (9.5%)	12 (3.7%)
HADS-A	**(0–7)**	**(8–10)**	**(11–21)**	**(0–8)**	**(9–11)**	**(12–21)**
12–14	149 (82.8%)	22 (12.8%)	8 (4.4%)	160 (88.9%)	12 (6.7%)	8 (4.4%)
15–18	123 (84.2%)	20 (13.7%)	3 (2.1%)	133 (91.1%)	10 (6.8%)	3 (2.1%)
Overall	272 (83.4%)	43 (13.2%)	11 (3.4%)	293 (89.9%)	23 (7.1%)	10 (3.1%)

Overall results and depending on age group (12–14: late childhood; 15–18: late adolescents).

Seventy percent of participants in the late childhood group had an anxiety score of 6 and a depression score of 3. At 90% of the distribution of all scores, HADS-A is at score 9 and HADS-D at score 7. Furthermore, 98% are within a score range of 12 for HADS-A and 11 for HADS-D. A similar frequency distribution is visible for athletes in the late adolescents group (**Figures 4H**, **5H**). Whilst percentiles and HAD Scale score are the same, the distribution frequency are slightly different. For example, at 50% HADS-D the density is above 0.2, whereas for HADS-A it is only slightly above 0.15. In addition, the density for 70% of the scores at score 3 HADS-D (0.15) is higher than 70% of distribution on the anxiety scale (<0.1). Similar frequencies between HADS-A and HADS-D are reached only at 90% of distribution for late adolescence group. In terms of cut-off values for severity of symptoms of anxiety and depression further information can be found in **Table 3**.

Sex: As illustrated in **Table 4**, female athletes showed a higher mean anxiety score but a lower mean depression score than male athletes. However, the Mann-Whitney-U Test indicated no significant differences between male and female athletes for the HADS-A ($p = 0.10$) and the HADS-D ($p = 0.46$). Regarding distribution, both HAD Scales were not normally distributed. HADS-A was positively skewed for males (0.9) and females (0.6) with a shift of the distribution curve to the left. HADS-D was also positively skewed for both genders (males:1.1; females: 1.7).

When looking at the density of the distribution of anxiety and depression for male and female athletes, differences in the frequency of scores are detectable (**Figures 4**, **5**). Male young athletes show a higher frequency (>0.15) of anxiety scores below or at 4 than female athletes (<0.15), which is equal to 50% for both genders (**Figures 4C,F**). Therefore, a larger proportion of male compared with female athletes are below the 50th percentile of all scores. The decline of frequencies above score 4 is greater in male than female athletes. This is illustrated by a greater density of scores for female athletes at the 70th, 80th, and 95th percentile, compared with male athletes (**Figure 4**). Regarding the depression scores, female athletes show a greater frequency (>0.2) of scores below or at 2 on the depression scale, which is equal to 50% of all scores for both genders (**Figures 5C,F**). The decline in frequency distribution is steeper in female athletes. This can be seen by the distribution of scores at the 80th percentile. However, whilst the scores for depression decrease steadily in male athletes, female athletes show a higher density (>0.05) at the 90th percentile and a lower density at the 98th percentile (**Figure 5**).

Overall, the lowest score for anxiety and depression was 0 for male and female athletes. The highest anxiety score was 14 for both male and female athletes, whereas the highest depression score was 12 for male and 15 for female athletes.

Regarding the severity of symptoms for anxiety and depression, more male athletes had subclinical scores for depression, whereas more female athletes showed subclinical scores for anxiety. In addition, female athletes had more clinical values for anxiety, whereas no statistically significant differences were found for depression, irrespective of the classification method (**Table 4**).

DISCUSSION

The aim of this cross-sectional study was to provide an overview of the general presence and severity of symptoms of anxiety and depression in young athletes as well as to examine potential age and sex differences. The first part of the discussion refers to the aspects of distribution of symptoms of anxiety and depression, their severity, and the observed age and sex differences. This is followed by an elaboration on future implications and limitations.

Distribution of Symptoms of Anxiety and Depression in Young Athletes

The distribution of anxiety and depression scores showed that 80% of young athletes are at or below an anxiety score of 7 and at or below a depression score of 5 on the HAD Scale. However, the remaining 20% showed anxiety and depression scores that are partially above subclinical and clinical relevant scores according to both Zigmond and Snaith (1983) and White et al. (1999). It has been argued that student athletes are at higher risk of developing anxiety and depression because of higher psychological, physical, and social demands compared to their non-athletic peers (Wylleman et al., 2004). Despite this, the overall anxiety and depression scores of the present study are lower compared to normative data reported for adolescents in Sweden, China, and Great Britain (White et al., 1999; Jörngården et al., 2006; Chan et al., 2010). In these studies, mean anxiety scores of up to 7.2 and mean depression scores of 5.4 were reported (White et al., 1999; Jörngården et al., 2006). However, these studies lack information on sport participation of the examined subjects. Furthermore, most of these studies

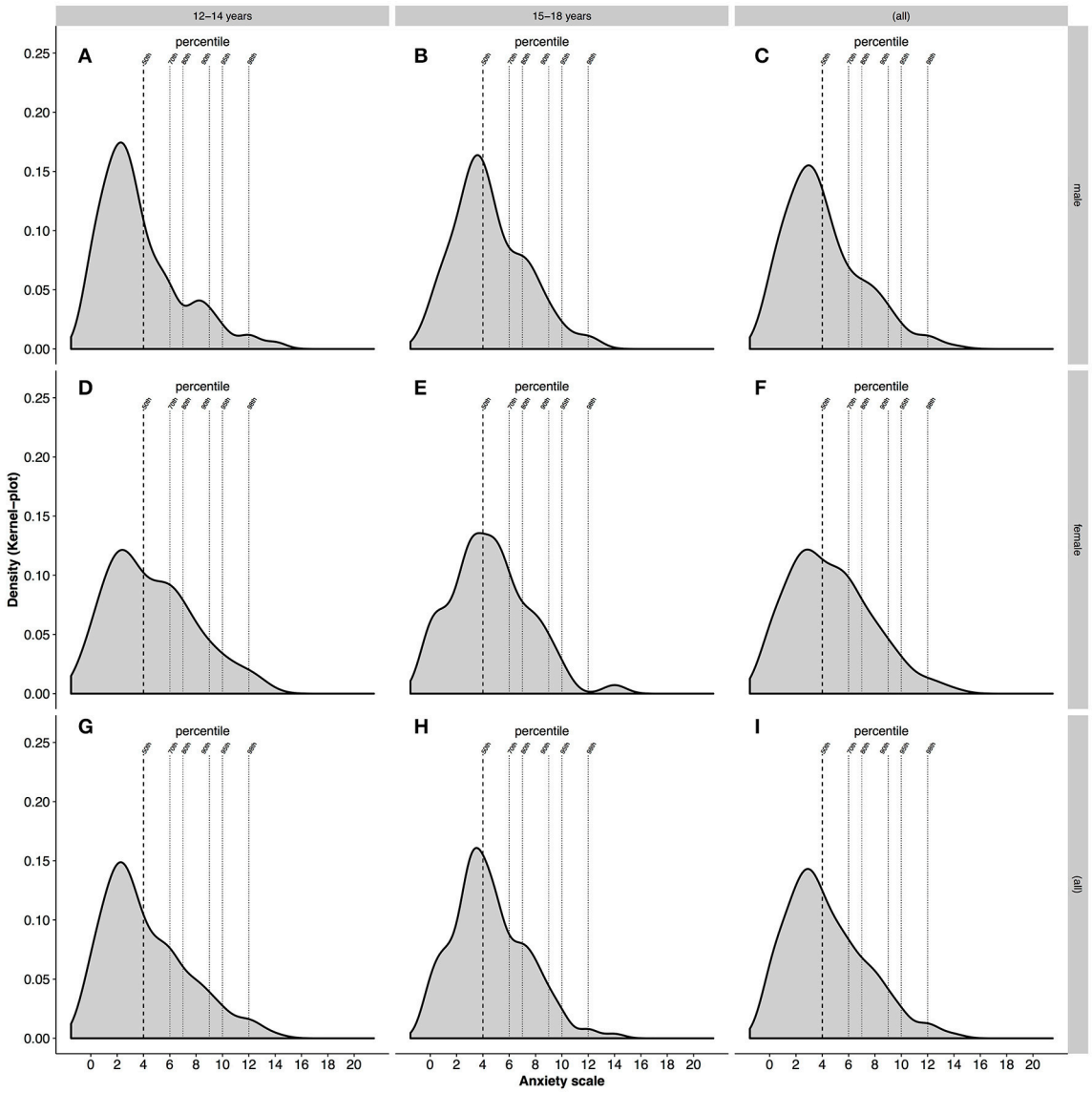


FIGURE 4 | Density of the distribution of anxiety. **(A–C)** Shows male athletes in late childhood, late adolescence and overall, respectively. **(D–F)** Shows female athletes in late childhood, late adolescents and overall, respectively. **(G,H)** Shows late childhood and late adolescents regardless of gender. **(I)** Shows the density of anxiety for all athletes.

did not report the frequencies of scores or how many possible or probable cases of anxiety or depression were found. The observed methodological inconsistencies between our study and the studies reported in the literature make it difficult to compare the study findings.

Compared to the existing literature, the present study demonstrated, that whilst mean anxiety or depression scores might seem low, there are participants that do report high scores on one or both subscales which is indicative for the need of individual analyses. In addition, there was a non-significant tendency toward higher anxiety than depression scores as seen by the z-score distribution. Longitudinal and cross-sectional studies found a positive relationship in the occurrence of anxiety and depression, in which it seems that anxiety precedes depression and the onset of depression is more likely in individuals with higher anxiety frequencies and is independent of age of the onset of anxiety (Beesdo et al., 2009). This could explain the shift toward higher anxiety than depression scores by individuals. However, this also indicates that young athletes with high anxiety scores are possibly at risk of developing depression as well.

At this point, we would like to suggest, that the use of percentiles in combination with the Z-score distribution might be another way of analyzing symptoms of anxiety and depression using the HAD Scale. Our findings clearly showed that the 95th percentile and the Z-score are equal on the anxiety scale (10). This again corresponds to the cut-off point for possible

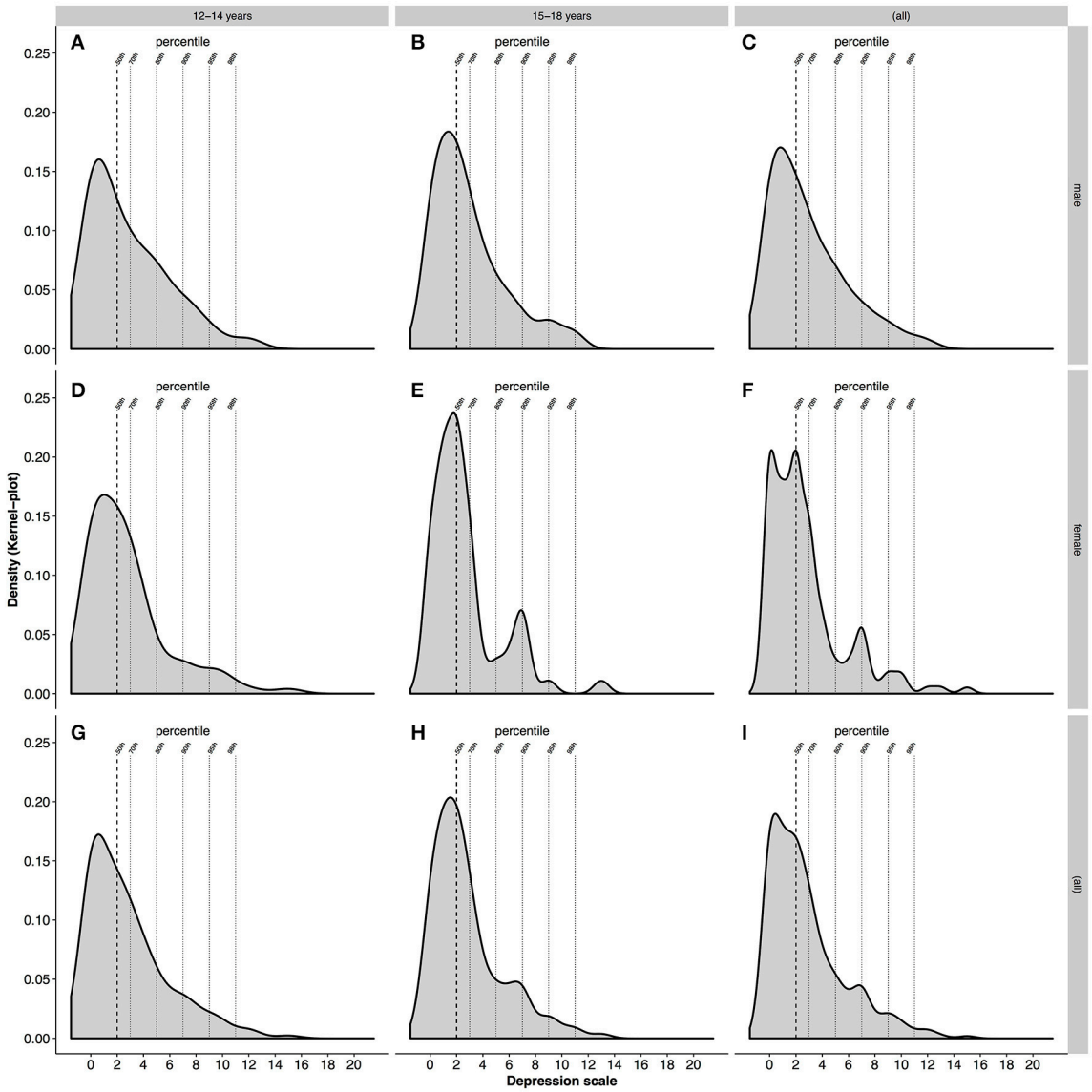


FIGURE 5 | Density of the distribution of depression. **(A–C)** Shows male athletes in late childhood, late adolescents and overall, respectively. **(D–F)** Shows female athletes in late childhood, late adolescents and overall, respectively. **(G,H)** Shows late childhood and late adolescents regardless of gender. **(I)** Shows the density of depression for all athletes.

cases (Zigmond and Snaith, 1983). In addition, **Figure 3** shows that Z-scores are well-suited to highlight and identify abnormal values.

Severity of Symptoms of Anxiety and Depression in Young Athletes

In the present study, subclinical and clinical scores of anxiety and depression in young athletes were detected. Previous research used different methodological approaches to examine severity for anxiety and depression. Both Zigmond and Snaith (1983) as well as White et al. (1999) validated the HAD Scale screening properties. Whilst the former tested it on an adult population, the later verified the validity for the use in adolescent populations. When comparing identified cases for the young athletic population more subclinical and clinically relevant cases for HADS-D were identified using White et al. (1999) cut-off values. However, for HADS-A less subclinical and clinically relevant cases were detected. White et al. (1999) used lower cut-off values for depression than for anxiety, arguing that lower cut-offs may minimize the risk of false negative diagnostics for depression and a higher cut-off for anxiety may minimize the risk of false positive diagnostics. This could by why higher cases for HADS-D and the lower cases for HADS-A of the present study.

Overall, the high frequencies and severities of anxiety and depression in adolescents might be explained by the transition phase "adolescents" which the athletes are confronted with

TABLE 4 | Identified cases as well as percentage for anxiety (HADS-A) and depression (HADS-D) depending on cut-off levels as reported by the literature and depending on sex.

	Zigmond and Snaith, 1983			White et al., 1999		
HADS-D	**No case (0–7)**	**Doubtful case (8–10)**	**Case (11–21)**	**No case (0–6)**	**Possible case (7–9)**	**Probable case (10–21)**
Male	156 (91.2%)	11 (6.4%)	4 (2.3%)	148 (86.5%)	17 (9.9%)	6 (3.5%)
Female	145 (93.5%)	7 (4.5%)	3 (1.9%)	135 (87.1%)	14 (9.0%)	6 (3.9%)
HADS-A	**(0–7)**	**(8–10)**	**(11–21)**	**(0–8)**	**(9–11)**	**(12–21)**
Male	146 (85.4%)	20 (11.7%)	5 (2.9%)	156 (91.2%)	10 (5.8%)	5 (2.9%)
Female	126 (81.3%)	23 (14.8%)	6 (3.9%)	137 (88.4%)	13 (8.4%)	5 (3.2%)

and go through. As mentioned previously, young athletes are faced with changes on various levels in their life. These may lead to an imbalance in their emotional homeostasis and therefore to the development of anxiety or depression (Spear, 2000). Regardless of this, we would like to emphasize that our analyses identified athletes with subclinically or clinically relevant symptoms in both HAD Scale subscales. It is recommended to monitor and accompany these athletes over a longer period of time to elucidate whether these symptoms are acute or chronic. As an effective means, relaxation or stress management techniques could be introduced (for example: https://medium.com/@kingsstudy/prevention-of-psychological-stress-in-youth-athletes-2c086bbf7640) to provide easy-to-administer but effective instruments for these athletes.

Age and Sex Differences Regarding the Severity of Symptoms of Anxiety and Depression in Young Athletes

In the present study, no significant differences were found between the age groups and symptoms of anxiety and depression. This is in contrast to previous research, that showed an increase in emotional distress between 13 and 15 years, 16 and 19 years, and 20 and 23 years (Jörngården et al., 2006). However, a possible explanation for this discrepancy in findings might be that anxiety and depression disorders tend to naturally grow and decline over time in a young age group (Beesdo et al., 2009). In addition, since this is a cross-sectional study, it can only give a momentary analytic view of symptoms of anxiety and depression. Only long-term analysis could confirm possible changes that occur during the different age phases of adolescents.

With regards to sex, no differences were found between anxiety and depression, although female adolescent athletes scored higher in both subscales of the HAD Scale. These findings are in contrast with previous research. Studies using the HAD Scale on the adolescent population found sex differences in the subscales anxiety and depression. White et al. (1999) reported significant higher anxiety and depression scores for female compared to male adolescents. Jörngården et al. (2006) observed higher anxiety scores for females but no sex differences in depression scores. Brand et al. (2013) reported that female adolescent athletes showed more frequently symptoms of anxiety and depression than their male peers. In addition, Chan et al. (2010) reported significantly higher anxiety scores for female compared to male adolescents but higher depression scores for male compared to female adolescents. This is of interest for results of the present study, although not significant, similar results were found. Female young athletes had higher mean anxiety scores, which was related to more subclinical and clinical cases. In contrast, male young athletes showed higher mean depression scores, which was accompanied by more subclinical cases than in female athletes. This implies a tendency toward sex differences, especially on a subclinical scale.

Potentially underlying reasons for the observed higher anxiety scores in females compared with males might be that male adolescents tend to be more confident, more open to contact with others (peers), and need less approval of others, whereas females tend to have higher levels of worry and lower levels of self-esteem (Byrne, 2000; Grossbard et al., 2009; Falgares et al., 2017). Of note, low self-esteem and self-blame have been found to be significant predictors of depressive and anxiety symptoms in adolescents (Garnefski et al., 2002).

Future Implications and Limitations

Future Implications

Anxiety can be defined as "a state of anticipatory apprehension over possible deleterious happenings" and "involves anticipatory affective arousal that is cognitively labeled as state of fright" (Bandura, 1988, p. 77). The process of arousal is affected by the balance between perceived coping capabilities and probable hurtful aspects of the environment (Bandura, 1988). Anxious states are accompanied by subjective distress and corresponding physiological changes in heart rate and catecholamine secretion (Bandura et al., 1985; Sanchez-Gonzalez et al., 2015). Risk factors for the development of anxiety are diverse and range from childhood abuse, neglect, or violence to low socio-economic status, female gender, and an intolerance to uncertainty (Stein and Sareen, 2015). In addition, persons with high levels of anxiety are at risk of developing depression and deliberate self-harm (Frances et al., 1992; Stein and Sareen, 2015).

Depression can be described as a state of having a negative view of the world, oneself and the future, as well as having a lack of interest with anhedonia and reduced energy (Willner et al., 2013; Belzug et al., 2015). There are various causes for the development of depression for instance early environmental factors such as lack of emotional contact with parents, traumatic experiences, or poor quality of parental care. All these may lead to low self-esteem and emotional instability (Willner et al., 2013).

In the present study, many of the described risk factors such as socio-economic status or parental relationship have not been explicitly investigated. Therefore, one cannot conclude that the high scores of anxiety and depression were caused by these risk factors, nor can one assume that the tight schedule of daily training, school, and competition are underlying causes.

It may be that a combination of different factors leads to high anxiety and depression scores in individual young athletes (Brettschneider, 1999; Merkel, 2013). Whilst the described risk factors are associated with the environment, a psychodynamic approach is concerned with interpersonal dynamics as well as life experiences that may lead to psychological maladaptation. This developmental approach deals with the process of self-definition and relatedness during adolescents and throughout life (Blatt and Luyten, 2009). Self-definition refers to the development of realistic, integrated and differentiated identity or sense of self. Relatedness comprises the ability of mature, intimate, reciprocal and mutually satisfactory interpersonal relationships. These two processes are equally important and work in a synergistic manner (Blatt and Luyten, 2009). Research shows that stability and quality of friendships during adolescents are positively related to the development of sense of self and lower levels of depressive symptoms (Kopala-Sibley et al., 2016). In addition, abnormal self-definition (self-criticism) and relatedness (dependency) are associated with anxiety and suicidality (Falgares et al., 2017). The feeling of self-criticism and dependency is accompanied by the feeling of hopelessness and affective temperament expression, which again is related to anxiety, depression and even suicidal behavior (Nkansah-Amankra et al., 2010; Iliceto et al., 2011).

What are the most relevant implications of the present study? How should legal representatives, coaches, and teachers act regarding the frequency of reported subclinical and clinically relevant scores?

Research shows that psychological problems often only mature in mid to late adolescents (Blatt and Luyten, 2009). Therefore, the high prevalence of subclinical and clinically relevant scores call for the need of intervention strategies that aid in the prevention of the development of psychological distress, as well as aid with already existing problems. Since environmental factors like parental relationship or socio-economic status cannot be controlled, one should focus on the teaching of coping strategies, self-efficacy, mindfulness, and stress reduction techniques to prevent the development of psychological symptoms and thereby teaching trust in one's self and one's ability to manage stressful situations. Research shows a reduction in anxiety and perceived stress through mindfulness, relaxation, and stress reducing techniques in the adolescent population (Foret et al., 2012). In addition, the implementation of coping strategies for adolescent athletes were found to increase self-efficacy (Reeves et al., 2011). Exercising self-efficacy can help reduce anxiety and increase optimism and hope for success (Bandura, 1988; Zagórska and Guszkowska, 2014).

Furthermore, research shows that young athletes might not be aware of the symptoms of psychological distress or where to seek help. In addition, young athletes are confronted with barriers that could stop them form help seeking. These include, worry about affecting ability to train, fearing what might happen, not knowing who to ask or lack of time (Gulliver et al., 2012). Therefore, it seems necessary to teach young athletes the awareness of psychological symptoms as well as introducing aforementioned techniques into the daily routine of young athletes (e.g., https://medium.com/@kingsstudy/prevention-of-psychological-stress-in-youth-athletes-2c086bbf7640). In addition, athletes should be given the possibility to seek help by a psychologist if needed.

Limitations

This study has various limitations that warrant discussion because they have not been considered or examined and may have therefore restricted the view on our results. There are several factors within the sporting context that might be related to the occurrences of symptoms of anxiety and depression such as injury status, playing position, and individual vs. team sport participation (Wolanin et al., 2015; Nixdorf et al., 2016; Prinz et al., 2016). Further, socio-economic status as well as parental care and relationship can affect the development of psychological symptoms (Beesdo et al., 2009; Willner et al., 2013; Stein and Sareen, 2015). In addition, the present study shows a cross-sectional view of the young athletes' population. However, the level of anxiety amongst adolescents tends to fluctuate over time (Beesdo et al., 2009). Therefore, identified cases may also fluctuate over time. Moreover, the HAD Scale relies on self-reported measurements, which are susceptible to bias. Research shows that prevalence rates of depression differ depending on the diagnostic instrument used. Whilst questionnaires can quantify severity and identify possible changes over time, structured clinical interviews are the gold standard for identifying clinical significance and potential treatment (Trask, 2004; Krebber et al., 2014). In addition, the HAD Scale investigates symptoms over the last 2 weeks, thereby limiting possible assessment of long-term psychological state of the young athlete. Therefore, further research should examine possible long-term changes of symptoms of anxiety and depression in adolescent athletes. Moreover, identified subclinical and clinical cases would have to be investigated further using structured clinical interviews.

CONCLUSION

To the best of our knowledge, this is the first study that examined distribution and prevalence rates of symptoms of anxiety and depression in young athletes with a focus on detecting clinically relevant findings. Our results show prevalence rates of up to 9.5% on a subclinical scale and up to 3.7% on a clinical scale. Moreover, we detected that some young athletes are at risk of developing symptoms of both anxiety and depression. However, our findings cannot be interpreted that there is a general risk in developing psychological disorders particularly in young athletes. The longitudinal and case based assessment of symptoms of anxiety and depression in young athletes might provide more information and insights over the long-term persistence and possible underlying causes of the symptoms.

AUTHOR CONTRIBUTIONS

CP, UG, and ML designed the experiment. ML and BG gathered data. SW, HG, and CP conducted data analysis. SW, CP, and HG wrote the manuscript. HG, CP, TS, and SW conducted graphical representation, K-JB and MH assisted with possible clinical psychological questions. All authors discussed the results

and its implications, commented and edited the manuscript at all stages, and approved the final version.

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