ADAPTATIONS TO ADVANCED RESISTANCE TRAINING STRATEGIES IN YOUTH AND ADULT ATHLETES

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ADAPTATIONS TO ADVANCED RESISTANCE TRAINING STRATEGIES IN YOUTH AND ADULT ATHLETES

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Table of Contents

EDITORIAL
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Editorial: Adaptations to Advanced Resistance Training Strategies in Youth and Adult Athletes

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Editorial on the Research Topic

Adaptations to Advanced Resistance Training Strategies in Youth and Adult Athletes

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"Resistance training" (RT), also termed "strength" or "weight training", has become one of the most popular types of exercise in recent times (Fleck and Kraemer, 2014). Specifically, RT refers to a specialized method of physical conditioning that involves the progressive use of a wide range of resistive loads, including body mass, and a variety of modalities such as machine-based training, free weight training, or plyometric training, to enhance physical fitness, sports-specific performance, and health (Faigenbaum and Myer, 2010; Fleck and Kraemer, 2014). There is abundant evidence on the effectiveness of RT programs on components of physical fitness (e.g., muscle strength, linear speed, change-of-direction speed), sports-specific performance (e.g., throwing/kicking velocity), and health (e.g., injury prevention) in young, as well as adult athletes (Faigenbaum et al., 2016; Lesinski et al., 2016; Moran et al., 2016; Lauersen et al., 2018; Chaabene et al., 2020; Saeterbakken et al., 2022). Accordingly, RT has been recommended as an important training type that should be integrated into all the stages of long-term athlete development to underpin optimal preparation in team and individual sports alike (Lloyd and Oliver, 2012; Granacher et al., 2016).

Of note, Rhea et al. (2003) demonstrated that training status is an important moderator variable in relation to RT-inducing adaptations with an apparent inverse relationship between training status and RT-related gains. In such cases, more advanced RT programs are necessary to provide sufficient training stimuli to maximise the chances of continued adaptation to this form of training (Kraemer and Ratamess, 2004; Schoenfeld et al., 2021). Advanced RT may constitute non-conventional RT methods and overload techniques such as superset training, whole-body/local vibration training, neuromuscular electrical stimulation training, complex training, and blood-flow restriction training (Krzysztofik et al., 2019; Schoenfeld et al., 2021). However, the effectiveness of these methods in improving physical fitness and sports-specific performance, as well as their underpinning mechanisms, are yet not fully described in youth and adult athletes. Therefore, this Research Topic in *Frontiers in Physiology* entitled "*Adaptations to Advanced Resistance Training Strategies in Youth and Adult Athletes*" aimed to gather knowledge on the effects (acute responses and/or chronic adaptations) of advanced RT on components of physical fitness, sports-specific performance and/or health, and their respective underlying mechanisms, on youth and adult athletes.

At the conclusion of this work, a total of fifty-one international authors from Africa, Asia, Australia, Europe, and South America, researching advanced RT strategies, contributed nine peer-reviewed articles to the Research Topic. In terms of article type, six original articles (cross-sectional, longitudinal), one systematic review with meta-analysis, one opinion article and one perspective article were included. A summary of the published works is displayed in **Table 1**.

TABLE 1 | Summary of all studies within the Research Topic including type of article, study design, athletes included, research objectives, and main findings.

References	Type of article	Study design	Athletes included	Research objective(s)	Main finding(s)
Aguilera-Castells et al.	Original research	Cross-sectional	Physically active individuals	To examine the effects of vibration during dynamic suspended exercise on muscle activity and perceived exertion	25 Hz vibration during the suspended supine bridge induced higher muscle activity and perceived exertion
Aloui et al.	Original research	RCT	Adolescent soccer players	To examine the effects of 8-week combined plyometric and short sprint training in youth soccer on physical fitness	Combined plyometric and short sprint training improved jump, linear sprint, change-of-direction, repeated sprint, and balance performances
Gentil et al.	Opinion	NA	NA	To discuss benefits and limitations of high-intensity multimodal training programs (e.g., CrossFit) in youth	When professionally supervised, high-intensity multimodal training can be an effective and safe means to improve fitness in youth.
Hamarsland et al.	Original research	RCT	Resistance-trained individuals	To compare the effects of volume-equated, 9-week resistance training frequency (2 vs. 4 x/wk) on gains in muscle strength and mass	Resistance training enhanced muscle strength and mass, irrespective from training frequency.
Mueller et al.	Original research	RCT	Adolescent athletes	To examine the effects of a 6-week trunk-specific sensorimotor vs. resistance training on trunk muscle strength and stability	Both training programs did not induce significant pre-post test changes in trunk muscle strength and stability.
Ramachandran et al.	Systematic review	Systematic literature review with meta-analysis	Healthy individuals	To systematically review and aggregate the effects of plyometric training on measures of balance	Plyometric training enhances static and dynamic balance, irrespective of participants' sex and age.
Sato et al.	Original research	RCT	Healthy university students	To compare the effects of 5 weeks of unilateral arm curl resistance training at different joint angles on elbow flexors strength and muscle thickness of the trained and non-trained arms	Unilateral arm curl resistance training at extended elbow joints induces greater muscle strength and thickness gains in the trained and untraining arm at extended elbow joint.
Schoeb et al.	Original research	Controlled trial	Youth alpine skiers	To introduce and evaluate the effects of a novel, 12-month injury prevention program on injury incidence	The injury prevention program reduced absolute injury rate and injury incidence rate.
Williams et al.	Perspective	Narrative review	NA	To explore the potential for parkour-based activities in the long-term athlete development of youth basketball players	Parkour could augment youth basketball players' movement skills and facilitate the transfer of conventional strength and conditioning forms to sport-specific skills

NA = not applicable; RCT = randomized controlled trial

In a cross-sectional study, Aguilera-Castells et al. examined the effects of vibrations, superimposed on to dynamic lower limb suspension exercises, on leg muscle activity in trained individuals. Men and women with approximately 4 years of suspension training experience performed suspended supine bridge and hamstring curl exercises with the legs attached to a suspension system. Vibrations at 25 and 40 Hz were applied during the suspension exercises whilst a 'no vibration' condition was also used. Higher muscle activity (i.e., gastrocnemius, semitendinosus) was observed during the suspended supine bridge exercise with superimposed vibrations. This was particularly apparent at 25 Hz when compared to the "no vibration" condition. It was concluded that the suspended supine bridge with superimposed vibration induced a higher stability requirement thus increasing the stabilizing role of the gastrocnemius and semitendinosus muscles.

In a randomized controlled trial, Hamarsland et al. studied the effects of RT frequency on measures of muscle strength and body composition in resistance-trained individuals. Participants conducted 9 weeks of progressive whole-body RT with a frequency of either two or four sessions per week but equal volume. Both training groups improved muscle strength and lean body mass to the same extent, irrespective of training frequency. Additionally, strength gains were more pronounced in less complex exercises than they were in more complex ones (i.e., hack squat over squat, chest press over bench press).

Williams et al. conducted a narrative review with the purpose of exploring the potential for parkour-based activities to be used as part of the long term athletic development of youth basketball players. It was argued that conventional training programs may insufficiently develop fundamental movement skills and the associated transfer to sports-specific tasks due to a narrow range of foundational movement and a lack of decision-making properties. Parkour was characterized by diverse and creative movements used to navigate through an exercise or an obstacle course. With reference to an ecological dynamics perspective, this may facilitate the development of fundamental movement skills and the transfer (i.e., "donation") of skills and abilities to other sports such as basketball. Complex training was suggested as a feasible training modality to be performed using parkour actions within the same training session as conventional RT exercises.

From a health-related perspective, Schoeb et al. investigated the effects of a novel injury prevention program in alpine skiing on the rate and incidence of injuries in young skiers. For a 12-month intervention period, young competitive alpine skiers in the intervention group performed an injury prevention program, specifically designed for the injury patterns observed in youth skiing (called $INSPA_{Int}$), in addition to their regular training. Skiers in the control group followed their regular training only. The $INSPA_{Int}$ program was designed as a 20 min home-based training session (with online/offline support) and focused on the strengthening of hamstring muscles (eccentric muscle actions), external hip rotators, and trunk muscles. The absolute rates of traumatic and overuse injuries were reduced by 33.5 and 30.1% respectively in the intervention compared with the control group. Moreover, the incidence rate of overuse injury was lowered by 40. 2% in the intervention group.

The nine articles in this Research Topic facilitated insight into the large field of RT and advanced strategies with the overarching goal being to detail sufficient training stimuli and to ensure ways to underpin further adaptation(s) in trained individuals. The scope of the advanced RT strategies ranged from variations in training determinants (i.e., training frequency), the inclusion of additional training tools (i.e., vibratory system) to conceptual frameworks in RT (i.e., Parkour, CrossFit). However, it must be highlighted that the conceptual frameworks are currently theory-driven and must therefore be validated as advanced RT strategies in future investigations. Moreover, only Aguilera-Castells et al. and Hamarsland et al. examined mechanistic measures of muscle activity and body composition, respectively, as study outcomes and this is an area that requires further attention in future original studies. Of note, RT-induced performance gains are frequently attributed to changes in muscle activity and/or muscle mass (Behm, 1995; Suchomel et al., 2018). Therefore, future research is still needed to understand the composition and subsequent effects of advanced RT programs, with particular emphasis on longitudinal studies which address both performance and mechanistic outcome measures.

AUTHOR CONTRIBUTIONS

OP, HC, JM, and AS wrote and edited the manuscript.

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ORIGINAL RESEARCH
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sEMG Activity in Superimposed Vibration on Suspended Supine Bridge and Hamstring Curl

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Traditionally in strength and conditioning environments, vibration has been transmitted using platforms, barbells, dumbbells, or cables but not suspension devices. This study aimed to examine the effects on the lower limb of applying superimposed vibration on a suspension device. Twenty-one physically active men and women performed supine bridge and hamstring curl exercises in three suspended conditions (non-vibration, vibration at 25 Hz, and vibration at 40 Hz). In each exercise condition, the perceived exertion scale for resistance exercise (OMNI-Res) was registered, and the electromyographic signal was assessed for gastrocnemius (medialis and lateralis), biceps femoris, semitendinosus, gluteus maximus, and rectus femoris. A linear mixed model indicated a significant fixed effect for vibration at 25 Hz and 40 Hz on muscle activity in suspended supine bridge ($p < 0.05$), but no effect for suspended hamstring curl ($p > 0.05$). Likewise, the Friedman test showed a significant main effect for vibration at 25 Hz and 40 Hz in suspended supine bridge ($p < 0.05$) but not for suspended hamstring curl ($p > 0.05$) on OMNI-Res. *Post hoc* analysis for suspended supine bridge with vibration at 25 Hz showed a significant activation increase in gastrocnemius lateralis ($p = 0.008$), gastrocnemius medialis ($p = 0.000$), semitendinosus ($p = 0.003$) activity, and for semitendinosus under 40 Hz condition ($p = 0.001$) compared to the non-vibration condition. Furthermore, OMNI-Res was significantly higher for the suspended supine bridge at 25 Hz ($p = 0.003$) and 40 Hz ($p = 0.000$) than for the non-vibration condition. Superimposed vibration at 25 Hz elicits a higher neuromuscular response during the suspended supine bridge, and the increase in vibration frequency also raises the OMNI-Res value.

Keywords: instability, vibration, lower limb, suspension training, electromyography

INTRODUCTION

Nowadays, strength and conditioning practices combine resistance exercises and other training methods such as eccentric overloads, unstable surfaces, and suspension devices for improving strength and power performance (Maté-Muñoz et al., 2014; Behm et al., 2015; Suchomel et al., 2019). Similarly, coaches and fitness enthusiasts have also used mechanical vibrations as an alternative or complement to strength and explosive training (Hammer et al., 2018). The effects of vibration training have been widely studied on neuromuscular performance (Alam et al., 2018), flexibility (Fowler et al., 2019), and balance control (Ritzmann et al., 2014; Sierra-Guzmán et al., 2018). This method transfers the vibratory stimulus on the muscle belly and tendon directly (local) or indirectly (e.g., vibrating platforms) to elicit the tonic vibration reflex (Cardinale and Bosco, 2003). Platforms are the most commonly used piece of equipment in sports training to transfer whole-body vibration (WBV) and modify the stimulus through the type of vibration (side-alternating vibration or synchronous vibration), frequency (in Hz), amplitude (peak to peak amplitude), position, and time of exposure (Cardinale and Wakeling, 2005; Issurin, 2005).

WBV has been combined with different training methods, and lower-body resistance exercises (bodyweight or extra loads) performed under static and dynamic conditions (Rittweger, 2010). Several studies have shown the positive effects of performing WBV squats or other exercises such as lunges or Bulgarian squats on muscle strength and jump ability (Rehn et al., 2006; Fort et al., 2012; Osawa et al., 2013). However, the effect of vibration training on dynamic exercises with heavy loads (squats) did not improve maximal strength and jump performance using WBV at 40 Hz (Rønnestad, 2004) or 50 Hz at < 1 mm of amplitude (Hammer et al., 2018). Contrarily, dynamic squat training (6 sets of 6 reps; with an individual optimal load) performed on a vibration platform (30 Hz at 4 mm of amplitude) combined with repeated sprint training (3 sets of 6 reps of 20 meters shuttle run with 180° change of direction) (Suarez-Arrones et al., 2014) or functional eccentric-overload exercises (8 exercises between 6 to 10 reps with an inertial load ranged from 0.27 $Kg{\cdot}m^{-2}$ to 0.11 $Kg{\cdot}m^{-2}$) (Tous-Fajardo et al., 2016) elicited higher performance than traditional resistance training (lunges, half-squats, and calf raises; 50–100% body mass) on sprint, change of direction, and jumping performance. Furthermore, blood flow restriction training combined with WBV resistance training (30 Hz and parallel squat with dynamic loading) improved critical power, overall capillary-to-fiber ratio, and total lean body mass in endurance-trained men (Mueller et al., 2014). Considering acute effects, Bush et al. (2015) reported a post-activation potentiation effect on knee extension torque after exposing healthy participants to a WBV dynamic squat with bodyweight resistance (30 Hz and 4 mm of amplitude). Additionally, Aguilera-Castells et al. (2019) showed that combined WBV (40 Hz) with a suspended device elicited higher muscle activity than the suspended condition for hip and thigh muscles in the dynamic lunge bodyweight resistance.

In the studies mentioned above, the WBV was provided with a vibration platform to assess the effects of combining vibration and resistance training on different neuromuscular performance variables such as maximal strength, mechanical power, jumping ability, or muscle activity. However, to transfer the vibratory stimulus to the upper body, several devices with superimposed vibration have been used in the past, such as dumbbells (Bosco et al., 1999; Cochrane and Hawke, 2007), bars (Poston et al., 2007; Mischi and Cardinale, 2009; Moras et al., 2010; Xu et al., 2013), and cables (Issurin and Tenenbaum, 1999; Issurin, 2010). Likewise, superimposed vibration has been used to study the training effects on the lower body. Thus, the addition of vibration (30 Hz at 2.5 mm of amplitude) had no effects during four weeks of dynamic calf-raise on a seated rig (75–90% 1RM) (Carson et al., 2010). However, superimposed vibration on a BOSU (35–40 Hz and 2 to 4 mm of amplitude) enhanced the reaction time of peroneus brevis, longus, and tibialis anterior in athletes with chronic ankle instability during six weeks of training (Sierra-Guzmán et al., 2017). Furthermore, surface electromyography (sEMG) has been used to evaluate the activity of different muscles during an exercise with superimposed vibration (Xu et al., 2015). Thus, Marín and Hazell (2014) found higher activation of the gastrocnemius medialis, vastus medialis, and multifidus during 60° knee flexion static half-squats with superimposed vibration on a BOSU (30 Hz and 50 Hz and 1 mm of amplitude) in comparison to the stable condition. To the best of our knowledge, there are only four devices with superimposed vibration allowing the lower body training. Two of these devices are similar to vibration platforms, consisting of a small platform to improve flexibility in gymnasts (Sands et al., 2006; Kinser et al., 2008) and a platform with a bi-engine that provides vibration on a leg press machine (Pujari et al., 2019). The other two devices are Vibrosphere (ProMedvi), a superimposed vibration wobble board (Cloak et al., 2013), and Vibalance (Viequipment), a platform that combines vibration with different degrees of instability even though neither of these devices superimposed vibration on suspension straps.

Although the squat and its variations are the most used resistance exercises in WBV, the most demanded actions in team sports are sprinting, jumping, and cutting, generating numerous lateral actions and unilateral movements that demand horizontal force production (Gonzalo-Skok et al., 2017). Hence, the use of functional equipment such as suspension straps allowing exercises in multiple planes (Bettendorf, 2010), the inclusion of exercises based on the force-vector theory such as the barbell hip thrust to improve horizontal force production (Loturco et al., 2018; Neto et al., 2019), and preventive training on the hamstrings muscle complex (Rey et al., 2017; Bourne et al., 2018a) are commonly used in strength and conditioning team-sport programs. In the last decade, injuries to the hamstrings complex have increased in different team sports, especially in soccer, with an injury rate ranging between 15 and 50% (Al Attar et al., 2017). To strengthen the hamstrings complex (biceps femoris, semitendinosus, and semimembranosus), different bilateral and unilateral exercises, such as the deadlift, supine bridge, leg curl, glute-ham raise, or Nordic Hamstring have been included in injury prevention programs (Bourne et al., 2017). Thus, the suspended supine bridge and the hamstring curl were selected in the current study because of their popularity in hamstrings preventive programs (Malliaropoulos et al., 2012; Youdas et al., 2015). On the one hand, the supine bridge is a bodyweight exercise demanding the posterior hip and thigh muscles as gluteus maximus and hamstrings (Jang et al., 2013; Kim and Park, 2016; Lehecka et al., 2017; Marín and Cochrane, 2021), and it is a recommended exercise for strengthening and prevent injuries in hamstrings and lower back muscles (Ekstrom et al., 2007). This exercise is considered a variation of the hip thrust, where back and feet are placed on the ground, thus increasing the difficulty by modifying the position of the feet on a bench or an unstable surface (i.e., suspension device) (Tobey and Mike, 2018). Conversely, the hamstring curl is considered an open kinetic chain knee dominant exercise (Malliaropoulos et al., 2015) that uses body weight as resistance and aims to develop the strength and endurance of the hamstring muscles (Dawes, 2017).

Accordingly, a vibratory system for suspension training has been designed to provide an indirect and superimposed vibration on the suspension device, allowing a wide range of exercises in different planes. Therefore, the main objective of the present study was to examine the effects of the vibration device on muscle activation in the dynamic suspended supine bridge and hamstring curl exercises. It was hypothesized that the superimposed vibration on the suspension device would obtain a superior muscle activation than the suspended condition without vibration in both exercises. Additionally, it was also hypothesized that the OMNI-Res perceived exertion scale for resistance exercise would be higher in the suspended condition with vibration than the condition without vibration in each of the two exercises.

MATERIALS AND METHODS

Participants

Twenty-one physically active participants males (n = 15, mean age = 23.3 ± 2.8 years, height = 1.8 ± 0.0 m, body mass = 77.8 ± 6.9 kg, body mass index = 24.1 ± 1.8 kg·m^{-2}, suspension training experience = 4.2 ± 1.5 years) and females (n = 6, mean age = 22.6 ± 1.0 years, height = 1.6 ± 0.0 m, body mass = 56.6 ± 2.9 kg, body mass index = 21.5 ± 1.7 kg·m^{-2}, suspension training experience = 3.8 ± 1.9 years) were voluntarily recruited to take part in the study. Participants experienced in suspension training for less than one year, not performing 30 min of physical activity at least three times a week, or having pain or injury related to cardiovascular, musculoskeletal, or neurological diseases were excluded from the study. Additionally, before the familiarization session, an informed consent form was provided and signed by all participants after receiving a detailed explanation, both in verbal and written form, of the experimental procedures, benefits, and risks of participating in the study. They also answered the Physical Activity Readiness Questionnaire (PAR-Q) to determine potential health risks associated with physical exercise (Warburton et al., 2011). Before the familiarization and test session, all participants were asked to refrain from high-intensity physical activity 24 h before the test session and avoid drinking, eating, or consuming stimulant substances (e.g., caffeine) 3–4 h before the test session. This study was approved by the Ethics and Research Committee Board in the Blanquerna Faculty of Psychology and Educational and Sport Sciences at Ramon Llull University in Barcelona, Spain, with reference number 1819005D. The requirements specified in the Declaration of Helsinki (revised in Fortaleza, Brazil, 2013) were complied with and implemented in all study protocols.

Experimental Design

A cross-sectional study design was carried out to determine the effect of a vibratory system for suspension training on muscle activation in different lower limb muscles. Participants performed supine bridge and hamstring curl exercises in three suspension conditions: (a) non-vibration, (b) vibration at 25 Hz, and (c) vibration at 40 Hz. In all the above-mentioned conditions, muscle activation of the rectus femoris, biceps femoris, semitendinosus, gluteus maximus, gastrocnemius medialis, and lateralis was assessed and compared using sEMG. Muscle activation was normalized and expressed as a percentage of maximum voluntary isometric contraction (% MVIC). In addition, the OMNI-Perceived Exertion Scale for Resistance Exercise (OMNI-Res) was recorded to compare perceived exertion in each exercise condition.

Procedures

A familiarization session was conducted one week in advance of the test session. In this session, participants performed two sets of five repetitions of each supine bridge and hamstring curl under suspended conditions (non-vibration, vibration at 25 Hz and 40 Hz), and the researchers collected anthropometric data such as age, height, and weight. The test session took place one week later in the morning at the same time as the familiarization session. The test session began with a standardized warm-up consisting of 10 min of cycle ergometer while maintaining a cadence of 100 W at 60 revolutions per minute, two sets of eight repetitions of a unilateral stiff-leg deadlift, two sets of five repetitions of Nordic hamstring assisted with an elastic band, and two sets of eight repetitions of unilateral straight knee bridge. Next, surface electrodes were placed on the dominant lower limb (Criswell and Cram, 2011), which was established subjectively by asking participants which leg they would use to kick a soccer ball (Meylan et al., 2009). Before performing the different supine bridge and hamstring curl conditions, maximal voluntary isometric contraction (MVIC) tests were performed on the rectus femoris, biceps femoris, semitendinosus, gluteus maximus, gastrocnemius medialis, and lateralis in order to obtain a baseline value and normalize the electromyographic signal (Halaki and Ginn, 2012). Afterward, participants performed the different supine bridge and hamstring curl conditions in a randomized order. For the suspended supine bridge exercise, the distance between the crista iliac and the cradle of the suspension device was standardized as 75% of the leg length, and the hip elevation was controlled with customized stoppers (similar to hurdles), starting the exercise with the lower back, arms, and hands in contact with the ground (**Figure 1**). For the suspended hamstring curl, the distance between the crista iliac and the device's cradles was also 75% of the leg length, and the starting position of the exercise was standardized by laying the lower back and gluteus on a foam surface with a height corresponding to 20% of the leg length. Participants were instructed to begin with a complete knee extension in this exercise, release the lower back and gluteus on the foam surface, keep their arms and hands flat on the floor, perform a knee flexion, and then return to the starting position (**Figure 2**). The participants were instructed

FIGURE 1 | Suspended supine bridge: upper **(A)** and lower **(B)** position.

to place their feet inside the suspension device cradles with plantar flexion and to hold this position during all the repetitions in both exercises.

From each dynamic condition of the exercise, participants performed five repetitions with a two-minute rest between attempts. The pace of each repetition was controlled with a metronome giving a rate of 60 beats per minute, and the range of movement was controlled with a positional encoder (WSB 16k-200; ASM Inc., Moosinning, DEU) by attaching the tether to the thigh or the cradle of the suspension device in the supine bridge and the hamstring curl, respectively.

The movement signal recorded by the positional encoder in each repetition of the exercises was used to determine the concentric and eccentric phases of the movement. The positional encoder signal was divided in two for each repetition, establishing that the concentric phase or the ascent phase for the suspended supine bridge ranged from the initial position to the maximum hip extension (highest position) and for the suspended hamstring curl from the initial position to the knee flexion (highest position). In both exercises, the eccentric phase ranged from the highest position to the initial position (lowest position). The positional encoder determined the beginning and the end of each repetition, thus establishing the range of motion in the same acquisition timeline of the BIOPAC MP-150 system (BIOPAC System, Inc., Goleta, CA, United States) sEMG signal. Those attempts that did not follow the proper technical execution indicated by the researchers were discarded and repeated, providing the two-minute rest between trials. A TRX Suspension Trainer (Fitness Anywhere, San Francisco, CA, United States) was used for both exercises, with the device anchored to the ceiling. The distance between the floor and the suspension device cradles was standardized as 30% of the leg length of each participant. A vibratory suspension training system was used under vibration conditions (25 Hz and 40 Hz) and fixed between the ceiling anchor point and the suspension device. The vibratory system provided vibration to the suspension device by converting the rotary motion of an electric motor into a vertical motion, which caused the displacement of a connecting rod with an amplitude of 8 mm (peak to peak), and the motor rotation frequency was regulated with a potentiometer.

Electromyography

The recording and analysis of sEMG of each muscle during each repetition under the suspended supine bridge and hamstring curl conditions (non-vibration, vibration at 25 Hz and 40 Hz) was performed with a six-channel BIOPAC MP-150 (sampling rate: 1.0 kHz) and AcqKnowledge 4.2 software (BIOPAC System, Inc., Goleta, CA, United States). Before placing the electrodes (Biopac EL504 disposable Ag-AgCl) over the rectus femoris, biceps femoris, semitendinosus, gluteus maximus, gastrocnemius medialis, and lateralis from the dominant leg, the skin area of the participants was prepared by shaving, exfoliating, and cleaning with alcohol to reduce impedance from dead surface tissues and oils. Following SENIAM recommendations (Hermens et al., 2000), the rectus femoris electrodes were placed at half the distance between the anterior superior iliac spine and

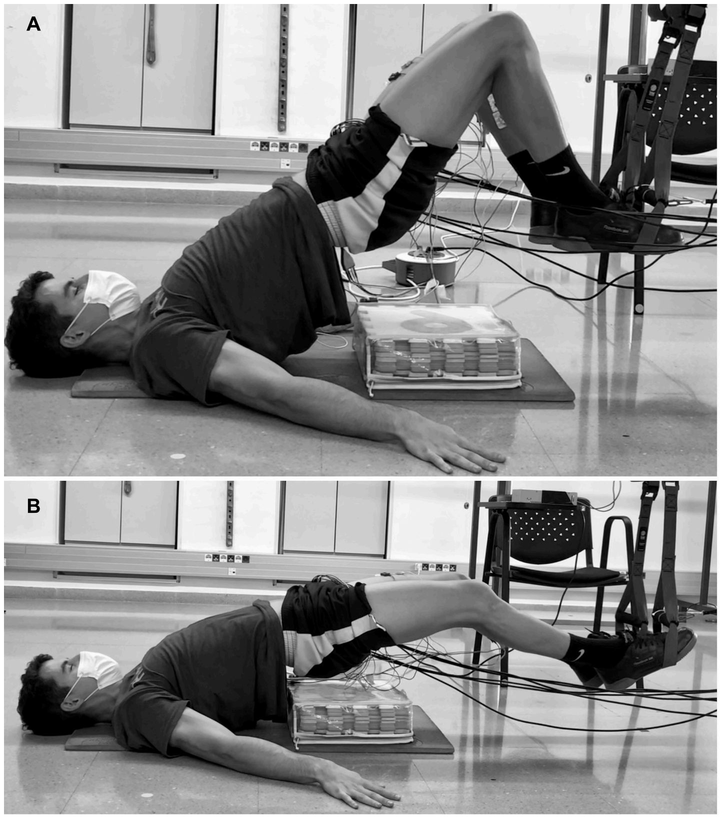

FIGURE 2 | Suspended hamstring curl: upper **(A)** and lower **(B)** position.

the superior part of the patella; for the biceps femoris and semitendinosus at half the distance between the ischial tuberosity and the lateral epicondyle (biceps femoris) or medial epicondyle (semitendinosus) of the tibia; the gluteus maximus at half the distance from the sacral vertebrae and the greater trochanter; for the gastrocnemius medialis over the most prominent bulge of the muscle, and in the gastrocnemius lateralis at 1/3 of the distance between the head of the fibula and the heel. All electrodes were placed at an inter-electrode distance of 2 cm and were oriented longitudinally to the direction of the muscle fibers. In addition, a reference electrode was placed on the crista iliac. The sEMG signal was bandpass filtered at 10–500 Hz using a 4th order 50 Hz Butterworth notch filter, and the root mean square (RMS) was calculated. In order to normalize the results of muscle activation of each of the muscles analyzed, MVIC tests were performed on the dominant leg with three MVIC of five seconds, recruiting gradually up to the maximum for two seconds and maintaining the MVIC for three seconds, with a three-minute rest between MVIC following Jakobsen et al.'s (2013) procedures. The position of each muscle used to achieve the MVIC was based on Konrad's (2006) protocol. Thus, the MVIC for the rectus femoris consisted of 90° seated single-leg knee extension; the MVIC for the biceps femoris and semitendinosus of 20–30° prone-lying single-leg knee flexion; the MVIC for the gluteus maximus in a supine-lying single hip extension; and the MVIC for the gastrocnemius medialis and lateralis in 90° seated ankle plantar flexion. All MVIC tests were against an immovable resistance; for the rectus femoris, biceps femoris, semitendinosus, and gluteus maximus, an ankle brace was used that was attached to a cable anchored to a stretcher. For the gastrocnemius medialis and lateralis, a horizontal leg press machine was used. The MVIC values obtained in each muscle mentioned above were used to normalize the RMS signal and report the muscle activation as % MVIC. For each exercise condition, the peak sEMG of each studied muscle during the concentric (ascending trajectory), and eccentric (descending trajectory) phase was analyzed, excluding the first and fifth repetition from the data analysis. Additionally, muscle activation levels recorded under the supine bridge and hamstring curl conditions were categorized as very high ($>$ 60% MVIC), high (41–60% MVIC, moderate (21–40% MVIC), and low ($<$ 21% MVIC) (Escamilla et al., 2010).

OMNI-Perceived Exertion Scale for Resistance Exercise

This scale was used to register the perceived subjective exertion experienced during the suspended supine bridge and hamstring curl conditions (non-vibration, vibration at 25 Hz and 40 Hz). Once participants completed an exercise condition, they were asked to assess their perception of exertion. Participants were instructed during the familiarization session to follow the instructions for the OMNI-Res assessment by Robertson et al.

(2003). During the familiarization and test session, a visual OMNI-Res scale was used, through which participants indicated the value of perceived exertion on a range from 0 to 10, where 0 indicated an extremely easy exertion (perception lower than that experienced during an unweighted repetition) and 10 an extremely hard exertion (perception higher than that experienced lifting 1 RM). The OMNI-Res values for each exercise condition were analyzed as mean OMNI-Res.

Statistical Analysis

Statistical data analyses were carried out using the SPSS statistical package version 26 (SPSS Inc., Chicago, IL, United States). G*Power (version 3.1.9.6; University of Dusseldorf, Dusseldorf, Germany) was used to calculate the sample size with power analysis and determined an effect size 0.29 SD with an α level of 0.05 and power at 0.95. All dependent variables showed a normal distribution, confirmed with the Shapiro-Wilk test, and met the inferential parametric assumptions, except the OMNI-Res. The global activity variable was calculated as the global mean of the six analyzed muscles. The effect of exercise condition on muscle activation (rectus femoris, biceps femoris, semitendinosus, gluteus maximus, gastrocnemius medialis and lateralis, and global activity) was assessed using a linear mixed model analysis considering the activation of each muscle as the dependent variable, the exercise condition as the fixed effect and the participants as a random effect. In case of a significant fixed effect, *post hoc* comparisons were made. Moreover, a non-parametric Friedman test was carried out to determine the effect of exercise conditions on the OMNI-Res. For significant main effects, a *post hoc* Wilcoxon test analysis with Bonferroni correction was applied. For pairwise comparison, Cohen's d effect size (Cohen, 1988) and 90% confidence intervals (CI) were also calculated. Effect size was interpreted as trivial ($d < 0.2$), small (d ranging from 0.2 to 0.6), moderate (d ranging from 0.6 to 1.2), large (d ranging from 1.2 to 2.0), and very large ($d > 2.0$) (Hopkins et al., 2009). Statistical significance was set at $p < 0.05$, and all data were expressed as mean ± standard error of the mean (SE).

RESULTS

The sEMG activity of each muscle and the global activity during the concentric and eccentric phase of the suspended supine bridge and the suspended hamstring curl under non-vibration, vibration at 25 Hz, and 40 Hz conditions are shown in **Tables 1**, **2**, respectively. Moreover, for the percentage of change of the analyzed muscles in the different suspended supine bridge and hamstring curl conditions, see **Supplementary Tables 1, 2**, respectively.

Suspended Supine Bridge

Supplementary Tables 3–5 shows the linear mixed model results. A significant fixed effect for exercise condition indicated that during the concentric phase, the suspended supine bridge with 25 Hz vibration showed a small increase with non-vibration condition for semitendinosus ($p = 0.003$, $d = 0.47$), gastrocnemius lateralis ($p = 0.008$, $d = 0.36$), and global activity ($p = 0.000$, $d = 0.60$). Moreover, the aforementioned conditions presented a moderate increase for gastrocnemius medialis (non-vibration vs 25 Hz vibration: $p = 0.000$, $d = 0.75$). The suspended supine bridge with 25 Hz vibration showed a small decrease with vibration at 40 Hz condition for gastrocnemius medialis ($p = 0.025$,

TABLE 1 | The sEMG activity for each analyzed muscle under suspended supine bridge conditions.

Exercise phase	Muscle group	Suspended supine bridge				
		Non-Vibration	Vibration at 25 Hz	Vibration at40 Hz		
		Mean ± SE	Mean ± SE	Mean ± SE	F	p
Concentric	Rectus femoris	1.7 ± 0.3	1.8 ± 0.4	2.0 ± 0.5	0.20	0.815
	Biceps femoris	19.1 ± 1.6	20.2 ± 1.6	19.6 ± 1.8	0.72	0.490
	Semitendinosus	19.7 ± 1.4	22.9 ± 1.5[a]	23.2 ± 1.7[a]	9.05	0.001
	Gluteus maximus	14.8 ± 1.7	16.1 ± 2.3	16.6 ± 2.2	1.79	0.178
	Gastrocnemius medialis	30.2 ± 2.0	37.4 ± 2.1[ab]	32.8 ± 1.8	9.71	0.000
	Gastrocnemius lateralis	36.5 ± 3.1	41.7 ± 3.1[a]	38.6 ± 3.1	5.19	0.010
	Global activity	20.3 ± 1.1	23.4 ± 1.0[a]	22.1 ± 1.1[a]	16.51	0.000
Eccentric	Rectus femoris	2.0 ± 0.3	1.9 ± 0.3	2.0 ± 0.3	0.25	0.780
	Biceps femoris	14.5 ± 1.3	16.5 ± 1.7	14.7 ± 1.4	3.11	0.055
	Semitendinosus	16.5 ± 1.3	18.1 ± 1.2[a]	18.3 ± 1.3[a]	4.73	0.014
	Gluteus maximus	8.6 ± 1.0	8.3 ± 0.8	8.6 ± 1.0	0.19	0.822
	Gastrocnemius medialis	24.4 ± 1.8	29.9 ± 1.9[a]	27.5 ± 1.9	8.91	0.001
	Gastrocnemius lateralis	37.6 ± 3.2	39.0 ± 2.9	36.4 ± 2.8	1.24	0.198
	Global activity	17.3 ± 0.9	18.9 ± 0.9[a]	17.9 ± 0.9	7.39	0.002

Data presented as normalized muscle activity (%MVIC); SE, standard error of the mean; Global activity, mean of the six muscles; [a]significantly different with non-vibration condition; [b]significantly different with vibration at 40 Hz condition.

TABLE 2 | The sEMG activity for each analyzed muscle under suspended hamstring curl conditions.

		Suspended hamstring curl				
Exercise phase	**Muscle group**	**Non-Vibration**	**Vibration at 25 Hz**	**Vibration at 40 Hz**	**F**	***p***
		Mean ± SE	**Mean ± SE**	**Mean ± SE**		
Concentric	Rectus femoris	1.3 ± 0.1	1.4 ± 0.1	1.2 ± 0.1	1.13	0.330
	Biceps femoris	23.6 ± 1.4	23.7 ± 1.3	24.0 ± 1.6	0.04	0.955
	Semitendinosus	24.9 ± 1.7	26.2 ± 1.6	25.8 ± 1.7	0.72	0.490
	Gluteus maximus	12.7 ± 1.1	13.1 ± 1.4	12.9 ± 1.1	0.16	0.848
	Gastrocnemius medialis	37.0 ± 3.0	37.6 ± 2.0	40.8 ± 3.4	1.61	0.210
	Gastrocnemius lateralis	52.8 ± 3.7	57.5 ± 3.8	56.2 ± 3.9	1.88	0.165
	Global activity	25.4 ± 1.1	26.5 ± 1.0	26.8 ± 1.2	2.60	0.086
Eccentric	Rectus femoris	1.4 ± 0.2	1.5 ± 0.2	1.8 ± 0.3	1.14	0.329
	Biceps femoris	22.0 ± 1.4	24.5 ± 1.7	22.6 ± 1.6	1.61	0.211
	Semitendinosus	20.6 ± 1.1	22.9 ± 1.5	22.5 ± 1.9	2.01	0.146
	Gluteus maximus	10.0 ± 0.8	11.7 ± 1.1	11.4 ± 1.0	3.48	0.060
	Gastrocnemius medialis	36.3 ± 2.1	37.0 ± 2.2	37.1 ± 2.2	0.17	0.838
	Gastrocnemius lateralis	51.5 ± 3.7	50.8 ± 3.6	51.2 ± 4.4	0.06	0.940
	Global activity	23.6 ± 0.9	24.7 ± 1.0	24.4 ± 1.1	1.85	0.169

Data presented as normalized muscle activity (%MVIC); SE, standard error of the mean; Global activity, mean of the six muscles.

d = −0.50). The semitendinosus and global activity showed a small increase between suspended supine bridge with 40 Hz vibration and non-vibration (p = 0.001, d = 0.46; p = 0.005, d = 0.34, respectively). For eccentric phase, the suspended supine bridge with 25 Hz vibration showed a small increase with non-vibration condition for semitendinosus (p = 0.046, d = 0.28) and global activity (p = 0.001, d = 0.40) and a moderate increase for gastrocnemius medialis (p = 0.000, d = 0.63). Additionally, the suspended supine bridge with 40 Hz vibration presented a small increase with non-vibration condition for semitendinosus (p = 0.024, d = 0.29). The standardized differences, expressed as Cohen d effect size, between exercise condition and muscle activity are shown detailed in **Figure 3**.

Suspended Hamstring Curl

The linear mixed model results are shown in **Supplementary Tables 6–8**. A non-significant fixed effect for exercise condition during the concentric phase neither eccentric phase was found on the analyzed muscles (**Table 2**). Additionally, the effect size analysis is shown in **Figure 4**.

OMNI-Perceived Exertion Scale for Resistance Exercise

Friedman test showed a significant main effect for suspended supine bridge [X^2 (2) = 26.462, p = 0.000] but not for suspended hamstring curl [X^2 (2) = 6.333, p = 0.052] on the OMNI-Res. Pairwise comparison showed a significantly higher OMNI-Res for suspended supine bridge with vibration at 40 Hz (4.86 ± 0.37) than for vibration at 25 Hz (4.33 ± 0.35, p = 0.024, d = 0.32 CI = −0.19, 0.83) and non-vibration condition (3.67 ± 0.40, p = 0.000, d = 0.67 CI = 0.15, 1.19). Moreover, OMNI-Res was significantly higher for suspended supine bridge with vibration at 25 Hz than for non-vibration condition (p = 0.003, d = 0.38 CI = −0.13, 0.89) (**Figure 5**). **Supplementary Table 9** shows the percentage of change for the OMNI-Res under suspended supine bridge and suspended hamstring curl conditions.

DISCUSSION

Superimposed vibration in a suspension device increased lower limb muscle activity in the supine bridge but not in the hamstring curl exercise. In the suspended supine bridge, a significant moderate increase of 14.8% (concentric phase) and a small increase of 9.7% (eccentric phase) was found under the 25 Hz vibration condition compared to the non-vibration global activity. Likewise, 40 Hz vibration significantly increased global activation by 8.7% (a small increase) during the concentric phase. Similarly, Marín and Hazell (2014) applied superimposed 30 Hz vibration on an unstable surface (BOSU) and found a higher muscle activity between 23.5% and 35% in the isometric half-squat compared to the unstable condition. The effect of additional vibration (30 Hz and 40 Hz with an amplitude of 4 mm) on unstable surfaces and suspension devices increased the demands of the exercise. Thus, eliciting a greater activation of the lower limb muscles (vastus medialis and lateralis, biceps femoris, and gluteus medius) during the suspended lunge combined with 40 Hz WBV than in unstable or suspended exercises without vibration (Aguilera-Castells et al., 2019). Understanding what exercises generate more muscle activation and under what conditions they do so is essential for practitioners. Previous scientific research reveals that different tasks involving the same muscle groups can present significantly different activation levels (Malliaropoulos et al., 2015); these findings are relevant in injury prevention and rehabilitation.

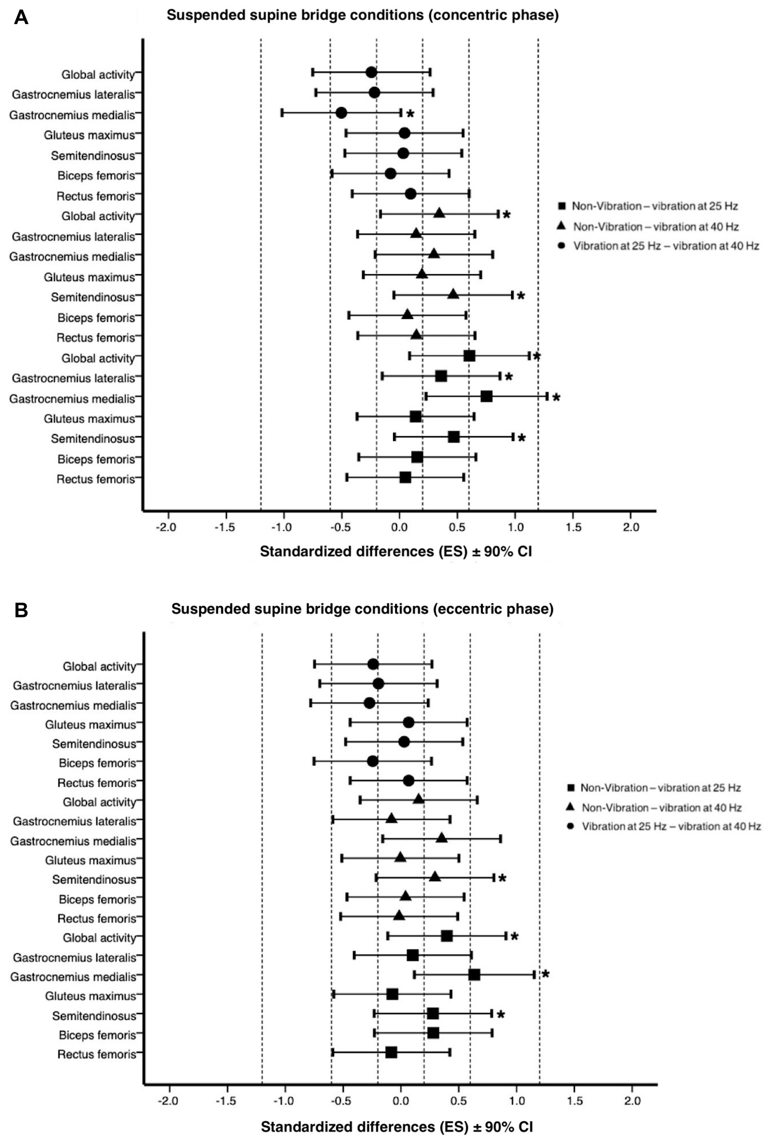

FIGURE 3 | Effects of suspended supine bridge conditions on muscle activity (%MVIC) at concentric **(A)** and eccentric phase **(B)** expressed as standardized differences (Cohen's *d*) ± 90% CI. Dotted line represents the effect size thresholds. * Significant differences at $p < 0.05$. ES, effect size; CI, confidence interval.

The effect of two different frequencies was studied in the present study, finding a small to moderate significant increase in semitendinosus, gastrocnemius medialis, and lateralis activation under 25 Hz vibration compared to the non-vibration condition. Likewise, there was a significantly small decrease in the gastrocnemius medialis activity at 40 Hz (**Figure 3**). Furthermore, no significant differences were found among frequencies for the other analyzed muscles. Overall, this study showed that performing the 25 Hz suspended supine bridge elicits a greater activation than at 40 Hz vibration in almost all the analyzed muscles. In the same vein, a progressive increase in vibration frequency (5 Hz to 30 Hz) gradually enhanced the neuromuscular response for the lower limb muscles (soleus, gastrocnemius, tibialis anterior, biceps femoris, vastus medialis, and rectus femoris), achieving the highest activations at 25 to 30 Hz frequencies (Ritzmann et al., 2013). On the other hand, 25 Hz vibration was consistently more demanding than 40 Hz vibration [concentric phase: biceps femoris (−3.0%, trivial), gastrocnemius medialis (−12.2%, small decrease), gastrocnemius lateralis (−7.4%, small decrease), global activity (−5.2%, small decrease); eccentric phase: biceps femoris (−10. 5%, small decrease), gastrocnemius medialis: (−8.0%, small decrease), gastrocnemius lateralis (−6.6%, trivial), global activity (−5.4%, small decrease)], per Cardinale and Lim (2003), who found lower but not significant muscle activity of 40 Hz vibration compared to 30 Hz. Regarding the effect of the different frequencies on the analyzed muscles, higher activation was found for the more proximal muscles exposed to the vibration. The

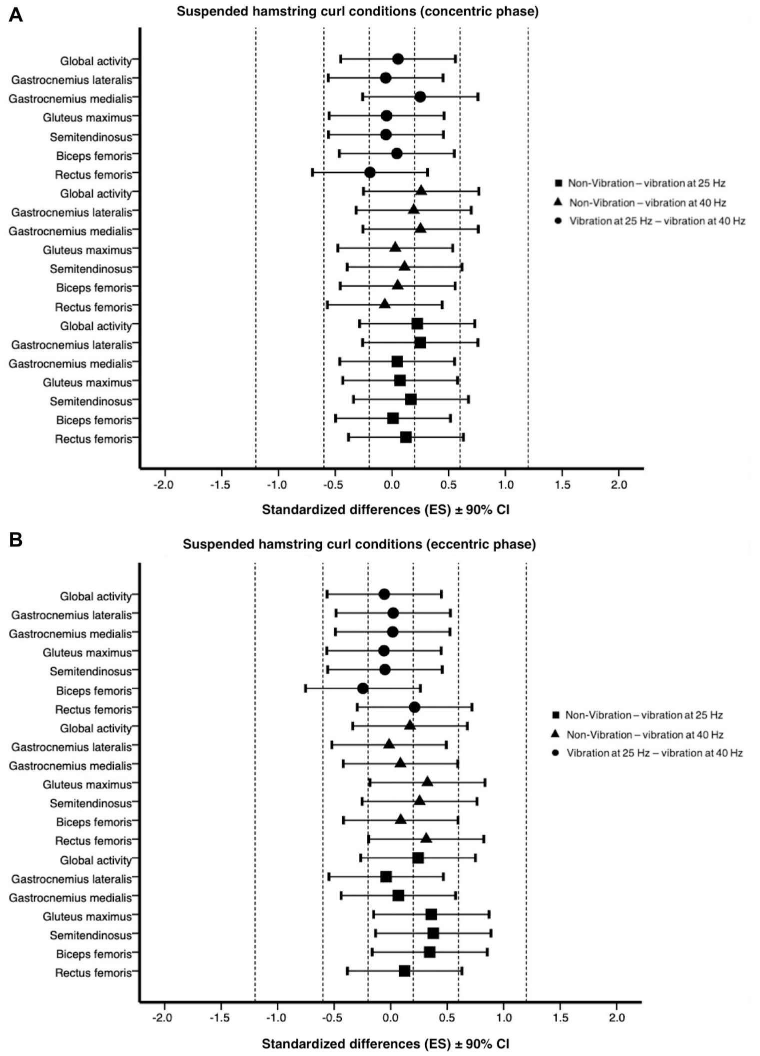

FIGURE 4 | Effects of suspended hamstring curl conditions on muscle activity (%MVIC) at concentric **(A)** and eccentric phase **(B)** expressed as standardized differences (Cohen's *d*) ± 90% CI. Dotted line represents the effect size thresholds. ES, effect size; CI, confidence interval.

additional effect of vibration at 25 Hz compared to the non-vibration suspended condition was significantly higher for the gastrocnemius (medialis and lateralis) and semitendinosus in the concentric and eccentric phase (from 9.8% to 23.8% with trivial to moderate effect). Previous studies also demonstrated that the more proximal to the vibration experimented higher activities than the more distal muscles (Hazell et al., 2010; Ritzmann et al., 2013). In this regard, the present study showed that in both vibration conditions (25 Hz and 40 Hz), the muscle excitation sequence (Neto et al., 2019), from higher to lower activation, was gastrocnemius lateralis, gastrocnemius medialis, semitendinosus, biceps femoris, gluteus maximus, and rectus femoris (**Table 1**). Thus, the magnitude of the neuromuscular response to the vibratory stimulus in those muscles that are closer to the most proximal joints (ankles) dissipates the effects of vibration for the more distal muscles, acting as a damper (Abercromby et al., 2007b). Indeed, the vibration induces different reflexes that favor increased muscle activation on the most proximal muscles, such as the tonic vibration reflex (Issurin, 2005; Ritzmann et al., 2010) or the stretch reflex on the soft tissues (Cardinale and Lim, 2003; Cochrane et al., 2009).

Of all analyzed muscles, gastrocnemius lateralis (41–60% MVIC) achieved a high activation under 25 Hz vibration and slightly lower (37.4% MVIC) for gastrocnemius medialis. Participants were asked to perform an ankle plantar flexion on the strap cradles instead of leaning their heels on the suspension cradles in the suspended supine bridge. Ritzmann et al. (2013) found that the variation of the foot position on the vibration platform increased the gastrocnemius medialis activity up to 48% (forefoot stance vs. normal stance). Although the feet remained in plantar flexion in the three suspended supine bridge conditions in the current study, the percentage of gastrocnemius activity significantly increased (14–23%, from small to moderate increase) under 25 Hz vibration to the non-vibration condition.

The lack of differences between the 40 Hz vibration and the non-vibration suspended condition could be explained because gastrocnemius is more predominantly activated at frequencies below 40 Hz (20, 25, and 30 Hz) (Di Giminiani et al., 2013), according to the findings of the present study (**Table 1**).

The hamstrings (biceps femoris and semitendinosus) muscle activity ranged from moderate to low (< 24% MVIC), with significant differences in semitendinosus activity at 25 Hz and 40 Hz in comparison to the non-vibration condition. However, following Abercromby et al. (2007a), the biceps femoris activity was slightly lower, with similar activation in all conditions. This low activation (< 21% MVIC) of the biceps femoris is related to 90° knee flexion in the suspended supine bridge. Ho et al. (2020) found a similar low activation (18% MVIC) of the biceps femoris in the dynamic supine bridge (90° knee flexion). However, the effect of WBV in the static supine bridge, maintaining the 90° of knee flexion, elicited a significant moderate activation (21–40% MVIC) of the biceps femoris at 30 Hz and 50 Hz, although the non-vibration condition also showed a moderate level of activation (27% MVIC). The authors supported that 50 Hz vibration was more demanding for the biceps femoris in the static supine bridge (Marín and Cochrane, 2021). Similarly, Hazell et al. (2007) found an increase in biceps femoris activation between 35 Hz and 45 Hz for dynamic and static squats. This suggested that superimposed vibration (25 Hz and 40 Hz) in the dynamic suspended supine bridge is insufficient to significantly stimulate the biceps femoris compared to the non-vibration condition significantly. Thus, an increased frequency of superimposed vibration on the suspension straps (> 40 Hz) and performing the exercise unilaterally, single-leg suspended supine bridge, could increase the demand of the biceps femoris to high activations (> 41% MVIC), as indicated by previous studies on sEMG on the single-leg supine bridge on the floor (Lehecka et al., 2017), or on a BOSU (Youdas et al., 2015). In this vein, the functional magnetic resonance imaging study conducted by Bourne et al. (2018b) found a predominant activation of the biceps femoris long head. Likewise, there could be several reasons for the small differences between the biceps femoris and semitendinosus in the suspended supine bridge. One reason is that the suspended exercise produces lateral instability, provoking a lateral rotation of the thighs and, consequently, an increased semitendinosus activity because of its role in counteracting this movement (Tobey and Mike, 2018). Furthermore, the amplitude of the vibrating machine (8mm, peak to peak) is suggested to provoke more horizontal oscillations and focus on the stabilizing structures that, in the present study, are stabilized by the semitendinosus (Cook et al., 2011). Another reason is that the necessity to keep the feet stable and maintain the anchor in a plumb line (perpendicular to the ground) of the suspension strap requires the participation of the posterior thigh muscles, similar to the feet-away hip thrust (Collazo García et al., 2020). This semi-stretched position provokes an increase in muscle tension and enhances the effects of the vibration in the hamstrings muscles (Cardinale and Lim, 2003; Marín and Cochrane, 2021). Overall, as a practical application, muscles with activations below 45% MVIC, such as biceps femoris and semitendinosus in suspended supine bridge conditions (non-vibration, 25 Hz and 40 Hz vibrations), would be targeted for muscular endurance, stabilization, and rehabilitation training programs (Ekstrom et al., 2007; Youdas et al., 2015).

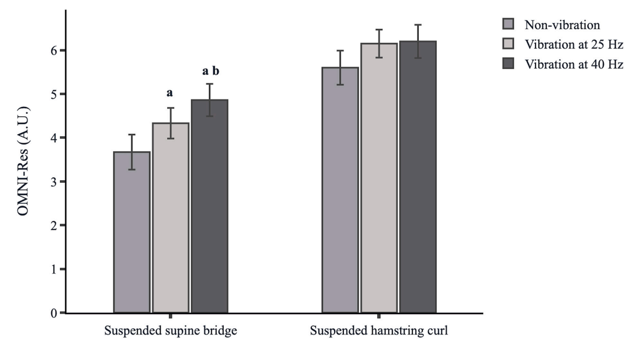

FIGURE 5 | OMNI-Res (mean ± SE) for suspended supine bridge and suspended hamstring curl under non-vibration, vibration at 25 Hz and vibration at 40 Hz conditions. Each bar represents the mean, and the error bar represent the standard error of the mean (SE). A.U., Arbitrary units; [a]significantly different with non-vibration condition; [b]significantly different with vibration at 25 Hz condition.

Although the barbell hip thrust is a very demanding exercise for gluteus maximus (> 60% MVIC) (Neto et al., 2019), the variation of suspended (and unloaded) exercise proposed in this study elicited low activation (< 23% MVIC) with a trivial and small effect among conditions (**Figure 3**). In this vein, previous studies have reported activation levels ranging from moderate to low (< 25% MVIC) for gluteus maximus in unloaded supine bridge on the floor (Ekstrom et al., 2007; Jang et al., 2013; Kim and Park, 2016). Thus, it appears that the suspended supine bridge (with an additional effect of vibration) is as demanding for the gluteus maximus as the traditional supine bridge exercise and are not sufficiently challenged to reach high and very high activation values (> 40% MVIC) in the gluteus maximus, as happens with the single-leg bridge (Ekstrom et al., 2007; Lehecka et al., 2017), the WBV supine bridge (Marín and Cochrane, 2021) or the barbell hip thrust (Contreras et al., 2016; Andersen et al., 2018; Williams et al., 2021). Therefore, although the gluteus maximus is the prime supine bridge mover, its activation is still low. Moreover, superimposed vibrations were dampened by the more proximal to vibration musculature, and the gluteus maximus were not overstimulated. In addition, the rectus femoris showed the lowest activation (< 2.0% MVIC) with a trivial effect in both phases of exercise without significant differences among conditions. Collazo García et al. (2020) showed a significantly (2.4%) lower rectus femoris activation in the feet-away barbell hip thrust (3.4% MVIC) compared to the original hip thrust condition (5.8% MVIC). Likewise, Lehecka et al. (2017) found similar rectus femoris activity in the unloaded single-leg bridge with 90° of knee flexion, agreeing with the present study results.

Conversely, as hypothesized, the additional effect of the superimposed vibration did not result in a significantly higher activation in any of the analyzed muscles, or the global activity, during the concentric and eccentric phases of the suspended hamstring curl (**Table 2**). Moreover, differences among exercise conditions ranged from trivial to small (**Figure 4**). Even though the muscle excitation sequence was similar to the suspended supine bridge. Thus, the activation increments of the most proximal muscles to the vibratory stimulus (gastrocnemius medialis and lateralis) were between 9% and 5% ranged from trivial to small increase in 25 Hz and 40 Hz vibration, respectively, to the non-vibration condition. The main difference in transmitting the vibration between the suspended supine bridge and the suspended hamstring curl was the suspension strap position. The straps remained in a plumb line in the supine bridge, whereas it acted as a pendulum in the suspended hamstring curl. Several studies suggested that vibration transmission via cable in pulley exercises such as biceps curl or one arm pulleying keep the perpendicular between the anchor point, vibration device, and handle to enhance the effects of local vibration (Bosco et al., 1999; Issurin and Tenenbaum, 1999; Issurin et al., 2012). Nevertheless, the pendulum motion in the suspended hamstring curl could attenuate vibration transmission because the vibratory system is designed to transmit the vibration. Moreover, it could be speculated that the pendulum motion could also exert a dampening effect by inhibiting the tonic vibratory reflex (Rittweger, 2010). On the other hand, the pendulum motion and plantar flexion to keep the feet on the cradles could explain the gastrocnemius activity in the suspended hamstring curl conditions. Additionally, Bettendorf (2010) suggested that the intensity variation in a suspended exercise is based on three fundamental principles. Thus, the pendulum principle could justify that the prime mover activations (biceps femoris and semitendinosus) in this study were slightly higher than low activations ($< 21\%$ MVIC) reported by Árnason et al. (2014) in the suspended hamstring curl without pendulum movement and lower than high and very high activations ($> 50\%$ MVIC) registered by Malliaropoulos et al. (2015) in the suspended hamstring curl with alternating knee flexion and pendulum motion.

Regarding OMNI-Res, the finding was that superimposed vibration increased the value of subjective perception of exertion compared to the non-vibration suspended condition around 10% (small increase) for both vibration frequencies in the suspended hamstring curl and from 18% to 32% (small to moderate increase) for the suspended supine bridge. Thus, it seems that the value of OMNI-Res increases progressively while increasing the vibration frequency, being consistent with the significant correlation ($r = 0.95$) between OMNI-Res and a range of vibration frequency (25 Hz to 45 Hz) and amplitudes (1 and 3 mm) found by Marín et al. (2011). Additionally, the validity and reliability of the intensity of exertion using subjective scales in exercises with superimposed vibration have been demonstrated for both vibration frequency and muscle activation (Marín et al., 2012).

There were some limitations in the study. The effect of superimposed vibration on suspended exercises has been assessed in physically active men and women, so the results obtained in the present study cannot be generalized to other populations. The footwear soles were different among participants, and since this area is the most exposed to vibration, this could slightly modify the vibratory stimulus due to the damping effect of the footwear soles. Therefore, future research should standardize the footwear for all participants. Likewise, the vibration transmitted through the suspension strap could have dissipated the vibration effect. While the distance between the suspension strap and the ground was standardized, it could be interesting to examine different suspension strap heights and their effects on muscle demand in the supine bridge in future studies. Another limitation was that the erector spinae and vastus (medialis and lateralis) requested in the supine bridge were not evaluated because the electromyography system employed only offers six channels. Further investigations could study the effects of superimposed vibration on neuromuscular performance in a loaded suspended supine bridge (kettlebell, barbells, weight plates) or variations of the exercise such as a single-leg or modifying the arm positions (crossed over the chest).

CONCLUSION

The additional effect of the superimposed vibration resulted in being more challenging for the suspended supine bridge than the suspended hamstring curl. Although the two vibration frequencies elicit the same activation level at the global activity level, the suspended supine bridge with a 25 Hz vibration provoked a higher activity of the most proximal muscles to the vibration device (gastrocnemius medialis, lateralis, and semitendinosus), with meaningless effects on the primary movers. Therefore, the amount of instability provoked by the suspended supine bridge with superimposed vibration increased the stabilizing role of the gastrocnemius and semitendinosus. In contrast, the anteroposterior movement of the suspended hamstring exercise seems to be less effective in transmitting the vibration. Regardless of the exercise, increasing the vibration frequency on the suspension device leads to a higher value of subjective perception of exertion (OMNI-Res).

Practical Application

The suspended supine bridge is as demanding as a traditional exercise for the gluteus maximus. However, the additional effect of the superimposed vibration in the suspended supine bridge provides greater gastrocnemius and hamstrings activity. Plantar flexion in the suspended supine bridge with superimposed vibration is a successful manner for strengthening the gastrocnemius, demanded in sports actions such as changes of direction, jumps, and sprints. Furthermore, this method allows dynamic tasks, changing the planes of the force production and offering a continuous exposition to vibration for the working muscles. Likewise, the increased instability generated through vibration to the suspension straps turns the suspended supine bridge into an exercise that demands the neutralization of the lateral rotation of the thighs, similar to other lateral actions in several sports actions. Moreover, superimposed vibration in a suspension device can complement traditional exercises such as the Nordic hamstring, leg curl, or deadlift to develop the strength and endurance of the hamstrings in strength and conditioning programs. Additionally, injury prevention and rehabilitation can benefit from the outputs of the present study to further evaluate the inclusion of superimposed vibration in the prescribed protocols since hamstrings injuries are prevalent in many sports.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Figshare (https://doi.org/10.6084/m9.figshare.14537001).

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics and Research Committee Board in the Blanquerna Faculty of Psychology and Educational and Sport Sciences at Ramon Llull University in Barcelona, Spain, with reference number 1819005D. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

JA-C, BB, AF-V, and JP contributed to the conception and design of the study. JA-C, JA-A, AF-V, and AM contributed to the acquisition of data. JA-C, JA-A, and AM analyzed the data. JA-C and BB wrote the original draft of the manuscript. BB and JP supervised the study. All authors wrote, edited, reviewed, and approved the submitted final version of the manuscript.

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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.2021.712471/full#supplementary-material

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The remaining 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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OPINION
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High-Intensity Multimodal Training for Young People: It's Time to Think Inside the Box!

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INTRODUCTION

Studies comparing children and adolescents from different periods have shown a decrease in physical activity and fitness in the last decades (Moliner-Urdiales et al., 2010; Runhaar et al., 2010; Cohen et al., 2011; Hardy et al., 2013; Santtila et al., 2018; Masanovic et al., 2020; Fühner et al., 2021). Low physical fitness is associated with poor metabolic health, independent of central adiposity (Lätt et al., 2018). Moreover, changes in physical fitness from childhood and adolescence to adulthood are related to metabolic health, physical activity levels, and bone mineral density (García-Hermoso et al., 2019; Mäestu et al., 2020), while both low cardiorespiratory fitness and muscle strength are associated with higher risk of premature death and disability (Ortega et al., 2012; Henriksson et al., 2019a,b). Obesity is another important concern (Wijnhoven et al., 2014; Ogden et al., 2016; Bentham et al., 2017), but previous studies have shown that increased physical activity might be associated with decreased adiposity (Hui et al., 2021) and can modulate the effects of genetic predisposition to obesity in young people (Todendi et al., 2021).

The negative impact of a sedentary lifestyle during early life has been largely debated (Faigenbaum et al., 2011; Faigenbaum and Myer, 2012; Stracciolini et al., 2013). In the early 60s, Kraus and Raab (1961) stressed the importance of physical activity for preventing diseases and suggested that the adverse health effect of physical inactivity was comparable to lack of vitamins or contagious diseases. Based on this, Faigenbaum et al. (2013) proposed a population-wide approach for identifying inactive children, prescribing interventions and raising public awareness.

Notwithstanding, some important barriers for physical activity adoption among children and adolescents might be considered, like perception of lack of safety, physical environment and lack of support (Stankov et al., 2012; Lu et al., 2014; Martins et al., 2014). It is also important to consider children and adolescents particularities (e.g., biological and behavior characteristics) when prescribing and evaluating exercise programs, since exercise programs designed for adults might be inadequate for them (Faigenbaum et al., 2013).

Previous studies suggested that young people naturally engage in intermittent activities (Bailey et al., 1995) and high intensity activities might be particularly beneficial to improve cardiorespiratory fitness (Baquet et al., 2003; Costigan et al., 2015), mental health (Leahy et al., 2020), body composition (Costigan et al., 2015; D et al., 2019) cardiovascular risk and metabolic health (Cooper et al., 2016; García-Hermoso et al., 2016; MA et al., 2021) in children and adolescents.

The purpose of the current article is to present the benefits of high-intensity multimodal training (HIMT) programs, such as CrossFit, to the youth, with a critical discussion about its potential benefits and concerns.

POTENTIAL BENEFITS

HIMT involves exercise programs that mix many different exercise modalities (e.g., weightlifting, powerlifting, gymnastic, calisthenic, plyometrics, running, and others) and train multiple physical capacities at the same time (e.g., cardiorespiratory, muscle strength, and flexibility) (Feito et al., 2019). The performance of high-intensity exercises in an intermittent and station-based fashion, might confer to HIMT characteristics similar from existing training methods such as circuit training and high-intensity interval training (Sobrero et al., 2017; Feito et al., 2019). Probably, the most popular form of HIMT is CrossFit; however, there are many other activities and names that might be included in this definition, like high-intensity functional training, cross-training and others.

HIMT programs are usually designed for improving physical fitness and motor skills, being characterized by high levels of effort, with a great stress in cardiorespiratory and neuromuscular systems (Timón et al., 2019). These activities have been reported to promote marked increases in muscle mass and strength and cardiorespiratory fitness, and reduce body fat (Murawska-Cialowicz et al., 2015; Brisebois et al., 2018; Carnes and Mahoney, 2019; Bahremand et al., 2020), which are, in some cases, higher than conventional activities (Bahremand et al., 2020). There is evidence that HIMT participants present high levels of satisfaction and motivation (Claudino et al., 2018) and perceive it as more enjoyable than conventional training (Heinrich et al., 2014).

CrossFit Teen and CrossFit Kids are similar programs adapted from CrossFit and designed specifically to improve fitness and resistance skill of young population. In agreement with the studies involving adults, such HIMT programs have shown to improve physical fitness in children and adolescents (Eather et al., 2016b; Garst et al., 2020), with high rates of attendance (94%) and satisfaction (4.2–4.6 out of 5) (Eather et al., 2016b). HIMT like CrossFit is usually performed inside a specific facility named "Box" (Feito et al., 2019); however, programs adapted for young people involves minimal equipment and can also be easily implemented at school setting (Eather et al., 2016b; Garst et al., 2020). In this context, the effects of HIMT on health-related fitness of students are comparable to those obtained with the regular participation in physical education classes (Garst et al., 2020).

The higher intensity achieved during HIMT seems to be an important aspect for cardiorespiratory fitness in the youth, since exercising at intensities above 80% of maximal heart rate might be important for this group (Baquet et al., 2003). Previous studies have suggested that young people might particularly benefit from high-intensity physical exercise, with improvements in body composition, metabolic, and cardiovascular health (Gist et al., 2014; Cooper et al., 2016; Eddolls et al., 2017; García-Hermoso et al., 2020), but also in other components like cognitive and mental health (Leahy et al., 2020). Regarding the latter, 8 weeks of HIMT intervention brings mental health benefits among adolescents at increased risk for psychological stress (Eather et al., 2016a). Thus, HIMT can be considered a helpful strategy to manage mental health issue in school-aged individuals.

The muscle strengthening component of HIMT might also be important for the youth, since muscle strength seems to has a strong association with health benefits (García-Hermoso et al., 2019) and mitigate the worsening of metabolic health associated with insufficient levels of physical activity (Gomes et al., 2017). Children and adolescents have lower levels of sexual hormones compared to adults, and also reduced strength and power when normalized by body mass (Dotan et al., 2012; Dotan, 2016). However, besides these apparent limitations, there are many studies showing that children and adolescents are capable of increasing muscle strength and mass in response to training (Faigenbaum et al., 1996; Pikosky et al., 2002; Granacher et al., 2011; Assunção et al., 2016). Of note, some of these studies involve children as young as 5 years old (Faigenbaum et al., 1999).

According to Faigenbaum et al. (2016), education and instruction on proper resistance training techniques and procedures should start early in life. Neuromuscular performance and muscle strength might positively predict motor competence in children (Wright et al., 2020) and higher motor competence during childhood is associated with sustained physical activity practice in adolescence (Larsen et al., 2015).

POTENTIAL CONCERNS

Injury risk is probably the main concern regarding HIMT in adults (Claudino et al., 2018). However, data reporting the prevalence or incidence of injury in young HIMT practitioners is scarce. A retrospective study about pediatric CrossFit-related injury found that the absolute number of CrossFit-related injury in young increased over time since CrossFit foundation (Stracciolini et al., 2020). This crescent CrossFit-related injury rate could be associated with the increased participation of young people in this modality, while the absence of relative risk analyses makes difficult to classify or compare injure rate with another training modality. The profile of CrossFit-related injury in the young might differ between sex and age, with higher proportion of lower limb injury in women, higher proportion of Shoulder injury in men, and higher proportion of trunk/spine for participant younger than 20 years old (Sugimoto et al., 2020). These findings might be of particular interest in order to develop safe HIMT for young practitioners.

Other possible concerns involving HIMT for adults, like insufficient recovery between exercises and sessions, concurrent effects and lack of specificity, might not be harmful or can even be advantageous when considering young people.

It has been suggested that recovery from high-intensity exercises (i.e., all out sprints and Wingate tests) is faster in children and adolescents when compared to adults (Bar-Or, 1995; Ratel et al., 2004). Moreover, children and adolescents seem to naturally engage in intermittent activities (Bailey et al., 1995) and studies have reported that they usually consider it enjoyable (Ratel et al., 2004; Malik et al., 2017, 2018).

The faster recovery in the young has also been reported in resistance training. Faigenbaum et al. (2008) compared the performance in the bench press exercise at 10 repetitions maximum (10RM) load between children, adolescents and adults. The results showed that children recovered faster than adolescents and adults, while adolescents recovered faster than adults. Therefore, using short interval lengths might not interfere with the results in younger people (Ramirez-Campillo et al., 2014, 2019b; Drury et al., 2021).

Regarding the recovery between sessions, a previous study by Soares et al. (1996) compared the recovery of children (12 years old) and adults (28 years old) after 5 sets of bench press performed to momentary muscle failure. According to the results, there were no changes in indirect markers of muscle damage [isometric strength and creatine kinase (CK) levels] 24 h after training in children, while adults did not recover for as long as 72 h. Similar findings were reported by Chen et al. (2014), that used muscle damaging protocols (5 sets of 6 maximal eccentric elbow flexions) and found that recovery was faster in children than adolescents and adults; and in adolescents when compared to adults. Later, Deli et al. (2017) compared the responses of boys (10–12 years old) and adults (18–45 years old) to maximal eccentric knee extensions and confirmed that children are less susceptible to exercise-induced muscle damage than adults. Children and adolescents seem to require less days to recover from a resistance exercise session than adults (Ramírez-Campillo et al., 2015) and a higher training frequency promotes higher increases in muscle strength in this group (Moran et al., 2017). Therefore, the concerns regarding insufficient recovery during HIMT might not be a problem for the young.

HIMT also can involves a large component of plyometric jumps, which might improve physical performance in young people and are safe over short term (De Freitas Guina Fachina et al., 2017; Assunção et al., 2018; Ramirez-Campillo et al., 2019a,b; Vera-Assaoka et al., 2020). However, it is important to remember that overuse injuries and tendinopathies are frequent in young athletes (Le Gall et al., 2006; Johnson et al., 2020), which might be due to an imbalance between muscle and tendon adaptation (Mersmann et al., 2014, 2016, 2017). Considering that resistance training might increase tendon strength (Kongsgaard et al., 2007; Martins et al., 2018), it is recommended to design programs with an adequate balance between plyometric (particularly high-impact jumps) and resistance training volumes, specially adolescents. The combination of resistance and plyometric training might also be beneficial for increasing performance (Zghal et al., 2019; Thapa et al., 2021). Radnor et al. (2017) studied the response of children of different maturity groups (pre- or post-peak height velocity) to a plyometric training, resistance training and combined training and reported that, irrespective of maturation, combined training provided the greatest improvements in performance.

The combination of resistance and aerobic training during HIMT might be a concern because of the potential concurrent effects. However, a systematic review with meta-analysis reported that concurrent training was more effective than single mode aerobic or resistance training in improving physical fitness in children and adolescents (Gäbler et al., 2018). Interestingly, the study revealed that concurrent training promoted higher increases on muscle power in young people when compared to strength training alone, which is the opposite to what have been reported in adults (Wilson et al., 2012).

There might be some concerns with the strengthening exercises used during HIMT, because this might be associated with risk of injury in children. However, the injury risk for these activities are lower than other sports, like soccer and basketball (Hamill, 1994), being considered safe for the youth (Falk and Eliakim, 2003; Malina, 2006; Faigenbaum et al., 2009).

Myer et al. (2009) evaluated injuries seen during emergency room visits associated with resistance training (weightlifting). The results revealed that accidental injuries decreased with age, while sprain/strain injuries increased. More than two thirds of the injuries sustained in the 8–13 group occurred in the heads, hands and feet and were most often related to "dropping" and "pinching". Therefore, it seems that children have lower risk of sprains and strains, but a higher risk of accidental injuries, suggesting the need for adequate (and qualified) supervision during training sessions.

Because of the highly fatiguing nature of HIMT, proprioception and exercise technique are likely altered, compromising safety and efficacy of such programs, particularly for those involving exercise that require complex technics such Olympic-style weightlift (e.g., snatches and clean, and jerks), as suggested by Hooper et al. (2014). Therefore, children and adolescents must be closely supervised during HIMT and, if necessary, training programs should be adapted for their individual characteristics.

The highly fatiguing nature of HIMT should also be considered when training close to academic tasks. Though HIMT might be beneficial to improve motor skills it can impair academic performance in middle school students, due to an impairment in concentration capacity (Garst et al., 2020). However, this seems to be controversial since other studies showed that high intensity training improves executive function, memory, and selective attention in children and adolescents (Ma et al., 2015; Moreau et al., 2017; Lind et al., 2019; Tottori et al., 2019). Therefore, the negative results found by (Garst et al., 2020) might be specific to the modality used (CrossFit) and not due to high intensity nature of the activity *per se*. There is a common belief that high effort, especially lifting weight might limit longitudinal growth in children and adolescent. However, exercise might positively influence longitudinal growth (Borer, 1995; Hills and Byrne, 2010) and there is no evidence that muscle strengthening activities have a negative impact on growth (Falk and Eliakim, 2003; Malina, 2006; Faigenbaum et al., 2009). In fact, HIMT might be even beneficial, since high intensity activities increase circulating human growth hormone in children and adolescents (Saggese et al., 1987; Eliakim and Nemet, 2008, 2013).

FINAL COMMENTS

Although there is no minimum age to start exercising (Myer et al., 2011; Faigenbaum et al., 2016), it is necessary to adapt training programs to the youngsters' biological and behavioral characteristics. Children and adolescents should be able to understand and follow instructions and they should receive

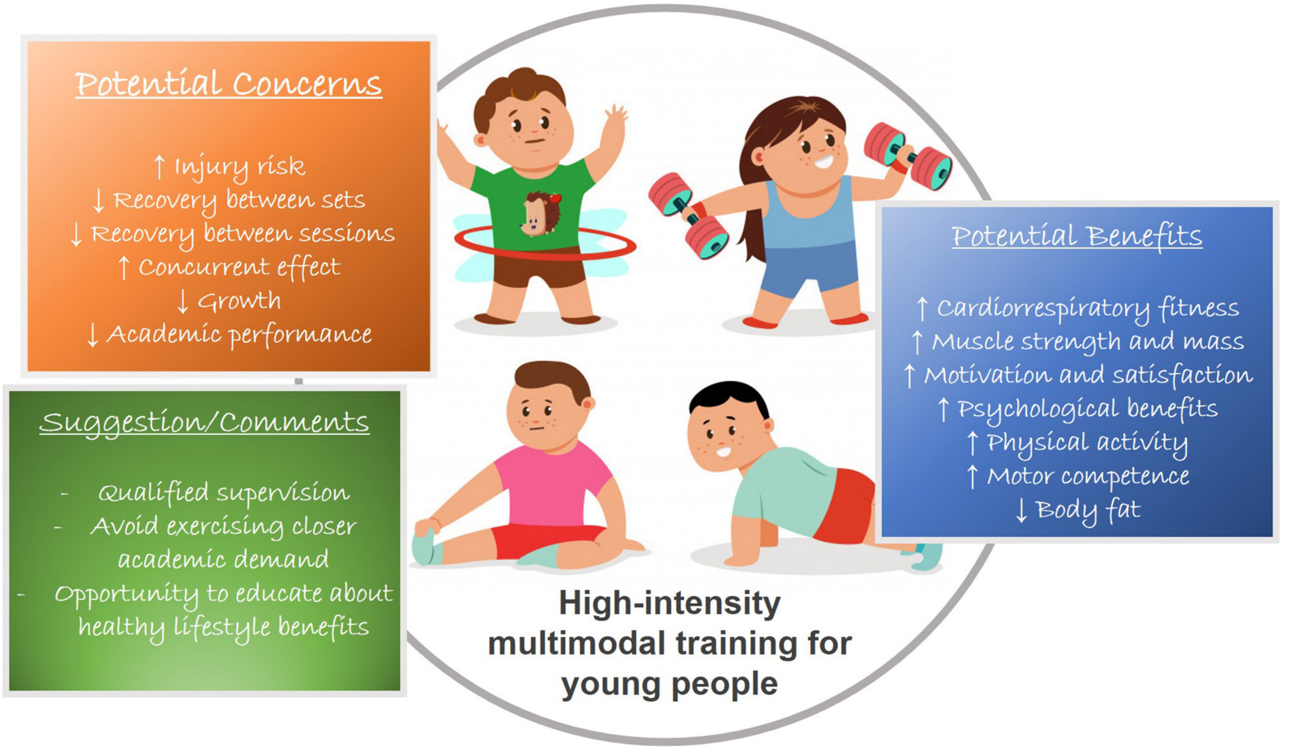

FIGURE 1 | Summary of benefits (Eather et al., 2016a,b), concerns (Hooper et al., 2014; Claudino et al., 2018; Garst et al., 2020), and suggestion/comments (Myer et al., 2011; Faigenbaum et al., 2016), regarding high-intensity multimodal training in young people.

safety instructions on lifting weights, proper spotting and equipment use.

Considering the competitive nature of some HIMT programs, it is important to remember that untrained youth tend to overestimate their physical performance, which might increase the risk of injury (Plumert and Schwebel, 1997). This highlights the importance of qualified supervision, which is further reinforced by the fact that direct supervision improves program adherence and the results in young people (Coutts et al., 2004).

Professionals involved with HIMT for children and adolescents need to acknowledge both their biological characteristics and psychological uniqueness. Professionals should be particularly sensitive to children and adolescents who are overweight/obese and with low physical capacities. Although they are the ones who potentially will get most benefit from HIMT, they are also the ones who might be more reluctant to adhere.

Some practical suggestions to improve adherence of obese pediatric population using HIMT, should be access to a gym, initial direction by a trainer, variety, and group-based activities (Peeters et al., 2012). Other important factor are the support of family and peer (Peeters et al., 2012; Salvy et al., 2012; Sundar et al., 2018); therefore, it is important to involve them in the exercise programs as much as possible. It is also important to provide constant feedback regarding improved fitness, since obese children might join exercise initially aiming at losing weight, but focused more on fitness over time (Peeters et al., 2012). Considering that mastering the activity is associated with less motivation (Sundar et al., 2018), we suggest choosing simple exercises and progress carefully.

In technical terms, the characteristics of HIMT, such as, the simultaneous development of many physical capacities and movements and exercise diversity might be particularly interesting for training young people. HIMT involves some important aspects for exercise adherence like variety and group-based, and might easily involve others like access to exercise facilities and supervision (Peeters et al., 2012). Many concerns like an increased risk of injury, insufficient recovery might not be troublesome for this group and are not difficult to address (**Figure 1**).

During HIMT exercise professionals might have an opportunity to promote positive changes in physical function and body composition in children and adolescents, as well as to promote improvements in mental health and psychosocial aspects. Moreover, this might be an important opportunity to educate them about the benefits of a healthy lifestyle and overcome the perceived barriers to being physically active. The increase in physical fitness might increase spontaneous participation in physical activity and sports (Eiholzer et al., 2010; Fransen et al., 2014). Therefore, HIMT might be seen as an end (to increase physical fitness) but also as a mean (to increase physical activity).

AUTHOR CONTRIBUTIONS

PG, CABdL, RLV, RR-C, and DS: conception, drafting the article, revising it critically, and final approval of the version to be published. All authors contributed to the article and approved the submitted version.

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Elbow Joint Angles in Elbow Flexor Unilateral Resistance Exercise Training Determine Its Effects on Muscle Strength and Thickness of Trained and Non-trained Arms

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Sato S, Yoshida R, Kiyono R, Yahata K, Yasaka K, Nunes JP, Nosaka K and Nakamura M (2021) Elbow Joint Angles in Elbow Flexor Unilateral Resistance Exercise Training Determine Its Effects on Muscle Strength and Thickness of Trained and Non-trained Arms. Front. Physiol. 12:734509. doi: 10.3389/fphys.2021.734509

The present study compared two unilateral arm curl resistance exercise protocols with a different starting and finishing elbow joint angle in the same ROM for changes in elbow flexors strength and muscle thickness of the trained and non-trained arms. Thirty-two non-resistance trained young adults were randomly assigned to one of the three groups: extended joint training (0°–50°; EXT, $n = 12$); flexed joint training (80°–130°; FLE, $n = 12$); and non-training control ($n = 8$). The exercise training was performed by the dominant arms twice a week for 5 weeks with gradual increases in the training volume over 10 training sessions, and the non-dominant (non-trained) arms were investigated for the cross-education effect. Maximal voluntary contraction torque of isometric (MVC-ISO), concentric (MVC-CON), and eccentric contractions (MVC-ECC), and thickness (MT) of biceps brachii and brachialis of the trained and non-trained arms were assessed at baseline and 4–8 days after the last training session. The control group did not show significant changes in any variables. Significant ($P < 0.05$) increases in MVC-ISO torque (16.2 ± 12.6%), MVC-CON torque (21.1 ± 24.4%), and MVC-ECC torque (19.6 ± 17.5%) of the trained arm were observed for the EXT group only. The magnitude of the increase in MT of the trained arm was greater ($P < 0.05$) for EXT (8.9 ± 3.9%) than FLE (3.4 ± 2.7%). The cross-education effect was evident for MVC-ISO (15.9 ± 14.8%) and MVC-CON (16.7 ± 20.0%) torque of the EXT group only. These results suggest that resistance training at the extended elbow joint induces greater muscle adaptations and cross-education effects than that at flexed elbow joint.

Keywords: maximal voluntary contraction torque, isometric, concentric, eccentric, cross-education effect, range of motion

INTRODUCTION

In resistance training, range of motion (ROM) is a factor influencing its effects on muscle adaptations (Schoenfeld and Grgic, 2020). Schoenfeld and Grgic (2020) showed in their recent systematic review article that performing resistance training through a full ROM induced greater effects on hypertrophy of the lower body musculature when compared with training with a partial ROM. They also stated that research on the effects of ROM on upper limb muscles was limited and conflicting. To the best of our knowledge, only two studies have examined the effects of ROM in upper limb muscle resistance training on muscle strength and muscle hypertrophy.

Pinto et al. (2012) reported that the increase in elbow flexion one-repetition maximum (1-RM) strength was significantly greater after a full ROM (0°–130° elbow flexion) protocol (26%) than a partial ROM (50°–100° elbow flexion) protocol (16%), but the increase in brachialis plus biceps thickness was similar between the full (10%) and partial ROM (8%) groups. Goto et al. (2019) compared a full ROM (0°–120° elbow flexion) and a partial ROM (45°–90° elbow flexion) triceps extension resistance training for changes in muscle strength and muscle cross-sectional area (CSA) of the elbow extensors performed by resistance-trained men three times a week for 8 weeks. They showed that the partial ROM group had significantly greater increases in maximum voluntary contraction (MVC) torque (40%) and CSA (49%) than the full ROM group (24, 28%). They speculated that the resistance training in partial than full ROM would induce greater intramuscular hypoxia, which would increase muscle protein synthesis, growth hormone, and mammalian targets of rapamycin (mTOR) signaling, inducing greater muscle adaptations. When a full and a partial ROM resistance exercise protocol are compared, not only the ROM *per se* but also muscle length in the ROM appears to affect its training effects. Thus, the effects of muscle length in a function of joint angle should be considered for resistance training protocols.

In relation to the muscle length effect, Noorkõiv et al. (2015) compared isometric resistance training of the knee extensors at a longer muscle length (75°–100° knee flexion) vs. a shorter muscle length (30°–50° knee flexion), performed 5 times of 5 s per session, 3 times a week for 6 weeks. They showed that maximal voluntary concentric contraction torque (12–13%) and knee extensor muscle volume (4.8–8.2%) increased significantly only after the longer muscle length training. In a dynamic resistance exercise study, Nunes et al. (2020) compared two types of bicep curl training with a cable-pulley system which induced greater torque at short muscle lengths vs. a barbell which could apply greater torque at long muscle lengths, performed three times a week for 10 weeks for changes in muscle strength and thickness of the elbow flexors. They showed that maximum voluntary isometric contraction (MVC-ISO) strength at a long muscle length (20° elbow flexion) increased significantly greater after the barbell (39%) than the cable-pulley training (30%) without a difference in biceps brachii thickness increase. Nosaka et al. (2005) compared two protocols of eccentric exercise of the elbow flexors with different starting positions of the elbow joint, 50°–0° elbow flexion (long muscle lengths) and 130°–80° elbow flexion (short muscle lengths), and showed greater muscle damage indicated by decreases in MVC-ISO strength and increases in muscle soreness, upper arm circumference, plasma creatine kinase and magnetic resonance image (MRI) T2 relaxation time after the long than short muscle length protocol. These studies suggest that dynamic resistance training effects are different between long and short muscle length protocols with the same range of motion. However, no previous study has investigated the effects of elbow joint ROM in which muscles are activated in different lengths (i.e., long vs. short muscle lengths) on muscle strength changes and muscle hypertrophy.

It has been reported that unilateral resistance training increases muscle strength in the contralateral non-trained homologous muscle, which is referred to as the cross-education effect (Manca et al., 2017, 2021). Manca et al. (2021) have concluded that the main mechanisms underpinning the cross-education effect are neural adaptations; particularly changes in cortical excitability in the primary motor and supplementary motor areas ipsilateral to the trained limb. A meta-analysis by Manca et al. (2017) showed that there was a positive correlation between the degree of muscle strength increase in the trained limb and that of the non-trained limb. Carr et al. (2021) have recently reported a greater reduction in maximal force due to fatigue after intermittent maximal isometric contractions at a long than a short muscle length in biceps brachii. In addition, Fariñas et al. (2019) mentioned that the set configuration causing more fatigue showed a greater adaptation of the central nervous system, which showed a greater cross-education effect in the non-trained arm. If the resistance training effects are affected by the muscle lengths, it may be that the cross-education effect is also different between the long and short muscle length protocols. However, this does not appear to have been investigated in the previous studies.

Therefore, the purpose of this study was to compare two unilateral arm curl protocols in which the ROM was the same, but the starting and finishing elbow joint angles were different; 0°–50° (more extended joint exercise, presumably long muscle lengths) and 80°–130° (more flexed joint exercise, presumably short muscle lengths) for changes in elbow flexors strength and biceps brachii and brachialis muscle thickness of the trained and non-trained arms following a short (5-week) training performed twice a week by untrained young adults. A previous study (Sato et al. [in press]) reported that the 5-week training with gradual increases in the training volume over 10 sessions increased muscle strength (22.5%) and muscle thickness (7.1%) of the elbow flexors. It was hypothesized that the magnitude of increases in the strength and muscle thickness would be greater for the extended than flexed joint protocol for both trained and non-trained arms.

MATERIALS AND METHODS

Study Design

A randomized repeated measures experimental design was used to compare the effects of unilateral elbow flexor resistance training at more extended joint angles (elbow joint angle: 0°–50°, EXT) and that at more flexed joint angles (80°–130°, FLE) on muscle strength and muscle thickness. The dependent variables consisted of maximum voluntary isometric contraction (MVC-ISO) torque at four different angles (10°, 50°, 90°, 130° elbow flexion), maximum voluntary concentric contraction (MVC-CON) torque at two angular velocities (60°/s, 180°/s), maximum voluntary eccentric contraction (MVC-ECC) torque at 60°/s and muscle thickness (MT) of biceps brachii and brachialis of the trained and untrained arms. In both EXT and FLE groups, the dominant arm was trained, and the non-trained arm was used to investigate the cross-education effect. A control group that did not perform the training was also included to examine changes in the variables over 5 weeks.

A familiarization session was set 1 week prior to the baseline measurements, and all participants practiced the MVC-ISO, MVC-CON, and MVC-ECC torque measurements on both trained (dominant) and non-trained (non-dominant) arms. The resistance training was performed twice a week with a rest period of at least 48 h between sessions for 5 weeks (Sato et al., 2021). All participants were instructed to refrain from any systematic training outside the study for the experimental period.

Participants

A total of 32 (19 male and 13 female) healthy university students who were free from any orthopedic disorders of the upper extremity, had no history of previous neuromuscular or chronic diseases, and had not performed a structured resistance training in the past 6 months, participated in the present study. They were allocated to the one of three groups randomly as follow; EXT group (n = 12; 7 male, 5 female; age: 20.7 ± 0.9 year; height: 167.1 ± 9.0 cm; body mass: 60.9 ± 11.4 kg), FLE group (n = 12; 8 male, 4 female; age: 21.4 ± 1.4 year; height: 165.7 ± 7.5 cm; body mass: 58.8 ± 9.9 kg), or control group (n = 8; 4 male, 4 female; age: 21.1 ± 0.6 year; height: 164.3 ± 6.6 cm; body mass: 57.2 ± 7.9 kg). There were no significant differences in age, height, and body mass among groups.

The effect size was estimated from the study by Pinto et al. (2012), who reported the effect size of 0.81 for the difference in muscle strength increase between a partial and a full ROM resistance training protocol of the elbow flexors. With a power of 0.95 and an α of 0.05, the sample size was estimated that at least 8 subjects were necessary for each group. Considering the estimation error, 12 subjects were recruited for the training groups, and 8 subjects were recruited for the control group. Among the 32 participants, all except one in the FLE group were right-hand dominant based on the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were briefed on the study purpose and procedures, and a written consent was obtained from each participant. This study was approved by the Ethics Committee of Niigata University of Health and Welfare. The study was conducted in conformity with the policy statement regarding the use of human subjects by the Declaration of Helsinki.

Training Protocol

The resistance training was performed by the dominant arm. Training intensity was increased progressively from 30% (1st session) to 50% (2nd and 3rd sessions), 70% (4th and 5th sessions), 80% (6th and 7th sessions), 90% (8th and 9th sessions), and 100% (10th session) of the MVC-ISO torque at 50° for the EXT, and at 90° for the FLE group measured before the training. The dominant arm of each participant was positioned on a preacher curl bench in a seated position, with 45° shoulder flexion and forearm supination (Nunes et al., 2020). Each session consisted of 3 sets of 10 repetitions (30 repetitions in total). The contraction tempo was indicated by a metronome, and each subject was instructed to move a dumbbell for the concentric phase and the eccentric phase in 2 s each. The range of motion was from 0° to 50° in the EXT group and from 80° to 130° in the FLE group (Nosaka et al., 2005). If a participant had difficulty controlling the dumbbell movement during training at a high intensity (80–100% MVC-ISO torque), the investigator assisted the participant for weaker elbow joint angles. The rest time between sets was 3 min. The total lifting weights of the dumbbell for 10 sessions were calculated for each subject in the EXT and FLE groups.

MVC-ISO, MVC-CON, and MVC-ECC Torque

MVC-ISO torque was measured at 10° (MVC-ISO_{10}), 50° (MVC-ISO_{50}), 90° (MVC-ISO_{90}), and 130° (MVC-ISO_{130}) elbow flexion in 45° shoulder flexion, with the trunk and pelvis being secured with a belt, for the trained (dominant) and non-trained (non-dominant) arms using an isokinetic dynamometer (Biodex System 3.0, Biodex Medical Systems Inc., Shirley, NY, United States). The MVC-ISO torque measurements for each angle were performed in a random order, but the measurements of the trained (dominant) arm were taken before those of the non-trained (non-dominant) arm. Each contraction lasted for 3 s, and two measurements were made for each angle with a 45-s interval (Tseng et al., 2020), and the average of the two measures was used for further analysis. The average of MVC-ISO_{10}, MVC-ISO_{50}, MVC-ISO_{90}, and MVC-ISO_{130} torque was also calculated as the average of the four angles (MVC-ISOave) torque and used for further analysis. During all measurements, verbal encouragement was provided to the participants.

The isokinetic dynamometer was also used to measure MVC-CON and MVC-ECC torque of the elbow flexors of the trained (dominant) and non-trained (non-dominant) arms in the same setting as that on MVC-ISO measures. MVC-CON torque was measured at 60°/s (MVC-CON_{60}) and 180°/s (MVC-ISO_{180}), and MVC-ECC torque was measured at 60°/s in this order. The rest time between measurements was 120 s, and the measurements for the trained (dominant) arm were performed before the non-dominant arm. The range of motion was 120° for the measurements, and the starting angle was 0° for MVC-CON, and 130° elbow flexion for MVC-ECC (Colson et al., 1999). MVC-CON and MVC-ECC torque was measured five times consecutively, and the maximum torque obtained was used for the subsequent analysis. The average of MVC-CON_{60} and

MVC-ISO$_{180}$ torque was also calculated as MVC-CON$_{ave}$ torque and used for further analysis. During all measurements, the investigator gave verbal encouragement to the participants.

Muscle Thickness

A total of biceps brachii and brachialis MT of the trained (dominant) and non-trained (non-dominant) arms was measured using B-mode ultrasonography with an 8-MHz linear probe (LOGIQ e V2; GE Healthcare Japan, Tokyo, Japan). The investigator minimized the pressure of the probe against the skin as much as possible, and the same investigator took all measurements at both baseline measurement (PRE) and post-training (POST). The measurement sites were 50% (MT$_{50}$), 60%(MT$_{60}$), and 70% (MT$_{70}$) of the lateral epicondyle of the humerus from the acromion. Each participant lay in the supine position on a bed with the arms placed at each side and the forearm supinated while relaxing the arms. Ultrasound measurements of the transverse-axis were repeated twice, and the MT of biceps brachii plus brachialis was measured as the distance from the inner edge of the fascia to the humerus (Abe et al., 2000; Sato et al., 2021). The average of the two measurements was calculated for each site and used for further analysis. The average value (MT$_{ave}$) of the MT at the 50, 60, and 70% sites was also calculated and used for further analysis.

Test-Retest Reliability of the Measurement

The reliability of test and retest for the measured values of MVC-ISO torque, MVC-CON torque, MVC-ECC torque, and MT was assessed by the coefficient variation (CV) and the intraclass correlation coefficient (ICC) using 6 healthy men (25.0 ± 3.7 y, 168.0 ± 4.8 cm, 61.2 ± 4.4 kg) with 1 week between the two measures without any training. The CV of the measurements for MVC-ISO$_{10}$, MVC-ISO$_{50}$, MVC-ISO$_{90}$, MVC-ISO$_{130}$, MVC-ISO$_{ave}$, MVC-CON$_{60}$, MVC-CON$_{180}$, MVC-ECC, and MT$_{ave}$ were 6.1 2.6, 4.0 2.2, 3.5 2.5, 1.7 1.7, 2.3 0.6, 2.0 1.7, 4.7 2.7, 2.3 1.3, and 1.0 0.4%, respectively, and the ICC for the measurements were 0.85, 0.93, 0.89, 0.89, 0.96, 0.98, 0.84, 0.96, and 0.98, respectively.

Statistical Analysis

Statistical analyses were performed using the SPSS version 24.0 (IBM Japan, Inc., Tokyo, Japan). The normality of the data was confirmed using a Shapiro-Wilk test. Group differences at the baseline were assessed using a one-way analysis of variance (ANOVA). A split-plot ANOVA with two factors [group (EXT vs. FLE vs. Control) × time (PRE vs. POST)] was used to compare between the groups for changes in MVC-ISO, MVC-CON, MVC-ECC torque, and MT in the trained arm and non-trained arm from pre- (PRE) to post-training (POST). Classification of effect size for the split-plot ANOVA results was based on ηp^2, and less than 0.01 was considered as a small, 0.02–0.1 was considered as a medium, and over 0.1 was considered as a large effect size (Cohen, 1988). A paired *t*-test with Bonferroni correction was used to determine significant differences between PRE and POST values when significant effects were found. Furthermore, when significant differences were found between PRE and POST values in the EXT and FLE groups, the magnitude of the change in each variable from PRE to POST was compared between the groups using a Man-Whitney *U*-test. The effect size (ES) was calculated as a difference in the mean values between pre- and post-training divided by the pooled SD (Cohen, 1988). ES of 0.00–0.19 was considered trivial, 0.20–0.49 was small, 0.50–0.79 was moderate, and ≥ 0.80 was large. In addition, an independent *t*-test was used to compare the total dumbbell weight lifted over the 10 sessions between the EXT and FLE groups. The differences were considered statistically significant at an alpha level of 0.05. Descriptive data are shown as mean ± standard deviations (SD).

RESULTS

Training

All participants in both training groups completed all training sessions as planned. The total dumbbell weight lifted in the 10 training sessions was 3,033 ± 617 kg in the EXT group and 4,251 ± 1,515 kg in the FLE group, and the total weight was lower ($p = 0.02$) for the EXT than FLE group. However, when the total dumbbell weight lifted was normalized by the baseline MVC-ISO$_{50}$ or MVC-ISO$_{90}$ torque (elbow flexor torque at the starting elbow joint angle) converted to "kg" using the acceleration of gravity (9.8) and forearm length, no significant difference ($p = 0.43$) between the EXT (212.0 ± 2.2) and FLE (213.6 ± 3.4) was evident.

MVC-ISO, MVC-CON, and MVC-ECC Torque

Changes in MVC-ISO, MVC-CON, and MVC-ECC torque of the trained and non-trained arms from pre- to post-training are shown in **Table 1**. For the trained arm, significant interaction effects were evident for MVC-ISO$_{50}$ ($p = 0.006$), MVC-ISO$_{90}$ ($p = 0.031$), MVC-CON$_{60}$ ($p = 0.009$), MVC-CON$_{180}$ ($p = 0.041$), and MVC-ECC ($p = 0.03$) torque, but not for MVC-ISO$_{10}$ and MVC-ISO$_{130}$ torque. A significant time effect was found for all torque measures except for MVC-ISO$_{90}$ and MVC-ISO$_{130}$ torque. The *post hoc* test showed that MVC-ISO$_{50}$ ($p = 0.014$, $d = 0.58$), MVC-ISO$_{90}$ ($p = 0.03$, $d = 0.51$), MVC-CON$_{60}$ ($p = 0.02$, $d = 0.65$), MVC-CON$_{180}$ ($p = 0.019$, $d = 0.57$), and MVC-ECC torque ($p < 0.01$, $d = 0.60$) increased only after EXT. No significant changes in all variables were observed for the control group.

For the non-trained arm, significant interaction effects were evident for MVC-ISO$_{50}$ ($p = 0.023$), MVC-ISO$_{90}$ ($p = 0.004$), and MVC-CON$_{60}$ ($p = 0.013$) torque, and a significant time effect was found for MVC-CON$_{60}$, MVC-CON$_{180}$, MVC-ECC torque. The *post hoc* test showed that MVC-ISO$_{50}$ ($p = 0.017$, $d = 0.44$), MVC-ISO$_{90}$ ($p = 0.012$, $d = 0.58$), and MVC-CON$_{60}$ torque ($p = 0.029$, $d = 0.79$) increased only after EXT. The FLE and control groups did not show any significant changes in the variables.

Figure 1 shows changes in MVC-ISO$_{ave}$, MVC-CON$_{ave}$ and MVC-ECC torque of individual participants and the group mean (± SD) values for the trained and non-trained arms. For the trained arm, the *post hoc* test showed that MVC-ISO$_{ave}$ ($p < 0.01$,

TABLE 1 | Changes (mean ± SD) in maximum voluntary isometric contraction (MVC-ISO) torque at four different angles (10°: MVC-ISO_{10}, 50°: MVC-ISO_{50}, 90°: MVC-ISO_{90}, and 130°: MVC-ISO_{130}), concentric contraction (MVC-CON) at two different velocities (60°/s: MVC-CON_{60}, 180°/s: MVC-CON_{180}), eccentric contraction (MVC-ECC), and muscle thickness (biceps brachii plus brachialis) at the 50% (MT_{50}), 60% (MT_{60}), and 70%(MT_{70}) of the proximal-distal distance of the upper arm of the trained and non-trained arms before (PRE) and after (POST) 5-weeks training at more extended elbow joint angles (EXT) or more flexed elbow joint angles (FLE), and control group without training.

		Trained arm			Non-trained arm		
Variables	**Group**	**Pre**	**Post**	**ANOVA results, partial η^2 (η_p^2)**	**Pre**	**Post**	**ANOVA results, partial η^2 (η_p^2)**
MVC-ISO_{10} (Nm)	EXT	25.0 ± 6.61	27.9 ± 6.5	**T:** $F = 13.10$, $\eta_p^2 = 0.31$	24.2 ± 5.2	25.8 ± 6.2	**T:** $F = 2.26$, $\eta_p^2 = 0.07$
	FLE	29.0 ± 9.1	31.7 ± 10.4	**G × T:** $F = 0.86$, $\eta_p^2 = 0.06$	26.8 ± 11.0	28.7 ± 11.7	**G × T:** $F = 0.29$, $\eta_p^2 = 0.02$
	Control	23.4 ± 5.5	24.4 ± 6.5		21.4 ± 8.1	21.7 ± 7.3	
MVC-ISO_{50} (Nm)	EXT	35.5 ± 8.6	40.5 ± 9.0*	**T:** $F = 4.52$, $\eta_p^2 = 0.14$	32.1 ± 9.3	36.1 ± 8.6*	**T:** $F = 1.17$, $\eta_p^2 = 0.04$
	FLE	42.3 ± 13.9	43.2 ± 14.3	**G × T:** $F = 6.23$, $\eta_p^2 = 0.31$	39.6 ± 17.0	39.9 ± 15.4	**G × T:** $F = 4.28$, $\eta_p^2 = 0.23$
	Control	38.7 ± 11.7	37.4 ± 12.0		35.0 ± 12.9	33.3 ± 11.5	
MVC-ISO_{90} (Nm)	EXT	37.7 ± 9.2	42.6 ± 9.8*	**T:** $F = 1.09$, $\eta_p^2 = 0.04$	33.8 ± 9.7	39.1 ± 8.6*	**T:** $F = 3.75$, $\eta_p^2 = 0.11$
	FLE	47.4 ± 17.6	49.0 ± 16.6	**G × T:** $F = 3.93$, $\eta_p^2 = 0.21$	42.4 ± 14.8	41.8 ± 14.6	**G × T:** $F = 6.69$, $\eta_p^2 = 0.32$
	Control	45.6 ± 16.6	42.6 ± 14.1		39.5 ± 12.4	39.3 ± 11.3	
MVC-ISO_{130} (Nm)	EXT	27.4 ± 8.0	33.3 ± 10.4	**T:** $F = 3.28$, $\eta_p^2 = 0.11$	25.1 ± 7.9	30.1 ± 9.6	**T:** $F = 1.90$, $\eta_p^2 = 0.06$
	FLE	33.5 ± 14.5	35.5 ± 14.6	**G × T:** $F = 1.87$, $\eta_p^2 = 0.12$	31.4 ± 12.5	31.0 ± 13.6	**G × T:** $F = 3.13$, $\eta_p^2 = 0.18$
	Control	38.8 ± 14.5	38.2 ± 13.4		34.0 ± 14.4	33.8 ± 11.0	
MVC-CON_{60} (Nm)	EXT	30.3 ± 8.4	35.4 ± 7.3*	**T:** $F = 6.99$, $\eta_p^2 = 0.19$	28.2 ± 6.0	33.1 ± 6.3*	**T:** $F = 4.74$, $\eta_p^2 = 0.14$
	FLE	33.1 ± 12.7	36.3 ± 11.7	**G × T:** $F = 5.54$, $\eta_p^2 = 0.28$	31.7 ± 12.2	32.4 ± 12.9	**G × T:** $F = 5.03$, $\eta_p^2 = 0.26$
	Control	32.7 ± 7.9	30.9 ± 9.0		29.9 ± 9.4	29.2 ± 8.8	
MVC-CON_{180} (Nm)	EXT	23.0 ± 7.2	27.0 ± 7.0*	**T:** $F = 6.56$, $\eta_p^2 = 0.19$	22.5 ± 6.7	25.0 ± 7.1	**T:** $F = 7.57$, $\eta_p^2 = 0.21$
	FLE	26.1 ± 8.7	26.6 ± 8.7	**G × T:** $F = 3.57$, $\eta_p^2 = 0.20$	23.9 ± 9.6	24.8 ± 9.5	**G × T:** $F = 1.89$, $\eta_p^2 = 0.12$
	Control	21.7 ± 5.8	22.2 ± 6.3		20.4 ± 5.3	20.8 ± 6.3	
MVC-ECC (Nm)	EXT	41.8 ± 12.1	48.4 ± 10.1*	**T:** $F = 11.5$, $\eta_p^2 = 0.28$	39.0 ± 10.7	43.1 ± 9.4*	**T:** $F = 9.07$, $\eta_p^2 = 0.24$
	FLE	45.1 ± 15.8	46.1 ± 15.6	**G × T:** $F = 3.99$, $\eta_p^2 = 0.22$	41.8 ± 15.4	42.4 ± 16.1	**G × T:** $F = 2.55$, $\eta_p^2 = 0.15$
	Control	48.0 ± 14.8	49.8 ± 14.5		45.2 ± 13.4	46.6 ± 12.9	
MT_{50} (mm)	EXT	21.8 ± 4.4	22.9 ± 4.2*	**T:** $F = 9.70$, $\eta_p^2 = 0.25$	20.6 ± 4.0	20.4 ± 4.9	**T:** $F = 0.10$, $\eta_p^2 < 0.01$
	FLE	21.9 ± 5.1	22.7 ± 5.1*	**G × T:** $F = 6.91$, $\eta_p^2 = 0.32$	20.5 ± 5.1	20.5 ± 4.8	**G × T:** $F = 0.92$, $\eta_p^2 = 0.06$
	Control	21.5 ± 4.2	21.1 ± 4.7		20.1 ± 4.0	20.2 ± 3.6	
MT_{60} (mm)	EXT	21.8 ± 4.1	23.3 ± 4.0*	**T:** $F = 25.4$, $\eta_p^2 = 0.47$	20.5 ± 4.6	20.6 ± 4.6	**T:** $F = 2.33$, $\eta_p^2 = 0.07$
	FLE	21.9 ± 5.3	23.0 ± 5.6*	**G × T:** $F = 5.93$, $\eta_p^2 = 0.29$	19.9 ± 4.9	20.2 ± 4.8	**G × T:** $F = 0.47$, $\eta_p^2 = 0.03$
	Control	21.3 ± 4.5	21.4 ± 4.7		20.3 ± 3.5	20.7 ± 3.7	
MT_{70} (mm)	EXT	23.7 ± 3.7	26.7 ± 3.6*	**T:** $F = 55.5$, $\eta_p^2 = 0.66$	21.9 ± 4.1	22.2 ± 4.1	**T:** $F = 7.71$, $\eta_p^2 = 0.21$
	FLE	23.5 ± 5.0	24.0 ± 5.0	**G × T:** $F = 27.7$, $\eta_p^2 = 0.66$	21.4 ± 5.0	21.6 ± 5.3	**G × T:** $F = 0.78$, $\eta_p^2 = 0.02$
	Control	22.8 ± 4.6	23.2 ± 4.4		21.8 ± 4.0	22.2 ± 3.8	

*The two-way ANOVA results (T: time effect, G × T: group × time interaction effect; F-value) and partial η^2 (η_p^2) are shown for the trained and non-trained arms. *: significant ($p < 0.05$) difference from the PRE value.*

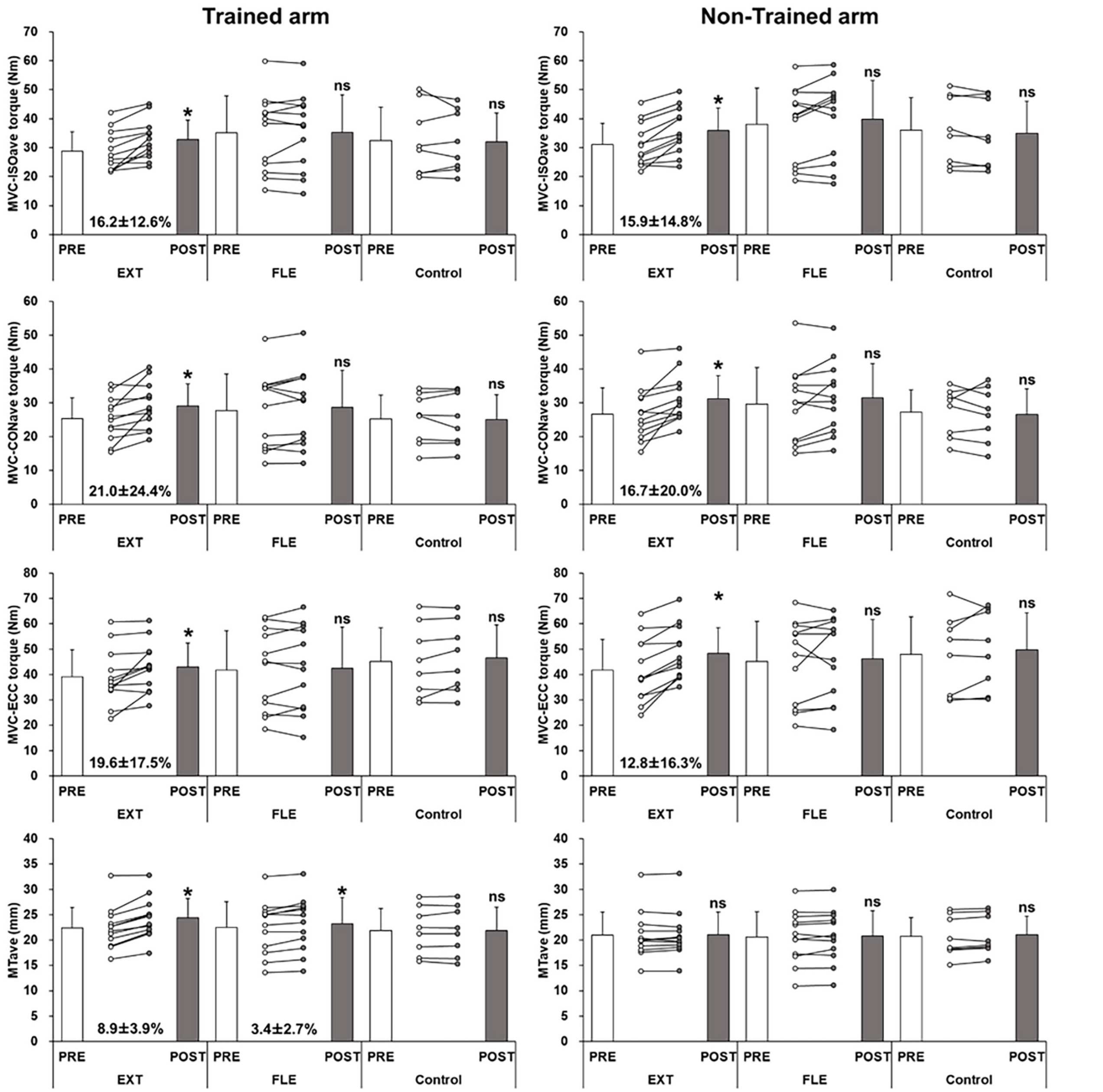

FIGURE 1 | Changes (mean ± SD, individuals) in average maximum voluntary isometric contraction torque of four different angles (MVC-ISO$_{ave}$), concentric contraction torque at two different velocities (MVC-CON$_{ave}$), eccentric contraction (MVC-ECC) torque, and muscle thickness at three positions (MT$_{ave}$) before (PRE) and after (POST) 5-week training at more extended elbow joint angles (EXT) or more flexed elbow joint angles (FLE), and for the control group without training in trained arm. *: significant ($p < 0.05$) difference from the PRE-value, ns: no significant difference from the PRE-value.

$d = 0.64$), MVC-CON$_{ave}$ ($p = 0.010$, $d = 0.62$) and MVC-ECC torque ($p < 0.01$, $d = 0.60$) increased only after EXT. In addition, for the non-trained arm, the *post hoc* test showed that MVC-ISO$_{ave}$ ($p < 0.01$, $d = 0.62$), and MVC-CON$_{ave}$ torque ($p = 0.028$, $d = 0.58$) increased only after EXT.

Biceps Brachii Plus Brachialis MT

Changes in MT of biceps brachii plus brachialis in the trained and non-trained arms from pre- to post-training are shown in **Table 1** and **Figure 1**. For the trained arm, significant interaction, as well as time effect, was evident for all measures. The *post hoc* test showed that MT_{50} and MT_{60} increased ($p < 0.05$) similarly after EXT and FLE, but MT_{70} increased ($p < 0.01$, $d = 0.82$) only after EXT. The increase in MT_{ave} was greater ($p < 0.01$) for the EXT (8.9 ± 3.9%) than FLE group (3.4 ± 2.7%). For the non-trained arm, no significant interaction effects in all MT variables, and a significant time effect was found for only MT_{70}. The control group did not show any changes in MT for both arms.

DISCUSSION

We tested the hypotheses; that (1) the increases in muscle strength and muscle thickness of the trained arm would be greater for the EXT than FLE group, and (2) the increases in muscle strength of the non-trained arm (i.e., cross-education effect) would be also greater for the EXT than FLE group. The results showed that (1) MVC-ISO$_{50}$, MVC-ISO$_{90}$, MVC-ISO$_{ave}$, MVC-CON$_{60}$, MVC-CON$_{180}$, MVC-CON$_{ave}$, and MVC-ECC torque of the trained arm increased significantly only for the EXT group; (2) muscle thickness (MT) of the trained arm increased greater for the EXT than FLE group; and (3) MVC-ISO$_{50}$, MVC-ISO$_{90}$, MVC-ISO$_{ave}$, MVC-CON$_{60}$, and MVC-CON$_{ave}$ torque of the non-trained arm increased significantly only for the EXT group. These results were in line with the hypotheses.

The magnitude of the change in MVC-ISO$_{90}$ torque of the trained arm after 10 training sessions in the EXT group was 14.1 ± 17.1% (**Table 1**). Tseng et al. (2020) reported 19% increase in MVC-ISO$_{90}$ torque in the trained arm after eccentric-only training of the elbow flexors performed once a week for 5 weeks with a gradual increase in the intensity from 10 to 100% of MVC-ISO$_{90}$ torque. This protocol was similar to that of the present study, but the number of sessions per week in the present study was doubled. When comparing to the increase found by Tseng et al. (2020), the magnitude of the increases in the MVC-ISO$_{90}$ torque in the present study was smaller. The greater increase in the strength in the study by Tseng et al. (2020) may be due to the focus on eccentric contractions. Valdes et al. (2021) reported that elbow flexor eccentric-only resistance training performed by the dominant (non-immobilized) arm 3 times a week with 80–120% of one concentric 1-RM load increased MVC-ISO strength (20.9%) greater than concentric-eccentric coupled resistance training (13.7%) in which 60–90% of 1-RM load was used for the same total training volume. It seems possible that eccentric-only resistance training is more effective for increasing muscle strength. It is interesting to compare the eccentric-only resistance training and conventional resistance training consisting of both eccentric and concentric contractions performed at long vs. short muscle length conditions for changes in MVC-ISO strength.

In the trained arm, significant increases in MVC-ISO$_{50}$, MVC-ISO$_{90}$, MVC-ISO$_{ave}$, MVC-CON$_{60}$, MVC-CON$_{180}$, MVC-CON$_{ave}$, and MVC-ECC torque were found only after EXT, indicating that the EXT was more effective than FLE for increasing muscle strength. It is important to note that the normalized total weight and time under the tension were the same between the EXT and FLE groups; thus the different training effects on the muscle strength were most likely due to the difference in the elbow joint angles in training, presumably a difference in muscle lengths. The exact difference in muscle lengths between EXT and FLE protocols was not known, but it was assumed that the biceps brachii and brachialis muscle lengths were longer in the EXT than FLE. Nosaka et al. (2005) compared maximal eccentric contractions of the elbow flexors from 50° flexion to a full extension (0°) and those from 130° to 80° flexion and found greater muscle damage for the former than the latter. They speculated that eccentric contractions at long muscle lengths induced greater muscle damage than those at short muscle lengths. The present study also used the same elbow joint ROM setting for the two conditions to those of the study by Nosaka et al. (2005), although the movements included both concentric and eccentric contractions in the present study. It seems likely that the EXT was performed at longer muscle lengths than the FLE, but this has to be confirmed in a future study.

The greater training effects by long than short muscle length resistance training have been reported. For example, Noorkõiv et al. (2015) compared long (knee joint angle: 87.5 ± 6.0°) and short (38.1 ± 3.7°) muscle length isometric training of the knee extensors consisting of 5 sets of 5-s maximal contractions performed three times a week for 6 weeks. They reported a significant increase in peak isokinetic concentric torque at 30°/s (13%) and 120°/s (12%) only for the long muscle length group. They also showed that only the long muscle length isometric contraction training increased maximal voluntary concentric contraction strength (Noorkõiv et al., 2015). McMahon et al. (2014) compared changes in isometric strength of the knee extensors at 70° of knee flexion between long muscle length (40–90° knee flexion) and short muscle length (0–50°) training protocols consisting of concentric and eccentric contractions at 55% 1-RM for the long muscle length condition and 80% 1-RM for the short muscle length condition performed three times a week for 8 weeks. They showed a significantly greater increase in MVC-ISO strength of the knee extensors for the long (26%) than short muscle length protocol (7%). They speculated that the long muscle length protocol imposed greater activation and metabolic demand in producing force than the short muscle length protocol, which might contribute to the greater strength increase after the long than short protocol (McMahon et al., 2014). Indeed, Carr et al. (2021) reported a greater reduction in maximal force due to fatigue after intermittent maximal isometric contractions at a long than a short muscle length in biceps brachii. This may also be the case for the present study, but the differences between the EXT and FLE protocols for muscle activity and mechanical stimuli are not known. As discussed below, it is also possible that the greater muscle hypertrophy induced by the EXT than FLE contributed to the greater increases in muscle strength after EXT. However, it should be noted that MVC-ISO$_{10}$ and MVC-ISO$_{130}$ did not show significant interaction effects (**Table 1**). This may be attributed to the low training volume in the present study, in which the training intensity was 10–30% of MVC in the first three out of 10 sessions. It may be that all muscle strength measures would have increased if more training sessions were added after the 10th session to increase the training volume.

Regarding the MT, the magnitude of increase in MT$_{ave}$ of the trained arm in the EXT group (8.6%) was greater than that of the FLE group (3.3%). It should be noted that a greater increase in MT was observed at the distal region of muscle (MT$_{70}$: 12.8%) than the proximal region (MT$_{50}$: 5.4%, MT$_{60}$: 7.1%) in the EXT group (**Table 1**). Muscle hypertrophy occurs in homogeneously between different regions in a muscle, and resistance training mode also influences the region-specific hypertrophy (Antonio, 2000; Franchi et al., 2014; Diniz et al., 2020). For example, Franchi et al. (2014) compared the changes in CSA of vastus lateralis muscle at different regions using MRI along after eccentric-only vs. concentric-only training of the knee extensors with 80% 1-RM load performed three times a week for 10 weeks. They reported that eccentric-only training and concentric-only training increased CSA in the mid-portion of the vastus lateralis by 7 and 11%, respectively, and in the distal portion by 8 and 2%, respectively, suggesting that muscle hypertrophy in the distal portion was greater after eccentric-only than concentric-only training. It may be that the training at longer muscle lengths produced greater brachialis hypertrophy due to greater mechanical stimuli generated especially in the long muscles in eccentric contractions.

In the non-trained arm, MVC-ISO$_{50}$, MVC-ISO$_{90}$, MVC-ISO$_{ave}$, MVC-CON$_{60}$, and MVC-CON$_{ave}$ torque increased significantly only after EXT, indicating a greater cross-education effect for the EXT. The lack of increase in the other muscle strength measures was probably due to the low intensity of training in the first half of the training period (1–3 sessions) and the lower training volume, as mentioned above. The factors that influence the magnitude of the cross-education effect include training intensity (Colomer-Poveda et al., 2020), muscle contraction type (Hortobagyi et al., 1997; Kidgell et al., 2015; Manca et al., 2017; Tseng et al., 2020; Valdes et al., 2021), number of sessions (Barss et al., 2018), and intervention duration (Manca et al., 2021). Some studies have reported that the cross-education effect is greater after eccentric than concentric resistance training (Hortobagyi et al., 1997; Kidgell et al., 2015; Tseng et al., 2020) or concentric-eccentric coupled training (Valdes et al., 2021). This may be attributed to the greater central nervous system adaptations, such as the reduction of intracortical and interhemispheric inhibition after eccentric than concentric resistance training (Kidgell et al., 2015).

Kidgell et al. (2015) reported that 4 weeks of maximal eccentric training of the wrist flexors resulted in greater reductions in both ipsilateral intracortical inhibition (32%) and silent period duration (15–27%) when compared with maximal concentric resistance training (2 and 4–8%, respectively). Moreover, Tseng et al. (2020) showed that MVC-ISO$_{90}$ torque in the non-trained arm increased by 11 and 5% for eccentric-only and concentric-only training, respectively, indicating superiority of eccentric to concentric training. In the present study, MVC-ISO$_{90}$ torque of the non-trained arm was increased 13% after EXT, which was similar to that reported by Tseng et al. (2020). It may be that muscle length during resistance training is also a factor affecting the cross-education effect. It is interesting to investigate whether eccentric-only training at longer muscle lengths produces a greater cross-education effect than coupled concentric-eccentric training or concentric-only training. Regarding MT, no cross-education effect was observed after either EXT or FLE in the present study. Previous studies also reported no significant muscle hypertrophy for the non-trained arm after unilateral resistance training (Kidgell et al., 2015; Tseng et al., 2020). Thus, the cross-education effect on muscle hypertrophy does not appear to exist.

The present study had several limitations. Firstly, the present study did not assess actual muscle length changes in EXT and FLE protocols. Thus the exact difference in the muscle length for its training effects, including the cross-education effect, was not known. Secondly, the intervention period (5 weeks) was short. A longer intervention period could have better clarified the adaptations in the trained and non-trained arms by EXT and FLE. Thirdly, MT was used as a parameter of muscle hypertrophy in the present study. Future studies should use magnetic resonance imaging which is the gold standard for measuring muscle volume. Fourthly, the present study used untrained young, healthy adults as participants. It is not known whether the results of the present study are applicable to trained individuals, older adults, and clinical populations. Lastly, neurophysiological measures such as electromyography and transcranial magnetic stimulation were not included in the present study. Future studies should examine the difference in the adaptation of the nervous system between EXT and FLE. With these limitations, the findings of the present study appear to show possible greater effects of long muscle length resistance training in rehabilitation and athletic training.

CONCLUSION

In conclusion, the 5-week unilateral progressive resistance training performed at more extended elbow joint (EXT) induced greater increases in muscle strength of trained arm and cross-education effect on the non-trained arm than that at flexed elbow joint angle (FLE), and an increase in muscle thickness of the trained arm was greater after EXT than FLE with the same time under tension. These results suggest that the EXT resistance exercise training is more effective than the FLE with the same ROM for the elbow flexors to increase both trained and non-trained contralateral arms muscle strength and muscle size in the trained arm. It seems likely that muscle length in resistance exercise training is an important factor for its outcomes. It is interesting to investigate if this is also the case for other muscles.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This study was approved by the Ethics Committee of the Niigata University of Health and Welfare, Niigata, Japan (Procedure #18442). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SS, KN, and MN designed the study, drafted, and revised the manuscript. SS, RY, RK, KaY, KoY, JN, and MN contributed to the data collection and analyses. JN made critical revisions to the manuscript. All authors approved the final version of the manuscript.

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PERSPECTIVE
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Parkour-Based Activities in the Athletic Development of Youth Basketball Players

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While ideas from long-term athlete development (LTAD) models have been adopted and integrated across different sports, issues related to early specialization, such as increased risk of injury and burnout, are still common. Although some benefits may be associated with early sport specialization, sports sampling is purported to be a more effective approach to the long-term health and wellbeing of children. Furthermore, the concept of developing what are commonly referred to as "fundamental movement skills" (FMS) is central to the rationale for delaying single sports specialization. However, in place of sports sampling, it appears that the practice of strength and conditioning (S&C) has become a driving force behind developmental models for youth athletes, highlighted by the growing body of literature regarding youth athletic development training. In this perspective piece, we explore how conventional S&C practice may insufficiently develop FMS because typically, it only emphasizes a narrow range of foundational exercises that serve a limited role toward the development of action capabilities in youth athletic populations. We further discuss how this approach may limit the transferability of physical qualities, such as muscular strength, to sports-specific tasks. Through an ecological dynamics lens, and using basketball as an example, we explore the potential for parkour-based activity within the LTAD of youth basketball players. We propose parkour as a training modality to not only encourage movement diversity and adaptability, but also as part of an advanced strength training strategy for the transfer of conventional S&C training.

Keywords: fundamental movement skills, non-linear pedagogy, youth athletes, strength training, affordance landscape

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INTRODUCTION

The notion of developing basic movement skills to provide foundations for more advanced and specialized forms of movement is not new (Hulteen et al., 2018). However, a concern in the development of youth sports has been the lack of emphasis on generalized fundamental movement skills (FMS) in favor of early specialization (Bridge and Toms, 2013; DiStefano et al., 2017; Liefeith et al., 2018). Although alternative terms exist (e.g., foundational movement skills, functional movement skills, and basic movement skills), typically, FMS encompass locomotor (e.g., running and jumping) and object control (e.g., catching, throwing, and kicking; Morgan et al., 2013; Barnett et al., 2016). Accordingly, FMS are considered foundational for the development of sports-specific skills, which if left undeveloped may limit future performance (Barela, 2013; Arede et al., 2019; Jukic et al., 2019). Indeed, the development of FMS ahead of specific sports skills is promoted within the long-term athlete development model (LTAD; Balyi, 2001), which has served as an influential framework for the training of young athletes in sporting organizations for over two decades (Collins and Bailey, 2012; Liefeith et al., 2018; Perreault and Gonzalez, 2021).

Through the development of FMS as well as participation in multiple sports-related activities throughout childhood, the premise of the LTAD model is to avoid early specialization and the associated risks relating to injury and burnout (Ford et al., 2011; Pichardo et al., 2018; Perreault and Gonzalez, 2021). However, despite recognition by sports organizations of the need for an LTAD strategy, the prevalence of injuries in youth sports, such as soccer and basketball, remains high (e.g., Read et al., 2016, 2018; Owoeye et al., 2020). While the original intention of the LTAD model was to be used as a framework for sports organizations to adapt and implement to suit their specific needs (Dowling et al., 2020), it has been argued that the development of FMS and general physical qualities remains marginalized in favor of sports-specific training (Liefeith et al., 2018; Williams et al., 2021).

Problematically, much debate exits with respect to FMS (e.g., Barnett et al., 2016; Hulteen et al., 2018; Newell, 2020). Indeed, youth-level basketball coaches have been found to have differing notions of FMS, as well as varying ideas as to whom might be responsible for their development (Williams et al., 2021). Consequently, sports organizations may have become reliant on the field of strength and conditioning (S&C) to develop FMS and general physical qualities. For example, within Basketball England's version of the LTAD model, the *Player Development Framework*, the S&C domain is responsible for the development of "all round quality of movement literacy." In relation to this, the meta-analysis by Collins et al. (2019) found that resistance training, which targets muscular strength, positively impacts FMS through neural adaptations (e.g., motor unit recruitment and firing). However, despite the benefits of youth-based S&C training, which includes reducing risk factors for injury and life-long engagement in physical activity (e.g., Faigenbaum et al., 2013; Zwolski et al., 2017; McQuilliam et al., 2020), conventional youth-based S&C practices may lead to the development of movement skills with limited relevance outside of the S&C domain. For example, the development of *athletic movement skills*, such as the overhead squat, hip hinge, and lunge patterns (Woods et al., 2017). Consequently, FMS may not be developed with sufficient diversity to provide underpinning movement capabilities for sports-specific skill development (Young, 2006; Young et al., 2015).

A potential strategy to enrich young athletes' FMS education is the implementation of parkour-related activities (Strafford et al., 2018, 2020). Parkour is an acrobatic sport incorporating a broad range of movement skills and motor abilities, which has been proposed as an activity to develop FMS and general athletic abilities for youth team sports (Strafford et al., 2018, 2020; Wormhoudt et al., 2018). Obtaining transferable athletic capabilities through the implementation of parkour derives from the concept of *donor sports*, which are purported to develop and facilitate the transfer of general movement skills and physical qualities to actions typically performed in a *target sport* (Travassos et al., 2018; Wormhoudt et al., 2018). Given that basketball is characterized by multidirectional movements (Montgomery et al., 2010), the development of youth basketball players would seemingly benefit from the running, jumping, vaulting, and climbing activities that characterize parkour (DeMartini, 2014).

Thus, in this perspective article, we explore the potential for parkour as a donor sport for the development of youth basketball players. In the next sections, we discuss the role of conventional youth-based S&C practice and its limitations, and present alternative perspectives on the development of movement capabilities through an ecological dynamics lens. It is through this lens that we propose parkour as a donor sport for the enriched development of FMS, as well as forming an advanced strength training strategy to facilitate transfer to basketball performance.

THE ROLE OF STRENGTH AND CONDITIONING IN LTAD

A body of research (e.g., DiStefano et al., 2010; Myer et al., 2011; Ayala et al., 2017; Pomares-Noguera et al., 2018) has demonstrated the efficacy of neuromuscular training programs on reducing risk factors for injury in youth populations. Furthermore, other forms of S&C training in youth populations are also supported empirically (Moran et al., 2018a,b, 2019). This includes evidence of windows of trainability for strength, speed, and plyometrics (Moran et al., 2018a,b, 2019). Collectively, this has resulted in the publication of position papers, such as the *National Strength and Conditioning Association's* LTAD position statement and the *British Journal of Sports Medicine's* position statement on youth resistance training, both of which recommend the concurrent development of muscular strength and movement skills in children and adolescents (Lloyd et al., 2014, 2016). Therefore, the role of S&C within the LTAD strategies of sports organizations should be regarded as highly important in reducing risk factors for injury as well as increasing physical performance capabilities (Faigenbaum et al., 2013; Zwolski et al., 2017; Pichardo et al., 2018).

Notwithstanding the aforementioned benefits, a concern relating to the conventional approach to youth-based S&C is the lack of representative movement dynamics for team sports, such as basketball. Indeed, when considered in the context of "open-skill" games that require decision making and a vast array of movement dynamics (Smith, 2016), athletic movement skills may not sufficiently reflect the requirements. To illustrate this, in basketball, offensive players require a large repertoire of action capabilities to evade their opponents, as do defending players who are required to react (Montgomery et al., 2010). Accordingly, it has been argued that to be effective, S&C programs for basketball players need to better represent the diversity of movement demands of the sport (Taylor et al., 2015). This contention may also include plyometric exercise, which provides a stimulus to improve jumping, sprinting, and change of direction capabilities through enhancement of the stretch-shortening cycle (Hernández et al., 2018; Ramirez-Campillo et al., 2020). Although these physical qualities are specific to basketball (Ramirez-Campillo et al., 2020), it has been argued that the importance of the strength-related qualities of agility performance is relatively diminished against the perceptual and decision-making components (Young et al., 2015). Moreover, youth guidelines relating to the prescription of plyometric exercise appear to limit the scope for movement diversity by placing an emphasis on technical proficiency in exercises, such as "in-place hops" ahead of progression to more elaborate jumping variations (Cronin and Radnor, 2019). While the safety of young athletes is of paramount importance, the youth guidelines for plyometric training may serve to discourage exploration and development of jumping skills that are more characteristic of sports, such as basketball.

Without devaluing the importance of conventional S&C training, it may be that despite its emphasis on developing broad FMS within the LTAD framework, there is scope to encourage a vaster array of action capabilities. We propose that the S&C domain further permeates the development of youth athletes by more thoroughly accounting for the decision-making properties and diverse array of movement dynamics that characterizes skilled motor performance. Accordingly, we consider the merit in adopting an ecological dynamics approach to motor learning.

ADOPTING AN ECOLOGICAL DYNAMICS PERSPECTIVE

The ecological dynamics framework is formed from both ecological psychology and dynamics systems theory (O'Sullivan et al., 2020; Rudd et al., 2020). Through the ecological psychology lens, information perceived from the environment specifies the parameters that dictate how a skill is performed (Frère and Hug, 2012). The opportunities for action that an individual perceives from their environment represent what is termed the *affordance landscape* (Davids, 2012; Heras-Escribano and De Pinedo-García, 2018; Savelsbergh and Wormhoudt, 2018). For example, a basketball player preparing to shoot will perceive information relating to the proximity of the defensive player, their own location on the court, and the time left on the shot clock. Collectively, this information will influence the dynamics of the shot with respect to the kinetics and kinematics (Gorman and Maloney, 2016). In a second example, a player in possession of the ball may detect the space between defenders as an opportunity to dribble and *drive* through to advance toward the basket. In this example, based upon the defenders positioning, the attacking player has different action possibilities (affordances) in regard to the direction they may drive (Esteves et al., 2011). Thus, perception of the environment and the subsequent action are considered to be coupled (Smith, 2016).

Within ecological dynamics, in place of fixed movement patterns, the ever-changing nature of information from the environment requires adaptability from the performer to coordinate the appropriate action (Davids et al., 2013; Rudd et al., 2020). In contrast to fixed movement patterns, muscle synergies, which represent neural organizations, enable a vast array of adaptable movement possibilities (Frère and Hug, 2012; Latash, 2012; Bizzi and Cheung, 2013). This is particularly pertinent to how adjustments to an ongoing movement skill occur in response to perturbations (e.g., unexpected changes to surfaces; Newell, 1991; Smith, 2016). Contributing to the vast array of action capabilities is the combination of anatomical characteristics, learned coordinative patterns, and changes to physical output (e.g., force production and stretch-shortening properties), which form an individual's *effectivities* (Witt and Riley, 2014; Wang and Bingham, 2019). Importantly, properties that form effectivities are continually altered across developmental stages of growth and maturation (Ribeiro et al., 2021), in turn necessitating the continual exploration of the affordance landscape with respect to an individual's action capabilities.

THE POTENTIAL OF PARKOUR

Despite popular media portraying parkour as an extreme sport consisting of only large-scale movements that are of high injury risk, such as jumping from buildings or between train carriages (Strafford et al., 2018), expert *Traceurs* have highlighted how contemporary parkour consists of a range of events (e.g., speed-runs and freestyle) which can be performed both in indoor and outdoor environments (Strafford et al., 2020). Hence, parkour is characterized by a variety of movements utilized to navigate obstacles and is practiced in various forms and contexts (Aggerholm and Højbjerre Larsen, 2017). The potential of parkour to enrich FMS is based upon the concept of donor sports, which is derived from the Athletic Skills Model (ASM; Wormhoudt et al., 2018). The ASM, which adopts an ecological dynamics perspective, purports that exposure to activities that share common characteristics (e.g., skills and abilities) can be transferred or "donated" to a target sport (Strafford et al., 2018; Rudd et al., 2020). Parkour invites different ways of moving based upon the performer's perception of surroundings and promotes creativity to navigate gaps and obstacles (Aggerholm and Højbjerre Larsen, 2017; Rudd et al., 2020). Given these characteristics, Strafford et al. (2018) propose that the incorporation of parkour-related activities could provide a platform for youth athletes to develop FMS that could be transferred to other sports. For example, the use of obstacle courses, termed *speed-runs*, which require the participant to navigate as efficiently as possible, can be used to encourage transferable agility skills (Strafford et al., 2021). Indeed, irrespective of the target sport, exposure to parkour-based activities, such as speed-runs, may be particularly pertinent during pre-adolescence, which is regarded as a period of sensitivity for developing FMS due to high levels of neural plasticity (Myer et al., 2015; Ng and Button, 2018). However, for the purposes of *fine tune* existing neural pathways and muscle synergies, and to take advantage of the still high levels of neural plasticity retained in adolescence (~13 years of age and above; Myer et al., 2013, 2015), parkour-based activities may continue to play an important role in athletic development.

Although currently, evidence directly examining the benefits of parkour training on basketball is limited, significant correlations between performance tests typically used in basketball (e.g., vertical jump and T-test) and performance in a parkour speed-run has been demonstrated (Strafford et al., 2021). Furthermore, Abellán-Aynés and Alacid (2016) present parkour as an effective training method for developing agility, horizontal, and vertical jump abilities. Alongside jumping and agility, parkour training interventions have also demonstrated improved cardiorespiratory fitness with increases in peak oxygen uptake, oxygen uptake at anaerobic threshold, heart rate at anaerobic threshold, and running speed at anaerobic threshold (Dvorak et al., 2017).

Regarding basketball, owing to similarities between actions, parkour-based activities may also be considered for their potential as a donor for the specific development of action capabilities in youth players. For example, in parkour, the *tic tac* action, which is characterized by pushing off of a wall with the ball of the foot to gain height (Witfeld et al., 2011), requires spatial orientation and use of perceptual information from the foot contact to determine the subsequent phase of the movement (Strafford et al., 2018). Therefore, this action may present developing basketball players with the opportunity to explore their capabilities to decelerate, propel, land, and then, move in a new direction. Furthermore, through what has been termed "synergistic adaptation," the introduction of strength training to youth basketball players will likely augment changes to force production that naturally occur as a result of growth and maturation (Moran et al., 2017; Peitz et al., 2018). In turn, this will alter the players' effectivities (force capabilities), which necessitates the continued exploration of the affordance landscape with respect to their action capabilities. To illustrate this, the use of plyometric training, which has been found to enhance the jumping capabilities of youth basketball players (Gonzalo-Skok et al., 2019), logically, enables players to express improved jumping capabilities within the game. For example, in the execution of rebounding the ball. Rebounding involves an offensive or defensive player aerially competing for possession of the ball after a missed shot attempt. However, depending upon the specific scenario presented, the player may be required to use various jumping actions to successfully rebound the ball (Krause and Nelson, 2018). Therefore, despite a player's enhanced force characteristics, in the absence of the players exploring their jump action capabilities beyond the plyometric regimen, there may be a limited transfer of the adaptations to sport-specific contexts. In this regard, parkour-based actions need not be advanced beyond those identified as relevant to the affordance landscape. Instead, the actions remain efficacious for the process of *recalibration*, which represents an updating of the mapping of the contributing units to the execution of a movement skill (Davids et al., 2012).

Although it may be argued that basketball-specific practice would better facilitate transfer of improved force-related capabilities, problematically, the greater levels of representativeness that basketball-specific practice presents may provide cognitive and decision-making demands that are too high (Farrow and Robertson, 2017). Therefore, youth players may fail to sufficiently explore the affordance landscape in relation their altered physical capabilities. This is not to appear contradictory to the premises of ecological dynamics already considered in regard to the coupling of perception and action; instead, it distinguishes between the effectivities (those impacted by S&C) of the individual player and the more complex environment that represents the sport (Woods et al., 2020). In this regard, affordances are both objective, for example, the properties of a given playing surface, and subjective, which relate to an individual's perception of their own capabilities (Davids et al., 2008). With reference to the latter, the detection of affordances therefore relates to an athlete's current effectivities (Wang and Bingham, 2019; Ribeiro et al., 2021). Where the properties of effectivities are enhanced through conventional S&C training, parkour movement training is proposed to sit between conventional S&C training and that of basketball-specific training. However, as with any training modality, caution should be exercised to avoid excessive workload being placed upon youth athletes, especially in the form of repetitive movement patterns (Leppänen et al., 2015). Notwithstanding this, when programmed appropriately, theoretically, the inclusion of parkour-based activities would enable the youth player to perceive their action capabilities and detect new affordances transferable to their sport.

APPLICATION AS AN ADVANCED STRENGTH TRAINING STRATEGY

An important consideration in the development of adolescent basketball players is that the number of basketball-specific practice hours will generally increase proportional to the time spent in other physical activities (Jayanthi et al., 2013). Therefore, the inclusion of parkour activities will likely be dependent on the constraints of time. Accordingly, at this stage of development, the use of parkour activities might form part of a more advanced strength training strategy and adopt a more thoughtful and individually tailored approach. In this regard, parkour activities should be considered by S&C coaches alongside an evaluation of the specific sporting action being targeted.

To account for time constraints, parkour activities could theoretically be embedded within the S&C program itself. For example, this could take the form of a complex training regimen, with parkour actions performed concurrently within the same training session as conventional S&C training exercises. Complex training has previously been shown as an effective method to improve sprint and vertical jump performance in young (<20 years) basketball players (Santos and Janeira, 2008; Freitas et al., 2017). Commonly, this training method requires athletes to perform a strength-oriented exercise, such as a barbell back squat followed by a plyometric-oriented exercise that shares similar mechanics, therefore providing a potentiating effect on the subsequent exercise (Santos and Janeira, 2008). Where the paired exercise in this example would typically include a jumping exercise, such as a countermovement jump (Freitas et al., 2017), vaulting activities or tic tac actions could be included in its place, or in combination through alternating sets. With regard to the latter, from an ecological dynamics perspective, this approach would challenge players to explore the affordance landscape under conditions of the post-activation potentiation response from the strength-oriented exercise, augmenting the neural contribution to the subsequent parkour action in each set of the exercise, as is the aim of complex training (Freitas et al., 2017). Moreover, the varied jumping patterns would present players with more varied landing challenges than those in conventional complex training, which may better prepare players for scenarios encountered within the sport. While currently, no known loading parameters exit for parkour-based actions, it would appear prudent to follow the guidelines for contacts that are typical of plyometric and complex training regimens. However, research is required to validate these suppositions.

SAFETY PRECAUTIONS

Parkour UK, the governing body for parkour in the United Kingdom, has developed its own risk-benefit assessment and provides standards relating to equipment and codes of practice. However, its growing popularity is illustrated by the emergence of YouTube videos displaying high-risk maneuvers in urban settings (DeMartini, 2014). Therefore, where parkour actions are being considered within the LTAD programs of young athletes, risk-benefit should be considered, and an emphasis placed on performing parkour safely. Moreover, when introduced, it should be stressed to the young athletes that the parkour activities are to be performed in supervised sessions only.

CONCLUDING REMARKS

Given the S&C domain's influence in the LTAD of youth athletic populations, we propose that the field expands its influence to capture both the decision-making and movement dynamics properties that may better represent the characteristics of sports performance. While the efficacy of conventional S&C is not in question, we have argued that through the adoption of concepts from the ecological dynamics' framework, the S&C domain might better equip children and adolescents with diverse and adaptable action capabilities. Moreover, this would develop perceptual aspects of performance, and the interdependency of environment and movement dynamics. From this perspective, the implementation of parkour as a donor sport for youth basketball players might enrich their action capabilities and facilitate the transfer of conventional forms of S&C to basketball performance.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors contributed to the writing of the manuscript. MW and BS conceived the presented idea. MW developed the application of parkour to basketball and how strength training modalities could be advanced with parkour-based activities. MW took the lead on writing the manuscript with BS very much influencing the work and contributing to the writing of the parkour and ecological dynamics aspects of the manuscript. JM provided critical thought relating to the LTAD and strength training elements. JM also contributed to the critical analysis and writing of the manuscript. JS contributed to the shape of the work and provided input relating to the ecological dynamics framework.

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SYSTEMATIC REVIEW
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Effects of Plyometric Jump Training on Balance Performance in Healthy Participants: A Systematic Review With Meta-Analysis

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Background: Postural balance represents a fundamental movement skill for the successful performance of everyday and sport-related activities. There is ample evidence on the effectiveness of balance training on balance performance in athletic and non-athletic population. However, less is known on potential transfer effects of other training types, such as plyometric jump training (PJT) on measures of balance. Given that PJT is a highly dynamic exercise mode with various forms of jump-landing tasks, high levels of postural control are needed to successfully perform PJT exercises. Accordingly, PJT has the potential to not only improve measures of muscle strength and power but also balance.

Objective: To systematically review and synthetize evidence from randomized and non-randomized controlled trials regarding the effects of PJT on measures of balance in apparently healthy participants.

Methods: Systematic literature searches were performed in the electronic databases PubMed, Web of Science, and SCOPUS. A PICOS approach was applied to define inclusion criteria, (i) apparently healthy participants, with no restrictions on their fitness level, sex, or age, (ii) a PJT program, (iii) active controls (any sport-related activity) or specific active controls (a specific exercise type such as balance training), (iv) assessment of dynamic, static balance pre- and post-PJT, (v) randomized controlled trials and controlled trials. The methodological quality of studies was assessed using the Physiotherapy Evidence Database (PEDro) scale. This meta-analysis was computed using the inverse variance random-effects model. The significance level was set at $p < 0.05$.

Results: The initial search retrieved 8,251 plus 23 records identified through other sources. Forty-two articles met our inclusion criteria for qualitative and 38 for quantitative analysis (1,806 participants [990 males, 816 females], age range 9–63 years). PJT interventions lasted between 4 and 36 weeks. The median PEDro score was 6 and no study had low methodological quality ($\leq$3). The analysis revealed significant small effects of PJT on overall (dynamic and static) balance ($ES = 0.46$; 95% $CI = 0.32–0.61$; $p < 0.001$), dynamic (e.g., Y-balance test) balance ($ES = 0.50$; 95% $CI = 0.30–0.71$; $p < 0.001$), and static (e.g., flamingo balance test) balance ($ES = 0.49$; 95% $CI = 0.31–0.67$; $p < 0.001$). The moderator analyses revealed that sex and/or age did not moderate balance performance outcomes. When PJT was compared to specific active controls (i.e., participants undergoing balance training, whole body vibration training, resistance training), both PJT and alternative training methods showed similar effects on overall (dynamic and static) balance ($p = 0.534$). Specifically, when PJT was compared to balance training, both training types showed similar effects on overall (dynamic and static) balance ($p = 0.514$).

Conclusion: Compared to active controls, PJT showed small effects on overall balance, dynamic and static balance. Additionally, PJT produced similar balance improvements compared to other training types (i.e., balance training). Although PJT is widely used in athletic and recreational sport settings to improve athletes' physical fitness (e.g., jumping; sprinting), our systematic review with meta-analysis is novel in as much as it indicates that PJT also improves balance performance. The observed PJT-related balance enhancements were irrespective of sex and participants' age. Therefore, PJT appears to be an adequate training regime to improve balance in both, athletic and recreational settings.

Keywords: plyometric exercise, human physical conditioning, resistance training, movement, postural control, exercise

INTRODUCTION

Balance is the constant process of maintaining the center of mass vertically aligned above the base of support (feet). Postural control relies on feedforward and feedback mechanisms producing sensory information through the visual, vestibular and proprioceptive systems that are integrated and processed within the central nervous system and result in effective and coordinated neuromuscular responses (Brachman et al., 2017). There is evidence that balance performance is task specific and therefore denoted as a skill and not an ability (Haddad et al., 2013; Fong et al., 2016; Dunsky et al., 2017; Khallaf, 2020). Accordingly, it can be divided into two categories, dynamic and static balance. Dynamic balance refers to the capacity to perform a task while maintaining or regaining a stable position during locomotion (Winter et al., 1990; Kibele et al., 2015). Static balance is defined as the capacity to maintain the center of mass above the base of support with minimal movement (Hrysomallis, 2011). Balance is not only an important prerequisite for the performance of everyday tasks and the avoidance of falls but also for the successful performance of sport-specific skills in athletic populations (Boccolini et al., 2013). There is evidence that performance in bipedal static balance significantly correlated ($r = 0.51$, $p < 0.05$) with shooting accuracy. Better balance performances were noted in athletes of higher compared with lower expertise level (Mason and Pengrim, 1986). Moreover, performance in bipedal static balance was significantly associated ($r = -0.29$ to -0.45, $p < 0.05$) with shooting accuracy in novice rifle shooters (Mononen et al., 2007). In addition, performance in dynamic bipedal balance significantly correlated ($r = 0.65$, $p < 0.05$) with maximum skating speed in male ice hockey players aged $\leq$ 20 years (Behm et al., 2005). Besides the reported associations with performance measures, balance performance appears to be related to injury risk. Of note, high school basketball players (males and females) with balance deficits had a sevenfold increase in the risk of sustaining ankle sprains (McGuine et al., 2000). A review of the literature found that balance deficits were associated with an increased risk of injuries, including ankle sprains, muscle-tendon and ligament injuries in athletes from various sports (Brachman et al., 2017).

With reference to the principle of training specificity (Behm and Sale, 1993), balance training is usually applied if the goal is to improve balance in healthy participants (Lesinski et al., 2015a,b; Gebel et al., 2018, 2020). However, less is known on potential transfer effects of other training types (e.g., plyometric jump training [PJT]) on measures of dynamic and static balance. Commonly, PJT includes exercises that have the potential to activate large muscle groups (e.g., quadriceps). A large number of PJT drills (e.g., drop jumps) are performed in the stretch shortening cycle (SSC). The SSC is characterized by muscle-tendon lengthening during the braking phase, followed by muscle-tendon shortening during the propulsion phase (Chmielewski et al., 2006; Ramírez-Campillo et al., 2018, 2020a). The inclusion of unilateral, bilateral jump/landing drills in different directions (e.g., vertical, horizontal, lateral) and on different surfaces (e.g., stable; unstable) may provide adequate training stimuli for the somatosensory system which is responsible for controlling the body segments in space (Zech et al., 2010; Hoch et al., 2011; Peterka, 2018). Therefore, PJT exercises challenge the neuromuscular system to a high degree (Witzke and Snow, 2000; Hewett et al., 2002). Given that PJT is a highly dynamic exercise type with various forms of dynamic jump-landing tasks, high levels of postural control are needed to successfully perform PJT exercises. Accordingly, PJT has the potential to not only improve measures of muscle strength and power but also balance (Myer et al., 2006; Huang et al., 2014; Surakhamhaeng et al., 2020). Of note, PJT exercises are often incorporated in neuromuscular or multimodal training programmes which amongst other exercise types combine balance and PJT drills with the goal to improve muscle strength, balance and reduce the risk of sustaining injuries (Zemková and Hamar, 2018; Caldemeyer et al., 2020; Crossley et al., 2020). However, with reference to the relevant literature, it is not possible to elucidate the independent or isolated effect of PJT exercises within a multimodal exercise programme. With regards to PJT as single intervention programme, the available literature showed controversial effects of PJT on measures of balance in different cohorts. While Ramírez-Campillo et al. (2015b) and Makhlouf et al. (2018) reported small-to-moderate PJT effects on dynamic (i.e., Y balance test [YBT]) and static balance (i.e., stork balance test) in youth soccer players, Meszler and Váczi (2019) as well as Asadi and Arazi (2012) showed no significant effects of PJT on dynamic (i.e., star excursion balance test [SEBT]) and static balance (i.e., single-leg balance test) in youth basketball players. Accordingly, it is timely to systematically aggregate the effects of PJT on balance performance in healthy participants.

The rationale to address the proposed research question through a systematic review with meta-analysis is manifold. First, a systematic review with meta-analysis allows to aggregate the results of the available peer-reviewed literature, potentially solving the issue of controversial effects of PJT on measures of balance reported in original research. Second, a limitation of studies exploring the effects of PJT interventions is that the study outcomes are based on rather small sample sizes. Of note, a low number (i.e., <10) of participants in experimental groups is very common among PJT interventions (Ramírez-Campillo et al., 2018, 2020c). The methodological limitation of underpowered studies may partially be addressed by conducting a systematic review with meta-analysis. Third, the number of PJT-related publications in general and the number of PJT studies focusing on the effects of training on balance performance in particular has tremendously increased (25-fold) between 2000 and 2017 (Ramírez-Campillo et al., 2018). Such an increase in rate of novel publications calls for constant updates of the literature. A systematic review with meta-analysis provides an overview of the currently available literature, favoring an adequate perspective for the advancement in the field through the reporting of strengths and gaps in the literature, limitations and shortcomings related to PJT interventions. Fourth, a meta-analysis allows to aggregate the sample sizes from different studies, and may provide not only high-quality evidence, but also new insights for practitioners that help to take evidence-based decisions regarding the implementation of PJT (Murad et al., 2016).

Therefore, the primary aim of this systematic review with meta-analysis was to determine the effects of PJT compared with active controls on dynamic and static balance in apparently healthy participants. We were additionally interested in elucidating the effects of PJT on balance performance compared with specific active controls (e.g., balance training). To our knowledge, this is the first systematic review with meta-analysis that examines the effects of PJT vs. active and passive controls on balance in apparently healthy participants.

METHODS

Procedures

A systematic literature review with meta-analysis was conducted following previously published recommendations (Liberati et al., 2009). The study was registered in PROSPERO (International Prospective Register of Systematic Reviews), an international database for systematic reviews prospectively registered by the Center for Reviews and Dissemination of the University of York (https://www.crd.york.ac.uk/prospero; CRD42021236748).

Literature Search

Computerized literature searches were conducted in the electronic databases PubMed, Web of Science, and SCOPUS. To conduct the literature search, we considered recommendations from the two largest scoping reviews that have previously examined PJT (Ramírez-Campillo et al., 2018, 2020c). Additionally, potentially relevant keywords were collected through expert opinion. In particular, 10 distinguished experts in the field of PJT (i.e., plyometric exercise), identified through the website *Experstcape* (https://expertscape.com), were contacted to list the most appropriate key words. Organized vocabulary (i.e., Medical Subject Headings: MeSH) were also incorporated. As a result, the following key words were introduced in the electronic databases in different combinations using a Boolean search strategy with the operators "AND" and "OR": jump, ballistic, complex, explosive, force, velocity, plyometric, stretch, shortening, and cycle.

Administration and Update of the Systematic Review

Electronic searches were conducted according to the specific characteristics of each electronic database search engine. After an initial search in April 2017 (Ramírez-Campillo et al., 2018), accounts were created in each of the respective databases, and through these, automatically generated email updates (PubMed alerts) were received with regards to the selected search terms. The search was refined in May 2019 (Ramírez-Campillo et al., 2020c), and updates were received daily (if available); studies were eligible for inclusion up to February 1st, 2021. The main advantage of this search approach is that it assumes that new knowledge will appear and allow improvements in sport/clinical decision-making. Indeed, the rate of PJT studies increased exponentially during the last years (Ramírez-Campillo et al., 2020c). As previously recommended (Van Der Vlist et al., 2021), we designed a protocol to extract the relevant information for this systematic review.

One of the authors (RRC) conducted the initial search and removed duplicates. Thereafter, the search results were analyzed according to the eligibility criteria. In selecting studies for inclusion, a review of all relevant titles was conducted before examination of the abstracts and full-texts. Following the formal systematic searches, additional manual searches were conducted using the authors' personal libraries and published narrative/scoping/systematic reviews and meta-analyses. Two authors (AR and US) independently screened the titles, abstracts and/or full-text versions of the retrieved studies. During the search and review process, potential discrepancies between the two authors regarding inclusion and exclusion criteria (e.g., type of control group, intervention adequacy) were resolved through consensus by including a third author (RRC).

Inclusion and Exclusion Criteria

A PICOS (participants, intervention, comparators, outcomes, and study design) approach was used to rate studies for eligibility (Liberati et al., 2009). The respective inclusion/exclusion criteria adopted in our meta-analysis were reported in **Table 1**.

Additionally, only full-text, peer-reviewed and original research were considered eligible for this meta-analysis. Books, book chapters, and congress abstracts, as well as cross-sectional papers, and training-related studies that did not focus on the effects of PJT exercises on balance performance (e.g., studies examining the effects of upper-body plyometric exercises) were excluded. We additionally excluded retrospective studies, studies in which the use of jump exercises was not clearly described, studies of which the abstract was available only, case reports, special communications, letters to the editor, invited commentaries, errata, overtraining studies, and detraining studies. In the case of detraining studies, if a training period was included prior to the detraining period, the study was considered for inclusion. Finally, in view of the potential difficulties of translating articles written in different languages—and the fact that 99.6% of the PJT literature is published in English (Ramírez-Campillo et al., 2018), only articles written in English were considered for this meta-analysis.

Data Extraction

Means and standard deviations (SDs) of balance tests (e.g., dynamic, static, unipedal, bipedal, eyes closed, and eyes open) were used to evaluate the effects of PJT vs. active controls (any sport-related activity) or specific active controls (a specific exercise type such as balance training). For studies reporting values other than means and SDs (e.g., median, range, interquartile range, standard error values) conversion was applied as previously recommended (Wan et al., 2014; Lee et al., 2015). Different balance tasks were considered (for a full description, see **Supplementary Table 1**) as these may reflect different physiological and biomechanical indicators relevant to overall balance performance (Hrysomallis, 2008; Ricotti, 2011). A high intraclass correlation coefficient ($\geq$0.8) and a low coefficient of variation ($<$7%) for different balance performance measures (e.g., anterior-posterior balance; medial-lateral balance; normal stance; perturbed stance; eyes open-closed; Y-balance test) has been reported previously (Ramírez-Campillo et al., 2015b); which is essential to ensure strong consistency between the analyzed studies within a meta-analysis (Liberati et al., 2009). In cases where the required data were not clearly or completely reported, the authors of the study were contacted for clarification. If no response was obtained from the authors (after two attempts), or if the authors could not provide the requested data, the study outcome was excluded from further analysis. If data were only displayed in the form of figures but not tables, the data were extracted using software to receive the relevant numbers (WebPlotDigitizer; https://apps.automeris.io/wpd/) to derive the relevant numerical data. This procedure has proven to be valid ($r = 0.99$, $p < 0.001$) (Drevon et al., 2017). Two authors (AR and US) performed data extraction independently, and discrepancies between authors (e.g., mean value for a given outcome, total number of participants in a group) were resolved through consensus with a third author (RRC).

Data were extracted from the included studies using a form created in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). Extracted data included the following information: the first author's name, study identification code (e.g., DOI), year of publication, PJT treatment description, description of the comparator (active vs. specific-active control), type of randomization, number of participants per group. We also extracted data regarding the participants' sex, age (years), body mass (kg), height (m), and previous experience with PJT. If applicable, the type and level (e.g., professional, amateur) of sport practice were also extracted. Regarding PJT programming parameters, we reported weekly frequency of training (days/week), duration (weeks), intensity level (e.g., maximal), and proxies of intensity (e.g., jumping height), jump box height (cm), number of total jumps completed during the intervention, types of jump drills performed, combination (if applicable) of PJT with another form of training type, rest time between sets (s), rest time between repetitions (s), rest time between sessions (hours), type of jumping surface (e.g., grass), type of progressive PJT overload (e.g., volume-based; technique-based), training period during the year (e.g., in-season), replaced (if applicable) portion of the regular training through PJT drills, tapering strategy (if applicable). A complete description of the PJT characteristics has been previously published (Ramírez-Campillo et al., 2018).

Methodological Quality of the Included Studies

The Physiotherapy Evidence Database (PEDro) scale was used to assess the methodological quality of the included studies, which were rated from 0 (lowest quality) to 10 (highest quality). The validity and reliability of the PEDro scale has been established previously (Maher et al., 2003; de Morton, 2009; Yamato et al., 2017). Additionally, its agreement with other scales (e.g., Cochrane risk of bias tool) has been reported (Moseley et al., 2019). Moreover, the PEDro scale is probably the most frequently used scale in the PJT literature. Accordingly, it helps to make comparisons between meta-analyses. According to cut-off scores, the methodological quality was rated as "poor" ($<$4), "fair" (4–5), "good" (6–8), and "excellent" (9–10) in some sub-fields, however, it is not possible to satisfy all scale items in some areas of physiotherapy practice (Cashin and McAuley, 2020). Therefore, as outlined in previous systematic reviews in the sub-field of

TABLE 1 | Selection criteria used in the meta-analysis.

Category	Inclusion criteria	Exclusion criteria
Population	Healthy participants, with no restrictions on their fitness level, sex, or age.	Participants with health problems (e.g., injuries, recent surgery).
Intervention	A plyometric jump training programme, defined as lower body unilateral or bilateral bounds, jumps, and hops that commonly utilize a pre-stretch or countermovement stressing the stretch-shortening cycle.	Exercise interventions not involving plyometric jump training or exercise interventions involving plyometric jump training programmes representing less than 50% of the total training load when delivered in conjunction with other training interventions (e.g., high-load resistance training).
Comparator	Active or passive control group.	Absence of a control group.
Outcome	At least one measure related to balance (dynamic; static) before and after the training intervention.	Lack of baseline and/or follow-up data.
Study design	Multi-arm trials.	Single arm trials/observational studies.

PJT, the methodological quality of PJT studies was interpreted using the following convention (Stojanović et al., 2017; Ramírez-Campillo et al., 2020d, 2021b): ≤3 points was considered as poor quality, 4–5 points was considered as moderate quality, and 6–10 points was considered as high quality. If trials were already rated and listed in the PEDro database, the respective scores were adopted. The methodological quality of each included study was assessed independently by two authors (AR and US), and any discrepancies between the two authors were resolved via consensus with a third author (RRC).

Summary Measures, Synthesis of Results, and Publication Bias

Studies were meta-analytically aggregated if three or more relatively homogeneous studies were available for the same outcome measure. Effect sizes (ES; Hedge's g) were calculated for each measure of balance using means and SDs from pre- and post-tests for each dependent variable. For studies that reported standard errors (Nobre et al., 2017; Ritzmann et al., 2018), SDs were calculated by multiplying the standard error with the square root of the sample size (Lee et al., 2015). Data were standardized using post-intervention SD values. The random-effects model was used to account for differences between studies that might impact PJT effects (Deeks and Higgins, 2008; Kontopantelis et al., 2013). The ES values were presented with 95% confidence intervals (95% CIs). The ES magnitudes were interpreted using the following scale: <0.2, trivial; 0.2–0.6, small; >0.6–1.2, moderate; >1.2–2.0, large; >2.0_4.0, very large; >4.0, extremely large (Hopkins et al., 2009). In studies including more than one intervention group, the sample size of the active and specific-active control group was proportionately divided to facilitate comparisons across multiple groups (Higgins and Deeks, 2008). The impact of study heterogeneity was assessed using the I^2 statistic, with values of <25%, 25–75%, and >75% representing low, moderate, and high levels, respectively (Higgins and Thompson, 2002). The risk of reporting bias was explored (with at least 10 studies) (Sterne et al., 2011) using the Egger's test (Egger et al., 1998), with $p < 0.05$ implying bias. To adjust for risk of reporting bias, a sensitivity analysis was conducted using the trim and fill method (Duval and Tweedie, 2000), with L_0 as the default estimator for the number of missing studies (Shi et al., 2019). All analyses were carried out using the Comprehensive Meta-Analysis software (Version 2.0; Biostat, Englewood, NJ, USA). The level of statistical significance was set at $p < 0.05$.

Moderator Analyses

Using a random-effects model and independent computed single factor analysis, potential sources of heterogeneity likely to influence the effects of PJT were selected a priori.

Subgroup Analyses

As the adaptive responses to PJT programmes may be affected by moderators such as sex (de Villarreal et al., 2009), age (Asadi et al., 2017; Moran et al., 2017a, 2019), and training background (Sáez de Villarreal et al., 2012), these factors were considered as potential moderator variables, using a categorical approach (e.g., male vs. female). Additionally, we examined the effects of PJT taking the different test situations into account (i.e., laboratory-based balance tests vs. field-based balance tests).

Single Factor Analyses

Single factor analyses were computed for the programmes parameter duration of intervention (number of weeks and total number of training sessions) (de Villarreal et al., 2009) and training frequency (number of weekly sessions) (de Villarreal et al., 2010) based on the reported influence of these variables on physical fitness adaptations to PJT. When appropriate, subgroup analyses and single factor analyses were divided using the median split technique (Moran et al., 2017b, 2018, 2019). The median was calculated if at least three studies provided data for a given moderator. Of note, if two experimental groups were included in a study with the same information for a given moderator (e.g., both experimental groups used a programme duration of 7 weeks), only one of the groups was considered in order to avoid an undue influence on the median calculation. In addition, to minimize heterogeneity, median values were calculated using only those studies that provided data for the outcome being analyzed. When appropriate, a logical defensible rationale was used instead of the median. A posteriori, moderator analyses were included for PJT studies that added training load to participants regular activities (e.g., sport practices) compared to those that replaced part of the regular activities with PJT.

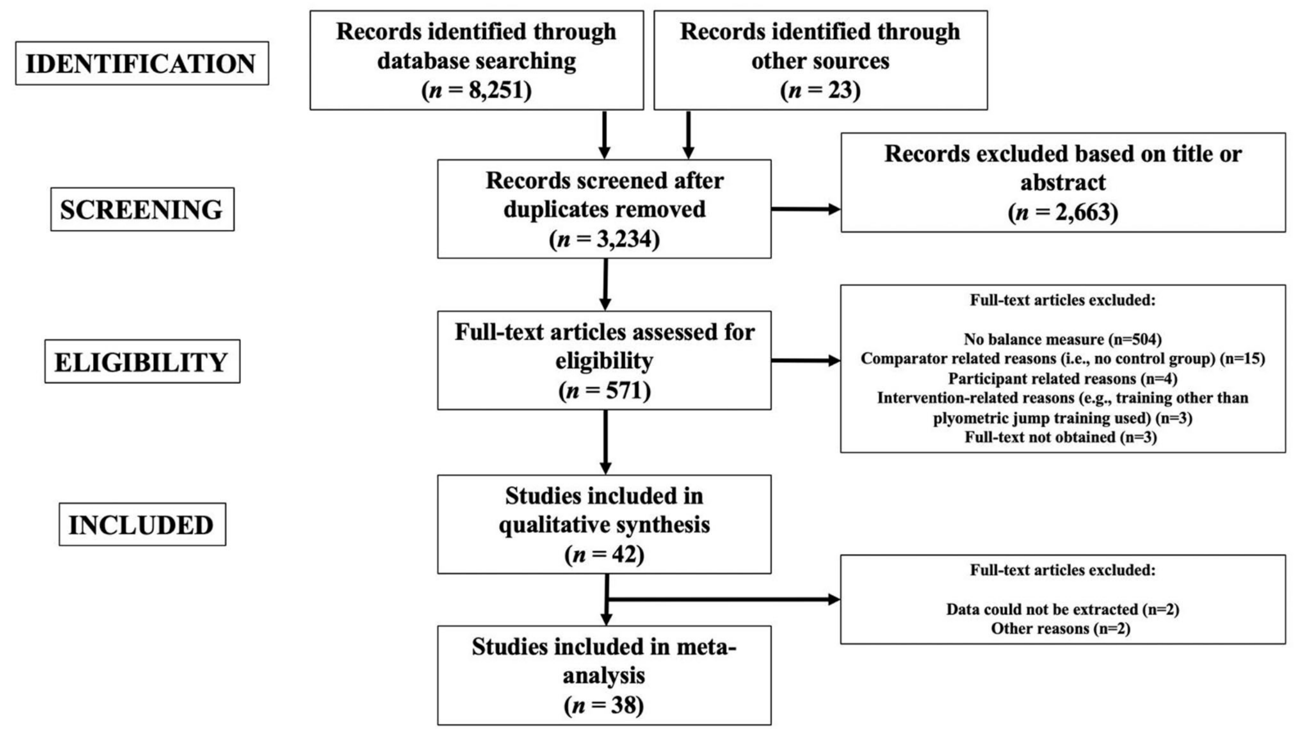

FIGURE 1 | The PRISMA flow diagram.

RESULTS

Study Selection

The search process identified 8,251 studies (2,632 from PubMed; 2,612 from SCOPUS; and 3,007 from WOS). **Figure 1** provides a flow chart illustrating the study selection process. Duplicate studies were removed ($n = 5{,}017$). After study titles and abstracts were screened, 2,663 studies were removed and 571 full-text studies were screened.

Forty-two studies were included for qualitative assessment: (Witzke and Snow, 2000; Myer et al., 2006; McLeod et al., 2009; Asadi and Arazi, 2012; Asadi, 2013; Chaouachi et al., 2014a,b; Faigenbaum et al., 2014; Huang et al., 2014; Piirainen et al., 2014; Asadi et al., 2015; Ramírez-Campillo et al., 2015a,b; Trecroci et al., 2015; Benis et al., 2016; Karadenizli, 2016; Kim and Park, 2016; Hopper et al., 2017; Nobre et al., 2017; Arabatzi, 2018; Makhlouf et al., 2018; Ritzmann et al., 2018; Alikhani et al., 2019; Cherni et al., 2019; Hammami et al., 2019a,b,c, 2020a,b,c; Jlid et al., 2019, 2020; Lovecchio et al., 2019; Meszler and Váczi, 2019; Tay et al., 2019; Akin and Kesilmiş, 2020; Bouteraa et al., 2020; Cigerci and Genc, 2020; Drouzas et al., 2020; Lee et al., 2020; Surakhamhaeng et al., 2020; Porrati-Paladino and Cuesta-Barriuso, 2021).

For meta-analysis, 38 studies were considered eligible: (Witzke and Snow, 2000; Myer et al., 2006; McLeod et al., 2009; Chaouachi et al., 2014b; Huang et al., 2014; Piirainen et al., 2014; Asadi et al., 2015; Ramírez-Campillo et al., 2015a,b; Trecroci et al., 2015; Benis et al., 2016; Karadenizli, 2016; Kim and Park, 2016; Hopper et al., 2017; Nobre et al., 2017; Arabatzi, 2018; Makhlouf et al., 2018; Ritzmann et al., 2018; Alikhani et al., 2019; Cherni et al., 2019; Hammami et al., 2019a,b,c, 2020a,b,c; Jlid et al., 2019, 2020; Lovecchio et al., 2019; Meszler and Váczi, 2019; Tay et al., 2019; Akin and Kesilmiş, 2020; Bouteraa et al., 2020; Cigerci and Genc, 2020; Drouzas et al., 2020; Lee et al., 2020; Surakhamhaeng et al., 2020; Porrati-Paladino and Cuesta-Barriuso, 2021).

Participant characteristics and PJT programmes of the included studies were detailed in **Tables 2**, **3**, respectively.

Methodological Appraisal of the Included Studies

According to the PEDro checklist, the median score was 6. Seven studies (4–5 points) showed moderate quality, and 35 studies were of high quality (6 points; no study scored above 6 points) (**Table 4**).

Study Characteristics

A total of 1,061 participants were analyzed in the intervention arms and 745 participants were assessed in the active control groups; of those $n = 142$ were specific-active controls (7 groups). The duration of the training programmes in the intervention and control groups ranged from 4 to 36 weeks and the frequency of weekly training sessions ranged from 1 to 3 in most studies, except for Ritzmann et al. (2018), in which 5–6 sessions/week were conducted. Of the 42 studies, 19 included PJT interventions

TABLE 2 | Participant's characteristics the included studies$.

Study	Randomized	N	Sex	Age (years)	Body mass (kg)	Height (m)	SPT experience	Fitness*	Sport
Akin and Kesilmiş (2020)	NR	20	M/F	15–19	NR	NR	NR	Normal	Taekwondo
Alikhani et al. (2019)	Yes	22	F	22	NR	NR	NR	Normal	Badminton
Arabatzi (2018)	Yes	24	M/F	9.3	36.3	1.3	No	Low	NA
Asadi and Arazi (2012)	Yes	18	M	18/ 20.4	76/60.3	1.8/1.8	No	High	Basketball
Asadi (2013)	Yes	20	M	20.2	78.5	1.82	NR	Normal	Basketball
Asadi et al. (2015)	Yes	16	M	20.1	76.4	1.85	NR	Moderate	Basketball
Benis et al. (2016)	Yes	28	F	20	62	1.72	NR	Moderate	Basketball
Bouteraa et al. (2020)	Yes	26	F	16.4	56.6	1.68	NR	Normal	Basketball
Chaouachi et al. (2014b)	Yes	26	M	13.7 /13.5	45.9/ 46.7	1.6/1.58	NR	Normal	Physical education students
Chaouachi et al. (2014a)	Yes	30	M	11	40.1	1.49	No	Normal	Judo
Cherni et al. (2019)	Yes	25	F	20.9/21	65.1/67.3	1.7/1.7	NR	High	Basketball
Cigerci and Genc (2020)	No	20	M	15.9/15.42	69.5/ 65	1.8 /1.7	NR	NCR	Basketball
Drouzas et al. (2020)$	Yes	45	M	9.9/10.0/10.2	39.3/36.1/38.5	1.4/1.34 /1.4	NR	Normal	Soccer
Faigenbaum et al. (2014)	Yes	40	M/F	7.6	29.5	1.24	No	Normal	NA
Hammami et al. (2019c)	Yes	41	F	13.5/13.3	42.6/42.3	1.4/1.4	NR	Moderate	Handball
Hammami et al. (2019a)	Yes	28	M	14.5/14.4	69.3	1.78	Yes	Moderate	Handball
Hammami et al. (2019b)	Yes	28	F	16.6	60.8	1.63	Yes	Moderate	Handball
Hammami et al. (2020a)	Yes	21	M	16.2/16.4/16.5	70.8/69.7/ 70.5	1.8/1.78/1.79	Yes	High	Handball
Hammami et al. (2020c)	Yes	34	F	15.8/15.8	64.2/63.0	1.66/1.67	Yes	High	Handball
Hammami et al. (2020b)	Yes	26	M	16.2/16.3/16.4	59.8/60.9/58.9$	1.78/1.77/1.78	NR	High	Soccer
Hopper et al. (2017)	Yes	23	F	12.1/12.3	50.7/53.3	1.64/1.63	No	Moderate	Netball
Huang et al. (2014)	Yes	20	M/F	23.20 /23.50	69.40/70.30$	169.30/ 170.60	NR	Normal	Mixed sports
Jlid et al. (2019)	Yes	28	M	11.8/ 11.6	36.5/ 34	1.43/1.42	NR	Moderate	Soccer
Jlid et al. (2020)	Yes	27	M	19/19	67.6/ 69.2	1.76/1.76	NR	Moderate	Soccer
Karadenizli (2016)	Yes	26	F	15.6/15.4	56.4/55.9	1.61/1.60	NR	Moderate	Handball
Kim and Park (2016)	Yes	28	F	23.5/23.2	70.2/70.3	1.78/1.76	NR	High	Volleyball
Lee et al. (2020)	Yes	14	M	22.0/23.57	69.57/66.57	1.72/1.73	NR	Moderate	Taekwondo
Lovecchio et al. (2019)	Yes	63	M	14–15	62.6/ 60.5	1.73/1.72	No	Normal	NA
Makhlouf et al. (2018)	Yes	57	M	11.1/10.98	36.9/37.22	1.45/1.45	No	Moderate	Soccer
McLeod et al. (2009)	No	62	F	15.6/16	58.9/62.3	1.7/1.71	No	Normal	Basketball
Meszler and Váczi (2019)	Yes	18	F	15.8/15.7	63.5/66.1	1.76/1.77	Yes	Moderate	Basketball
Myer et al. (2006)	Yes	19	F	15.9/15.6	61.4/66.4	1.69/1.68	Yes	Normal	Volleyball (primary sport)
Nobre et al. (2017)	Yes	59	M	9.8	41.6/43.5	1.31/1.31	No	Low	NA
Porrati-Paladino and Cuesta-Barriuso (2021)	Yes	20	M	63/56	84/77	1.76/ 1.76	No	Low	NA
Porrati-Paladino and Cuesta-Barriuso (2021)	Yes	15	F	21.11/22.38	61.83/66.16	1.63/1.62	NR	Moderate	Soccer
Ramírez-Campillo et al. (2015b)	Yes	54	M	11.0	43.5	1.46	No	Moderate	Soccer
Ramírez-Campillo et al. (2015a)	Yes	40	M	11.6	40.0	1.44	No	Moderate	Soccer
Ritzmann et al. (2018)	Yes	23	M	30	77	1.81	No	Low	NA
Surakhamhaeng et al. (2020)	Yes	20	M/F	27.70 /25.10	70.42/65.70	1.69/ 1.65	NR	Low	NA
Tay et al. (2019)	Yes	26	M/F	24.1/ 23.0	59.7/ 62.0	1.64/ 1.67	NR	Low	NA
Trecroci et al. (2015)	Yes	24	M	11.3	48.8	1.53	NR	Moderate	Soccer
Witzke and Snow (2000)	No	53	F	14.6/14.5	61/61	1.64/1.65	NR	Normal	NA

**Fitness was classified here as it was in the recent review by Ramírez-Campillo et al., 2020c: (i) NR; (ii) high encompasses professional/elite athletes with regular enrolment in national and/or international competitions, or highly trained participants with 10 training hours per week or 6 training sessions per week and a regularly scheduled official or friendly competition; (iii) moderate encompasses non-elite/professional athletes with a regular attendance in regional and/or national competitions, between 5.09.9 training hours per week or 35 training sessions per week and a regularly scheduled official or friendly competition; and (iv) normal encompasses recreational athletes with <5 training hours per week with sporadic or no participation in competition.*

The age, height and body mass have been mentioned for experimental/control groups.

$Denotes values for studies with more than one experimental group.

F, female; M, male; NA, not applicable; NR, no reported; SPT, systematic experience with plyometric jump training.

TABLE 3 | Characteristics of PJT interventions the included studies.

Authors	Freq	Dur	Int	BH (cm)	NTJ	Tply	Combined	RBS (s)	RBR (s)	RBTS (hrs)	Tsurf	PO	TP	Replace	Tapering
Akin and Kesilmiş (2020)	3	6	NR	NR	NR	Mix	Yes	NR	NR	NR	NR	NP	IS	A	No
Alikhani et al. (2019)	3	6	NR	NR	NR	Mix	No	NR	NR	NR	NR	I+V+T	NA	A	No
Arabatzi (2018)	3	4	NR	NA	3,600	Mix	No	120	NA	NR	Elastic	V	NA	NA	No
Asadi and Arazi (2012)	3	8	Maximal	NA	1,188	Mix	No	60/180	NR	48	Water+land	I+V	NR	A	Yes
Asadi (2013)	2	6	Maximal	45	1,620	Mix	No	120	NR	48–120	NR	No	IS	A	No
Asadi et al. (2015)	2	6	Maximal	45	2,160	Mix	No	120	NR	72	NR	NP	PS	A	No
Benis et al. (2016)	2	8	NR	NA	>360	Mix	Yes	180	NR	24	NR	T+V	NR	R	No
Bouteraa et al. (2020)	2	8	Maximal	40–60	1,588	Mix	Yes	90	NR	48–120	NR	V+T +I	IS	R	No
Chaouachi et al. (2014b)	3	8	Maximal	NR	2,240	Mix	No	NR	NA	NR	NR	V+T	NA	NA	Yes
Chaouachi et al. (2014a)	2	12	Maximal	NR	1,080	Mix	No	180	NR	72	NR	V	NA	R	Yes
Cherni et al. (2019)	2	8	Maximal	40, 50	1,584	Mix	No	NR	NR	48	NR	I+V+T	IS	R	No
Cigerci and Genc (2020)	3	8	NR	NA	3,024	Mix	NO	180	60	48	NR	V+T	NR	A	No
Drouzas et al. (2020)	2	10	Max	10,15,20	721	Mix	No	NR	NR	48	NR	I+V+T	IS	A	Yes
Faigenbaum et al. (2014)	2	8	NR	NA	∼544	Mix	Yes	NR	NR	48	NR	V	NA	NA	No
Hammami et al. (2019c)	2	9	Maximal	25, 30	630	Mix	No	90	0	48	NR	I+V+T	IS	R	No
Hammami et al. (2019a)	2	8	NR	30,40	1,536	Mix	Yes	90	NR	NR	NR	V	IS	R	No
Hammami et al. (2019b)	2	10	NR	30,40	1,920	Mix	Yes	60–120	NA	48–120	NR	No	IS	R	No
Hammami et al. (2020a)	3	7	NR	30,40	594	Mix	No	NR	NR	48	Wood	V+T	IS	R	No
Hammami et al. (2020c)	2	10	Maximal	25–40	720	Mix	No	30	0	>48	NR	I+V+T	IS	R	No
Hammami et al. (2020b)	2	10	Maximal	30, 40	960	Mix	No	30/60	NA	>48	NR	I+V+T	IS	R	No
Hopper et al. (2017)	3	6	NR	NA	1,080	Mix	Yes	NR	60	48–72	NR	I+T	IS	A	No
Huang et al. (2014)	3	6	NR	16	2,736	Mix	No	120	NA	NR	NR	T	NR	NR	No
Jlid et al. (2019)	2	8	NR	20,30	1,596	Mix	No	NR	NR	>48	NR	V+T	IS	A	No
Jlid et al. (2020)	2	6	NR	30,50	2,112	Mix	No	60	15	>48	Grass turf	V+T	IS	R	No
Karadenizli (2016)	2	10	NR	40	2,336	Mix	Yes	60–180	NR	48- 120	NR	V+T	IS	A	No
Kim and Park (2016)	3	8	NR	20, 30	3,072	Mix	No	NR	NA	NR	NR	V+I+T	NR	NR	No
Lee et al. (2020)	2	8	NR	NCR	NR	Mix	No	30	NA	48	NR	I	NR	NR	No
Lovecchio et al. (2019)	NCR	6	NR	10	NR	Mix	Yes	60	0	48–72	NR	NP	NA	NA	No
Makhlouf et al. (2018)	2	8	Maximal	NR	1,826	Mix	Balance	NR	NR	NR	NR	T+V	NR	A	Yes
McLeod et al. (2009)	2	6	NR	NA	2,380 s + 268 rep + 20 m	Mix	Yes	NR	NR	NR	NR	V+T	PS	NR	No
Meszler and Váczi (2019)	2	7	Maximal	25,35,50	1,420	Mix	No	120–300	NA	>48	NR	V+T	IS	A	Yes
Myer et al. (2006)	3	7	Maximal	NR	NR	Mix	Yes	NR	NR	24,48,96	NR	T	PS	NR	NCR

(Continued)

TABLE 3 | Continued

Authors	Freq	Dur	Int	BH (cm)	NTJ	Tply	Combined	RBS (s)	RBR (s)	RBTS (hrs)	Tsurf	PO	TP	Replace	Tapering
Nobre et al. (2017)	2	12	NR	10–40	1,980	Mix	NR	NR	NR	48	NR	V+ I+T	NA	NA	No
Porrati-Paladino and Cuesta-Barriuso (2021)	1–3	12	Maximal	NR	690	DJs	No	NR	NR	NA	NR	I	NA	NA	No
Porrati-Paladino and Cuesta-Barriuso (2021)	3	6	NR	NA	NCR	Mix	Yes	30/20	NA	NR	NR	I+V	NR	A	No
Ramírez-Campillo et al. (2015b)	2	6	Maximal	NA	2,160	Mix	No	60	15	48	GPT	V	IS	R	No
Ramírez-Campillo et al. (2015a)	2	6	Maximal	NA	1,610	Mix	No	60	15	>48	GPT	Yes	IS	R	No
Ritzmann et al. (2018)	5,6	8,6	NR	NA	3,744	Mix	No	NR	NR	∼24	Sledge jump system	NR	NA	NA	NR
Surakhamhaeng et al. (2020)	3	6	NR	NA	2,160	Mix	No	60	NA	NR	Stable-unstable	I+T	NA	A	No
Tay et al. (2019)	2	6	NR	NA	NR	U	No	60	NA	NR	Trampoline	I+V	NA	A	No
Trecroci et al. (2015)	2	8	NR	NA	2,100	RJ	No	30–40–60	NR	NR	Artificial turf	V	IS	R	NR
Witzke and Snow (2000)	3	36	Maximal for some drills	24, 36–72	NR	Mix	Yes	NR	NR	NR	Mixed (mats, grass, concrete, wood)	V+ I+T	NA	NR	No

A, add; APT, aquatic plyometric training; BH, box height; Dur, duration (weeks); Freq, frequency of training (days/ week); GPT, ground plyometric training; Int, intensity; IS, in-season; LPT, Land Plyometric Training; Mix, mixed PJT involved a combination of two or more of the following jumping drills, vertical, horizontal, bilateral, unilateral, repeated, non-repeated, lateral, cyclic, sport-specific (SS), slow stretch-shortening cycle, fast stretch-shortening cycle; NA, non-applicable; NP, non-progressive; NR, not reported; NTJ, number of total jumps (usually counted as jumps per each leg); PE, physical education; PJT, plyometric jump training; PO, progressive overload, in the form of either volume, intensity, type of drill, or a combination of these; PS, pre-season; R, replace; RBR, rest time between repetitions (only when the PJT programme incorporated non-repeated jumps); RBS, rest time between sets or exercise; RBTS, rest between training sessions; Repl, replace, denoting if the athletes replace some common drills from their regular training with PJT drills. If not, the PJT load was added to their regular training load; RT, resistance training; Surf, type of surface used during the intervention; T, technique; TP, training period; Tply, type of PJT drills used; Tsurf, type of surface; V, volume.

TABLE 4 | Methodological quality of the included studies using the PEDro rating scale.

Study name	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Total*	Study quality
Akin and Kesilmiş (2020)	1	0	0	0	0	0	0	1	1	1	1	4	Moderate
Alikhani et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6	High
Arabatzi (2018)	1	1	0	1	0	0	0	1	1	1	1	6	High
Asadi and Arazi (2012)	1	1	0	1	0	0	0	1	1	1	1	6	High
Asadi (2013)	1	1	0	1	0	0	0	1	1	1	1	6	High
Asadi et al. (2015)	1	1	0	1	0	0	0	1	1	1	1	6	High
Benis et al. (2016)	1	1	0	1	0	0	0	1	1	1	1	6	High
Bouteraa et al. (2020)	1	1	0	1	0	0	0	0	1	1	1	5	High
Chaouachi et al. (2014b)	1	1	0	1	0	0	0	1	1	1	1	6	High
Chaouachi et al. (2014a)	1	1	0	1	0	0	0	1	1	1	1	6	High
Cherni et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6	High
Cigerci and Genc (2020)	1	0	0	1	0	0	0	1	1	1	1	5	Moderate
Drouzas et al. (2020)	1	1	0	1	0	0	0	0	1	1	1	5	Moderate
Faigenbaum et al. (2014)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hammami et al. (2019c)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hammami et al. (2019a)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hammami et al. (2019b)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hammami et al. (2020a)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hammami et al. (2020c)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hammami et al. (2020b)	1	1	0	1	0	0	0	1	1	1	1	6	High
Hopper et al. (2017)	1	1	0	1	0	0	0	1	1	1	1	6	High
Huang et al. (2014)	1	1	0	1	0	0	0	1	1	1	1	6	High
Jlid et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6	High
Jlid et al. (2020)	1	1	0	1	0	0	0	1	1	1	1	6	High
Karadenizli (2016)	1	1	0	1	0	0	0	1	1	1	1	6	High
Kim and Park (2016)	1	1	0	1	0	0	0	1	1	1	1	6	High
Lee et al. (2020)	1	1	0	1	0	0	0	1	1	1	1	6	High
Lovecchio et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6	High
Makhlouf et al. (2018)	1	1	0	1	0	0	0	1	1	1	1	6	High
McLeod et al. (2009)	1	0	0	1	0	0	1	0	1	1	1	5	Moderate
Meszler and Váczi (2019)	1	1	0	1	0	0	0	1	1	1	1	6	High
Myer et al. (2006)	1	1	0	1	0	0	0	0	1	1	1	5	Moderate
Nobre et al. (2017)	1	1	0	1	0	0	0	1	1	1	1	6	High
Porrati-Paladino and Cuesta-Barriuso (2021)	1	1	0	1	0	0	0	1	1	1	1	6	High
Porrati-Paladino and Cuesta-Barriuso (2021)	1	1	0	1	0	0	0	0	1	1	1	5	Moderate
Ramírez-Campillo et al. (2015b)	1	1	0	1	0	0	0	1	1	1	1	6	High
Ramírez-Campillo et al. (2015a)	1	1	0	1	0	0	0	1	1	1	1	6	High
Ritzmann et al. (2018)	1	1	0	1	0	0	0	1	1	1	1	6	High
Surakhamhaeng et al. (2020)	1	1	0	1	0	0	0	1	1	1	1	6	High
Tay et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6	High
Trecroci et al. (2015)	1	1	0	1	0	0	0	1	1	1	1	6	High
Witzke and Snow (2000)	1	0	0	0	0	0	0	1	1	1	1	4	Moderate

A detailed explanation for each PEDro scale item can be accessed at https://www.pedro.org.au/english/downloads/pedro-scale.
*From a possible maximal punctuation of 10.

performed at maximal intensity, while the remaining studies did not provide any details regarding PJT intensity.

Regarding the reporting of adverse health effects of PJT, 12 studies (Myer et al., 2006; Ramírez-Campillo et al., 2015a,b; Benis et al., 2016; Nobre et al., 2017; Makhlouf et al., 2018; Hammami et al., 2019b,c, 2020a,b,c; Jlid et al., 2019) reported no adverse health events due to PJT. Two studies (Kim and Park, 2016; Porrati-Paladino and Cuesta-Barriuso, 2021) reported drop outs due to injuries. While in the study of Porrati-Paladino and Cuesta-Barriuso (2021), the injuries were unrelated to PJT, there is no such information in the study of Kim and Park (2016). The remaining 24 included studies failed to report specific information regarding adverse health effects.

A total of 274 balance measures were applied among the 38 included studies (7.2 measurements per study). From the 38 studies which were considered eligible for this meta-analysis, 29 studies used tests of dynamic balance (e.g., Y balance test) and 24 studies tests of static balance (e.g., flamingo balance test). If several tests were included in one study which all deemed to measure static or dynamic balance, Cochrane-based decision rules were applied (**Supplementary File 1**).

Concerning dynamic balance, 169 tests were applied among 29 studies (5.8 measurements per study). The dynamic tests were further divided into field-based tests (YBT, 14 studies; SEBT, 8 studies; backward walk test, 1 study; dynamic balance error scoring system test [BESS], 1 study), and laboratory-based dynamic balance test (6 studies; mainly involving subjects standing on unstable surfaces over balance and force-platforms).

A total of 105 static measurements were applied among 24 studies (4.4 measurements per study). The static tests were further divided into field-based tests (standing stork test; flamingo test; static BESS test; Romberg test; 14 studies) and laboratory-based static tests (10 studies; mainly involving subjects standing on stable surfaces over balance and force-platforms).

The balance measurement and assessment protocols for each of the included studies in the meta-analysis was detailed in **Supplementary Table 1**.

Results From Meta-Analysis

Overall Static and Dynamic Balance

Thirty-eight studies ($n = 1{,}156$; 48 experimental groups, 32 active control groups, 7 specific-active control groups) provided balance data including dynamic and static tests. There was a significant small effect of PJT on overall balance compared to baseline performance (i.e., pre PJT intervention) ($ES = 0.46$; 95% $CI = 0.32$–0.61; $p < 0.001$; $I^2 = 55.2\%$; Egger's test $p = 0.152$; **Figure 2**).

Dynamic Balance

Twenty-nine studies provided information of PJT on dynamic balance (i.e., overall, all dynamic tests included), involving 37 experimental and 31 control groups ($n = 933$; 24 active and 7 specific-active). There was a significant small effect of PJT on dynamic balance compared to baseline performance ($ES = 0.50$; 95% $CI = 0.30$–0.71; $p < 0.001$; $I^2 = 57.0\%$; Egger's test $p = 0.459$; **Figure 3**).

Field-Based Tests of Dynamic Balance

Twenty-two studies provided data for field-based tests of dynamic balance, involving 26 experimental and 22 control groups ($n = 648$; 18 active and 4 specific-active). There was a significant small effect of PJT on field-based tests of dynamic balance compared to baseline performance ($ES = 0.52$; 95% $CI = 0.26$–0.78; $p < 0.001$; $I^2 = 60.3\%$; Egger's test $p = 0.944$; **Figure 4**).

Laboratory-Based Tests of Dynamic Balance

Six studies provided data for dynamic balance, measured through laboratory-based equipment, involving 9 experimental and 7 control groups ($n = 164$; 5 active and two specific-active). There was a non-significant small effect of PJT on dynamic balance, measured through laboratory-based equipment vs. baseline performance ($ES = 0.28$; 95% $CI = -0.03$–0.59; $p = 0.073$; $I^2 = 0.0\%$; Egger's test $p = 0.346$; **Figure 5**).

Static Balance

Twenty-four studies provided data on static balance tests involving 33 experimental and 24 control groups ($n = 873$; 21 active and 3 specific-active). There was a significant small effect of PJT on static balance compared to baseline performance ($ES = 0.49$; 95% $CI = 0.31$–0.67; $p < 0.001$; $I^2 = 37.1\%$; Egger's test $p = 0.012$, with adjusted values equal to the observed values after the application of the Duval and Tweedie's trim and fill method; **Figure 6**).

Field-Based Tests of Static Balance

Twelve studies provided data for field-based static balance tests involving 17 experimental and 12 control groups ($n = 414$; 11 active and 1 specific-active). There was a significant small effect of PJT on static balance compared to baseline performance ($ES = 0.44$; 95% $CI = 0.09$–0.79; $p = 0.013$; $I^2 = 69.5\%$; Egger's test $p = 0.003$, with adjusted values similar to the observed values after the application of the Duval and Tweedie's trim and fill method; **Figure 7**).

Laboratory-Based Tests of Static Balance

Ten studies provided data for laboratory-based static balance tests involving 14 experimental and 10 control groups ($n = 303$; nine active and one specific-active). There was a significant small effect of PJT on laboratory-based static balance tests vs. baseline performance ($ES = 0.48$; 95% $CI = 0.24$–0.71; $p < 0.001$; $I^2 = 0.0\%$; Egger's test $p = 0.856$; **Figure 8**).

Plyometric Jump Training Compared to Specific-Active Controls

Seven studies compared the effects of PJT vs. specific-active controls (balance training, 3 studies; whole body vibration training, 1 study; resistance training, 3 studies) on measures of dynamic and static balance. The comparison involved 7 experimental ($n = 69$) and 7 specific-active controls ($n = 73$). Both PJT and specific-active controls showed similar balance effects pre- and post- PJT intervention ($p = 0.534$ between conditions). If the effects of single mode balance training (3 studies) were contrasted with PJT, similar results were obtained ($p = 0.510$).

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Akin and Kesilmis 2020 female D	-0.177	0.598	0.357	-1.348	0.995	-0.295	0.768	0.99
Akin and Kesilmis 2020 male D	0.952	0.590	0.348	-0.204	2.108	1.614	0.106	1.01
Alikhani et al. 2019 D	1.282	0.455	0.207	0.390	2.174	2.817	0.005	1.36
Arabatzi, 2018 S	1.127	0.426	0.182	0.292	1.963	2.644	0.008	1.44
Asadi et al. 2015 D	0.902	0.499	0.249	-0.076	1.879	1.807	0.071	1.23
Benis et al. 2016 D	0.578	0.375	0.141	-0.157	1.313	1.541	0.123	1.62
Bouterra et al., 2020 D	0.944	0.412	0.170	0.137	1.751	2.293	0.022	1.49
Bouterra et al., 2020 S	1.364	0.434	0.188	0.514	2.215	3.145	0.002	1.42
Chaouachi et al., 2014 PJT D	0.496	0.474	0.225	-0.433	1.425	1.047	0.295	1.30
Chaouachi et al., 2014 PJT S	0.259	0.469	0.220	-0.661	1.178	0.552	0.581	1.31
Chaouachi et al., 2014 PJT+balance D	0.680	0.480	0.230	-0.260	1.619	1.417	0.156	1.28
Chaouachi et al., 2014 PJT+balance S	1.095	0.498	0.248	0.118	2.071	2.197	0.028	1.23
Cherni et al, 2019 D	0.308	0.390	0.152	-0.456	1.071	0.790	0.429	1.56
Cherni et al, 2019 S	1.020	0.413	0.171	0.210	1.830	2.469	0.014	1.49
Cigerci and Genc, 2020 D	0.265	0.430	0.185	-0.579	1.108	0.615	0.539	1.43
Drouzas et al. 2020 bilateral S	0.000	0.358	0.128	-0.702	0.702	0.000	1.000	1.68
Drouzas et al. 2020 unilateral S	0.000	0.358	0.128	-0.702	0.702	0.000	1.000	1.68
Hamami et al., 2019b D	0.000	0.367	0.135	-0.719	0.719	0.000	1.000	1.64
Hamami et al., 2019b S	-0.000	0.367	0.135	-0.719	0.719	-0.000	1.000	1.64
Hamami et al., 2019c D	0.093	0.367	0.135	-0.627	0.813	0.253	0.800	1.64
Hamami et al., 2019c S	0.117	0.367	0.135	-0.603	0.836	0.317	0.751	1.64
Hammami 2019a D	1.099	0.330	0.109	0.453	1.745	3.334	0.001	1.78
Hammami 2019a S	-0.330	0.309	0.095	-0.935	0.275	-1.069	0.285	1.86
Hammami 2020a gym D	1.727	0.604	0.365	0.543	2.912	2.858	0.004	0.98
Hammami 2020a gym S	0.258	0.518	0.268	-0.757	1.272	0.498	0.619	1.18
Hammami 2020a sand D	1.860	0.607	0.368	0.671	3.050	3.066	0.002	0.97
Hammami 2020a sand S	5.575	1.110	1.231	3.400	7.750	5.024	0.000	0.39
Hammami et al. 2020b D	-0.229	0.336	0.113	-0.888	0.429	-0.682	0.495	1.76
Hammami et al. 2020b S	-0.170	0.336	0.113	-0.827	0.488	-0.506	0.613	1.76
Hammami et al. 2020c loaded D	0.681	0.480	0.230	-0.259	1.621	1.420	0.156	1.28
Hammami et al. 2020c loaded S	1.029	0.495	0.245	0.059	1.999	2.079	0.038	1.24
Hammami et al. 2020c unloaded D	0.113	0.477	0.227	-0.821	1.047	0.237	0.813	1.29
Hammami et al. 2020c unloaded S	-0.090	0.476	0.227	-1.024	0.844	-0.189	0.850	1.29
Hopper et al., 2017 D	0.167	0.406	0.165	-0.629	0.963	0.410	0.682	1.51
Huang et al.. 2014 S	0.436	0.434	0.188	-0.415	1.286	1.004	0.315	1.42
Jild et al. 2019 D	0.924	0.387	0.150	0.165	1.683	2.387	0.017	1.57
Jild et al. 2020 D	0.296	0.376	0.141	-0.440	1.033	0.789	0.430	1.61
Karadenizli, 2016 D	0.000	0.381	0.145	-0.747	0.747	0.000	1.000	1.59
Karadenizli, 2016 S	0.119	0.381	0.145	-0.628	0.866	0.312	0.755	1.59
Kim and Park 2016 S	-0.348	0.370	0.137	-1.073	0.377	-0.941	0.347	1.63
Lee et al. 2020 D	-0.258	0.503	0.253	-1.244	0.727	-0.514	0.607	1.22
Lovecchio et al. 2019 S	0.417	0.255	0.065	-0.084	0.917	1.631	0.103	2.07
Makhlouf et al. 2018 PJT+agility D	0.973	0.426	0.182	0.137	1.809	2.281	0.023	1.44
Makhlouf et al. 2018 PJT+agility S	0.967	0.426	0.182	0.131	1.802	2.268	0.023	1.44
Makhlouf et al. 2018 PJT+balance D	1.405	0.444	0.197	0.535	2.275	3.164	0.002	1.39
Makhlouf et al. 2018 PJT+balance S	1.261	0.436	0.191	0.406	2.117	2.890	0.004	1.41
McLeod et al. 2009 BESS D	1.661	0.296	0.088	1.081	2.241	5.611	0.000	1.91
McLeod et al. 2009 S	0.527	0.260	0.068	0.017	1.036	2.026	0.043	2.05
McLeod et al. 2009 SEBT D	1.268	0.280	0.078	0.720	1.817	4.532	0.000	1.97
Meszler and Vaczi 2019 S	-0.011	0.449	0.202	-0.891	0.868	-0.026	0.980	1.37
Myer et al. 2006 D	0.115	0.444	0.197	-0.756	0.986	0.259	0.796	1.39
Nobre et al. 2017 D	0.285	0.276	0.076	-0.256	0.827	1.033	0.302	1.98
Piirainen et al 2014 D	0.436	0.436	0.190	-0.419	1.290	1.000	0.317	1.41
Porrati-Paladino and Cuesta-Barriuso 2021 D	-0.196	0.488	0.239	-1.153	0.762	-0.401	0.689	1.26
Ramirez-Campillo et al., 2015 bil+unil D	0.469	0.527	0.278	-0.563	1.502	0.891	0.373	1.16
Ramirez-Campillo et al., 2015 bil+unil S	0.913	0.544	0.296	-0.154	1.979	1.678	0.093	1.11
Ramirez-Campillo et al., 2015 bilateral D	0.427	0.526	0.276	-0.603	1.458	0.813	0.416	1.16
Ramirez-Campillo et al., 2015 horizontal S	0.262	0.593	0.351	-0.900	1.424	0.442	0.659	1.00
Ramirez-Campillo et al., 2015 unilateral D	0.271	0.510	0.260	-0.728	1.270	0.531	0.595	1.20
Ramirez-Campillo et al., 2015 unilateral S	0.289	0.510	0.260	-0.711	1.288	0.566	0.571	1.20
Ramirez-Campillo et al., 2015 ver+hor S	0.481	0.598	0.357	-0.691	1.653	0.805	0.421	0.99
Ramirez-Campillo et al., 2015 vertical S	0.152	0.591	0.350	-1.007	1.310	0.256	0.798	1.01
Ramriez-Campillo et al., 2015 bilateral S	0.373	0.525	0.275	-0.655	1.401	0.711	0.477	1.16
Ritzman et al., 2018 S	1.005	0.429	0.184	0.164	1.845	2.343	0.019	1.44
Surakhamhaeng et al., 2020 D	-1.419	0.484	0.234	-2.366	-0.471	-2.934	0.003	1.27
Surakhamhaeng et al., 2020 S	0.184	0.429	0.184	-0.658	1.025	0.428	0.669	1.43
Tay et al. 2019 D	0.113	0.380	0.145	-0.632	0.858	0.297	0.767	1.60
Tay et al. 2019 S	-0.295	0.382	0.146	-1.044	0.453	-0.773	0.439	1.59
Trecroci et al. 2015 D	0.185	0.395	0.156	-0.589	0.959	0.468	0.640	1.55
Witzke and Snow 2000 S	0.332	0.273	0.075	-0.203	0.867	1.215	0.224	2.00
	0.462	0.075	0.006	0.316	0.608	6.181	0.000	

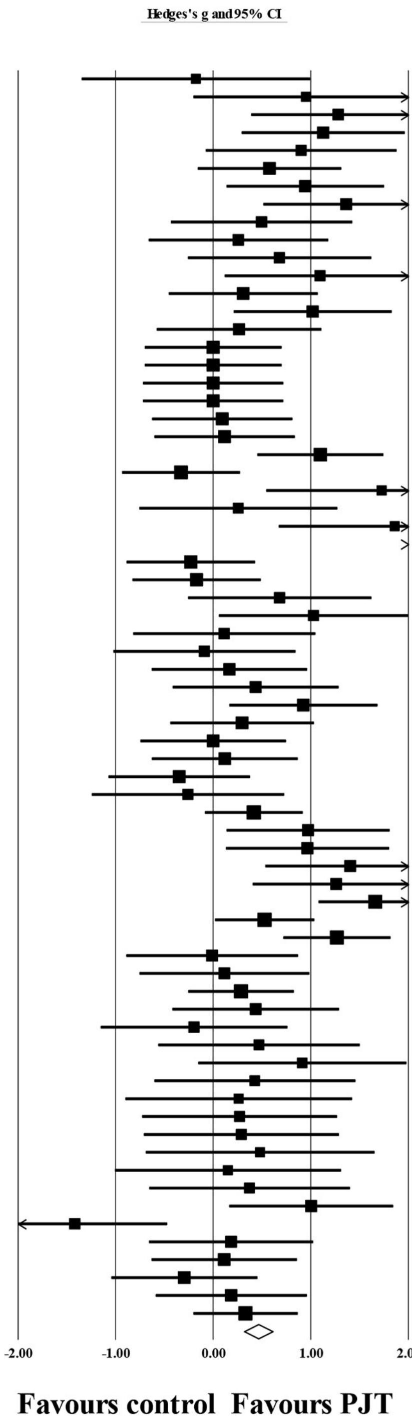

FIGURE 2 | Forest plot of changes in overall balance (i.e., all dynamic and static tests included) in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

Replacement of Regular Training With Plyometric Jump Training

When studies added PJT to participant's regular training activities, small significant overall balance improvement were noted post-PJT intervention ($ES = 0.35$; $p = 0.014$), similar to those studies that replaced part of the regular training with PJT ($ES = 0.47$; $p < 0.001$). No statistically significant difference was found ($p = 0.494$).

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Akin and Kesilmis 2020 female	-0.177	0.598	0.357	-1.348	0.995	-0.295	0.768	1.91
Akin and Kesilmis 2020 male	0.952	0.590	0.348	-0.204	2.108	1.614	0.106	1.95
Alikhani et al. 2019	1.282	0.455	0.207	0.390	2.174	2.817	0.005	2.58
Asadi et al. 2015	0.902	0.499	0.249	-0.076	1.879	1.807	0.071	2.35
Benis et al. 2016	0.578	0.375	0.141	-0.157	1.313	1.541	0.123	3.04
Bouterra et al., 2020	0.944	0.412	0.170	0.137	1.751	2.293	0.022	2.82
Chaouachi et al., 2014 PJT	0.496	0.474	0.225	-0.433	1.425	1.047	0.295	2.48
Chaouachi et al., 2014 PJT+balance	0.680	0.480	0.230	-0.260	1.619	1.417	0.156	2.45
Chemi et al, 2019	0.308	0.390	0.152	-0.456	1.071	0.790	0.429	2.95
Cigerci and Genc, 2020	0.265	0.430	0.185	-0.579	1.108	0.615	0.539	2.71
Hammami 2019a	1.099	0.330	0.109	0.453	1.745	3.334	0.001	3.33
Hamami et al., 2019b	0.000	0.367	0.135	-0.719	0.719	0.000	1.000	3.09
Hamami et al., 2019c	0.093	0.367	0.135	-0.627	0.813	0.253	0.800	3.09
Hammami 2020a sand	1.860	0.607	0.368	0.671	3.050	3.066	0.002	1.88
Hammami 2020a gym	1.727	0.604	0.365	0.543	2.912	2.858	0.004	1.89
Hammami et al. 2020b	-0.229	0.336	0.113	-0.888	0.429	-0.682	0.495	3.29
Hammami et al. 2020c loaded	0.681	0.480	0.230	-0.259	1.621	1.420	0.156	2.45
Hammami et al. 2020c unloaded	0.113	0.477	0.227	-0.821	1.047	0.237	0.813	2.46
Hopper et al., 2017	0.167	0.406	0.165	-0.629	0.963	0.410	0.682	2.85
Jlid et al. 2019	0.924	0.387	0.150	0.165	1.683	2.387	0.017	2.97
Jlid et al. 2020	0.296	0.376	0.141	-0.440	1.033	0.789	0.430	3.04
Karadenizli, 2016	0.000	0.381	0.145	-0.747	0.747	0.000	1.000	3.00
Lee et al. 2020	-0.258	0.503	0.253	-1.244	0.727	-0.514	0.607	2.33
Makhlouf et al. 2018 PJT+balance	1.405	0.444	0.197	0.535	2.275	3.164	0.002	2.64
Makhlouf et al. 2018 PJT+agility	0.973	0.426	0.182	0.137	1.809	2.281	0.023	2.74
McLeod et al. 2009	1.268	0.280	0.078	0.720	1.817	4.532	0.000	3.66
McLeod et al. 2009.	1.661	0.296	0.088	1.081	2.241	5.611	0.000	3.55
Myer et al. 2006	0.115	0.444	0.197	-0.756	0.986	0.259	0.796	2.64
Nobre et al. 2017	0.285	0.276	0.076	-0.256	0.827	1.033	0.302	3.69
Piirainen et al 2014	0.436	0.436	0.190	-0.419	1.290	1.000	0.317	2.68
Porrati-Paladino and Cuesta-Barriuso 2021	-0.196	0.488	0.239	-1.153	0.762	-0.401	0.689	2.40
Ramirez-Campillo et al., 2015 bilateral	0.427	0.526	0.276	-0.603	1.458	0.813	0.416	2.22
Ramirez-Campillo et al., 2015 unilateral	0.271	0.510	0.260	-0.728	1.270	0.531	0.595	2.30
Ramirez-Campillo et al., 2015 bil+unil	0.469	0.527	0.278	-0.563	1.502	0.891	0.373	2.22
Surakhamhaeng et al., 2020	-1.419	0.484	0.234	-2.366	-0.471	-2.934	0.003	2.43
Tay et al. 2019	0.113	0.380	0.145	-0.632	0.858	0.297	0.767	3.01
Trecroci et al. 2015	0.185	0.395	0.156	-0.589	0.959	0.468	0.640	2.92
	0.503	0.106	0.011	0.296	0.710	4.755	0.000	

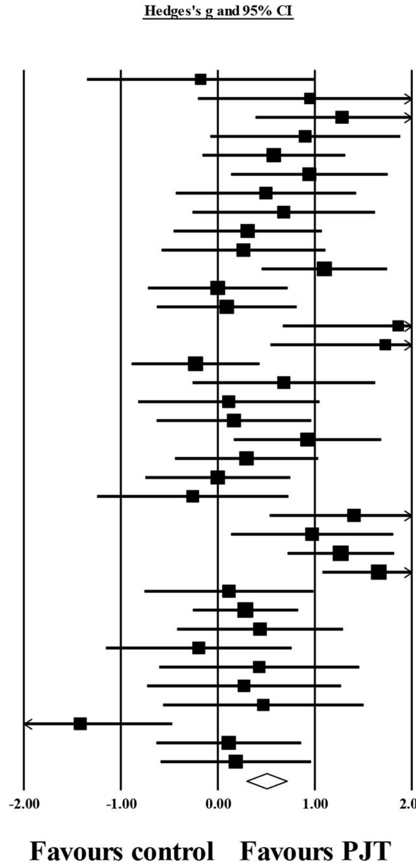

FIGURE 3 | Forest plot of changes in overall dynamic balance (i.e., all dynamic tests included) in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

Moderator Analyses

Using a random-effects model, potential sources of heterogeneity likely to influence the effects of PJT were analyzed. A short summary of the outcomes is provided below. More detailed information can be found in **Supplementary File 2**.

Sub-group Analyses

Participant's sex and age did not moderate the effects of PJT on measures of balance. Additionally, if laboratory-based ($ES = 0.41$) vs. field-based ($ES = 0.49$) tests of balance were taken into consideration, the type of test did not moderate the PJT effects on measures of dynamic and static balance ($p = 0.574$). However, significant ($p = 0.047$) difference in the magnitude of effects sizes were found for overall balance ($p = 0.047$) with the largest effects in basketball ($ES = 0.83$), followed by soccer ($ES = 0.48$), handball ($ES = 0.43$), and non-athletic populations ($ES = 0.20$).

Single Factor Analyses of Programming Parameters

With regards to weekly training frequency, significantly greater effects ($p = 0.044$) were found for PJT programmes with a frequency of $\leq$2 sessions/week ($ES = 0.89$) compared with to >2 weekly sessions ($ES = 0.05$) on measures of dynamic balance. No other programming parameter moderated the observed effects of PJT on measures of balance.

DISCUSSION

This meta-analysis aimed to examine the effect of PJT on balance performance. Overall findings of this study revealed that, compared to active controls, PJT showed moderate effects on overall balance, dynamic and static balance, irrespective of participants' sex or age. Additionally, PJT produced similar balance improvements compared to other training types (e.g., balance training).

Comparison of PJT With Balance Training

Balance training is applied if the goal is to improve dynamic and static balance in athletes and non-athletic populations (Behm and Sale, 1993). Previous meta-analyses have shown that balance training is effective in improving balance in healthy youth aged 9–19 years (ES range: 0.61–1.03) (Gebel et al., 2018, 2020), healthy young adults aged 16–40 years (ES range: 0.32–1.29) (Lesinski et al., 2015a) and healthy older adults aged

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Alikhani et al. 2019	1.282	0.455	0.207	0.390	2.174	2.817	0.005	3.66
Asadi et al. 2015	0.902	0.499	0.249	-0.076	1.879	1.807	0.071	3.36
Benis et al. 2016	0.578	0.375	0.141	-0.157	1.313	1.541	0.123	4.26
Bouterra et al., 2020	0.944	0.412	0.170	0.137	1.751	2.293	0.022	3.97
Chaouachi et al., 2014 PJT	0.496	0.474	0.225	-0.433	1.425	1.047	0.295	3.52
Chaouachi et al., 2014 PJT+balance	0.680	0.480	0.230	-0.260	1.619	1.417	0.156	3.49
Cigerci and Genc, 2020	0.265	0.430	0.185	-0.579	1.108	0.615	0.539	3.83
Hamami et al., 2019b	0.000	0.367	0.135	-0.719	0.719	0.000	1.000	4.32
Hamami et al., 2019c	0.093	0.367	0.135	-0.627	0.813	0.253	0.800	4.32
Hammami 2019a	1.099	0.330	0.109	0.453	1.745	3.334	0.001	4.63
Hammami 2020a gym	1.727	0.604	0.365	0.543	2.912	2.858	0.004	2.73
Hammami 2020a sand	1.860	0.607	0.368	0.671	3.050	3.066	0.002	2.72
Hammami et al. 2020b	-0.229	0.336	0.113	-0.888	0.429	-0.682	0.495	4.58
Hammami et al. 2020c loaded	0.681	0.480	0.230	-0.259	1.621	1.420	0.156	3.49
Hammami et al. 2020c unloaded	0.113	0.477	0.227	-0.821	1.047	0.237	0.813	3.51
Hopper et al., 2017	0.167	0.406	0.165	-0.629	0.963	0.410	0.682	4.02
Jild et al. 2019	0.924	0.387	0.150	0.165	1.683	2.387	0.017	4.16
Jild et al. 2020	0.296	0.376	0.141	-0.440	1.033	0.789	0.430	4.25
Lee et al. 2020	-0.258	0.503	0.253	-1.244	0.727	-0.514	0.607	3.33
Makhlouf et al. 2018 PJT+agility	0.973	0.426	0.182	0.137	1.809	2.281	0.023	3.86
Makhlouf et al. 2018 PJT+balance	1.405	0.444	0.197	0.535	2.275	3.164	0.002	3.74
McLeod et al. 2009	1.268	0.280	0.078	0.720	1.817	4.532	0.000	5.04
Porrati-Paladino and Cuesta-Barriuso 2021	-0.196	0.488	0.239	-1.153	0.762	-0.401	0.689	3.43
Surakhamhaeng et al., 2020	-1.419	0.484	0.234	-2.366	-0.471	-2.934	0.003	3.46
Tay et al. 2019	0.113	0.380	0.145	-0.632	0.858	0.297	0.767	4.22
Trecroci et al. 2015	0.185	0.395	0.156	-0.589	0.959	0.468	0.640	4.10
	0.520	0.131	0.017	0.264	0.777	3.976	0.000	

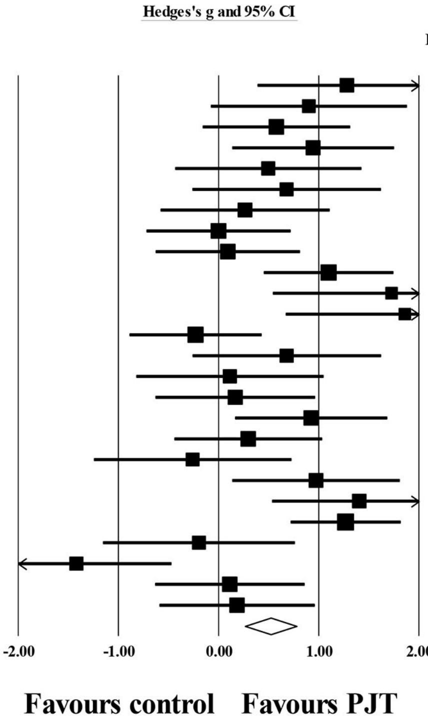

FIGURE 4 | Forest plot of changes in dynamic balance, measured through field-based tests, in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Akin and Kesilmis 2020 female	-0.177	0.598	0.357	-1.348	0.995	-0.295	0.768
Akin and Kesilmis 2020 male	0.952	0.590	0.348	-0.204	2.108	1.614	0.106
Cherni et al, 2019	0.308	0.390	0.152	-0.456	1.071	0.790	0.429
Karadenizli, 2016	0.000	0.381	0.145	-0.747	0.747	0.000	1.000
Myer et al. 2006	0.115	0.444	0.197	-0.756	0.986	0.259	0.796
Piirainen et al 2014	0.436	0.436	0.190	-0.419	1.290	1.000	0.317
Ramirez-Campillo et al., 2015 bilateral	0.427	0.526	0.276	-0.603	1.458	0.813	0.416
Ramirez-Campillo et al., 2015 unilateral	0.271	0.510	0.260	-0.728	1.270	0.531	0.595
Ramirez-Campillo et al., 2015 bil+unil	0.469	0.527	0.278	-0.563	1.502	0.891	0.373
	0.282	0.157	0.025	-0.026	0.590	1.795	0.073

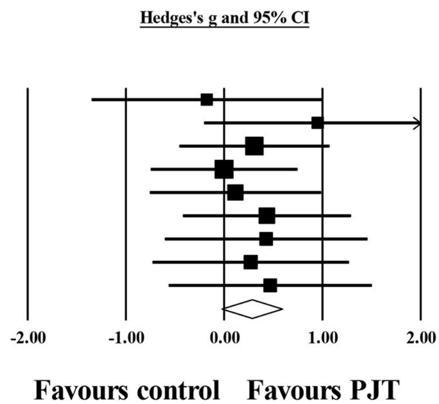

FIGURE 5 | Forest plot of changes in dynamic balance, measured through laboratory-based equipment, in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

≥65 years (ES range: 0.44–1.93) (Lesinski et al., 2015b). Our meta-analysis indicated that besides balance training, PJT is also an effective exercise type to improve balance in healthy participants. However, the observed balance improvements following PJT were somewhat lower ($ES < 0.52$) compared to the magnitudes of balance improvement in the aforementioned balance training studies. The impact of a training programme on performance depends on the type of exercise administered during the training sessions. This is well in line with the principle of training specificity (Behm and Sale, 1993). Of note, our meta-analysis revealed that when PJT was compared with balance training, both training types induced similar balance adaptations ($p = 0.510$ between training methods). Plyometric jump training has the potential to improve muscle strength, power, and balance through primarily neural adaptations (Lee et al., 2020). Compared to other training types, PJT exercises

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Arabatzi, 2018	1.127	0.426	0.182	0.292	1.963	2.644	0.008	2.98
Bouterra et al., 2020	1.364	0.434	0.188	0.514	2.215	3.145	0.002	2.92
Chaouachi et al., 2014 PJT	0.259	0.469	0.220	-0.661	1.178	0.552	0.581	2.62
Chaouachi et al., 2014 PJT+balance	1.095	0.498	0.248	0.118	2.071	2.197	0.028	2.41
Chemi et al, 2019	1.020	0.413	0.171	0.210	1.830	2.469	0.014	3.11
Drouzas et al. 2020 unilateral	0.000	0.358	0.128	-0.702	0.702	0.000	1.000	3.70
Drouzas et al. 2020 bilateral	0.000	0.358	0.128	-0.702	0.702	0.000	1.000	3.70
Hammami 2019a	0.330	0.309	0.095	-0.275	0.935	1.069	0.285	4.33
Hamami et al., 2019b	0.000	0.367	0.135	-0.719	0.719	0.000	1.000	3.59
Hamami et al., 2019c	0.117	0.367	0.135	-0.603	0.836	0.317	0.751	3.59
Hammami 2020a sand	5.575	1.110	1.231	3.400	7.750	5.024	0.000	0.62
Hammami 2020a gym	0.258	0.518	0.268	-0.757	1.272	0.498	0.619	2.28
Hammami et al. 2020b	0.170	0.336	0.113	-0.488	0.827	0.506	0.613	3.97
Hammami et al. 2020c loaded	1.029	0.495	0.245	0.059	1.999	2.079	0.038	2.43
Hammami et al. 2020c unloaded	0.090	0.476	0.227	-0.844	1.024	0.189	0.850	2.57
Huang et al.. 2014	0.436	0.434	0.188	-0.415	1.286	1.004	0.315	2.92
Karadenizli, 2016	0.119	0.381	0.145	-0.628	0.866	0.312	0.755	3.43
Kim and Park 2016	0.348	0.370	0.137	-0.377	1.073	0.941	0.347	3.56
Lovecchio et al. 2019	0.417	0.255	0.065	-0.084	0.917	1.631	0.103	5.14
Makhlouf et al. 2018 PJT+balance	1.261	0.436	0.191	0.406	2.117	2.890	0.004	2.89
Makhlouf et al. 2018 PJT+agility	0.967	0.426	0.182	0.131	1.802	2.268	0.023	2.98
McLeod et al. 2009	0.527	0.260	0.068	0.017	1.036	2.026	0.043	5.06
Meszler and Vaczi 2019	0.011	0.449	0.202	-0.868	0.891	0.026	0.980	2.79
Ramriez-Campillo et al., 2015 bilateral	0.373	0.525	0.275	-0.655	1.401	0.711	0.477	2.23
Ramirez-Campillo et al., 2015 unilateral	0.289	0.510	0.260	-0.711	1.288	0.566	0.571	2.33
Ramirez-Campillo et al., 2015 bil+unil	0.913	0.544	0.296	-0.154	1.979	1.678	0.093	2.11
Ramirez-Campillo et al., 2015 vertical	0.152	0.591	0.350	-1.007	1.310	0.256	0.798	1.86
Ramirez-Campillo et al., 2015 horizontal	0.262	0.593	0.351	-0.900	1.424	0.442	0.659	1.85
Ramirez-Campillo et al., 2015 ver+hor	0.481	0.598	0.357	-0.691	1.653	0.805	0.421	1.83
Ritzman et al., 2018	1.005	0.429	0.184	0.164	1.845	2.343	0.019	2.96
Surakhamhaeng et al., 2020	0.184	0.429	0.184	-0.658	1.025	0.428	0.669	2.96
Tay et al. 2019	0.295	0.382	0.146	-0.453	1.044	0.773	0.439	3.42
Witzke and Snow 2000	0.332	0.273	0.075	-0.203	0.867	1.215	0.224	4.86
	0.487	0.091	0.008	0.308	0.665	5.343	0.000	

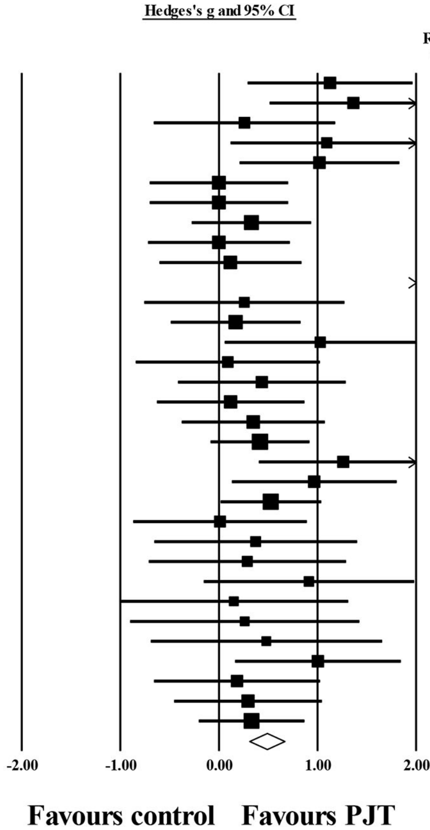

FIGURE 6 | Forest plot of changes in overall static balance (i.e., all static tests included) in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

involve the braking (eccentric) and propulsion (concentric) phases performed in the SSC which, when applied over longer periods, improve muscle strength, power, and speed (Komi and Gollhofer, 1997; Taube et al., 2012). Since high levels of muscle power are crucial to maintain or regain balance during everyday (e.g., stumbling) and sport-related activities (e.g., jump-landing tasks) (Vetrovsky et al., 2019), PJT appears to be an adequate means to promote balance through increases in muscle power (Vetrovsky et al., 2019). A limitation is that only three studies were available for direct meta-analytical comparison between PJT and balance training. Further research needs to be conducted which contrasts different training types (including balance training) with PJT to better understand this subject.

Potential Moderators of PJT-Related Effects

Previous studies suggested a maturational threshold that moderates responses (i.e., jumping) to PJT in youth (de Villarreal et al., 2009; Moran et al., 2017a). However, for balance-related outcomes, our analyses revealed no effect of sex (or age) on dynamic and static balance after PJT. Therefore, PJT seems effective to improve balance across the maturational spectrum, taking participants' fitness levels and motor competence into consideration. However, future studies should elucidate whether maturation, sex or training experience interact with PJT and balance outcomes. In addition, we found a comparable effect of <2 vs. >2 weekly PJT sessions on most of the analyzed balance measures. Moreover, the SEBT improved more after PJT with a frequency of ≤2 sessions per week ($ES = 0.89$) as compared to >2 sessions per week ($ES = 0.05$), which may be related to the greater number of including unilateral, bilateral, vertical and horizontal drills during training sessions with a lower overall PJT frequency. This higher jump drill density during a single session may provide a more demanding balance stimulus (Ramírez-Campillo et al., 2015a,b). In addition, a lower weekly PJT frequency may allow players to devote more time to other aspects of their physical conditioning (Ramírez-Campillo et al., 2020b). These findings also emphasize the importance of PJT contents rather than PJT volume (Ramírez-Campillo et al., 2015b). Therefore, rather than PJT frequency, other PJT programming parameters such as the type of jump exercise might have a greater impact on balance adaptations. For example, insufficient PJT volume, intensity, or a combination of both, may mask even greater balance improvements due to PJT with higher training frequency (Vetrovsky et al., 2019)." Additionally, the PJT studies that added

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bouterra et al., 2020	1.364	0.434	0.188	0.514	2.215	3.145	0.002
Chaouachi et al., 2014 PJT	0.259	0.469	0.220	-0.661	1.178	0.552	0.581
Chaouachi et al., 2014 PJT+balance	1.095	0.498	0.248	0.118	2.071	2.197	0.028
Drouzas et al. 2020 unilateral	0.000	0.358	0.128	-0.702	0.702	0.000	1.000
Drouzas et al. 2020 bilateral	0.000	0.358	0.128	-0.702	0.702	0.000	1.000
Hammami 2019a	-0.330	0.309	0.095	-0.935	0.275	-1.069	0.285
Hamami et al., 2019b	-0.000	0.367	0.135	-0.719	0.719	-0.000	1.000
Hamami et al., 2019c	0.117	0.367	0.135	-0.603	0.836	0.317	0.751
Hammami 2020a - PS	5.575	1.110	1.231	3.400	7.750	5.024	0.000
Hammami 2020a - P	0.258	0.518	0.268	-0.757	1.272	0.498	0.619
Hammami et al. 2020b	-0.170	0.336	0.113	-0.827	0.488	-0.506	0.613
Hammami et al. 2020c - LP	1.029	0.495	0.245	0.059	1.999	2.079	0.038
Hammami et al. 2020c - UP	-0.090	0.476	0.227	-1.024	0.844	-0.189	0.850
Lovecchio et al. 2019	0.417	0.255	0.065	-0.084	0.917	1.631	0.103
Makhlouf et al. 2018 PJT+balance	1.261	0.436	0.191	0.406	2.117	2.890	0.004
Makhlouf et al. 2018 PJT+agility	0.967	0.426	0.182	0.131	1.802	2.268	0.023
Tay et al. 2019	-0.295	0.382	0.146	-1.044	0.453	-0.773	0.439
	0.442	0.179	0.032	0.092	0.792	2.476	0.013

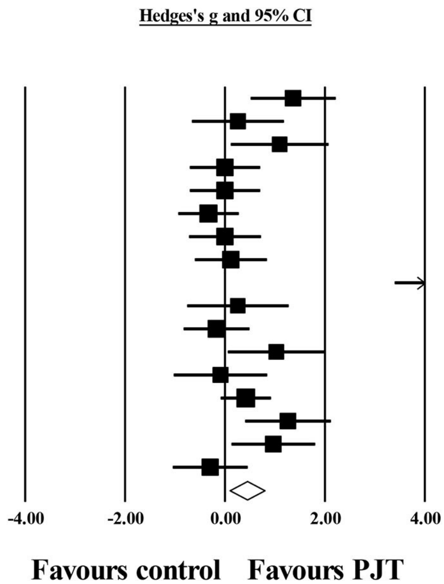

FIGURE 7 | Forest plot of changes in static balance, measured through field-based tests, in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
Arabatzi, 2018	1.127	0.426	0.182	0.292	1.963	2.644	0.008	7.62
Cherni et al, 2019	1.020	0.413	0.171	0.210	1.830	2.469	0.014	8.12
Huang et al.. 2014	0.436	0.434	0.188	-0.415	1.286	1.004	0.315	7.36
Karadenizli, 2016	0.119	0.381	0.145	-0.628	0.866	0.312	0.755	9.53
Meszler and Vaczi 2019	-0.011	0.449	0.202	-0.891	0.868	-0.026	0.980	6.88
Ramriez-Campillo et al., 2015 Bilateral	0.373	0.525	0.275	-0.655	1.401	0.711	0.477	5.04
Ramirez-Campillo et al., 2015 Unilateral	0.289	0.510	0.260	-0.711	1.288	0.566	0.571	5.33
Ramirez-Campillo et al., 2015 Uni+Bi	0.913	0.544	0.296	-0.154	1.979	1.678	0.093	4.68
Ramirez-Campillo et al., 2015 Vertical	0.152	0.591	0.350	-1.007	1.310	0.256	0.798	3.96
Ramirez-Campillo et al., 2015 Horizontal	0.262	0.593	0.351	-0.900	1.424	0.442	0.659	3.94
Ramirez-Campillo et al., 2015 Ver+Hor	0.481	0.598	0.357	-0.691	1.653	0.805	0.421	3.88
Ritzman et al., 2018	1.005	0.429	0.184	0.164	1.845	2.343	0.019	7.54
Surakhamhaeng et al., 2020	0.184	0.429	0.184	-0.658	1.025	0.428	0.669	7.52
Witzke and Snow 2000	0.332	0.273	0.075	-0.203	0.867	1.215	0.224	18.59
	0.475	0.118	0.014	0.244	0.705	4.031	0.000	

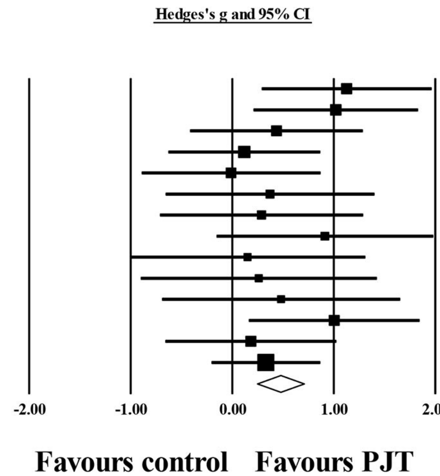

FIGURE 8 | Forest plot of changes in static balance, measured through laboratory-based equipment, in participants that completed a plyometric jump training (PJT) program compared to participants allocated as controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of each study. The diamond reflects the overall result.

training load to participant's regular activities showed a small significant overall balance improvement ($ES = 0.35$), similar to those studies that replaced parts of their regular training with PJT ($ES = 0.47$). Therefore, further research concerning the influence of PJT dosage on balance is required to better understand this subject.

Our analysis found greater PJT-related balance improvements in athletes (ES range: 0.43–0.84) compared to non-athletic populations (ES: 0.20). A qualitative analysis of the studies conducted with non-athletic populations revealed that the included participants were aged 9–65 years. Training-induced improvements maybe diminished in older compared with younger adults. The studies that examined athletic populations had an age range of 9–23 years. The differences in age between athletic and non-athletic populations could be responsible for the different effect sizes. These findings suggests that athletes may be physiologically predisposed to greater balance-related adaptations with latter training interventions (Lauber et al., 2021). This finding is similar to the greater balance improvement noted in athletes compared to non-athletic populations after balance training (Lesinski et al., 2015a). To be able to perform various multidirectional movements such as jumping, linear sprints and change of direction tasks, balance is an essential prerequisite for sport-specific performance in sports such as soccer, basketball and handball (Ramírez-Campillo et al., 2015b, 2020b). Athletes regularly perform these movements during training practice as well as matches. With reference to their training history, athletes may have developed better kinesthetic awareness and body control compared to non-athletes (Davlin, 2004). This, in turn, may have resulted in larger PJT effects on overall balance. This is in line with previous literature, suggesting that improved kinesthetic awareness and body control through the application of balance training before PJT, would induce greater improvements in balance performance after PJT (Hammami et al., 2016).

Adverse Health Effects Derived From PJT Interventions

There were no intervention-related injuries reported in the studies included in our meta-analysis. The relative safety of PJT programmes has been previously reported (Mason and Pengrim, 1986; Markovic and Mikulic, 2010; Ramírez-Campillo et al., 2020c). PJT interventions may actually reduce the risk of injury, provided they are adequately programmed and performed under supervision (Rössler et al., 2014, 2016). However, this type of training should not be recommended to unfit athletes or adults with low strength/power levels, poor motor competency and an inability to decelerate their body mass during landing tasks (Ramírez-Campillo et al., 2020c). There is ample evidence in the literature regarding the risk of higher PJT volumes on risk of injury, especially in female athletes (Brumitt et al., 2016, 2018). Given that a reduction in PJT volume correlate with reduced overload-induced inflammation from large eccentric loads (Choi, 2014; Fransz et al., 2018), lower PJT volumes appear to be better suited to improve overall balance. While none of the included studies reported adverse health effects, 23 studies did not report participants' previous experience with PJT. Moreover, there was no information regarding the movement quality during plyometric jump drills and progressive overload in any of the included studies. Even though a potential relation has been reported previously between movement competency and PJT progression (Lloyd et al., 2011, 2016; Meylan et al., 2014) along with some factors potentially associated with the safety of PJT drills (Davies et al., 2015), conclusive evidence is still lacking. Further, there is also paucity in regards of the exact dosage and progression of programming parameters in PJT (Chmielewski et al., 2006) and in terms of the use of adequate proxies of PJT (Ebben, 2007; Ramírez-Campillo et al., 2018). Therefore, further research should be conducted to receive a better understanding of this topic. Further, 24 of the included studies in this meta-analysis failed to report specific information regarding adverse health effects. This reflects a larger problem in sports sciences and produces unbalanced accounts, as authors report the main effects, but not the adverse health effects.

Methodological Quality

Even though all included studies were of moderate-to-high quality, none of the studies scored more than 6 points on the PEDro scale. According to the available evidence in the literature, previous systematic PJT review (Bedoya et al., 2015; Stojanović et al., 2017) have rated the published studies in this area as medium quality using the PEDro scale. A few potential reasons for this could be due to the difficulties in conducting studies that include blinding of participants and therapists. A recent PJT scoping review of Ramírez-Campillo et al. (2020c) highlighted several methodological shortcomings based on the analysis of 420 studies, with the most prominent issue being an incomplete description of training intervention characteristics, and difficulties with the randomization process and the incorporation of control groups, particularly among highly-trained athletes. Even though the included studies in our meta-analysis generally reported a clear description of the training interventions, a few key programming parameters such as rest between sets, repetitions and training intensity were not clearly reported in a few studies. Future PJT studies should try to provide a better description of all the parameters that were considered while designing the training programme to improve overall methodological quality.

Potential Physiological Mechanisms Responsible for Balance Improvement After PJT

Our results revealed small (up to $ES = 0.56$) PJT-related improvements in measures balance compared to active controls. Compared to PJT-related improvements of other physical fitness and athletic traits (e.g., linear sprint speed; vertical jump performance; small to large $ES = 0.60–2.24$) (Shi et al., 2019; Ramírez-Campillo et al., 2020a,d), the observed balance improvements were small but meaningful and achieved the level of statistical significance. These findings are in agreement with previous studies, where PJT improved balance by promoting anticipatory postural adjustments (Gantchev and Dimitrova, 1996). Repeated exposure to balance challenges during PJT (e.g., landings) favors proactive or feedforward adjustments that appropriately activate muscles before landing (Marigold and Patla, 2002; Paillard et al., 2006). The sensitivity of the afferent feedback loops can also be improved using PJT (Borghuis et al., 2008). The PJT programmes in our meta-analysis combined unilateral, bilateral, horizontal and vertical jumping exercises which is in line with the requirements of multiple direction actions required in different sports (e.g., soccer). The improvements can also be attributed to reduced agonist-antagonist co-activation of lower-limbs muscles (Lloyd, 2001) or changes in proprioception and neuromuscular control (Hewett et al., 2002). PJT induces different neuromuscular adaptations potentially related to postural control (Ramírez-Campillo et al., 2021a), such as an increased neural drive, improved inter-muscular coordination, changes in muscle size and architecture, and/or changes in single-fiber mechanics, as well as changes in muscle-tendon mechanical-stiffness (Markovic and Mikulic, 2010). Some of these adaptations may improve balance. However, the discussion of mechanisms underlying improved balance after PJT remain speculative in our meta-analysis, with further empirical research needed to elucidate such mechanisms.

LIMITATIONS

There are a few limitations of our study that should be emphasized. First, additional analyses regarding PJT frequency, duration, and total sessions could not be performed for all balance performance measures due to limited availability of studies (less than three) for at least one programming parameter. This limitation was also apparent with respect to PJT intensity, which was not reported in several studies. Second, even though the included studies did not specify any adverse health events associated with the PJT interventions, it remains unclear whether there was an attempt by the researchers to comprehensively record all possible negative responses. Therefore, to expand our knowledge on the safety of this type of training, future studies should report injuries, pain, or other adverse events related to PJT. Third, we could not compute a meta-analysis for all dynamic and static balance tests (e.g., balance-error score system) due to limited availability of studies reporting these outcomes. Fourth, the moderator effect of subgroups (e.g., age, sex, training background) could not be determined for all balance measures due to limited number of studies. Fifth, most participants in the included studies were relatively young (<30 years of age), and although our moderator analyses indicated no effect of age on PJT related balance outcomes there is a need to study this issue with master athletes and even older adults. In this sense, our results are somewhat limited in their generalizability, and demonstrate that there is a gap on the literature. Finally, we did not include articles written in languages other than English. However, considering that only 0.4% of peer-reviewed PJT studies are written in non-English languages (Ramírez-Campillo et al., 2018), this issue probably had a trivial impact on our findings. Despite these limitations, our systematic review with meta-analysis makes a novel and significant contribution to the existing literature and highlights the benefits of PJT if the goal is to not only improve muscle strength and power but also balance.

Practical Applications

Findings from this study have practical implications for coaches and practitioners. First, the results of this meta-analysis demonstrate the effectiveness of PJT on measures of dynamic and static balance. Given that balance represents a foundational fitness component for the performance of everyday (e.g., walking on uneven ground) and sport-related activities (e.g., change-of-direction tasks), it should be promoted through balance training and/or PJT (Behm et al., 2010; Gebel et al., 2018). More specifically, our sub-analyses indicate that PJT as positive effects on balance, irrespective of age and sex that are even comparable to those of balance training. However, caution is needed when it comes to the prescription of PJT to avoid overload and subsequent injuries. Third, the implementation of PJT is inexpensive compared to other training methods, requiring little or no equipment, usually involving drills with the body mass used as load (Ramírez-Campillo et al., 2020b). Additionally, PJT may be conducted in a relatively small space, which may be an important advantage during certain scenarios (e.g., encountering pandemic restrictions) where athletes may be forced to train at home (Gentil et al., 2020). Moreover, PJT is a highly variable exercise type compared with other training methods (e.g., flexibility, endurance). This is of particular importance for young athletes (Ward et al., 2007). Fourth, our meta-analysis revealed that other types of training practices such as resistance, balance and whole-body vibration training elucidated similar effects on balance performance compared to PJT. Plyometric exercises appear to induce adaptive processes in the muscle (Moran et al., 2021; Ramírez-Campillo et al., 2022) and the neural system (Ramírez-Campillo et al., 2022) that promote dynamic and static balance performance and kinesthetic control (Lee et al., 2020). Therefore, PJT might not only be a useful tool for increasing muscle power output of the lower limbs, but also balance (Vetrovsky et al., 2019).

CONCLUSIONS

To our knowledge, this is the first meta-analysis to have specifically evaluated the effect of PJT on overall, dynamic and static balance in healthy participants. A total of 1,806 participants, divided into experimental and control groups, were analyzed in our meta-analysis. This large sample size is a strength of the current systematic review and meta-analysis as it addresses the issue of underpowered studies due to smaller sample size, commonly occurring in PJT literature. Our findings demonstrate that compared to active controls, PJT is effective in enhancing various measures of balance performance (dynamic and static), irrespective of the sex and age of the participants. Further, PJT induced similar improvements in balance performance when compared to other training methods (e.g., balance training). Therefore, PJT can also be used as a potential training method for improving balance performance, in conjunction with other physical characteristics such as muscular strength and power. Although our moderator analysis revealed no particular dose-response trend, from 38 studies included in the meta-analysis, the PJT interventions lasted an average of 8 weeks, and the mean weekly frequency of PJT was 2 sessions/week. These programming variables may be considered to improve dynamic and static balance performance by practitioners while designing and implementing PJT programme in the athletic and non-athletic population. Our study further indicated that athletes show greater improvement in balance measures (dynamic and static) compared to non-athletes. Therefore, PJT might be a useful addition to their training regimen to improve balance performance during various dynamic athletic movements. The studies included in our meta-analysis did not report any training related injuries in the recruited participants. Therefore, our systematic review and meta-analysis further confirm the safety and efficacy of PJT in healthy participants of different sex, age and sporting background.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

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

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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.2021.730945/full#supplementary-material

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Equal-Volume Strength Training With Different Training Frequencies Induces Similar Muscle Hypertrophy and Strength Improvement in Trained Participants

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The main goal of the current study was to compare the effects of volume-equated training frequency on gains in muscle mass and strength. In addition, we aimed to investigate whether the effect of training frequency was affected by the complexity, concerning the degrees of freedom, of an exercise. Participants were randomized to a moderate training frequency group (two weekly sessions) or high training frequency group (four weekly sessions). Twenty-one participants (male: 11, female: 10, age: 25.9 ± 4.0) completed the 9-week whole-body progressive heavy resistance training intervention with moderate (n = 13) or high (n = 8) training frequency. Whole-body and regional changes in lean mass were measured using dual-energy x-ray absorptiometry, while the vastus lateralis thickness was measured by ultrasound. Changes in muscle strength were measured as one repetition maximum for squat, hack squat, bench press, and chest press. No differences between groups were observed for any of the measures of muscle growth or muscle strength. Muscle strength increased to a greater extent in hack squat and chest press than squat and bench press for both moderate (50 and 21% vs. 19 and 14%, respectively) and high-frequency groups (63 and 31% vs. 19 and 16%, respectively), with no differences between groups. These results suggest that training frequency is less decisive when weekly training volume is equated. Further, familiarity with an exercise seems to be of greater importance for strength adaptations than the complexity of the exercise.

Keywords: skeletal muscle, resistance training, training frequency, hypertrophy, strength, trained individuals

INTRODUCTION

Resistance training is an essential tool in the pursuit of athletic performance (McGuigan et al., 2012) and for improving health (El-Kotob et al., 2020). To optimize the effects of resistance training, the manipulation of several factors, primarily training volume, load, and frequency, is central (American College of Sports Medicine, 2009). The current recommendations on training frequency, defined as the number of sets or training sessions on a given muscle group performed within a given timeframe, have been criticized for being based on limited evidence

(Grgic et al., 2018; Ralston et al., 2018; Schoenfeld et al., 2019). The latest meta-analyses suggest a limited role for training frequency, given that the weekly training volume is kept identical between groups (Grgic et al., 2018; Ralston et al., 2018; Schoenfeld et al., 2019). However, in the current literature, studies isolating frequency by keeping total weekly volume matched between groups are limited; most include untrained participants and compare training frequencies of one to three sessions per week. As trained individuals are more likely to have greater training frequencies than less trained individuals, and the frequencies used are likely to be greater than those investigated in most studies (Strömbäck et al., 2018), a need for more research on this group has been expressed (Grgic et al., 2018; Ralston et al., 2018). To our knowledge, there are ten published studies on volume equated resistance training frequency in trained individuals published to date (McLester et al., 2000; Schoenfeld et al., 2015; Brigatto et al., 2018; Colquhoun et al., 2018; Gentil et al., 2018; Gomes et al., 2019; Lasevicius et al., 2019; Saric et al., 2019; Zaroni et al., 2019; Johnsen and van den Tillaar, 2021). Five of these studies have focused on higher frequencies than 3 days per week (Colquhoun et al., 2018; Gomes et al., 2019; Saric et al., 2019; Zaroni et al., 2019; Johnsen and van den Tillaar, 2021). Zaroni et al. (2019) reported greater muscle hypertrophy but no differences in strength gain when comparing one (lower body) and two (upper body) weekly sessions with five sessions per week in young, trained men. Apart from this study, there seems to be no difference in muscular adaptations when comparing one and five (Gomes et al., 2019), two and four (Johnsen and van den Tillaar, 2021), or three and six (Colquhoun et al., 2018; Saric et al., 2019) weekly training sessions in young trained men.

Although the current evidence for a beneficial effect of higher training frequencies in trained individuals is weak, it is based on small studies with limited power to detect small but meaningful differences between protocols. Thus, there is a need for more data to be able to make precise and evidence-based recommendations. In addition, there are several theoretical advantages to increased training frequency. The protein synthetic response to a training stimulus is considered to last for at least 24–48 h after a bout of resistance exercise in untrained individuals (MacDougall et al., 1995; Phillips et al., 1997; Burd et al., 2011). A higher training frequency may therefore allow for more time with a net positive protein balance and greater muscular adaptations to resistance training. In contrast to untrained individuals, exercise-induced elevations of protein synthesis appear to last only about 24 h after resistance exercise in resistance-trained individuals (Damas et al., 2015). Thus, the advantages of higher training frequencies may increase with training status. Further, it has been suggested that distributing training volume across several days may reduce fatigue during the sessions (Dankel et al., 2016) and reduce recovery time between sessions (Pareja-Blanco et al., 2020). This may allow for greater training loads, potentially resulting in superior muscular adaptations to resistance training. Lastly, more frequent neuromuscular stimuli may optimize motor learning, increasing strength through neurological factors (Shea:2000dt). This may be more pronounced in complex multi-joint, free weight lifts, with greater degrees of freedom, compared with simpler single joint or machine-based exercises. Although neurological adaptations are primarily expected to occur at the beginning of training, antagonist inhibition has been shown to improve also after years of exercise (Balshaw et al., 2019). To the best of our knowledge, no study has yet explored whether exercise complexity influences the potential benefits of training frequency in trained individuals.

Therefore, the current study aimed to compare the effects of two and four weekly volume equated heavy resistance training sessions on gains in muscle mass and -strength in resistance-trained men and women. Further, we investigated whether the effect of training frequency was influenced by the complexity of the exercises. We hypothesized that a volume equated weekly training frequency of four sessions per week would result in greater muscular adaptations and strength gains than two sessions per week. We further hypothesized that the benefits of a higher training frequency would be greater in more complex exercises (squat and bench press) compared to less complex exercises (hack squat and chest press).

MATERIALS AND METHODS

Ethical Approval

The study was performed according to the ethical standards established by the *Declaration o*f Helsinki 2013 and was approved by the Local Ethical Committee at the Inland Norway University of Applied Sciences (20/03749) and pre-registered in a Norwegian public database (Norwegian Center for Research, project number 300667). All participants signed an informed consent form before participation.

Participants

Thirty-four moderately resistance-trained men and women volunteered to participate in the study. To be included in the study, participants had to be between 18 and 35 years of age, free of injury, performed one resistance-training workout per week on average over the last 6 months, and be familiar with the powerlifting exercises squat and bench press. Participants were randomized into a high-frequency group (HF) (n = 17) and a low-frequency group (LF) (n = 17) stratified by sex, age, years of resistance training experience, and 1 repetition maximum (RM) results from the first test. Participants who had more than 10 days without a workout or were not able to complete 95% of the planned sets were excluded (n = 3). Due to the ongoing sars-CoV-2 pandemic, the number of participants who were allowed to exercise simultaneously was controlled and training times were strict. Participants who were unable to attend these times, due to quarantine (n = 3) or sars-CoV-2 infection (n = 1), were excluded (n = 3). Three participants were unable to complete the study due to injuries and three participants dropped out of the study due to personal reasons. Thus, 21 participants were included in the analysis (HF: n = 8, LF:n = 13).

Experimental Design

The intervention consisted of a 9-week training period (see **Table 1**). While the total amounts of weekly sets and training load (RM) were identical, the HF and LF groups performed

TABLE 1 | Training protocol.

Group	Day 1 exercise: sets	Day 2 exercise: sets	Day 3 exercise: sets	Day 4 exercise: sets	Total weekly sets	Repetitions and load
High frequency	Squat: 2	Hack squat: 2	Squat: 2	Hack squat: 2		First workout: 70% 1RM Week 1–3: 12RM Week 4–6: 10RM Week 7–9: 8RM
	Hack squat: 1	Squat: 1	Hack squat: 1	Squat: 1		
	Bench press: 2	Chest press: 2	Bench press: 2	Chest press: 2		
	Chest press: 1	Bench press: 1	Chest press: 1	Bench press: 1		
	Lat pulldowns: 2	Seated row: 2	Lat pulldowns: 2	Seated row: 2		
Total workout sets	**8**	**8**	**8**	**8**	**32**	
Low frequency	Squat: 4		Hack squat: 4			
	Hack squat: 2		Squat: 2			
	Bench press: 4		Chest press: 4			
	Chest press: 2		Bench press: 2			
	Lat pulldowns: 4		Seated row: 4			
Total workout sets	**16**		**16**		**32**	

4 and 2 sessions per week, respectively. Thus, HF performed half the training volume of the LF per workout. The training period was divided into three blocks based on RM number: week 1–3: 12RM, week. If failure was reached before the intended repetition range, the resistance was quickly reduced to allow for the remaining repetitions to be completed. If participants were able to complete more than the intended repetitions the set was performed to failure and the resistance was increased at the next set. Each week, the exercise order was rotated to balance the number of workouts, starting with a more complex exercise (squat and bench press) and a less complex exercise (hack squat and chest press in a machine). Four minutes of rest was given between each set. To equate the warm-up sets across each week, LF performed two sets (12 reps of 30% 1RM and 12 reps of 50% 1RM), whereas HF performed four sets (2×12 reps of 30% 1RM and 2×12 reps of 50% 1RM). There was a strong focus on completing all sets in every workout. All sessions were supervised by trained personnel. To counteract a potential effect of differences in protein intake participants were provided 20 g of whey protein mixed in water after each workout. To balance the protein supplementation, the protein was also ingested the day after workouts in the low-frequency group. Before and after the training period, participants performed a set of 1RM tests (squat, hack squat, bench press, and chest press) and underwent a dual-energy x-ray absorptiometry scan (DXA) and an ultrasound scan of the vastus lateralis muscle from both legs.

Testing Procedures

The participants were instructed to avoid exercise and strenuous physical activity for 48 h before all tests. Instructional videos explaining the 1RM testing procedures were emailed to and watched by all participants before testing. Before the 1RM test, participants warmed up for 5 min on a rowing ergometer (Concept 2 inc., Vermont, VT, United States) with an intensity of 9–11 on the 6–20 Borg-scale (Borg, 1982), followed by two sets of 20 walking lunges and two sets of 10 shoulder rotations using a wooden dowel. On the first 1RM test, individual settings were established for each participant, and identical settings were used on subsequent testing. The 1RM tests were performed by completing single repetitions with increasing load and 4 min of rest between each repetition. The goal was to reach 1RM on the tenth repetition. After attaining 1RM for squat and bench press, participants had a 30-min break with a small meal before completing the 1RM tests for hack squat and chest press. The meal was identical at all 1RM tests within an individual participant but differed between participants. The squat and bench press were performed in a Tteka BN-02 combo (TTEKA company, Montreal, QC, Canada). The execution of the squat and bench press was performed according to the standardization of the International Powerlifting Federation (2021) technical rules, except the grip width in the bench press, which was set to be 81 cm from the fifth finger to the fifth finger. The hack squat was performed in a Cybex International Hack Squat (Cybex International, Inc., Massachusetts, MA, United States). Joint angles were measured using a goniometer. The correct depth was set as a hip joint angle of $\leq 90°$ and a knee joint angle smaller than 90°. Foot placement was adjusted to 22.5, 27.5 (middle of the plate), or 32.5 cm to achieve the intended hip and knee angles. The correct depth for each participant was noted on a vertical measuring band attached to the hack squat. Chest press was performed in a Cybex Converging Plate Loaded Chest Press (Cybex International, Inc., Massachusetts, MA, United States). The chest press started with arms in the extended position and was finished with arms returned to the extended position. A band was attached between the handles, and an accepted 1RM required the band to touch the chest at *proc. xiphoideus*. During the lift, the whole foot remained in contact with the floor, the buttocks in contact with the seat and the back, shoulder blades, and head in contact with the back support. A test leader controlled all 1RM attempts.

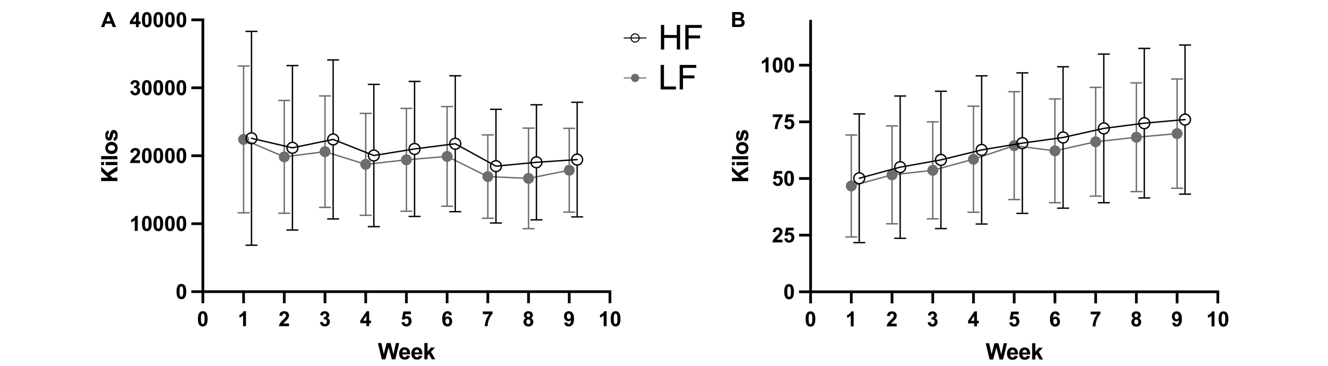

FIGURE 1 | Weekly training volume **(A)** and average load **(B)** with 2 (LF) and 4 (HF) weekly sessions during a 9-week resistance training intervention.

Body composition was determined using a dual-energy x-ray absorptiometry (DXA) (Lunar Prodigy, GE Healthcare, Madison, WI, United States) after an overnight fast and was analyzed following the protocol of the manufacturer, using the software of the manufacturer. The participants were placed in the supine position with a neutral neck position. Hands were semi-pronated and arms were placed close to the border of the measurement area to simplify the post-scan measurements. The foot position was standardized in a neutral position using a foam rubber cast (10 cm between heels) with negligible absorbance. Regions of interest were used to analyze different body regions. Dividing lines between arms and thorax were drawn through the glenohumeral joint. Dividing lines between the thorax and legs were drawn midway through the femoral neck at a 90-degree angle to the femoral neck. All DXA scans were performed by a researcher blinded to subject randomization. The intraclass correlation (ICC) for lean body mass in our lab is 0.99. The muscle thickness of m. vastus lateralis of both legs were measured using B-mode ultrasonography (SmartUs EXT-1 M, Telemed, Vilnius, Lithuania) with a 39 mm 12 MHz, linear array probe. Image depth was set to 8 cm, frequency to 12 Hz, the dynamic range was set to 72 dB, and the gain was set to 43%. Longitudinal images were obtained ~50% distally from the trochanter major toward the femoral lateral epicondyle. Three images were captured before and after the training intervention. The probe's position was marked on the skin and subsequently marked on a soft transparent plastic sheet superimposed on the thigh. Landmarks such as moles and scars were also marked on the plastic sheet for relocation of the probe during post-training measurements. Furthermore, pre-test images were used to locate anatomical landmarks on the post-test images to ensure the same measuring location. During analysis, pre and post-images from the same participant were analyzed consecutively using the Fiji software macro tool "Simple Muscle Architecture Analysis" (Seynnes and Cronin, 2020). The average muscle thickness of the three images from each leg was averaged, and the average of both legs at the given time point was used for further analyses. All ultrasound measures were performed by a researcher blinded to subject randomization. ICC for ultrasound measures of vastus lateralis in our lab is 0.96. After the training period, the DXA and ultrasound were measured between 48 and 96 h after the last training session.

Statistical Analysis

Statistical analyses were performed using jamovi (version 1.6.23.0 for mac; the jamovi project, retrieved from www.jamovi.org) and GraphPad Prism (version 9.2.0 for mac; GraphPad Software, La Jolla, CA, United States). The effect of HF *vs*. LF on study variables was analyzed using ANCOVA, with post-intervention outcomes as dependent variables and baseline values and sex as covariates. Pearson's correlation coefficients (*r*) were calculated for changes in 1RM and lean mass. The effect of HF *vs*. LF in simple and complex exercises and training volume and load were analyzed by a two-way ANOVA with repeated measures. Furthermore, the effect size (ES) was calculated as Cohen's *d* using the mean pre-post change in HF minus the mean pre-post change in LF, divided by the pooled pre-test standard deviation (Morris, 2008). Outcomes are reported with standard deviation unless otherwise specified. A two-tailed *P*-value less than 0.05 was considered significant.

RESULTS

Muscle Strength

The weekly training volume and load are displayed in **Figure 1**. Both groups improved 1RM in squat (HF: 16.3 ± 5.2 kg, LF: 14.8 ± 4.2 kg), hack squat (HF: 33.4 ± 13.9 kg, LF: 34.4 ± 9.7), bench press (HF: 7.5 ± 3.5, LF: 7.7 ± 3.0 kg), and chest press (HF: 15.9 ± 13.8 kg, LF: 15.0 ± 5.0 kg) during the training intervention. The improvements in 1RM did not differ between groups (see **Table 2** and **Figure 2**).

Lean Mass and Muscle Thickness

Lean mass (HF: 1.14 ± 2.0 kg, LF: 1.46 ± 1.38 kg), lean leg mass (HF:0.35 ± 0.79 kg, LF:0.64 ± 0.63 kg), lean trunk mass (HF:0.41 ± 1.17 kg, LF:0.66 ± 0.93 kg), lean arm mass (HF:0.38 ± 0.40 kg, LF:0.18 ± 0.24 kg), and vastus lateralis thickness (HF:0.51 ± 0.22 cm, LF:0.48 ± 0.18) improved in both groups. There were no differences between groups for any of the measures of muscle growth (see **Table 2** and **Figure 1**).

TABLE 2 | Comparisons between groups are based on estimated marginal means.

	ANCOVA HF vs. LF			
	Mean effect	***P***	**ES**	**95% CI**
Lean mass total	−0.1 kg	0.897	−0.07	−1.09 to 0.97
Lean mass legs	−0.4 kg	0.296	−0.54	−1.61to 0.54
Lean mass trunk	0.0 kg	0.969	−0.02	−0.99 to 1.04
Lean mass arms	0.2 kg	0.210	0.61	−0.41 to 1.63
VL thickness	−0.00 cm	0.950	−0.03	−1.01 to 0.95
1RM total	5.5 kg	0.637	0.3	−0.79 to 1.25
1RM squat	4.2 kg	0.192	0.69	−0.41 to 1.79
1RM hack squat	−1.27 kg	0.824	−0.11	−1.11 to 0.89
1RM bench press	0.7 kg	0.676	0.20	−0.80 to 1.21
1RM chest press	2.7 kg	0.554	0.26	−0.74 to 1.26

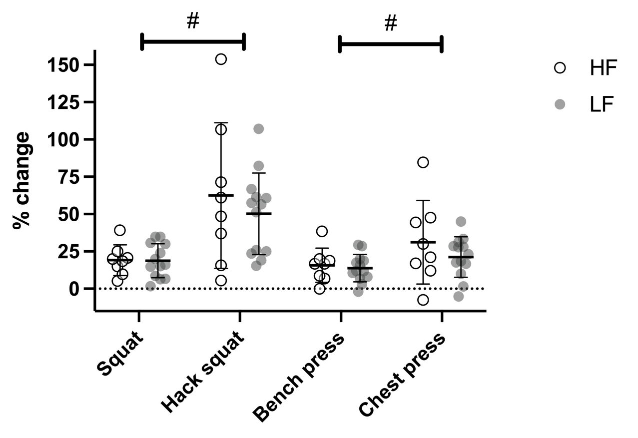

FIGURE 2 | Percent changes in one repetition maximum for squat, hack squat, bench press, and chest press. Horizontal lines are averages with error bars representing SD. #Difference between simple and complex exercises, $p < 0.05$.

Complex vs. Simpler Exercises

The hack squat 1RM (HF: 62.5 ± 48.8%, LF: 50.2 ± 23.6%) increased more in relative terms than the squat 1RM (HF: 19.1 ± 10.3%, LF: 18.7 ± 8.6%) in both groups ($P < 0.01$ for both). Chest press 1RM increased more in relative terms than bench press 1RM in HF (31.2 ± 27.9% and 15.8 ± 11.5%, respectively, $P = 0.011$) but not in LF (13.8 ± 7.4% and 21.3 ± 7.8%, respectively, $P = 0.171$). Combining both groups 1RM in the less complex exercises increased more than more complex exercises (Lower body: 18.9 ± 10.7% vs. 54.9 ± 36.3%, $P < 0.00$; Upper body: 14.6 ± 9.9% vs. 25.0 ± 20.2%, $P = 0.001$). The differences between squat and hack squat, and bench press and chest press did not differ between groups. There was a significant correlation between changes in 1RM for all exercises (squat – hack squat: $r = 0.64$, squat – bench press: $r = 0.83$, squat – chest press: $r = 0.69$, hack squat – bench press: $r = 0.74$, hack squat – chest press: $r = 0.73$, bench press – chest press: $r = 0.78$, $p > 0.001$ for all). There were no significant correlations between changes in muscle strength and changes in muscle mass.

DISCUSSION

The current study found that in moderately resistance-trained individuals distributing weekly resistance training volume into two or four workouts did not result in different outcomes for 1RM, lean mass, or vastus lateralis thickness. Further, muscle strength in complex exercises does not benefit more from a higher training frequency than in simpler exercises.

In line with most previous studies, weekly training frequency seems to be subordinate to training volume in terms of increasing muscle mass, given training volume is kept identical within each week (Colquhoun et al., 2018; Gomes et al., 2019). Our finding goes against the theoretical benefit of multiple upregulations of stimulating protein synthesis and thus increased anabolic stimulus with an increased frequency. This could result from a suboptimal training stimulus when the training volume was distributed across 4 days. However, previous studies suggest that relatively small training volumes can produce a robust muscle protein synthetic response in resistance-trained and active individuals (Burd et al., 2010, 2011). Several recent contributions may help shed more light on this discrepancy. Evidence suggests that volume-sensitive long-term adaptations of translational capacity, rather than repeated acute changes in translational efficiency, are associated with hypertrophy (Figueiredo, 2019; Hammarström et al., 2020). This is further supported by the lack of measurable differences in myofibrillar protein synthesis over 7 days with a matched training volume distributed across one or five workouts (Shad et al., 2021). Alternatively, the manipulation of resistance training variables may be secondary to other intrinsic factors. At least when a sufficient stimulus is provided, as suggested by Damas et al. (2019) who elegantly displayed remarkable stability within individuals despite manipulating resistance training variables, in contrast to a substantial between-individual variability.

It has been suggested that an increased training frequency may enhance neural adaptations to a greater extent in more complex exercises compared with simple exercises (Shea et al., 2000). Given a more complex movement pattern, we expected strength in squat and bench press to increase more compared with hack squat and chest press in the HF group when compared with the LF group. To the best of our knowledge, this is the first study to investigate this effect from a resistance training perspective. Contrary to our hypothesis, 1RM increased more in the less complex exercises. The difference was surprisingly large given the exercises had similar movement patterns and were trained with the same weekly volume. This is possibly explained by the participants having considerably more experience with squat and bench press than hack squat and chest press (see **Table 3**). Thus, our data suggest familiarity with an exercise to be of greater importance than the complexity of the exercise when it comes to improvements in muscle strength.

Although the relative changes in 1RM differed between similar exercises, we observed moderate to strong correlations between these changes in all measured exercises. This may suggest that changes in e.g., both squat and hack squat 1RM to a large extent, should represent changes in leg strength as a phenomenon. However, as these correlations exist between all

TABLE 3 | Descriptive data of participants before and after 9 weeks of heavy resistance exercise.

Characteristic	HF pre	HF post	LF pre	LF post
N (♂/♀)	3/5	3/5	8/5	8/5
Age (years)	26.8 ± 3.9		25.5 ± 4.3	
Body mass (kg)	80.7 ± 15.7		74.6 ± 12.8	
Lean mass (kg)	53.7 ± 12.4	54.8 ± 12.4	53.7 ± 9.4	55.2 ± 12.1
Lean mass legs (kg)	18.5 ± 4.7	18.9 ± 4.4	18.2 ± 3.1	18.8 ± 4.4
Lean mass trunk (kg)	25.9 ± 5.5	26.3 ± 5.5	25.9 ± 4.8	26.6 ± 4.7
Lean mass arms (kg)	6.1 ± 2.2	6.4 ± 2.2	6.4 ± 1.6	6.6 ± 1.7
Body fat (%)	31.9 ± 4.9	31.6 ± 4.3	25.1 ± 6.9	24.4 ± 6.0
Vastus lateralis thickness (cm)	2.4 ± 0.5	2.9 ± 0.4	2.6 ± 0.4	3.1 ± 0.4
Squat 1RM (kg)	106 ± 56	122 ± 56	96 ± 37	110 ± 34
Hack squat 1RM (kg)	88 ± 61	122 ± 57	89 ± 52	123 ± 53
Bench press 1RM (kg)	70 ± 42	78 ± 40	70 ± 31	78 ± 30
Chest press 1RM (kg)	93 ± 67	108 ± 60	97 ± 52	112 ± 49
Weekly sessions squat	1.5 ± 0.9		1.3 ± 0.8	
Weekly sessions hack squat	0.3 ± 0.9		0 ± 0	
Weekly sessions bench press	1.2 ± 1.1		1.2 ± 0.9	
Weekly sessions chest press	0.5 ± 0.9		0.6 ± 0.6	
Resistance training age (years)	3.6 ± 2.2		3.5 ± 1.3	

Weekly sessions are an estimate of the weekly average number of sessions including the exercise over the last 6 months. Values are average ± SD.

measured exercises, they may well be driven by the training state of the participants. It is expected that the weaker participants will improve more for all exercises during the training intervention. Accordingly, the baseline 1RM performance did correlate negatively with changes in 1RM during the intervention (from −0.83 to −0.94, $p < 0.001$ for all measures). Strength is often considered a relatively universal trait. However, the present and previous data (Harris et al., 2007) suggest that a significant part of improvements in strength are specific to the given exercise and may differ significantly between similar exercises trained identically over a training period.

The current study has several strengths, among these a full supervision of all workouts, a 100% attendance, and a direct measure of muscle growth. However, it shares the limitation of a relatively short intervention period with the rest of the current training frequency literature in trained individuals. Even with a 3-week cutback, due to corona restrictions, the current 9-week study is longer than the previous 6- to 8-week interventions (Colquhoun et al., 2018; Gomes et al., 2019; Zaroni et al., 2019; Johnsen and van den Tillaar, 2021). Training protocols with equated training volume, but different training frequencies are not expected to result in large differences in adaptations. Consequently, longer interventions may be needed to discern differences between them. Measures of muscle thickness were only obtained at one point along the vastus lateralis. Previous studies have shown non-uniform hypertrophy in the quadriceps in response to resistance exercise (Narici et al., 1996). Recently, drop sets were reported to induce greater gains in hypertrophy for the rectus femoris, but not vastus lateralis, compared with traditional resistance exercise training (Varović et al., 2021). Consequently, we cannot exclude the possibility of regional differences in hypertrophy within or between muscles. Still, any potential regional differences were not large enough to be observed with the DXA measures. Given the large intraindividual variability and limited resources, a unilateral approach to further investigate the effects of training frequency seems sensible, at least for muscle growth where cross-learning is unlikely to occur (MacInnis et al., 2017). Furthermore, if two exercise regimens are compared in a contralateral manner in resistance-trained individuals, it is our belief that potential cross-learning effects on strength too will be minimal.

CONCLUSION

In conclusion, the current study did not show an effect of resistance training frequency on changes in muscle strength and muscle growth when weekly resistance training volume was kept identical in moderately resistance-trained individuals. Further, higher resistance training frequency did not result in greater improvements in strength for complex exercises compared to simpler exercises.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Local Ethical Committee at Inland Norway University of Applied Sciences (20/03749). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

HH, HM, OS, PJ, HR, and BR contributed to the conception and design of the study. HM, OS, PJ, and HR conducted the training intervention. HH, HM, OS, PJ, and HR performed the testing. HH wrote the first draft of the manuscript. HM, OS, PJ, HR, and BR wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Combined Plyometric and Short Sprint Training in U-15 Male Soccer Players: Effects on Measures of Jump, Speed, Change of Direction, Repeated Sprint, and Balance

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This study examined the effect of 8 weeks of biweekly combined plyometric and short sprint training into the typical within-season training schedule of youth male soccer players. Participants were allocated at random to an experimental group (EG; n = 17, age: 14.6 ± 0.5 years, body mass: 60.5 ± 7.1 kg, height: 1.64 ± 0.08 m, body fat: 11.3 ± 1.4%) and a control group (CG; n = 17, age: 14.6 ± 0.4 years, body mass: 61.0 ± 3.9 kg, height: 1.67 ± 0.05 m, body fat: 11.8 ± 1.4%). Measures obtained pre- and post-intervention included vertical and horizontal jump performances (i.e., squat jump (SJ), countermovement jump with aimed arms (CMJA), and five-jump test (FJT)) and sprint performances (i.e., 10 and 30 m sprint). In addition, change-of-direction ability (sprint with 90° Turns (S90°) and sprint 9–3–6–3–9 m with backward and forward running (SBF)), repeated shuttle sprint ability (RSSA), and dynamic balance performance (Y balance test) were measured pre- and post-intervention. The EG experienced higher jump (all $p < 0.05$; $d \geq 0.71$), sprint (all $p < 0.05$; $d \geq 0.64$), change-of-direction ability (all $p < 0.05$; $d \geq 0.66$), RSSA (all parameters except the fatigue index $p < 0.01$; $d \geq 0.71$), and dynamic balance (all $p \leq 0.05$; $d \geq 0.50$) improvement compared to the CG. Adding biweekly combined plyometric and short sprint training to standard training improves the athletic performance of youth male soccer players (under 15 (U15)).

Keywords: stretch-shortening cycle, short sprints training, plyometric training, training youth, soccer

INTRODUCTION

Competitive soccer match play is characterized by high-intensity intermittent activity patterns, whereby players are required to repeatedly sprint, turn, jump, and accelerate/decelerate which places the substantial neuromuscular load on players (Spencer et al., 2005; Stølen et al., 2005). Therefore, the ability of lower limb musculature to produce a high power output is an important fitness trait in soccer players (Wisløff et al., 2004). Speed and power are believed to be the variables predicting success in youth soccer (Reilly et al., 2000a). Specifically, sprint ability over short distances, agility performance, and vertical jumping are discriminative in terms of elite and sub-elite young soccer players (Reilly et al., 2000b). In professional soccer, various players commonly sprint over a distance between 200 and 1,100 m in a match (Rampinini et al., 2007; Andrzejewski et al., 2013). However, the average duration of sprints performed during a soccer match is typically short, ranging from 2 to 4 s (Stølen et al., 2005), with the sprint representing 1–11% of that distance (Mohr et al., 2003). Notably, 96% of sprints are less than 30 m, and 49% are less than 10 m (Stølen et al., 2005).

One specific type of power training that is easy to administer and therefore popular is plyometric jump training (PJT) (Ramirez-Campillo and Castillo, 2020; Ramirez-Campillo et al., 2021a; Sole and Ramírez-Campillo, 2021). PJT consists of exercises which take advantage of the stretch-shortening cycle (SSC) of the muscle (Komi and Gollhofer, 1999; Taube et al., 2012). Typically, plyometric jump exercises (PJT) can be performed with short (< 250 ms) or long ground contact times (> 250 ms), i.e., fast or slow SSC times (Duda, 1988; Sands et al., 2012; Faigenbaum and Chu, 2017). The utilization of the SSC enhances neural and musculotendinous ability to produce maximal force over a short duration (Wang and Zhang, 2016). Regardless of age, gender, sport, and expertise in training, plyometric training consistently results in improved vertical jumping, agility, and sprinting (Andrade et al., 2018; Ramirez-Campillo and Sanchez-Sanchez, 2020; Ramirez-Campillo et al., 2021b). In a systematic review, plyometric training increased power output in 13 of the 16 included studies, with effects ranging from 2 to 31% (Markovic and Mikulic, 2010). Furthermore, even in a short duration of less than 8 weeks, bilateral jumping coupled with unilateral drills enhanced performance (Markovic and Mikulic, 2010; Wang and Zhang, 2016).

Recently, combination training appears *en vogue* and is an efficacious tool for improving athletic performance. In this context, all of the combined sprint and plyometric (Ferley et al., 2020; Hammami et al., 2020; Kargarfard et al., 2020), agility and balance (Zemková and Hamar, 2010), plyometric and change-of-direction (Makhlouf et al., 2018; Hammami et al., 2019; Aloui et al., 2021), plyometric and sled (Prieto et al., 2021), balance and plyometric (Bouteraa et al., 2020; Guo et al., 2021), and plyometric and resistance (Almoslim, 2016; Ramirez-Campillo et al., 2018a; Fischetti et al., 2019) training programs have been effective to enhance muscle power. In addition, some recent research has indicated that combined training is superior to stand-alone approaches for increasing power and output capabilities (Chaouachi et al., 2014; Beato et al., 2018; Zghal et al., 2019; Ferley et al., 2020; Guo et al., 2021). Previous studies have recommended the continuation of combined plyometric and short sprint training into the soccer season to increase athletic performances. Hammami et al. (2020) found that such training enhanced jump performance, sprint performance, change-of-direction ability, and repeated change-of-direction ability, in youth male under 17 (U17) soccer players. Also, Sáez de Villarreal et al. (2015) reported significant increases in jump performance, sprint performance, and change-of-direction ability following combined plyometric-speed training and technical drills work, in youth male under 15 (U15) soccer players.

In fact, combined plyometric and short sprints seem to be the least scientifically investigated combination training mode than the others mentioned previously such as plyometrics and resistance, plyometrics and sled, and balance and plyometrics. To our knowledge, despite the above literature, there is a paucity of data concerning the efficacy of combined plyometric and short sprints on physical performance in youth male soccer players. Therefore, this study evaluated the effects of replacing normal training during the season with combined plyometric and short sprint training in elite male U15 soccer players. Herein, we examined vertical and horizontal jump performances (i.e., squat jump (SJ), countermovement jump with aimed arms (CMJA), five-jump test (FJT)), sprint performance (i.e., 10 and 30 m sprint), change-of-direction ability (sprint with 90° Turns (S90°) and sprint 9–3–6–3–9 m with backward and forward running (SBF)), repeated shuttle sprint ability (RSSA), and dynamic balance performance (Y balance test).

We hypothesized that replacing some of the regular in-season training with a biweekly intervention of this type would increase both horizontal and vertical jump performances, sprint performance, and the change-of-direction ability after 8 weeks.

MATERIALS AND METHODS

Participants

Thirty-four participants of all positions from a single male soccer team in the National First Division, with a playing experience of 4.4 ± 0.8 years, were participated. Prior to participation, participants were deemed fit to participate in the study, without orthopedic or other conditions which would preclude them from undertaking the plyometric and change-of-direction training. Subjects were randomly allocated to an experimental group (EG; n = 17, age: 14.6 ± 0.5 years, body mass: 60.5 ± 7.1 kg, height: 1.64 ± 0.08 m, body fat: 11.3 ± 1.4%) and a control group (CG; n = 17, age: 14.6 ± 0.4 years, body mass: 61.0 ± 3.9 kg, height: 1.67 ± 0.05 m, body fat: 11.8 ± 1.4%). There was no baseline difference between the groups in anthropometric characteristics ($p \geq 0.05$). Participants were without any problems regarding health status and physical condition as they had completed a 6-week preseason training period of 5-6 sessions each week.

TABLE 1 | Details of general training routine during the week performed by both control and experimental group over the 8-weeks intervention.

Days	Objectives
Mondays	Rest
Tuesdays	Aerobic capacity training and defensive tactics training
Wednesdays	Aerobic power training and defensive tactics training
Thursdays	Power anaerobic training and defensive and offensive tactics training
Fridays	Technical training and offensive tactics training
Saturdays	Technical training and offensive tactics training
Sunday	Official matches

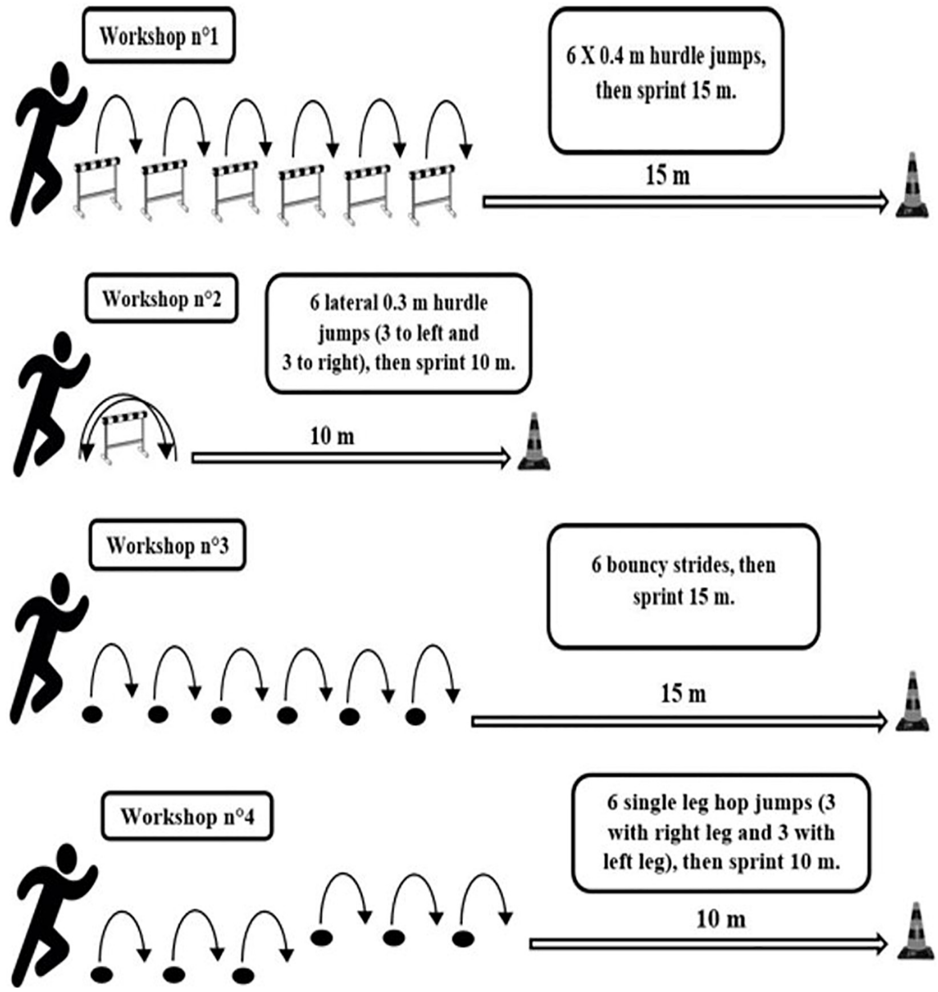

FIGURE 1 | Exercise used in the combined plyometric training program.

Experimental Design

Both groups undertook five training sessions per week (∼90 min each session), plus a competitive match one time per week. Conditioning training was completed two times per week, with the first session developing aerobic fitness through small-sided games while the second session targeted anaerobic fitness with resistance (40-60% 1 RM). The controls maintained their normal training schedule throughout the 2 months of the intervention, whereas the EG replaced the technical-tactical part of their standard regimen by combined plyometric and short sprint training. Participants also engaged in the 60-min school physical education sessions weekly (**Table 1**).

The University Institutional Review Committee for the ethical human experimentation approved the interventional study (pre- and post-design, CG vs. EG), which was in line with current national laws and regulations (reference number: KS000002020; date of approval: November 10, 2020). Participants (and their guardians, in the case of minors) gave written informed consent. Two familiarization sessions preceded the testing period by 2 weeks, which was 2 months into the competitive season.

Combined Plyometric and Short Sprint Training

The training group undertook four sessions or workshops, biweekly (**Figure 1**). Workshops commenced with plyometric exercises (i.e., hurdle jumps, lateral hurdle jumps, bouncy strides, and single-leg hop jumps) and ended with a short sprint of 10-15 m (**Table 2**). The total number of ground contacts per session was gradually increased throughout the intervention (from 72 to 144 ground contacts per session), as well as the number of sets (from 3 to 6 sets) for each workshop. The number of contacts per set was maintained at 6 contacts. A 90-s rest interval was planned between each set of exercises to allow sufficient recovery time (Negra et al., 2016). Jump training protocols were supervised by a qualified instructor. The training protocol was based on previously published recommendations for training volume and intensity from the study by Bedoya et al. (2015). Furthermore, the sprint training protocol was based on previously published recommendations for sprint distances (Sáez de Villarreal et al., 2015; Kargarfard et al., 2020).

TABLE 2 | Plyometric components introduced into the program of the experimental group.

Week	Workshop 1	Workshop 2	Workshop 3	Workshop 4	Total (contact)
1	3 Repetitions	3 Repetitions	3 Repetitions	3 Repetitions	72
2	3 Repetitions	3 Repetitions	3 Repetitions	3 Repetitions	72
3	4 Repetitions	4 Repetitions	4 Repetitions	4 Repetitions	96
4	4 Repetitions	4 Repetitions	4 Repetitions	4 Repetitions	96
5	5 Repetitions	5 Repetitions	5 Repetitions	5 Repetitions	120
6	5 Repetitions	5 Repetitions	5 Repetitions	5 Repetitions	120
7	6 Repetitions	6 Repetitions	6 Repetitions	6 Repetitions	144
8	6 Repetitions	6 Repetitions	6 Repetitions	6 Repetitions	144

TABLE 3 | Interclass correlation coefficient (ICC, 95% confidence intervals (CI)) and coefficient of variation (CV) for all performance tests.

	ICC (95% CI)	CV (95%CI) [%]
Sprint times		
10 m (s)	**0.95** (0.91-0.98)	**1.6** (1.2-2.1)
30 m (s)	**0.93** (0.89-0.97)	**1.9** (1.6-2.3)
Change of direction test		
S90° (s)	**0.93** (0.90-0.96)	**1.7** (1.4-2.2)
SBF (s)	**0.91** (0.88-0.95)	**1.8** (1.5-2.3)
Vertical jump		
SJ (cm)	**0.94** (0.90-0.98)	**2.0** (1.6-2.5)
CMJA (cm)	**0.92** (0.88-0.96)	**2.2** (1.8-2.7)
Horizontal jump		
FJT (m)	**0.84** (0.80-0.88)	**4.1** (3.6-4.5)
Y-balance test		
Right support leg		
Anterior direction (cm)	**0.96** (0.91-0.99)	**4.5** (4.0-4.9)
Posteromedial direction (cm)	**0.95** (0.91-0.98)	**4.8** (4.0-5.2)
Posterolateral direction (cm)	**0.93** (0.90-0.98)	**4.8** (4.0-5.3)
Left support leg		
Anterior direction (cm)	**0.95** (0.90-0.98)	**4.6** (4.1-5.1)
Posteromedial direction (cm)	**0.93** (0.89-0.98)	**4.8** (4.2-5.3)
Posterolateral direction (cm)	**0.92** (0.88-0.97)	**4.7** (4.1-5.2)

ICC > 0.75 and CV < 10% marked in bold.

Testing Schedule

Tests were conducted at least 3 days after the last competitive match and 5-9 days after the previous training session. Testing took place on a tartan surface integrated into the weekly training schedule of players and a standardized warm-up preceded each test. Tests were conducted on three separate days in the following order:

- Day 1: anthropometric assessment, SJ, CMJA, S90°;
- Day 2: Y balance test, 10 and 30 m sprint, SBF;
- Day 3: FJT and RSSA.

The 10 and 30 m sprint performance, S90°, SBF, SJ, CMJA, FJT, Y balance test, and the RSSA have all been previously described in detail (Sporis et al., 2010; Hammami et al., 2020; Negra et al., 2020) so are not repeated in this study to avoid self-plagiarism and for brevity. Anthropometric characteristics (body mass and body fat percentage) were evaluated barefoot in the morning after an overnight fast, with bioelectrical impedance analysis (BIA) (BC-602, Tanita Co., Tokyo, Japan; Sitko et al., 2020). Each test was explained and demonstrated by one of the trained assessors before the athlete started practice trials. The same assessor supervised the same test station during pre- and posttest to ensure consistency. A 90-s rest interval was planned between each set of exercises to allow sufficient recovery time (Negra et al., 2016).

Statistical Analyses

All statistical analysis was conducted using SPSS version 28.0 for Windows (IBM, Armonk, NY, United States). Normal distribution was tested using the Shapiro–Wilk test. The results showed that the majority of parameters showed normal distribution (76%). However, 24% (9/37) of the other parameters are not normally distributed (body fat: $p = 0.023$, SJ 1: $p = 0.017$, SJ 2: $p = 0.006$, CMJA 1: $p = 0.002$, FJT 1: $p = 0.001$, FJT 2: $p = 0.039$, repeated sprint ability (RSA) fatigue index 1: $p = 0.016$, anterior direction of left leg 2: $p = 0.010$, and posteromedial direction of left leg 2: $p = 0.034$). Homogeneity of variance was determined using the Levene's test. Notably, 38% (6/16) of variance tests indicated a missing of homogeneity of variance (SJ: $p = 0.012$, sprint 10 m: $p = 0.038$, RSA best time: $p = 0.032$, RSA mean time: $p = 0.042$, RSA fatigue index: $p < 0.001$, and posteromedial direction of left leg: $p = 0.027$).

A sample size calculation (nQuery Advisor 4.0; Statistical Solutions, Saugus, MA, USA) provided a sample size with $n = 7$ in each group. The calculation is based on a mean difference of 0.4 s in 10 m sprint using a two-sided t-test with the α level of 0.05 and a pooled SD of 0.3 s, with a statistical power of 0.8 (Bortz, 1999).

Independent samples t-tests examined baseline intergroup differences. Paired sample t-tests tested for pre-to-post performance changes within each group. Training effects were assessed by mixed factorial 2-way (group × time) ANOVA with repeated measures. Subsequently, Tukey's *post-hoc* tests examined pairwise differences. Alpha levels are reported as exact p-values as suggested by the American Statistical Association (Hurlbert et al., 2019). Effect sizes are reported as Cohen's d and are interpreted as trivial (< 0.20), small (≥ 0.20–0.49), moderate (≥ 0.50–0.79), and large (≥ 0.80) (Cohen, 1988). Percentage changes were calculated as ((post-training value − pre-training value)/pre-training value) × 100. Reliability was assessed using intraclass correlation coefficients (ICCs) (Vincent, 1995) and the

TABLE 4 | Vertical and horizontal jump test, sprint times, and change of direction performance performances in experimental and control group before and after 8-weeks intervention.

	Experimental (n = 17)			Paired t-test		Control (n = 17)			Paired t-test		ANOVA (group x time)	
	Pre	Post	% Δ	P	ES	Pre	Post	% Δ	P	ES	p	ES
Vertical jump												
SJ (cm)	24.5 ± 3.13	29.1 ± 3.36	19.1 ± 2.03	< 0.001	1.43	24.5 ± 2.00	25.4 ± 2.09	3.74 ± 1.19	< 0.001	0.45	0.006	0.71 (medium)
CMJA (cm)	30.8 ± 2.93	36.9 ± 3.14	20.0 ± 2.64	< 0.001	2.02	30.7 ± 2.98	31.9 ± 2.90	3.82 ± 0.99	< 0.001	0.39	0.001	0.86 (large)
Horizontal jump												
FJT (m)	9.33 ± 0.63	10.7 ± 0.64	15.0 ± 1.49	< 0.001	2.20	9.53 ± 0.68	10.0 ± 0.65	4.93 ± 1.44	< 0.001	0.70	0.004	0.74 (medium)
Sprint												
10 m (s)	2.07 ± 0.10	1.84 ± 0.08	−11.1 ± 1.60	< 0.001	2.51	2.03 ± 0.16	1.98 ± 0.15	−2.64 ± 0.56	< 0.001	0.35	0.006	0.71 (medium)
30 m (s)	5.23 ± 0.34	4.75 ± 0.28	−8.98 ± 1.24	< 0.001	1.51	5.19 ± 0.28	5.08 ± 0.26	−2.07 ± 0.48	< 0.001	0.40	0.012	0.64 (medium)
Change of direction Performance												
S90° (s)	7.67 ± 0.33	7.00 ± 0.28	−8.65 ± 0.85	< 0.001	2.18	7.71 ± 0.32	7.50 ± 0.30	−2.69 ± 0.61	< 0.001	0.67	0.003	0.76 (medium)
SBF (s)	9.12 ± 0.35	8.38 ± 0.36	−8.14 ± 0.68	< 0.001	2.08	9.10 ± 0.41	8.85 ± 0.40	−2.79 ± 0.66	< 0.001	0.63	0.011	0.66 (medium)

coefficients of variation (CVs) over consecutive pairs of intra-participant trials (Schabort et al., 1998). Vertical and horizontal jump parameters, sprint parameters, change-of-direction ability, and balance performance had an ICC > 0.80 and a CV < 5% (**Table 3**). Data are reported as mean ± SD.

RESULTS

Reliability is summarized in **Table 3**. ICC and CV, including 95% CI, show acceptable reliability for all variables. No parameter showed between-group differences at baseline.

Training Effects on Jump Performance

There were interaction effects (group × time) for vertical and horizontal jump performances, with the EG outperforming the CG in terms of improvement from pre- to post-intervention (SJ: Δ19%, $p < 0.01$, d = 0.71; CMJA: Δ20%, $p < 0.05$, d = 0.86; FJT: Δ15%, $p < 0.05$, d = 0.74; **Table 4**).

Training Effects on Sprint Performance

There was a training effect (group × time) on sprint performance, with the EG improving more than CG (10 m sprint: Δ−11%, $p < 0.01$, d = 0.71; 30 m sprint: Δ−9%, $p < 0.05$, d = 0.64; **Table 4**).

Training Effects on Change-of-Direction Ability

There was a training effect for S90° and SBF with the EG improving more than CG (S90°: Δ−9%, $p < 0.01$, d = 0.76; SBF: Δ−8%, $p < 0.05$, d = 0.66; **Table 4**).

Training Effects on Repeated Shuttle Sprint Ability

For the ability to perform RSS, the RSSA test also showed group × time interactions for most of its parameters (RSSA best and RSSA mean), with time decreases of Δ−8% ($p < 0.01$, d = 0.72) and Δ−8% ($p < 0.01$, d = 0.71; **Table 5**).

Training Effects on Balance Performance

There was a training effect on Y balance test performance with the EG improving more for balance measured on both legs (anterior: Δ11%, p = 0.05, d = 0.50; posteromedial: Δ10%, $p < 0.05$, d = 0.59; posterolateral: Δ16%, $p < 0.05$, d = 0.54 for right support leg). For the left support leg, we found similar results (anterior: Δ11%, $p < 0.05$, d = 0.53; posteromedial: Δ10%, $p < 0.05$, d = 0.66; posterolateral: Δ15%, $p < 0.05$, d = 0.54; **Table 5**).

DISCUSSION

This study tested the efficacy of an 8-week combined plyometric and short sprint training program at improving measures of athletic performance in elite adolescent soccer players. We observed that replacing some aspects of typical training with combined plyometric and short sprint training improved vertical and horizontal jump performances, sprinting, change-of-direction ability, the ability to RSS, and balance.

Effect of Training on Jump Performance

The ability to jump is a distinctive feature of success in adult and young soccer players (Söhnlein et al., 2014; Ramirez-Campillo et al., 2018b). Therefore, developing the ability of a soccer player to generate vertical power quickly is likely to be advantageous for the competition (Oliver et al., 2021). The results of this study suggest the intervention effects on vertical and horizontal jump performances (**Table 4**). Our findings are confirmed by Hammami et al. (2020) who observed improvements in vertical and horizontal jump performances following combined plyometric and short sprint training in male U17 soccer players. In addition, Sáez de Villarreal et al. (2015) reported significant increases in vertical jump performance following combined plyometric-speed training and technical drills work, in male youth soccer players (U15). Jump performance augmentation could be the result of neuromuscular adaptations such as greater neural drive of agonist muscles, changes in mechanical stiffness of tendons, size changes and/or the architecture of muscles, and changes in the mechanics of single fibers

TABLE 5 | Repeated sprint shuttle ability test performances and Y-balance test performances in experimental and control group before and after 8-weeks intervention.

	Experimental (n = 17)			Paired t-test		Control (n = 17)			Paired t-test		ANOVA (group x time)	
	Pre	Post	% Δ	p	ES	Pre	Post	% Δ	p	ES	P	ES
Repeated Shuttle Sprint Ability parameters												
Fastest time (s)	8.30 ± 0.41	7.63 ± 0.40	−8.07 ± 0.71	< 0.001	1.64	8.32 ± 0.22	8.10 ± 0.24	−2.57 ± 0.53	< 0.001	0.93	0.006	0.72 (medium)
Mean time (s)	8.45 ± 0.43	7.76 ± 0.41	−8.10 ± 0.68	< 0.001	1.64	8.42 ± 0.23	8.21 ± 0.24	−2.56 ± 0.56	< 0.001	0.93	0.006	0.71 (medium)
Fatigue index (%)	1.76 ± 0.55	1.72 ± 0.48	0.01 ± 9.51	0.408	0.63	1.28 ± 0.24	1.28 ± 0.25	0.85 ± 9.30	0.844	0.02	0.848	0.06 (small)
Y-balance test - Right support leg												
Anterior direction (cm)	82.5 ± 7.67	92.2 ± 8.07	10.5 ± 1.00	< 0.001	1.22	85.2 ± 6.39	87.9 ± 7.95	3.03 ± 0.63	< 0.001	0.42	0.048	0.50 (medium)
Posteromedial direction (cm)	101 ± 7.73	112 ± 7.79	9.83 ± 1.42	< 0.001	1.43	105 ± 6.45	108 ± 6.34	2.73 ± 0.80	< 0.001	0.46	0.022	0.59 (medium)
Posterolateral direction (cm)	55.2 ± 7.54	65.3 ± 8.43	15.6 ± 1.05	< 0.001	1.26	56.9 ± 7.52	58.7 ± 7.78	3.10 ± 0.80	< 0.001	0.24	0.033	0.54 (medium)
Y-balance test - Left support leg												
Anterior direction (cm)	86.1 ± 6.60	96.4 ± 8.16	10.6 ± 1.50	< 0.001	1.39	87.7 ± 7.70	90.1 ± 7.94	2.67 ± 0.89	< 0.001	0.31	0.037	0.53 (medium)
Posteromedial direction (cm)	106 ± 8.64	118 ± 8.33	9.87 ± 2.10	< 0.001	1.37	101 ± 5.38	104 ± 5.30	2.43 ± 1.17	< 0.001	0.47	0.011	0.66 (medium)
Posterolateral direction (cm)	55.4 ± 6.38	65.1 ± 7.11	14.9 ± 0.88	< 0.001	1.43	56.5 ± 7.95	58.4 ± 8.18	3.24 ± 0.94	< 0.001	0.23	0.035	0.54 (medium)

(Maffiuletti et al., 2002; de Villarreal et al., 2009; Thomas et al., 2009). Other potential mechanisms include (i) changes in muscle activation strategies (or intermuscular coordination) during vertical jumps, especially during the preparatory phase jump; and (ii) changes in the stretch reflex excitability (Bishop and Spencer, 2004; de Villarreal et al., 2009).

Effect of Training on Sprint Performance

Stølen et al. (2005) reported that 96% of sprint bouts during soccer match play are shorter than 30 m, with 49% being shorter than 10 m. The present results showed significant intervention effects in the EG compared to the CG for 10 and 30 m sprint performance. This corroborates findings reported by Sáez de Villarreal et al. (2015), who examined the efficacy of combined plyometric-speed training and technical drills work in youth male soccer players (U15) and noted improved sprint performance over 5 and 10 m. Moreover, Kargarfard et al. (2020) investigated the effects of combined plyometric and short sprint exercises in youth male under 19 (U19) soccer players. They reported improved sprint performance over 30 m. The improved sprint performance observed in this study may be useful for soccer players as it would correspond to an advantage in duels sprints, which can allow players to reach the ball before the opponent (Stølen et al., 2005).

Effect of Training on Change-of-Direction Ability

During soccer match play, players perform many accelerations and sprints at maximum speed (Haugen et al., 2014), with and without changes in direction (Bloomfield et al., 2007; Barnes et al., 2014). The present investigation demonstrated the intervention effects on the change-of-direction ability. There are few studies evaluating the effectiveness of combined plyometric and short sprint training program on change-of-direction ability, in soccer players (Sáez de Villarreal et al., 2015; Hammami et al., 2020; Kargarfard et al., 2020). This study corroborates the results obtained by Sáez de Villarreal et al. (2015), who studied the effects of combined plyometric-speed training and technical drills work in youth male soccer players (U15). They noted improvements in change-of-direction ability. Indeed, Kargarfard et al. (2020) observed significant increases in change-of-direction ability, following combined plyometric and short sprint training, in youth male soccer players (U19). Improvements in the change-of-direction ability necessitate rapid development of strength, eccentric force production in the lower limbs, and a rapid change from eccentric muscle to concentric contraction in the knee extensors. Plyometric training can enhance these factors (Miller et al., 2006; Sheppard and Young, 2006).

Effect of Training on Repeated Shuttle Sprint Ability

The present study demonstrated intervention effects on all RSSA parameters except the fatigue index. Our results are in line with those of Hammami et al. (2020) who reported improvement in all repeated change-of-direction ability parameters except the fatigue index in male U17 soccer players following combined plyometric and short sprint training. In contrast, our results contradict those reported by Kargarfard et al. (2020) who reported no improvements in RSA following combined plyometric and short sprint training in male U19 soccer players. Improvements in RSA may correspond to increased running efficiency (Balsalobre-Fernández et al., 2016) or increased tendon stiffness (Markovic and Mikulic, 2010), which allows a faster transfer of force from the contracting muscles, reducing reaction times, and improving change-of-direction ability (Markovic and Mikulic, 2010; Balsalobre-Fernández et al., 2016). Although maximum sprint speed is one of the performance composites of anaerobic performance in repeated sprints (Girard et al., 2011), other factors determining inter-sprint recovery and maintenance of performance are required to enhance RSA (da Silva et al., 2010; Girard et al., 2011).

Effect of Training on Balance Performance

Chimera et al. (2004) reported that incorporating plyometric exercises into athlete training reduces the risk of injury by improving the functional stability of the leg joints. Our study seems to be the first to examine the effects of the combined plyometric and short sprint training program on balance performance, in male U15 soccer players. Our results of improved balance disagree with those obtained by Hammami et al. (2020) who examined the efficacy of combined plyometric and short sprints, in male U17 soccer players and reported no improvements in static and dynamic balance performance. Differences in the combined plyometric and short sprint training program (duration, intensity, frequency, and type of exercise) and in methodology (age group and competitive level of the study population; duration of intervention) could contribute to these discrepancies. Improvements in balance reduced the risk of lower limb injury in soccer players (Lloyd, 2001). In the context of increased athletic performance (Zech et al., 2010), data from the present investigation emphasize the importance of plyometric training as an effective injury-reduction strategy in young athletes. A systematic review (Hübscher et al., 2010) showed evidence of the effectiveness of balance training in reducing the incidence of certain types of sports injuries among adolescent and young athletes during pivoting sports. Recently, Rivera et al. (2017) reported that balance training programs were effective in reducing the incidence rates of ankle sprains, including those with and those without a history of ankle sprains, in soccer players. In addition, the increased balance may be related to an improvement in lower extremity muscle co-contraction (Lloyd, 2001) or the changes in proprioception and neuromuscular control (Michailidis et al., 2019).

CONCLUSION

Notably, the 8-week, biweekly, in-season, combined plyometric and short sprint training improves strength and balance performance in elite youth soccer players (U15). Therefore, male youth soccer players may benefit from combined plyometric and short sprint training during the competitive season and yield positive results in the performance measures. Practically speaking, the total training time was only 15–30 min per session, which can be incorporated into a habitual soccer training two times per week.

Limitations of this study are the relatively small sample size, although this is consistent with a squad size of this age and ability, and those results are applicable to one particular category of youth soccer players and cannot be extrapolated to other sexes or age groups. In future studies, plyometric or sprint training should be examined separately and in combination to study the effect of these programs on different athletic performances in young soccer players. It is important to determine what exactly (i.e., plyometrics, sprinting, or combination) improves performance. However, this would necessitate considerably greater resource commitment. Further research is needed in other age groups, female soccer players, and other skill levels to verify the effectiveness of combined plyometric and short sprint training.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Review Board of Research Unit (UR17JS01) Sport Performance, Health & Society, Higher Institute of Sport and Physical Education, Ksar-Saîd, University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

GA and MC contributed to conceptualization. GA contributed to methodology, software, formal analysis, investigation, data curation, writing—original draft preparation, and project administration. GA, MC, and TB contributed to validation. MC contributed to resources and supervision. SH and LH contributed to writing—review and editing. EB contributed to visualization. RS contributed to funding acquisition. All authors have read and agreed to the published version of the manuscript.

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The $ISPA_{Int}$ Injury Prevention Programme for Youth Competitive Alpine Skiers: A Controlled 12-Month Experimental Study in a Real-World Training Setting

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Evidence-based injury prevention programmes for youth competitive alpine skiers are widely absent. The aims of this controlled 12-month experimental study were to introduce a novel injury prevention programme targeted to the injury patterns of youth skiers, called $ISPA_{Int}$, and to compare the differences in injury occurrence between an intervention group (IG) additionally performing the $ISPA_{Int}$ programme and an independent, historical control group (CG) following their regular training routines. None of the skiers of the CG were part of the IG and vice versa. The study was directly conducted within the real-world youth development structures of skiers competing at the under 16 years (U16) level in Switzerland. Seventy-one skiers (aged 14.4 ± 0.3 years) assigned to the IG were compared to 58 age- and gender-matched controls. The IG was offered the $ISPA_{Int}$ programme with the recommendation to perform it at least once per week. Skiers' adherence to this recommendation was surveyed but not enforced. Injuries were recorded using the Oslo Sports Trauma Research Centre Questionnaire. Primary outcomes were the absolute injury rates (number of injuries/100 athletes per season) and epidemiological incidence proportion (number of injured athletes/100 athletes per season). The secondary outcome was the average 2-weekly prevalence of traumatic knee, knee overuse, and lower back overuse injuries. There were lower absolute rates of all traumatic injuries [rate/risk difference, RD: −57.1 (−98.1, −16.0); rate/risk ratio, RR: 0.665 (0.485, 0.884)] and overuse injuries [RD: −35.9 (−71.0, −0.7); RR: 0.699 (0.493, 0.989)] in the IG than in the CG. Likewise, the epidemiological incidence proportion for all overuse injuries was smaller in the IG [RD: −28.4 (−44.8, −12.0); RR: 0.598 (0.435, 0.822)], while the proportion of skiers suffering from traumatic injuries did not significantly differ between the groups. Notably, the IG particularity differed from the CG in the average 2-weekly prevalence of knee trauma, knee overuse, and lower back overuse complaints, three of the major injury-related hot spots in youth skiers. Based on these promising results, the $ISPA_{Int}$ programme may have great potential to prevent injuries in youth competitive alpine skiers, and the underlying exercises should be considered complementary training content at the U16 level.

Keywords: athletes, traumatic injuries, overuse injuries, neuromuscular performance, injury prevention, alpine skiing

INTRODUCTION

The benefits of exercise-based injury prevention programmes have been demonstrated in several competitive sports (Junge et al., 2002; Mandelbaum et al., 2005; Michaelidis and Koumantakis, 2014; Riva et al., 2016; Soomro et al., 2016; Mehl et al., 2018; Petushek et al., 2018; Webster and Hewett, 2018; Huang et al., 2020; Pas et al., 2020). However, to the best of our knowledge, apart from a single study specifically focusing on anterior cruciate ligament (ACL) injuries (Westin et al., 2020), evidence-based injury prevention programmes tailored to the specific injury patterns of U16 competitive alpine skiers are lacking.

Typically, exercise-based injury prevention programmes aim at improving athletes' neuromuscular and proprioceptive performance (Mandelbaum et al., 2005). Effective prevention, however, should be based on sport- and age-specific programmes that consider the epidemiology, mechanisms, and contextual factors of the injuries of the athletes to be protected (van Mechelen et al., 1992; Sugimoto et al., 2016; Plummer et al., 2019). Accordingly, real-world implementation factors should already be taken into consideration in both the development and evaluation phases of sports injury prevention programmes (Bolling et al., 2018; O'brien et al., 2021).

Regarding injury epidemiology, competitive alpine skiing is known as a sport with relatively high injury rates (Florenes et al., 2009; Westin et al., 2012; Bere et al., 2013a; Hildebrandt and Raschner, 2013; Haaland et al., 2016; Müller et al., 2017; Alhammoud et al., 2020; Fröhlich et al., 2020a,b; Peterhans et al., 2020; Schoeb et al., 2020). Particularly striking is the high number of injuries occurring in youth skiers, namely, the under 16-years (U16) category (Schoeb et al., 2020). During the competitive season, the average 2-weekly prevalence was 12.9% for traumatic injuries and 16.1% for overuse injuries. Traumatic injuries in youth skiers primarily relate to the knee, while overuse injuries most frequently affect the knee and lower back (Schoeb et al., 2020). Certainly, there were other locations of injury, but the aforementioned body parts were by far the most frequently affected (Schoeb et al., 2020).

With respect to injury mechanisms, our current knowledge is limited to the level of elite skiers, while studies on youth skiers are widely lacking (Spörri et al., 2017b). Nevertheless, it is plausible to assume similar injury mechanisms, since, at least in the case of traumatic knee injuries, the injury patterns are comparable (Fröhlich et al., 2020a; Schoeb et al., 2020). Mechanisms of severe knee injuries, such as anterior cruciate ligament (ACL) ruptures, typically include a boot-induced drawer of the tibia relative to the femur (Bere et al., 2011a). In other ACL injury mechanisms, dynamic knee valgus plays a key role (Bere et al., 2013b). This tibial anterior drawer can be effectively counteracted by increased eccentric hamstring strength, while dynamic knee valgus collapse may be antagonised by superior leg axis stability. Moreover, excellent stability of the trunk may prevent skiers from getting "out-of-balance" (often preceding the inciting event of traumatic injuries; Bere et al., 2014).

With regard to knee and back overuse injuries, the inherent movement structures and relative loading patterns of modern skiing techniques can be considered nearly equivalent regardless of the level of competition, since the underlying physics are the same (Howe, 2001). In this connection, superior leg axis stability may prevent the accumulation of excessive nonaxial knee joint loadings (valgus malalignments), which typically occur while skiing (Zorko et al., 2015). Furthermore, excellent abilities to stabilise the trunk can antagonise the combined occurrence of frontal bending, lateral bending, and torsion in vibration-exposed and highly loaded spines, which is typical for skiing (Spörri et al., 2015, 2017a).

Therefore, the aims of this controlled experimental study were 2-fold: (1) to introduce a novel injury prevention programme targeted to the specific injury patterns of youth competitive alpine skiers of the U16 category, hereinafter called $ISPA_{Int}$ (short for "Injury Screening and Prevention—Alpine Skiing"); and (2) to compare the differences in injury occurrence between an intervention group additionally performing the $ISPA_{Int}$ programme once a week over a 12-month period in their real-world training setting and age-matched controls following their regular training routines.

MATERIALS AND METHODS

Study Design

This study (registered at: http://www.clinicaltrials.gov; ID: NCT04021576) was designed as a controlled 12-month experimental study in a real-world training setting of youth competitive alpine skiers. The recruited participants passed through an observation period (first study year; November 2017 to November 2018) and an intervention period (second study year; November 2018 to November 2019). Both study years started with the beginning of the competition season. Based on this pool of data and the specific enrolment/allocation/analysis procedure illustrated in **Figure 1** and further described below, participants were allocated to two *independent* groups (i.e., an intervention group—IG vs. a historical control group—CG). To illustrate this in principle, skiers born in 2003 and 2004 typically went through both the observation and intervention periods in 2 consecutive years. The data of the

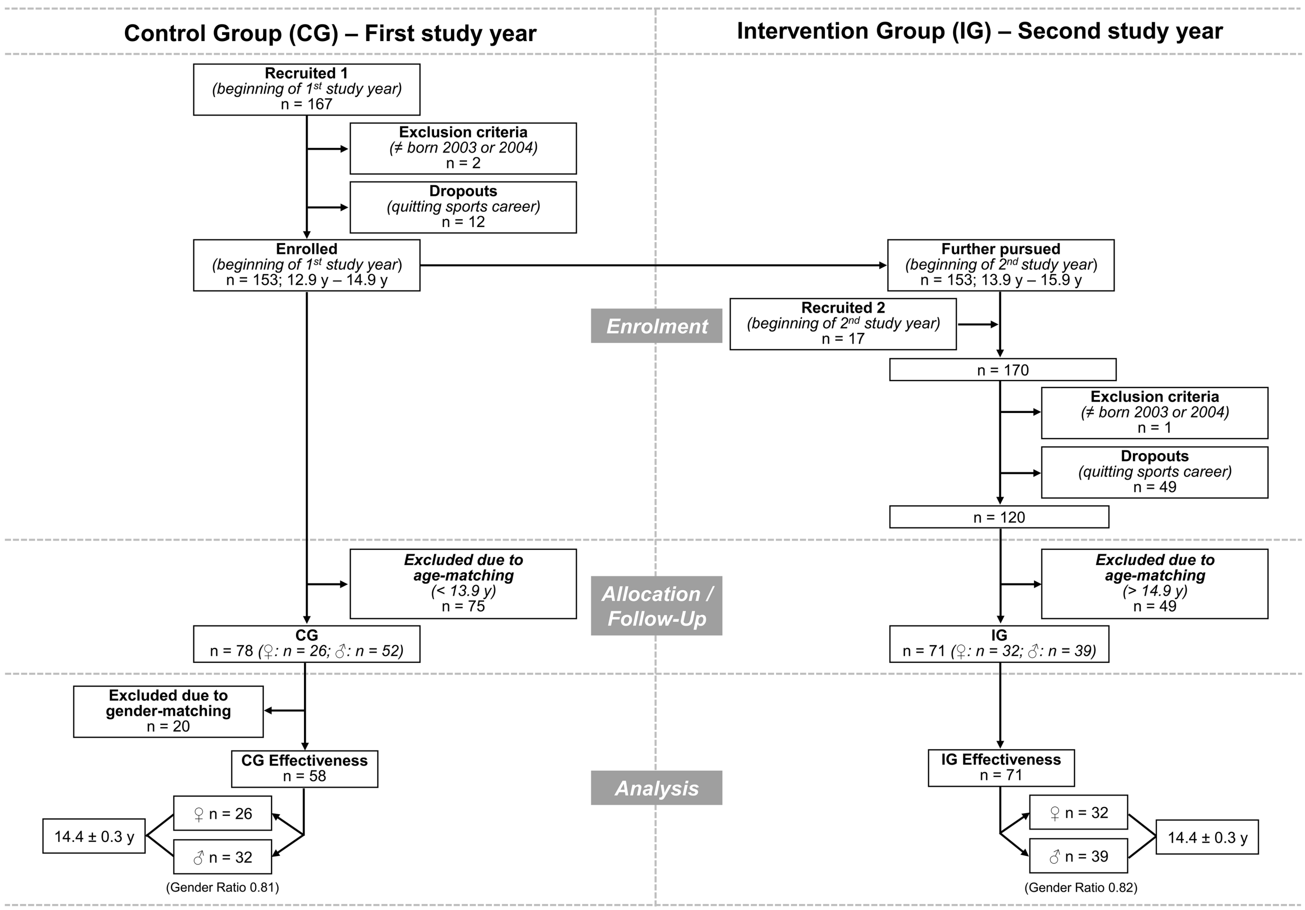

FIGURE 1 | Flow chart of the enrolment, allocation/follow-up, and analysis procedure.

skiers born in 2003 that were collected during the observation period (= first study year) were used for the historical CG, and the data of the skiers born in 2004 that were collected during the intervention period (= second study year) served as the basis for the IG. Accordingly, none of the skiers of the historical CG were part of the IG and vice versa. The exact process of age and gender matching is further described in the corresponding subchapter. The study was designed in such a way that neither the skiers nor the coaches knew about an upcoming intervention period (= second study year). The IG was offered the $ISPA_{Int}$ programme with the recommendation to perform it once per week. The CG followed their regular training regimes without specific preventative training instructions. Finally, the occurrence of traumatic and overuse injuries was compared between the two groups. The study protocol was approved by the cantonal ethics committee Zurich (KEK-ZH-NR: 2017-01395 and 201801807) and is in conformity with the Helsinki Declaration and national laws. All participants signed an informed consent form. If they were younger than 14 years, their legal guardians signed instead.

Recruitment

Out of a potential sample of approximately 220 youth competitive alpine skiers of the U16 category in Switzerland, a total of 184 athletes were recruited for a larger study program within the ISPA project (167 at the beginning of the first study year; 17 at the beginning of the second study year; **Figure 1**). The inclusion criterion was being part of a certified regional performance centre (RLZ/CRP) of Swiss-Ski, i.e., representing the best skiers of their age. Eligible participants were identified based on actual RLZ/CRP team lists and were recruited through official invitation letters and local information events. For the current study, skiers were excluded if they were not born in 2003 or 2004 (i.e., not aged between 12.9 and 14.9 years at the beginning of the first study year). This applied for two participants during the first study year and one during the second study year (**Figure 1**). A previous study included data of the same initial pool of potential participants (Schoeb et al., 2020); however, the dataset of the historical controls (first study year) in the current study is not identical due to a different purpose and therefore different eligibility criteria. Sampling bias was minimised by the free choice of participation, i.e., each skier could decide whether to participate without negative consequences for the nonparticipating athletes.

Study Dropouts

Study dropouts were particularly noticeable after the competition season in spring as a direct consequence of not being selected for one of the relevant youth development programmes and were in all cases due to the termination of the participants' competitive sports careers (12 dropouts during the first study year; 49 dropouts during the second study year; **Figure 1**). There were no study dropouts due to injury (all injured participants continued their biweekly health reporting until the end of the study year) or simply stopped participation in the study.

Age- and Gender-Matching

Due to the study design using a historical CG (first year: observation; second year: intervention), systematic age-matching became indispensable (**Figure 1**). Accordingly, the second years' data of the younger skiers (born in 2004 and aged 13.9–14.9 years at this time) served for the IG, while age-matched controls relied on the first years' data of the older skiers (born in 2003 and aged 13.9–14.9 years at that time). Moreover, to directly compare the IG and CG, the corresponding groups were gender-matched. The 20 male participants of the CG who were excluded due to gender-matching were selected by means of a random generator. Finally, 129 youth skiers (aged 14.4 ± 0.3 years), 71 skiers assigned to the IG, and another 58 age- and gender-matched controls (CG), were included in the analysis.

Randomisation and Blinding

As this study was designed as a 12-month experimental study in a real-world training setting of youth competitive alpine skiers with a historical CG and the participants successively passed through an observation period and an intervention period, randomisation and blinding of the participants was not applicable. The resulting study limitations are further discussed below.

Intervention

The $ISPA_{Int}$ programme was developed based on knowledge about alpine skiing-specific injury mechanisms as outlined in the introduction (Bere et al., 2011a,b, 2014; Raschner et al., 2012; Spörri et al., 2015, 2017a,b; Zorko et al., 2015; Jordan et al., 2017; Steenstrup et al., 2018) and was designed as a complementary 20 min home training programme. $ISPA_{Int}$ was available online with video instructions for illustration purposes and as a hard copy to allow offline usage. $ISPA_{Int}$ included three main exercise families: (1) eccentric hamstring strength (Dynamic Bridging, Nordic Hamstring Exercise); (2) leg axis stability by strengthening the external hip rotators (Deep Single Leg Pistol Squats); and (3) trunk stability by improving the strength and neuromuscular coordination of the trunk muscles (Dynamic Planking, Deadbug Bridging). For a more detailed description of $ISPA_{Int}$, refer to the online **Supplementary Material**. Again, the intervention group (IG) was offered the $ISPA_{Int}$ programme with the recommendation to perform it once per week en bloc and exactly as described. The CG followed their regular training regimes without specific preventative training instructions.

Injury Surveillance

All participants prospectively reported their injuries using the Oslo Sports and Trauma Research Centre (OSTRC)-questionnaire on health problems with 2-week measurement intervals (Clarsen et al., 2014). For data collection and database management, the electronic data capture tool *REDCap®* was used. Every second Monday, an automatic e-mail with a personal questionnaire link was sent to all participants. An automatic reminder followed 2 days later. In case participants did not respond within 3 days, the study team contacted them and their parents personally *via* text message. The questionnaire link remained valid until 7 days after sending.

At the end of each study year, all participants underwent supplementary retrospective medical interviews and clinical examinations, verifying the correctness and completeness of all OSTRC questionnaire-based data entries. During these interviews, all prospective data entries in the online OSTRC questionnaire were discussed and checked together with each participant. Any discrepancy between the online questionnaire and interview data was manually corrected in the database based on the clarifying interview content. Potential recall bias was counteracted by fusing the retrospective information with the prospectively collected data, and in case someone could not remember during the interview, the online entries that were collected prospectively over the year were given priority.

Based on the self-reported classifications in the OSTRC-questionnaires, each documented injury was classified as either *traumatic* or *overuse* injury. A traumatic injury was defined as any physical complaint with a clearly identifiable inciting event; for overuse injuries, such an event was absent. Additionally, injuries were subcategorised as being *substantial* when leading to moderate to severe reduction in training volume or sports performance or to complete inability to participate (i.e., option 3, 4, and 5 in either question 2 or 3 of the OSTRC questionnaire), as defined by Clarsen et al. (2014).

Outcomes

Baseline Characteristics

Each participant underwent a baseline assessment at the beginning of the first and second study years. Anthropometric measures were assessed, including *body height*, sitting height (measuring tape with 0.5 cm intervals), and *body mass* (weighing device with a 0.1 kg scale). To determine each participant's *maturity offset* (the time before or after maximal growth rate) and subjects' age at peak height velocity (*APHV*), the noninvasive methodology proposed by Mirwald and Colleagues was used (Mirwald et al., 2002; Malina et al., 2007; Sherar et al., 2007; Müller et al., 2015).

Adherence to Intervention

All participants of the IG were asked to perform the $ISPA_{Int}$ programme at least once per week en bloc and exactly as described. Participants' adherence to this recommendation was surveyed but not enforced. The IG participants' adherence to the $ISPA_{Int}$ programme was assessed by an additional question attached to the OSTRC questionnaire, namely, "please enter the number of training sessions in the last 2 weeks or since the last questionnaire was filled in, in which you have carried out the ISPA prevention programme." Answers were provided as integers.

Response Rates

Response rates to the prospective OSTRC questionnaires and supplementary retrospective interviews were monitored and, with the exception of reminders, were not enforced by negative consequences for nonresponse.

Primary Outcome

The primary outcome measure was the incidence of traumatic and overuse injuries, both assigned to an *all* and *substantial* injury category according to their severity. Injury incidence was expressed as the *absolute injury rates* (i.e., number of injuries/100 athletes per season), as well as *epidemiological incidence proportion*, an estimator of the overall injury risk to suffer at least one injury during one season (i.e., the number of injured athletes/100 athletes per season).

Secondary Outcome

The secondary outcome measure was the OSTRC questionnaire-based measure *average 2-weekly prevalence* of traumatic knee injuries, knee overuse injuries, and lower back overuse injuries, representing the most typical health issues in alpine skiers (Fröhlich et al., 2020a; Schoeb et al., 2020).

Sample Size

Under the assumption of a 50% reduction in the U16 alpine skier-specific *absolute rates* of traumatic injuries (132.3 injuries/100 athletes per season) and overuse injuries (112.3 injuries/100 athletes per season) reported previously by Schoeb et al. (2020), i.e., Cohen $d > 0.575$, $\alpha = 0.05$, and $1-\beta = 0.90$ and an allocation rate of 71/58 = 1.224, an *a priori* power analysis revealed that a total sample size of at least $n = 108$ skiers (IG $n = 59$; CG $n = 49$) would provide sufficient power for analysing the effect of $ISPA_{Int}$.

Statistical Analysis

Baseline characteristics of the IG and the CG were presented as the *mean* ± *SD*, and corresponding group differences were analysed by unpaired sample *t* tests ($p < 0.05$). Injury incidence was reported as *absolute injury rates*, as well as *epidemiological incidence proportions* along with their 95% CIs. Differences in injury incidence between the IG and the CG were analysed using the absolute association measures *rate/risk difference* (*RD*), i.e., IG incidence—CG incidence, as well as the relative association measures *rate/risk ratio* (*RR*), i.e., IG incidence/ CG incidence, and were reported along with corresponding 95% CIs. Moreover, potential differences were statistically tested based on the Poisson model and *Z*-tests (*z* score > 1.96). Finally, the OSTRC questionnaire-based 2-weekly prevalence of traumatic knee, knee overuse, and lower back overuse injuries (i.e., according to Schoeb et al. (2020), the most typical health issues in youth skiers) was visualised over time, and the IG and CG were compared based on unpaired sample *t* tests ($p < 0.05$).

RESULTS

Baseline Characteristics, Adherence to Intervention, and Response Rates

After age- and gender-matching, there were no significant differences in any of the baseline characteristics (**Table 1**). The IG performed the $ISPA_{Int}$ programme on average 0.8 ± 0.6 times/week (min: 0.0 times/week; max: 2.4 times/week). Despite being offered the $ISPA_{Int}$ programme, six of the 71 skiers of the IG did not use the programme at all. The average OSTRC questionnaire response rates for the IG and the CG were 93.0 ± 4.5 and 97.7 ± 3.0, respectively. The participation rate in the supplementary retrospective interviews was 100.0% for both groups.

IG to CG Differences

Primary Outcome Measures

The IG to CG differences with respect to the absolute injury rates are presented in **Table 2**. Compared to the CG, there were lower rates of all traumatic injuries in the IG [RD: −57.1 (−98.1, −16.0) injuries/100 athletes per season; RR: 0.665 (0.485, 0.884)] and overuse injuries [RD: −35.9 (−71.0, −0.7) injuries/100 athletes per season; RR: 0.699 (0.493, 0.989)]. Moreover, the rate of substantial overuse injuries was lower in the IG than in the CG [RD: −25.6 (−48.5, −2.7) injuries/100 athletes per season; RR: 0.536 (0.309, 0.930)], while the rates of substantial traumatic injuries did not significantly differ between the groups.

The IG to CG differences with respect to the epidemiological incidence proportion are summarised in **Table 3**. The risk of suffering at least one overuse injury of any severity during the season was significantly lower in the IG than in the CG [RD: −28.4 (−44.8, −12.0) injured athletes/100 athletes per season; RR: 0.598 (0.435, 0.822)]. The same applies to substantial overuse injuries [RD: −16.5 (−31.9, −1.0) injured athletes/100 athletes per season; RR: 0.545 (0.305, 0.973)], while the proportion of athletes suffering from traumatic injuries (both all and substantial) did not significantly differ between the groups.

TABLE 1 | Baseline characteristics and intervention adherence.

	Intervention group (*n* = 71)	**Control group (*n* = 58)**
Age (years)	14.4 ± 0.3	14.4 ± 0.3
Female/male ratio (–)	0.82	0.81
Body mass (kg)	52.5 ± 8.9	52.6 ± 8.6
Body height (cm)	163.4 ± 7.0	163.2 ± 7.2
Maturity offset (y)	0.9 ± 1.0	0.8 ± 1.1
APHV (y)	13.4 ± 1.0	13.6 ± 1.1
$ISPA_{Int}$ adherence (# sessions per week)	0.8 ± 0.6	–

Baseline data are expressed as the mean ± SD or ratio. Based on an unpaired sample t-test, there were no significant differences between the IG and the CG at p < 0.05. Tests were backed up by bias-corrected accelerated (BCa) bootstrapping with 10,000 samples. APHV, age at peak height velocity; $ISPA_{Int}$, injury prevention programme tailored to youth skiers.

TABLE 2 | Injury incidence expressed as absolute injury rates (i.e., the number of injuries/100 athletes per season) of traumatic and overuse injuries for the intervention group (IG) and control group (CG).

	Number of injuries		Absolute injury rates (# *injuries/100 athletes per season*)			Rate ratio (RR)	*z*-score
	IG (*n* = 71)	CG (*n* = 58)	IG (*n* = 71)	CG (*n* = 58)	Rate difference (RD)		
All							
Traumatic injuries	77	96	108.5 (82.4, 132.7)	165.5 (132.4, 198.6)	−57.1 (−98.1, −16.0)	0.655 (0.485, 0.884)	2.726
Overuse injuries	59	69	83.1 (61.9, 104.3)	119.0 (90.9, 147.0)	−35.9 (−71.0, −0.7)	0.699 (0.493, 0.989)	1.998
Substantial							
Traumatic injuries	58	61	81.7 (60.7, 102.7)	105.2 (78.8, 131.6)	−23.5 (−57.2, 10.3)	0.777 (0.542, 1.113)	1.364
Overuse injuries	21	32	29.6 (16.9, 42.2)	55.2 (36.1, 74.3)	−25.6 (−48.5, −2.7)	0.536 (0.309, 0.930)	2.188

Incidence data are expressed as absolute injury rates with 95% CIs in parentheses. Rate differences (RDs) and rate ratios (RRs) are presented as association measures representing the absolute and relative rate reductions, respectively. Level of significance based on the Poisson model and Z-tests for comparing absolute injury rates between groups: z score > 1.96.

TABLE 3 | Injury incidence expressed as the epidemiological incidence proportion, an estimator of the overall injury risk to suffer at least one injury during one season (i.e., the number of injured athletes/100 athletes per season), of traumatic and overuse injuries for the intervention group and control group.

	Number of injured athletes		Epidemiological incidence proportion (# *injured athletes/100 athletes per season*)			Risk ratio (RR)	*z*-score
	IG (*n* = 71)	CG (*n* = 58)	IG (*n* = 71)	CG (*n* = 58)	Risk difference (RD)		
All							
Traumatic Injuries	48	39	67.6 (66.3, 68.9)	67.2 (65.7, 68.8)	0.4 (−15.9, 16.6)	1.005 (0.790, 1.280)	−0.044
Overuse Injuries	30	41	42.3 (40.9, 43.6)	70.7 (69.2, 72.2)	−28.4 (−44.8, −12.0)	0.598 (0.435, 0.822)	3.230
Substantial							
Traumatic Injuries	39	33	54.9 (53.6, 56.3)	56.9 (55.2, 58.6)	−2.0 (−19.2, 15.2)	0.965 (0.710, 1.313)	0.224
Overuse Injuries	14	21	19.7 (18.6, 20.8)	36.2 (34.6, 37.8)	−16.5 (−31.9, −1.0)	0.545 (0.305, 0.973)	2.095

Incidence data are expressed as epidemiological incidence proportions with 95% CIs in parentheses. Risk differences (RDs) and risk ratios (RRs) are presented as association measures representing the absolute and relative risk reductions, respectively. Level of significance based on the Poisson model and Z-tests for comparing injury incidences between groups: z score > 1.96.

Secondary Outcome Measures

Figure 2 illustrates the average 2-weekly prevalence of the most typical health issues in alpine skiers over time.

The average 2-weekly prevalence of knee trauma, knee overuse, and lower back overuse injuries of any severity over the entire observation period was significantly lower in the IG than in the CG (**Table 4**).

DISCUSSION

The most important finding of the study was the significantly lower absolute rates of all traumatic injuries (−33.5%) and overuse injuries (−30.1%) in the IG than in the CG. Similarly, the epidemiological incidence proportion for all overuse injuries was 40.2% lower in the IG, while the number of skiers who suffered at least one traumatic injury per season did not significantly differ between the groups. It was also found that the average 2-weekly prevalence of knee trauma, knee overuse, and lower back overuse complaints (any severity) was lower in the IG than in the CG.

The $ISPA_{Int}$ Programme—Promising Results Toward Effective Injury Prevention in Youth Competitive Alpine Skiers

As shown in this controlled experimental study, the youth skiers performing the $ISPA_{Int}$ programme on average 0.8 ± 0.6 times/week over a 12-month period in addition to their regular training regimens showed lower absolute rates of traumatic and overuse injuries. This equally applies to both the *all* and *substantial* injury categories, with the exception of substantial traumatic injuries, which may be difficult to prevent given the high speeds and forces involved in skiing (Gilgien et al., 2014). Likewise, the proportion of youth skiers suffering from at least one overuse injury was lower in the IG. This proportion, however, was not significantly smaller for traumatic injuries, which might be explained by the high number of traumatic injuries occurring in youth skiers (more than 1.3 traumatic injuries per athlete per season; Schoeb et al., 2020). Accordingly, despite the smaller total number, not every prevented injury means one affected athlete less.

The absolute rates of all traumatic and overuse injuries differed between the IG and CG by 33.5 and −30.1%, respectively.

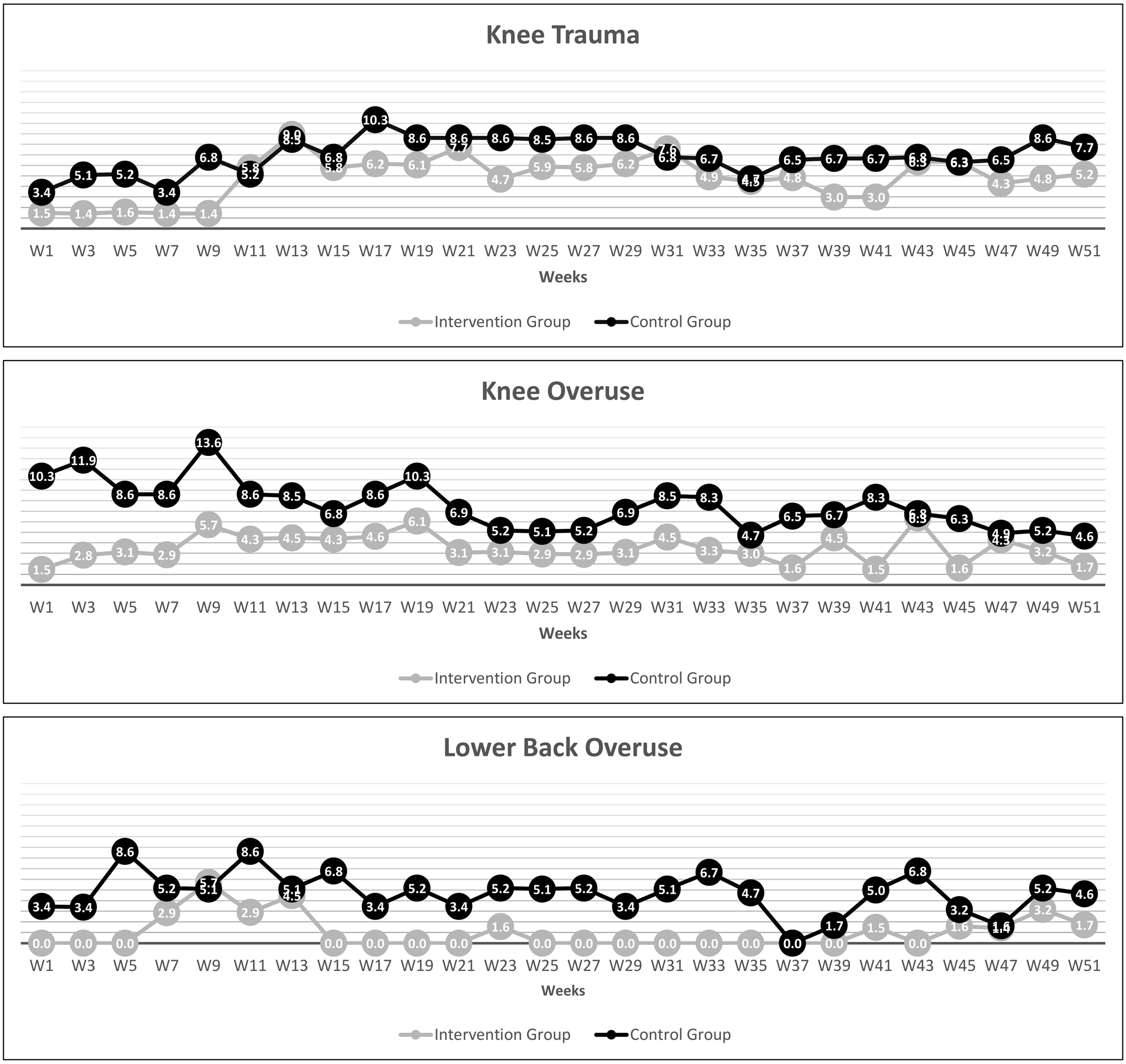

FIGURE 2 | Time course of the average 2-weekly prevalence for knee trauma, knee overuse, and lower back overuse complaints (any severity) over the 12-month observation period.

TABLE 4 | Average 2-weekly prevalence of knee trauma, knee overuse, and lower back overuse complaints (any severity), representing the most frequent health issues in alpine skiers.

Injury type	Average 2-weekly prevalence (%)		*p* value	Cohen *d*	Power
	Intervention Group (*n* = 71)	Control Group (*n* = 58)			
Knee trauma	4.8 (4.0, 5.6)	6.9 (6.3, 7.6)	<0.001	−0.974	1.000
Knee overuse	3.5 (3.0, 4.0)	7.5 (6.7, 8.4)	<0.001	−1.466	1.000
Lower back overuse	1.0 (0.4, 1.6)	4.7 (3.9, 5.4)	<0.001	−1.427	1.000

Prevalence data are expressed as the mean percentage values with 95% CIs in parentheses. Level of significance based on unpaired sample t tests and backed up by bias-corrected accelerated (BCa) bootstrapping with 10,000 samples: $p < 0.05$. Substantial health problems were defined in accordance with Clarsen et al. (2014).

Similar effect magnitude ranges have been reported in previous randomised controlled trials assessing the efficacy of neuromuscular and proprioceptive injury prevention programmes in different sports (Soomro et al., 2016; Petushek et al., 2018; Webster and Hewett, 2018; Huang et al., 2020). Knowing that the effect of an intervention is presumed to decrease as testing moves from efficacy to effectiveness to dissemination and implementation research stages, the results of the current controlled experimental study that was conducted under unenforced real-world implementation conditions can be considered promising. Moreover, in addition to the recent study by Westin et al. (2020) who reported a 45% reduction in the ACL injury incidence rate in U18 skiers, this is the first exercise-based prevention study focusing on younger skiers and different types of injuries.

Notably, the IG differed from the CG in the average 2-weekly prevalence of traumatic knee injuries, knee overuse injuries, and lower back overuse injuries, three of the major injury-related hot spots in youth skiers (Westin et al., 2012; Müller et al., 2017; Fröhlich et al., 2020a,b; Peterhans et al., 2020; Schoeb et al., 2020). This may confirm that the aetiology-based derivation of the $ISPA_{Int}$ programme described in the introduction is sound and that the programme may be effective in counteracting the typical sport-specific injury mechanisms and adverse loading patterns (Bere et al., 2011a,b, 2014; Spörri et al., 2015, 2017a; Zorko et al., 2015; Steenstrup et al., 2018). However, to conclusively confirm our controlled experimental observations, further randomised controlled trials are required.

Potential Real-World Implementation Pitfalls and Countermeasures

Implementing a sports injury prevention programme in a real-world setting is challenging (Donaldson et al., 2017), which is why incorporating the context of the implementation setting is of great importance (Durlak and DuPre, 2008). Accordingly, we have set on a simple complementary training programme that can be conducted anytime and anywhere within 20 min. Moreover, it was matched to the athletic long-term development strategy of Swiss-Ski.

Additionally, how an injury prevention programme is delivered and supported is known to play an important role in its effect (Durlak and DuPre, 2008). Consequently, high-quality implementation should build upon a partnership between programme developers (researchers) and programme implementers (gatekeepers and end users; Donaldson et al., 2017). In our study, the skiers and their direct personal environment (e.g., coaches and parents) were actively involved in programme development and implementation, an approach that is also strongly recommended for later nonstudy-related scaling-ups of $ISPA_{Int}$.

Why Our Prevention Efforts Should Focus on Youth Competitive Alpine Skiers

Overall, the high injury rates and risks observed in this study further highlight the substantial burden of injury in skiers of the U16 category (Schoeb et al., 2020). In fact, it is known that during phases of accelerated growth around APHV, neuromuscular adaptation processes are decelerated (Backous et al., 1988), making youth skiers especially prone to injuries (Fröhlich et al., 2020b; Peterhans et al., 2020; Schoeb et al., 2020). Moreover, in view of an up to 15 times higher rate for a second injury after ACL reconstruction in adolescent athletes (Paterno et al., 2012), as well as a 1–6-fold higher risk of osteoarthritis development after knee injury (Poulsen et al., 2019), preventing a skiers' first severe injuries at the youth level must be a priority.

Additionally, our finding of fewer injuries occurring in the IG, just additionally performing a simple 20′ home-based prevention programme, underlines the great preventative potential in this specific target group. Unlike many other youth sports, the training of U16 skiers is still semi-professional, and not all skiers have access to health management experts such as team physicians or physiotherapists.

Methodological Considerations

A first limitation of the study might be seen in the lack of randomisation due to the use of a historical control group. The well-known confounding factors of calendar age/biological maturity and sex (Schoeb et al., 2020) were addressed by systematic age- and gender-matching. The potential confounding effect of participants becoming more aware of the injury problem throughout the study was counteracted by not providing participants with direct feedback on interim findings (such as the general injury risks observed in the entire study population) or recommendations on possible countermeasures during the study year. The only exception was the $ISPA_{Int}$ programme that was offered to the IG at the beginning of the second study year. Nevertheless, in a complex and multifactorial system of injury causation, some risk of bias from unknown confounding factors may remain, which certainly limits the conclusions that can be drawn regarding cause and effect. However, as already stated above, the study was conducted within the real-world youth development structures of the Swiss national ski federation (Swiss-Ski). The potential to intervene in such an existing training structure, as well as the pool of potential study participants (i.e., youth competitive alpine skiers of the U16 category in Switzerland), was therefore certainly limited. Under such circumstances, the reasons for choosing a historical control group were twofold: (1) a randomised controlled trial, i.e., instructing certain randomly assigned athletes to perform a specific prevention programme while controlling them with their direct teammates, would have introduced a substantial risk for crossover effects; and (2) a cluster randomised trial would not have been a feasible alternative, as such an approach is known to require a larger number of participants to obtain equivalent statistical power (Campbell et al., 2004). Thus, both alternatives would have severely undermined the validity of the current study.

A second limitation may be seen in the fact that the programme was only conducted once a week for approximately 20 min. However, if one transfers the theoretical effects of efficacy studies to the real world, as was done in this study, a prevention programme certainly suffers from a so-called "voltage drop" (Chambers et al., 2013), i.e., a decreased effect, and a once-a-week implementation may be much more realistic than the 2–3 sessions usually investigated in standard randomised controlled trials. Thus, the reduction in injury rate of approximately one third observed in this study can at least be related to a realistic frequency of intervention and an actual compliance that can be realistically achieved.

A third limitation of the study is that a simple home-based injury prevention programme does not allow any quantity and quality control by an experienced coach or physiotherapist. This has been counteracted by defining a programme that is self-explanatory and by providing detailed exercise descriptions and video tutorials that highlight the key points for exercise execution. Nevertheless, at the youth level of competitive alpine skiing, a simple home-based training programme is likely to be better suited to the real-world training structures of youth competitive alpine skiers than multimodal 1:1 training with a professional health expert or personal trainer.

A fourth limitation of the study is the self-reported type of data, which relies on the correctness and quality of the answers provided. This may imply the risk of suffering from recall and/or reporting bias. Recall bias was counteracted by prospective data collection with 2-week intervals (OSTRC questionnaire), which also allowed the recall of less severe injuries. Reporting bias was antagonised by supplementary retrospective interviews at the end of each study year aiming to verify the correctness and completeness of the self-reported data. If a relevant injury had not been reported due to the lack of a biweekly questionnaire response, the missing injury would have been discovered and entered into the database *via* the supplementary interview. Accordingly, despite slightly lower OSTRC questionnaire response rates in the IG than in the CG, the merged data quality can be considered equivalent.

Finally, regarding overuse injuries to the knee, there was an apparent difference in the average 2-weekly prevalence between the IG and the CG at baseline, without the exact reasons being known. Accordingly, the mean 12-month difference between the IG and CG in terms of overuse injuries to the knee must be interpreted with some caution.

CONCLUSION

Based on the promising results of this controlled experimental study, the $ISPA_{Int}$ programme (a sports injury prevention programme including exercises for eccentric hamstring strength, leg axis stability, and trunk stability) may have great potential to prevent traumatic and overuse injuries in youth competitive alpine skiers, and the underlying exercises should be considered fundamental complementary training content at the U16 level.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because their access is restricted to protect the interests of the project partner Swiss-Ski and their athletes. Requests to access the datasets should be directed to joerg.spoerri@balgrist.ch.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Cantonal ethics committee Zurich (KEK-ZH-NR: 2017-01395 and 2018-01807). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

JS and WF conceptualised and designed the study. JS recruited the participants and organised the data collection. TS, SF, and JS collected the data and processed the data and performed the statistical analysis. EV advised on the evaluation methodology. TS, SF, WF, EV, MF, and JS substantially contributed to the interpretation of data. TS and JS drafted the current manuscript. All authors contributed to the article and approved the submitted 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.2022.826212/full#supplementary-material

File A | $ISPA_{Int}$ programme in English.

File B | $ISPA_{Int}$ programme in German.

File C | $ISPA_{Int}$ programme in French.

File D | $ISPA_{Int}$ programme in Italian.

Video 1 | Dynamic bridging.

Video 2 | Nordic hamstring exercise.

Video 3 | Single leg squat (Floor).

Video 4 | Single leg squat (Box).

Video 5 | Dynamic planking.

Video 6 | Deadbug bridging.

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Effect of Six-Week Resistance and Sensorimotor Training on Trunk Strength and Stability in Elite Adolescent Athletes: A Randomized Controlled Pilot Trial

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Intervention in the form of core-specific stability exercises is evident to improve trunk stability. The purpose was to assess the effect of an additional 6 weeks sensorimotor or resistance training on maximum isokinetic trunk strength and response to sudden dynamic trunk loading (STL) in highly trained adolescent athletes. The study was conducted as a single-blind, 3-armed randomized controlled trial. Twenty-four adolescent athletes (14f/10 m, 16 ± 1 yrs.;178 ± 10 cm; 67 ± 11 kg; training sessions/week 15 ± 5; training h/week 22 ± 8) were randomized into resistance training (RT; $n = 7$), sensorimotor training (SMT; $n = 10$), and control group (CG; $n = 7$). Athletes were instructed to perform standardized, center-based training for 6 weeks, two times per week, with a duration of 1 h each session. SMT consisted of four different core-specific sensorimotor exercises using instable surfaces. RT consisted of four trunk strength exercises using strength training machines, as well as an isokinetic dynamometer. All participants in the CG received an unspecific heart frequency controlled, ergometer-based endurance training (50 min at max. heart frequency of 130HF). For each athlete, each training session was documented in an individual training diary (e.g., level of SMT exercise; 1RM for strength exercise, pain). At baseline (M1) and after 6 weeks of intervention (M2), participants' maximum strength in trunk rotation (ROM:63°) and flexion/extension (ROM:55°) was tested on an isokinetic dynamometer (concentric/eccentric 30°/s). STL was assessed in eccentric (30°/s) mode with additional dynamometer-induced perturbation as a marker of core stability. Peak torque [Nm] was calculated as the main outcome. The primary outcome measurements (trunk rotation/extension peak torque: con, ecc, STL) were statistically analyzed by means of the two-factor repeated measures analysis of variance ($\alpha = 0.05$). Out of 12 possible sessions, athletes participated between 8 and 9 sessions (SMT: 9 ± 3; RT: 8 ± 3; CG: 8 ± 4). Regarding main outcomes of trunk performance, experimental groups showed no significant pre–post difference for maximum trunk strength testing as well as for perturbation compensation ($p > 0.05$). It is concluded, that future interventions should

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exceed 6 weeks duration with at least 2 sessions per week to induce enhanced trunk strength or compensatory response to sudden, high-intensity trunk loading in already highly trained adolescent athletes, regardless of training regime.

Keywords: core, training intervention, trunk stability, exercise, perturbation

INTRODUCTION

A relevant task of the trunk is the compensation of external forces and loads to ensure the stability as well as the performance of the trunk or the entire body in everyday life and in high-performance sports (Cresswell et al., 1994; Hodges et al., 2001; Kibler et al., 2006; Borghuis et al., 2008; Hibbs et al., 2008; Calatayud et al., 2015). To protect the spine from repetitive and sudden excessive loads, an enhanced trunk stability is described as beneficial (Kibler et al., 2006; Borghuis et al., 2008; Hibbs et al., 2008; Wilson et al., 2014; Calatayud et al., 2015). Conversely, reduced trunk stability is considered a risk factor for the development of low back pain and lower extremity injuries, and also impairs athletic performance (Zazulak et al., 2007). The definition of trunk stability remains controversial. Trunk stability is defined by the ability to maintain "trunk balance" despite external mechanical forces or "neuro-muscular failure." (Granata and England, 2006; Reeves et al., 2007, 2011; Reeves and Cholewicki, 2009). Although the concept of trunk stability is rather vague, there is strong evidence that strength capacity as well as sensorimotor control are relevant factors for a rapid compensation of external loading and perturbations, especially in high-performance sport (Gruber and Gollhofer, 2004; Gruber et al., 2006; Kibler et al., 2006; Gruther et al., 2009; Choi et al., 2010; Wirth et al., 2016). Besides, the trunk performance here represents the overall functional performance capacity including both, strength capacity as well as stability as response to sudden dynamic, high-intensity trunk loading induced by external perturbations. The term is used to summarize the different functional areas that contribute to the motoric performance capacity of the trunk.

Intervention in the form of active exercises is evident to improve trunk stability (Wang et al., 2012; Saragiotto et al., 2016; Wirth et al., 2016; Mueller and Niederer, 2020; Niederer et al., 2020; Niederer and Mueller, 2020). Various strengthening exercises have been used and have been shown to be effective (Hibbs et al., 2008; Stuber et al., 2014). Significantly, in addition to the focus on trunk strengthening exercises, further training methods involving neuromuscular, sensorimotor training or combinations of these have emerged in the last years (Saragiotto et al., 2016; Arampatzis et al., 2017; Mueller et al., 2018b; Niederer et al., 2020). Core-specific sensorimotor exercises are an effective method to improve the neuromuscular activity of the trunk musculature and consequently improve trunk stability (Arampatzis et al., 2017; Mueller et al., 2018a,b). Sensorimotor training emphasizes activation of the deep trunk muscles (Hodges and Moseley, 2003), improves muscle control, and enhances inter- and intramuscular coordination (Gruber and Gollhofer, 2004). In particular, for resistance training and sensorimotor training, the benefits in terms of maximal eccentric and concentric trunk strength and peak torque in sudden dynamic trunk loading (STL) situations have not been systematically elucidated, while the differential effect of resistance and sensorimotor training remains an open question. Optimizing trunk stability and trunk strength contains the greatest potential for preventive effects. Even though adaptations to strength training are generally evident after eight to twelve weeks of training, Mueller et al. (2018b) proofed significant enhancements in high-intensity trunk loading response (to sudden perturbations) in healthy, well-trained adults already after 6 weeks of resistance or sensorimotor training. It remains unclear if this training regime (two sessions per week á 1 h for 6 weeks) could also lead to similar improvements in adolescent athletes, as there is existing evidence that even in adolescents 6 weeks of resistance training are evident to enhance upper and lower body performance (Faigenbaum et al., 2007).

Consequently, the aim of this study was to investigate and compare the effect of a six-week sensorimotor and a resistance training program on maximum isokinetic trunk strength and response (peak torque) to sudden high-intensity trunk loading. Improvement in isokinetic trunk strength and response to sudden high-intensity trunk loading was expected for participants in the two experimental groups compared to the control group.

MATERIALS AND METHODS

Study Design

The study was conducted as a single-blind (investigator), 3-armed randomized controlled trial with 6-week intervention phase and two measurement days pre/post-intervention (M1/M2). Participants were allocated to either the two experimental groups, which received sensorimotor training (SMT) or resistance training (RT), or the control group (endurance training).

The study was registered at the German Clinical Trial Register (DRKS Trial Registration No.: DRKS00000776). Potential participants were screened and examined by a sports medicine physician to determine eligibility before baseline assessment and randomization to the intervention groups (**Figure 1**).

Participants

Healthy adolescent elite athletes from the elite schools of sports of the federal state of Brandenburg (Germany) were recruited *via* the university outpatient clinic (e.g., athletes receiving annual health check-ups) and existing contacts with training groups at the Olympic Center. Elite schools of sports are special types of school, which ensure talented young elite athletes will be encouraged to their full potential and will also attain their educational qualifications. Inclusion criteria were an age between

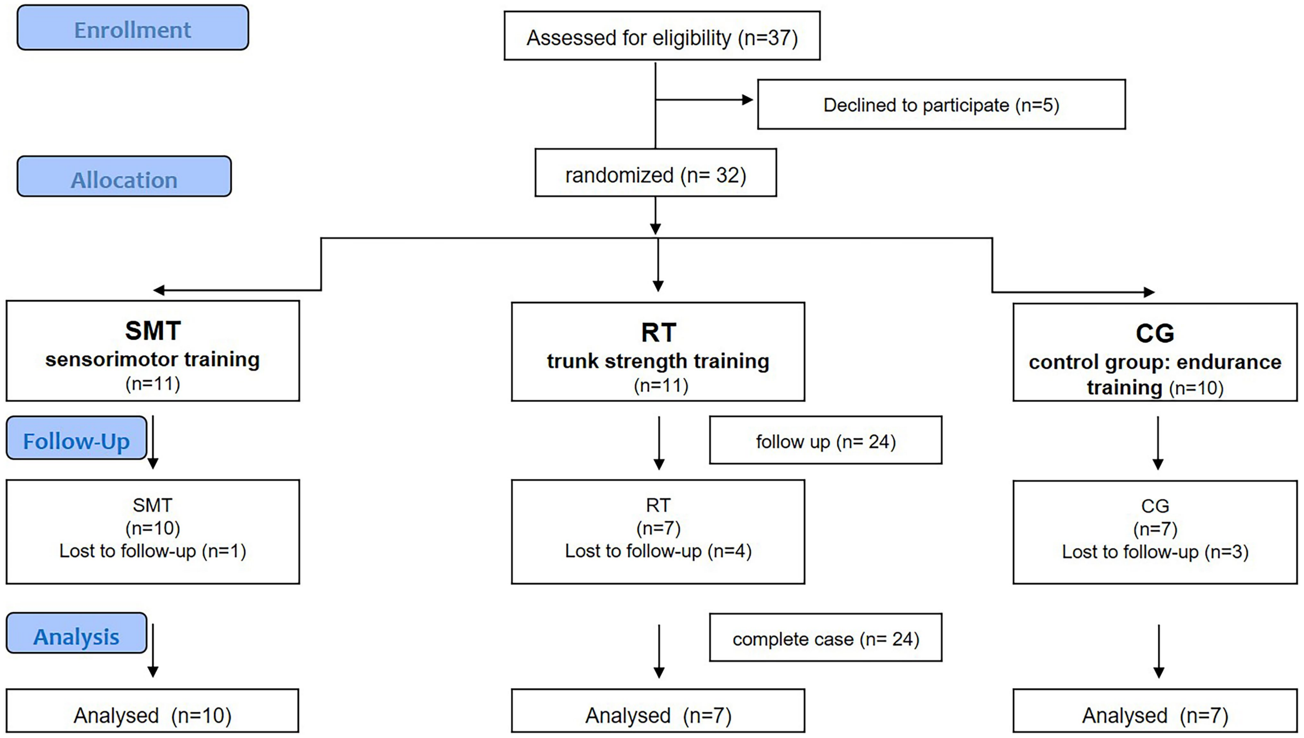


FIGURE 1 | Study flowchart.

11 and 17 years, both genders and being an elite athlete at the elite school of sport. Exclusion criteria were acute infection, pregnancy, any illness that would contraindicate exercise, and (low) back pain. All participants and their legal guardian were informed of the study and the specific testing procedures in a personal conversation with the principal investigator and through written study information during their stay at the university outpatient clinic. Before voluntary participation in the study, the legal guardians and the children provided written informed consent. The University Ethical committee approved all procedures conducted during the study.

Thirty-two adolescent athletes were included in the study and randomly assigned into SMT, RT, and CG, with $n = 24$ participants eligible for final analysis (**Figure 1**). The randomization list, generated by "randomization.com," was kept in a locked cabinet. A research assistant not involved in the outcome assessment revealed the group allocation. Participants' baseline characteristics are displayed in **Table 1**, separated by intervention and control groups. There was no statistically significant difference in any of the baseline characteristics between the groups ($p > 0.05$).

Intervention

Participants in both intervention groups (SMT; RT) were instructed to perform standardized, center-based training for 6 weeks, 2 times per week, at a duration of 60 min each session. Intervention groups consisted of 3 to 4 participants and were instructed by experienced therapists. Both interventions had matched overall training volumes and started with a 5-min general physical warm-up using different exercises, such as jumping jacks.

SMT consisted of four different core-specific sensorimotor exercises using instable surfaces (**Figure 2**). Each type of stabilizing exercise was carried out for 60 s with 4 sets. Rest between sets and between the tasks was standardized to 2 min. The exercise level was adapted on an individual basis every week. This was done by the therapist by increasing the difficulty of the four basic exercises, for example, by adding unstable surfaces or additional movement task. All athletes in the SMT group received verbal feedback from the therapists focusing on movement quality and error correction while performing the exercises.

We applied maximal strength training, in line with recommendations for general progressive strengthening (American College of Sports Medicine, 2009). Due to the 6-week intervention, improvements would be linked predominantly to adaptations of the intramuscular coordination. RT consisted of four trunk strength exercises using strength training machines for lateral flexion and rotation (Extension Bench and Torso Rotation, Cybex International, Inc. United States), as well as an isokinetic dynamometer for flexion and extension (CON-TREX MJ/TP 1000, Physiomed Elektromedizin AG, Germany; Mueller et al., 2018b). All strengthening exercises were executed at moderate velocity for three sets of eight repetitions and an intensity of 85% of the individual's maximum strength capacity. The rest period between the sets and exercises was 2 min. The intensity (85%) of the rotation and lateral flexion strengthening exercises was

TABLE 1 | Anthropometric and training characteristics of the study participants at baseline for control (CG), resistance training (RT) and sensorimotor training (SMT) groups [mean ± SD].

Group	n (m/f)	Age [yrs]	Body mass [kg]	Body height [cm]	Sport disciplines [n]	Training-volume [h/week]	Back pain begin of measurement day [VAS; cm]
CG (*n*=7)	3/4	16 ± 1	68 ± 10	181 ± 11	Triathlon: *n*=2 Rowing: *n*=3 Canoeing: *n*=2	22 ± 11	0.6 ± 0.9
SMT (*n*=10)	5/5	16 ± 1	65 ± 10	179 ± 11	Triathlon: *n*=3 Rowing: *n*=4 Canoeing: n=3	24 ± 6	0.3 ± 0.8
RT (*n*=7)	2/5	16 ± 1	71 ± 13	175 ± 9	Triathlon: *n*=3 Rowing: *n*=2 Canoeing: *n*=2	22 ± 8	0.4 ± 0.5

CG, control group; SMT, sensorimotor training group; RT, resistance training group.

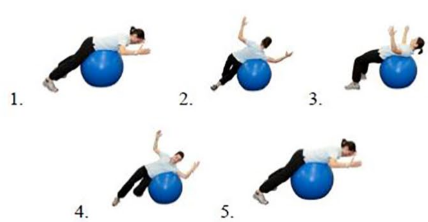
	Exercise	Dosage		Hints
A	Sit & Balancing on Swiss Ball	sets: 4 á 60sec rest: 2 minutes		- without contact of the feet with the ground
B	Kneeling on Swiss Ball with Pelvic Rocker	sets: 4 á 60sec rest: 2 minutes		- without contact of the feet with the ground
C	Supine position on 2 sissel pillows	sets: 4 á 60sec rest: 2 minutes		- 2 Sissel cushions (90°/90° position of the legs; arms have no contact with the floor)
D	Spin on Swiss Ball	sets: 4 á 3 repetitions per side rest: 2 minutes		- Rotate around own axis only with leg contact on the floor

FIGURE 2 | Sensorimotor training (SMT) intervention exercises.

determined by means of the 1-repetition maximum (1RM) method. Trunk flexion and extension were trained in eccentric mode (30°/s; ROM: 55°), and intensity (85%) was determined using the isokinetic maximum strength test. The intensity was redefined every 2 weeks to ensure an individualized, progressive resistance training (1RM; maximum isokinetic strength test). All athletes received verbal feedback on the quality of movement execution for exercise 1 and 2, as well as any necessary error correction. For the execution of exercise 3 and 4 in the isokinetic dynamometer, visual biofeedback on the achievement of 85% intensity from the individual maximum strength test was provided.

All participants in the CG received an unspecific heart frequency controlled endurance training (50 min at max. Heart frequency of 130 HF) on a bicycle ergometer, treadmill ergometer, or arc trainer (randomized ergometer).

For each athlete, each training session was documented in an individual training diary with the most important information about each training session (e.g., level of SMT exercise; 1RM for strength exercise, pain). Low back pain was monitored by use of a VAS (0–10 cm) in regular intervals throughout each training session. Besides, all participating athletes followed their regular training routines **Table 1** with the presented hour of training per weeks next to the applied intervention.

Experimental Protocol and Outcome Measures

Moreover, the procedures of the experimental protocol were described elsewhere (Mueller et al., 2018b). However, the experimental protocol at both assessment point (M1/M2) was identically: Initially, anthropometrics and training habits [overall training time (h/week), sports discipline] were assessed. Afterward, all participants were screened and examined by a sports medicine physician to determine eligibility before baseline assessment followed by randomization to the intervention groups and/or experimental protocol. All participants were assessed before intervention (baseline = M1) and after intervention (post = M2) by a blinded assessor. At both assessment points (M1/M2), outcomes were measured in the following order: back pain, isokinetic trunk rotation strength, response to sudden, high-intensity trunk rotation loading, isokinetic trunk extension strength, response to sudden, high-intensity trunk extension loading and, finally, back pain was re-assessed.

Back Pain

Back pain intensity was measured, as a control parameter to account for pain or injury development, at rest and after high-intensity strength testing protocol on a 10 cm visual analogue scale [VAS (cm)].

Isokinetic Trunk Strength

Trunk rotator and extensor isokinetic concentric and eccentric strength were assessed with an isokinetic dynamometer. All participants underwent a general physical warm-up of at least 10 min on a treadmill before isokinetic testing. For (right-sided) trunk rotation strength testing, participants were placed before an angular dynamometer (CON-TREX WS, Physiomed Elektromedizin AG, Germany) in a seated position, with a rotational range of motion of 63° (Mueller et al., 2018b). Trunk strength measurements for extension were performed in a standing position (CON-TREX MJ/TP 1000, Physiomed Elektromedizin AG, Germany). Participants were fixed to the dynamometer with adjustable adapters at the lower leg and knee, as well as two non-stretching belts at the hip and upper body. The range of motion was set to 55° (Mueller et al., 2018b). Trunk strength measurements included an additional 60s warm-up and familiarization trial for each test situation, performed at a moderate intensity. Additionally, preceding all measurements, an identical practice trial with submaximal effort was performed. Resting time between the warm-up and each maximum strength test was standardized to a minimum of 1 min. Maximum strength in rotation and extension was tested in concentric (30°/s, con) and eccentric (30°/s, ecc) modes, performing five repetitions.

Response to Sudden, High-Intensity Trunk Loading

Sudden dynamic trunk loading was applied as a represent for trunk stability. Sudden, high-intensity trunk loading was induced during an additional eccentric mode (30°/s) by means of a superimposed customized perturbation (acceleration from 30°/s to 330°/s within 120 ms for trunk rotation and 150°/s within 250 ms for trunk extension; STL).

Verbal encouragement was given throughout the entire test to ensure participants' maximum effort. The outcome measurements analyzed for all test modes were peak torque [Nm] in trunk extension (Ext) and trunk rotation (Rot), calculated as the mean of the three peak torque values from five repetitions (Müller et al., 2007). The reproducibility of the novel STL test was proven in a prior pilot study (STL: ICC: 0.94, test–retest variability: 8.53 ± 6.33%; bias±1.96SD: 8.16 ± 64.8 Nm; $n = 10$; Engel et al., 2013; Mueller et al., 2018b).

Data Analysis

All data were documented in a case report form if not captured by a computer. The data were transferred, manually from the case report forms (CRF), into a database for further statistical analysis. For all data, a plausibility check was performed. Further analyses followed the intention-to-treat principle. Statistical analysis was done descriptively (means ± standard deviation (SD), means with upper/lower 95% confidence interval (CI)) for baseline, post-intervention test (M1, M2), and the pre–post difference. The primary outcome measurements (trunk rotation/extension peak torque: con, ecc, STL) were statistically analyzed by means of the 2-factor repeated measures analysis of variance ANOVA ($\alpha = 0.05$; JMP, SAS Institute®).

A power analysis to calculate sample size was not performed. The number of subjects to be included was based on previous published studies with comparable outcomes (Arampatzis et al., 2017; Mueller et al., 2018b). $N = 20$ subjects per group will be included. Mueller et al. (2018b) estimated a minimum sample size of 14 participants per group.

RESULTS

Flow and Characteristics of Participants Through the Study

Of the 37 participants that were screened, all met the inclusion criteria, five declined participation and 32 participants were therefore included in the study. One participant in the SMT group, four athletes out of the RT group and three athletes out of the CG did not complete the study (**Figure 1**). The loss of participants was especially due to the missing of measurement M2. Rescheduled time windows for final measurement (M2) were also not met without giving reasons. No specific pattern between the three groups could be identified for the non-appearance or cancellation of the second measurement. Therefore, 24 adolescent athletes (14f/10 m; 16 ± 1 yrs.; 178 ± 10 cm; 67 ± 11 kg; training sessions/week 15 ± 5; training h/week

22 ± 8) were included into final analysis. The baseline characteristics (anthropometrics, training data, outcomes) of the three groups are shown in **Table 1**. There are no statistical significant differences ($p > 0.05$) between the three groups for all baseline characteristics (age, body height/weight, training hours per week). Regular training routine of all athletes included athletic (resistance and endurance) as well as technical (sport-specific) training parts. The precentral distribution of these parts did not differ significantly between the two experimental and the control group ($p > 0.05$). The athletes included into the SMT as well as in the RT group reported a distribution of 58% endurance, 30% resistance, and 12% technical training. The athletes in the CG group reported a distribution of 65% endurance, 25% resistance and 10% technical training for their regular training.

Training Compliance

Training documentation revealed on average 8 (SD: ±3) executed training sessions by the RT group, 9 (SD: ±3) by the SMT group and 8 (SD: ±4) by the CT group out of a maximum of 12 possible training sessions. Overall, this resulted in 1.4 ± 0.5 sessions per week for all participating athletes (training session/week: SMT: 1.5 ± 0.5; RT: 1.3 ± 0.5; C: 1.4 ± 0.6).

Back Pain

Back pain intensity did not change between the two measurement days M1 and M2 for any of the three groups (e.g., VAS (at the beginning of each measurement day): SMT 0.3 ± 0.8 (M1)/0.3 ± 0.6 (M2); RT: 0.4 ± 0.5 (M1)/0.7 ± 1.1 (M2); CG: 0.6 ± 0.9 (M1)/06. ± 1.5 (M2); $p > 0.05$).

Main Outcomes (Isokinetic Strength/STL)

Results of the isokinetic strength and STL testing for trunk rotation as well as trunk extension (M1/M2) are presented in **Table 2** and displayed in **Figures 3, 4** for all three groups. No significant differences were present over time (M1/M2; $p > 0.05$) for all outcome measures in any of the groups.

Regarding main outcomes of trunk performance (isokinetic strength/STL), no statistically significant differences could be observed between the intervention and control groups ($p > 0.05$). No significant group by time interaction ($p > 0.05$) could be observed for all presented outcome measures. The power (*post hoc* power analysis) of the outcomes reached between 0.06 (STL in rotation) to 0.34 (STL in extension) for the RT group and between 0.05 (eccentric testing in rotation) to 0.33 (concentric testing in rotation) for the SMT group.

DISCUSSION

The primary aim of this randomized controlled trial was to enhance trunk strength capacity as well as response to sudden high-intensity loading, known to be a relevant risk factors for back pain (Hodges and Moseley, 2003; Borghuis et al., 2008), through a 6-week sensorimotor or resistance training in elite adolescent athletes. The results suggest that two additional sessions of sensorimotor or resistance training per week over 6 weeks are not sufficient to improve trunk strength or compensatory response to sudden, high-intensity trunk loading in already highly trained adolescent athletes.

With regards to the primary outcomes of trunk performance, both experimental groups (SMT/RT) showed no significant pre–post difference for maximum strength in concentric and eccentric testing for trunk rotation as well as for trunk

TABLE 2 | Absolute values of mean (95% CI) peak torque [Nm] for baseline (M1) and post-intervention measurements (M2) for each group in trunk rotation and extension for isokinetic concentric, eccentric and sudden trunk loading (STL).

Outcome	Day	Groups					
		CG		RT		SMT	
		Mean	(95% CI)	Mean	(95% CI)	Mean	(95% CI)
Trunk rotation							
con	M1	70	(59–82)	69	(62–75)	64	(53–76)
	M2	66	(55–78)	71	(59–84)	68	(57–80)
ecc	M1	68	(55–81)	69	(59–79)	67	(55–78)
	M2	68	(56–81)	72	(55–89)	67	(60–75)
STL	M1	144	(90–198)	168	(141–194)	160	(148–173)
	M2	163	(137–189)	164	(126–201)	155	(141–169)
Trunk extension							
con	M1	208	(173–243)	183	(140–226)	181	(153–209)
	M2	201	(137–265)	177	(135–219)	173	(157–189)
ecc	M1	264	(212–316)	253	(200–307)	217	(177–257)
	M2	250	(173–327)	251	(200–302)	220	(192–247)
STL	M1	337	(261–414)	315	(256–374)	276	(234–318)
	M2	329	(260–398)	330	(264–396)	270	(237–304)

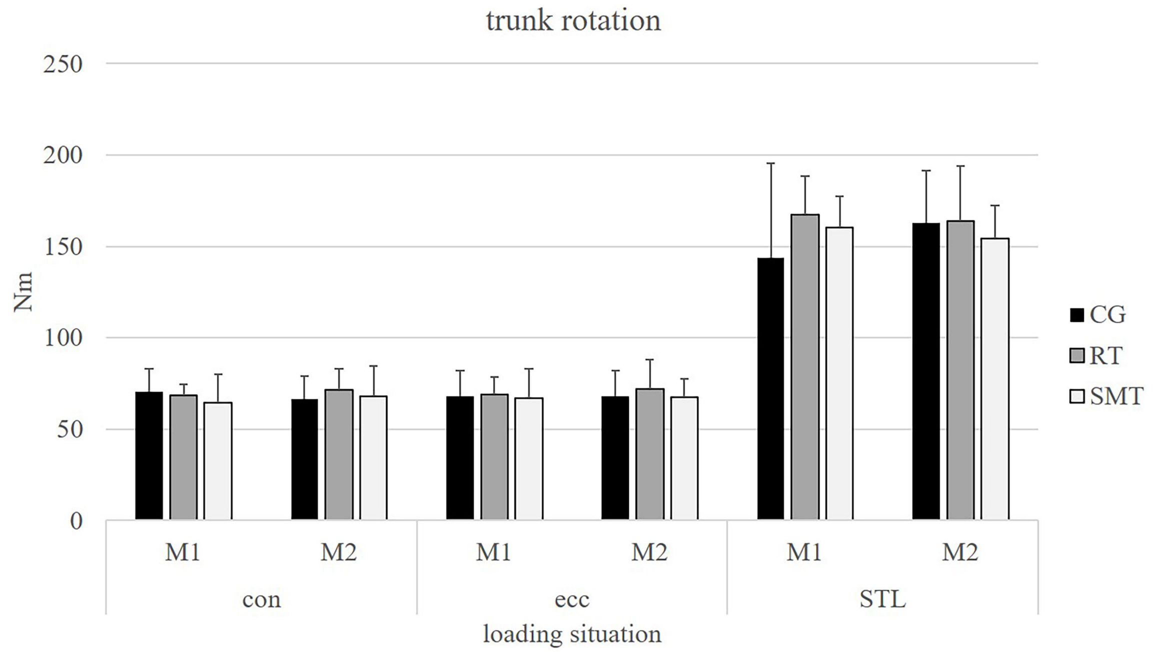


FIGURE 3 | Absolute values of mean (mean ± SD) peak torque [Nm] for baseline (M1) and post-intervention measurements (M2) for each group in trunk rotation isokinetic concentric, eccentric, and sudden trunk loading (STL) testing.

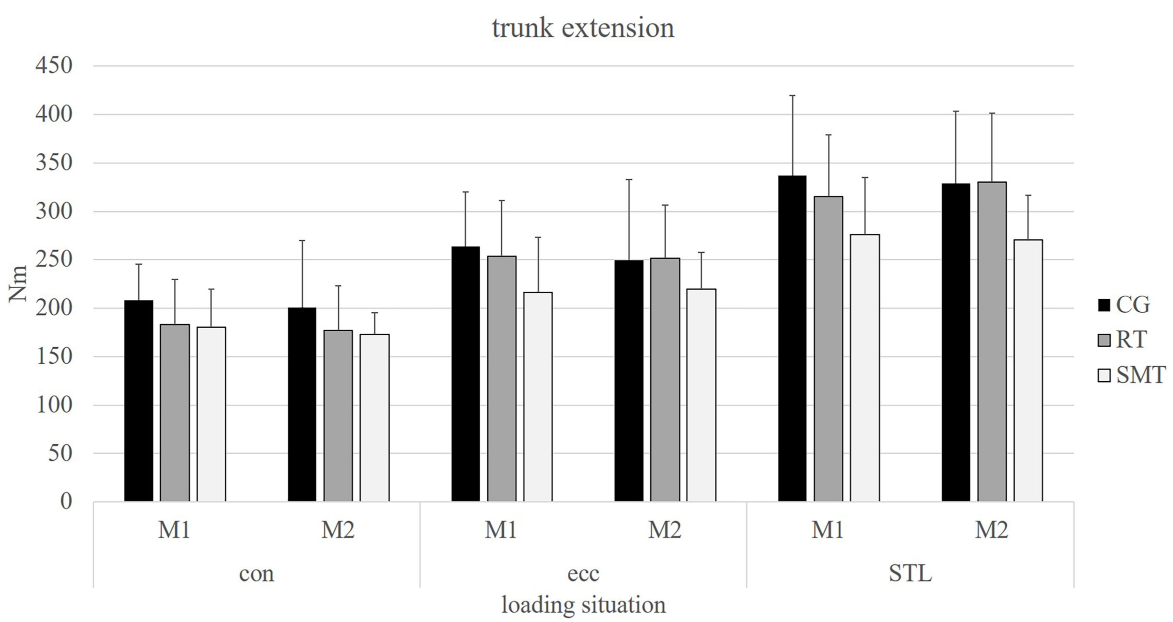


FIGURE 4 | Absolute values of mean (mean ± SD) peak torque [Nm] for baseline (M1) and post-intervention measurements (M2) for each group in trunk extension isokinetic concentric, eccentric, and sudden trunk loading (STL).

extension. In addition, the results presented show that neither training program increased peak torque in response to sudden, high-intensity trunk loading. However, this is in contrast to previous results reported for adult (recreational and elite) athletes (Arampatzis et al., 2017; Mueller et al., 2018b). It has to be discussed whether the applied STL test on the isokinetic dynamometer is a suitable measurement situation for the assessment of dynamic trunk stability. As the applied sensorimotor intervention consists of four exercises that address rather directly the trunk stability but not directly the balance ability in case of static upright postural control of the entire body, an isolated trunk stability test can be considered reasonable (Mueller et al., 2018b). Moreover, Mueller et al. (2018b) could proof a statistically significant improvement for peak torque in response to sudden high-intensity trunk loading with a comparable study design and test setup. The reason for these shown differences could on the one hand be that the already high training volume of the adolescent athletes, leading to rather unexpectedly small strength gains in isokinetic mode. This is supported by the condition of reduced remaining adaptation capacity with increased training level also known from elite adult athletes. On the other hand, Mueller et al. (2018b) prescribed three training sessions per week. Therefore, it has to be discussed, that the prescribed dosage of two sessions per week in our study was too low for these already highly trained adolescent athletes with a weekly training level of more than 20 h. In this context, the discussion of athletes' adherence to the intervention can possibly be used as an additional explanation. The adolescent athletes in this study showed a limited adherence (70%) to the implementation of an additional intervention for two sessions per week. Although two sessions per week were prescribed, the athletes only attended an average of 1.3 to 1.5 sessions per week. In this context, it additionally has to be discussed if an intervention duration of 6 weeks (with two sessions per week) may have been too short to be able to achieve neuromuscular adaptations and strength gains (Lesinski et al., 2016). Arampatzis et al. (2021) implemented a perturbation-based exercise intervention with a large proportion of sensorimotor exercises for two times per week á 25 min over a period of 1 year in adolescent athletes aged 13–18 yrs. The authors were able to proof significant increase of trunk extensor and flexor strength (Arampatzis et al., 2021). Moreover, Lesinski et al. (2016) reported in their systematic review that short-term resistance training is already effective in adolescent athletes and should last 9–12 weeks.

In addition, when comparing the intervention programs, similar results in trunk isokinetic strength and STL were not expected for the two experimental groups. In this context, it is relevant to elucidate whether training adaptations approached differently (SMT and RT) lead to a similar response in the outcomes studied. (Gruber and Gollhofer, 2004; American College of Sports Medicine, 2009). Intervention adaptations after RT could be speculated to focus primarily on a muscular level, in contrast to a more neuronal component for SMT training, leading to the same functional outcome in the short term of 6 weeks (Gruber and Gollhofer, 2004; Taube et al., 2007; Ratamess et al., 2016). For both interventions, but especially for RT, we expected higher effects on the isokinetic strength outcomes, since the exercise programs were designed with valid training volumes, intensities, and duration (American College of Sports Medicine, 2009). It could be speculated that the already well-trained participants would have needed an even higher training amount to additionally adapt to on top of their high baseline trunk strength.

Core-specific exercise programs for the treatment and prevention of chronic non-specific low back pain can improve trunk performance, leading to a reduction in the recurrence of low back pain or pain relief (Hibbs et al., 2008; Choi et al., 2010; Mannion et al., 2012). However, studies are limited and assess trunk stability most often indirectly *via* performance tests, isolated maximum strength tests, and muscular activity measurements (Leetun et al., 2004; Kibler et al., 2006; Borghuis et al., 2008; Hibbs et al., 2008). This may not apply to dynamic trunk stability in high-intensity loading situations that occur in high-performance sport. The test setup presented here accounts for this issue using STL. A higher peak torque response could be interpreted as a noticeable increase in reactive load compensation after intervention. In consequence, this should be interpreted as a complex neuromuscular response counteracting external sudden trunk loading. In light of the knowledge of differences in perturbation compensation responses for healthy persons compared to those with low back pain, the results might be meaningful not only for prevention, but also for rehabilitation strategies (Cholewicki et al., 2000; Radebold et al., 2000). In addition, the STL test appears to be feasible for the adolescent athletes studied, as no complaints were documented and no back pain occurred.

Certain limitations have to be taken into account when interpreting the results. The inclusion of male and female adolescent athletes may have increased variance and influenced the impact of the intervention. Besides, we did not assess the maturity status of each participant since we assume independently of this positive adaptations. However, the different individual stage of development might have influenced on the extend of adaptation. As mentioned above, the six-week resistance training seem to be too short to explore muscular adaptation mechanism. Furthermore, because the study focuses on measuring peak torque, it is not able to provide detailed physiological explanations at the neuronal level without adding, for example, surface electromyographic measurements (Gruber et al., 2006; Taube et al., 2007). The control group was not a passive control group due to the fact, that whole training groups were participating in the study. For ethical reasons, all athletes out of one training group, including those randomly assigned to the control group, had to be offered a physical activity. The choice of exercise content (endurance) for the control group was based on the knowledge that endurance training at a low heart rate (120 bpm) has no significant effects on maximum strength and neuromuscular control of the trunk. The low sample size has to be stated as a major limiting factor, leading to a low power, of the study. Our results must thus be interpreted with care as explorative pilot findings and should be proven or disproven by future studies. Besides, the higher loss of participants in the RT and CG group as opposed to the SMT group may have influenced the results.

It can be concluded, that two additional bouts of sensorimotor or resistance training per week are not sufficient to improve trunk performance. Therefore, future interventions should exceed 6 weeks duration with at least two sessions per week to induce enhanced trunk strength or compensatory response to sudden, high-intensity trunk loading in already highly trained adolescent athletes, regardless of training regime. The high-intensity sudden trunk loading (STL) protocol seems to be certainly feasible and valid for the assessment of trunk stability in the adolescent elite athletes studied, as no back pain occurred. In addition, the validation of the presented intervention programs as well as the innovative trunk loading tests (STL) should also be performed in athletes with back pain in future research.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Potsdam Ethic Commission. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: FM, SM, JM, JS. Data collection: SM, JS, JM. Analysis and interpretation of results: FM, SM, JM. Draft manuscript preparation: SM, JM. All authors contributed to the article and approved the submitted version.

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