Heliyon 10 (2024) e33063

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Maturation-specific enhancements in lower extremity explosive strength following plyometric training in adolescent soccer players: A systematic review and meta-analysis

Lunxin Chen [a,1], Ruixiang Yan [a,1], Lin Xie [a,1], Zhiyong Zhang [a], Wenfeng Zhang [b,2,**], Hengtong Wang [b,2,*]

[a] *Digitalized Strength and Conditioning Training Laboratory, Guangzhou Sport University, Guangzhou, China*
[b] *School of Athletic Training, Guangzhou Sport University, Guangzhou, China*

ARTICLE INFO

Keywords:
Plyometric training
Soccer player
Explosive strength
Maturation

ABSTRACT

Background: For adolescent soccer players, good sprinting and jumping abilities are crucial for their athletic performance. The application of plyometric training on boosting explosive strength in adolescent soccer players is contingent upon the maturation phase, which can mediate the training-induced adaptations.
Purpose: This systematic review and meta-analysis aim to explore the maturation effect of plyometric training on the lower limb explosive power of adolescent soccer players, with vertical countermovement jump (CMJ) and 20-m sprint as the main outcome indicators.
Methods: An extensive search of the literature was carried out on various databases including PubMed, Web of Science, Scopus, ProQuest, and the China National Knowledge Infrastructure (CNKI), covering the time period from the establishment of each database to February 6, 2023. The search was conducted using English keywords such as 'Plyometric,' 'Adolescent,' 'football,' and 'Explosive strength.' This study utilized the Cochrane risk of bias assessment tool to conduct a standardized quality evaluation of all the included literature. Additionally, the Review Manager 5.4 software was employed to perform data analysis on all the extracted data.
Results: A total of 17 studies involving 681 adolescent soccer players aged 10 to 19 were included. Plyometric training significantly improved CMJ performance across different maturation stages, especially in the post-peak height velocity stage (POST-PHV) [MD = 4.35, 95 % CI (2.11, 6.59), $P < 0.01$, $I^2 = 60$ %]. The pre-peak height velocity stage (PRE-PHV) showed the next best improvement [MD = 3.00, 95 % CI (1.63, 4.37)], while the middle-peak height velocity stage (MID-PHV) showed the least improvement [MD = 2.79, 95 % CI (1.16, 4.41), $P < 0.01$, $I^2 = 49$ %]. However, improvements in 20 m sprint ability were only observed in the PRE-PHV [MD = −0.06, 95 % CI (−0.12, 0), $P < 0.01$, $I^2 = 0$ %] and MID-PHV [MD = −0.18, 95 % CI (−0.27, −0.08), $P < 0.01$, $I^2 = 0$ %] stages.
Conclusion: Plyometric training serves as a potent strategy for boosting the lower limb explosive strength of adolescent soccer players, and the training effect is closely related to the players'

* Corresponding author.
** Corresponding author.
E-mail address: 11093@gzsport.edu.cn (H. Wang).
[1] On behalf of the co-first authors.
[2] On behalf of Correspondence.

https://doi.org/10.1016/j.heliyon.2024.e33063
Received 28 December 2023; Received in revised form 12 June 2024; Accepted 13 June 2024
Available online 15 June 2024
2405-8440/

biological maturity. Considering biological maturity is a key aspect that this study deems essential for the formulation of effective training programs for these adolescent players.

1. Introduction

Soccer is widely celebrated for its extensive appeal, especially among children and adolescents [1–4]. During a 90-min professional soccer match, athletes routinely carry out a series of explosive movements, such as kicking the ball, tackling, jumping, turning, sprinting, and changing pace [5,6]. Throughout a standard soccer match, players typically engage in short sprints of 2–4 s within a 90-s interval, accounting for approximately 3 % of the total match time [7,8], and 1–11 % of the total distance covered [8,9]. While sprinting ability is essential, improving jumping ability can provide players with an advantage in aerial duels, interceptions, and shooting, while also enhancing their explosive strength and technical skills [10,11]. Therefore, abilities in sprinting and jumping, which are pivotal to the game, are essential for soccer players' success.

Plyometric training, recognized for its effectiveness, serves as a scientifically validated approach to augment the explosive strength of athletes [12–17], making it highly applicable to soccer players [18]. A unique muscle activation pattern, referred to as the stretch-shortening cycle (SSC) [19,20], underpins the efficacy of plyometric training, encompassing eccentric, isometric, and concentric muscle actions [21]. This cycle efficiently utilizes stored elastic energy and the stretch reflex mechanism to improve explosiveness [22,23]. However, in the case of adolescents, the development of lower limb explosive strength is influenced not only by training interventions but also by various other factors, with maturation being one of the primary determinants.

Identical training interventions may yield different effects during different maturation stages in adolescents [24], suggesting that training adaptations may vary across maturation periods [25]. Biological maturation, which is the process of an individual progressing towards maturity, is one of the primary factors influencing these adaptations [12]. This process differs in terms of timing and velocity, and the maturation of different bodily systems is also asynchronous [26]. The adolescent stage epitomizes a paramount epoch of intrinsic evolution, underscored by swift transformations and maturation within the body's neurological and physiological systems [27]. Specifically, adolescents in the pre-pubertal phase exhibit high neuro-muscular plasticity [28]., while adolescents in mid-puberty experience significant increases in growth hormone and testosterone levels, which promote the development of muscle fiber types and muscle mass [25,29–31]. These physiological and neurological developments can significantly impact training outcomes. However, the level, rate, and timing of biological maturity vary among individuals [32,33]. Given this variability, it is particularly recommended in the Long-Term Athlete Development (LTAD) model to use the age at PHV rather than chronological age to assess changes in body size, composition, and physiological performance during adolescents' growth spurts [34]. This approach helps to more accurately describe the biological and physiological characteristics associated with adolescent growth peaks and provides a scientific basis for designing targeted training plans.

Considering the well-established benefits of plyometric exercises for enhancing the explosive power of the lower limbs among adolescent soccer players, the intricacies of maturation-related training responses are a notable concern. Specifically, uncertainty persists regarding whether plyometric exercises, when integrated into maturation phases, can yield more pronounced adaptations surpassing those of the natural maturation process in isolation. Given the importance, research must focus on the relationship between plyometric training and maturation's role in developing lower-limb explosive strength in adolescent soccer players. For this purpose, this study aiming to explore the maturation effects of plyometric training on the explosive strength of adolescent athletes, using the countermovement jump (CMJ) and 20-m sprint as outcome measures.

2. Information and research methods

2.1. Search strategy

The present systematic review and meta-analysis executed a comprehensive search of five databases, namely PubMed, Web of

Table 1
Presentation of literature search process.

Databases	Search process	Search period
PubMed、 Web of Science、Scopus、ProQuest、CNKI	#1 TS = ("Lower limb explosive strength" OR "Explosive strength" OR "explosive force" OR "Explosive power" OR "power" OR "Countermovement jump" OR "CMJ" OR "squat jump" OR "SJ" OR "standing long jump" OR "SLJ" OR "drop jump" OR "DJ" OR "sprint performance" OR ″10 m" OR ″20 m" OR ″30 m" OR ″50 m" OR "vertical jump" OR "VJ") #2 TS = ("Adolescent" OR "Adolescents" OR "Adolescence" OR "Teens" OR "Teen" OR "Teenagers" OR "Teenager" OR "Youth" OR "Youths" OR "Female Adolescent" OR "Female Adolescents" OR "Male Adolescent" OR "Male Adolescents" OR "Child" OR "Children") #3 TS = ("plyometric" OR "plyometrics" OR "PT" OR "pliometrique" OR "entrainement pliometrique" OR "salto pliome'trico" OR "velocidad") #5 #1 AND #2 AND #3	The search period spanned from the inception years of the respective databases to February 6, 2023

Science, Scopus, ProQuest, and China National Knowledge Infrastructure (CNKI), with the search period extending from the databases' inception to February 6, 2023. The search terms used included Plyometric, Adolescent, Teenagers, Children, Football, Soccer, Lower limb explosive strength, and Explosive power. The study has been registered according to the relevant protocol (PROSPERO: CRD42023485762). As an example, the search results from Web of Science are presented in Table 1 below.

2.2. Study selection

This systematic review and meta-analysis strictly followed the PICOS principles of evidence-based medicine to formulate the literature inclusion criteria (Table 2). The meticulous application of this well-established framework ensured the scientific rigor and systematic nature of the research methodology employed in this study.

The analysis encompassed a total of 17 studies, with the process of inclusion and exclusion detailed in Fig. 1.

2.3. Data extraction

The use of EndNote X9 software enabled the elimination of duplication across all the included literature. After finalizing the selection of relevant literature, two researchers gathered the data using Microsoft Excel spreadsheets as the primary tool for data organization. Meticulous attention was paid to collating essential information, including author details, publication chronology, participant demographics (such as age, maturation stage, and gender), pre- and post-intervention outcomes, and comprehensive intervention details (duration, training frequency, duration, and protocols for both experimental and control groups). To address any inconsistencies in data extraction, an additional researcher independently conducted the extraction process and made a conclusive decision. For all studies included in the review, data from both pre- and post-intervention tests were recorded as mean ± standard deviation. The research team then standardized these values into change scores ± standard deviation for the subsequent analysis. When full-text articles or specific data were not readily available, the strategy involved contacting the corresponding authors to obtain the necessary documentation. Studies were only excluded due to lack of access to the full text if, after these attempts, the required information remained unavailable.

2.4. Assessment of risk of bias

The quality of each article was independently assessed by two researchers using the Cochrane Risk of Bias assessment tool to conduct a comprehensive evaluation of the literature. The assessment results were categorized as 'low risk of bias,' 'unknown risk of bias,' or 'high risk of bias' for each domain. Based on the assessment results, the articles were assigned into three different quality levels: A, B, or C. Specifically, if the number of domains with a 'low risk of bias' was four or more, the article was designated as level A; if the number was between two and three, it was designated as level B; if the number was one or none, it was designated as level C [13].

2.5. Statistical analysis

Data analysis was executed using the Review Manager 5.4 software (RevMan, The Nordic Cochrane Centre, Copenhagen, Denmark). For the purpose of enhancing the study's credibility and impact, we limited meta-analysis and subgroup analysis to those outcome measures that included at least four complete sets of experimental data [36]. To standardize the units of the measures (e.g., converting all length units to centimeters), this study utilized the mean difference (MD) as a summary effect measure, accompanied by a 95 % confidence interval for all outcome measures in the final analysis. Using the I-squared (I^2) statistic, the study evaluated the degree of heterogeneity across included studies, revealing the proportion of variation that is not due to chance. When I^2 was less than 25 %, the heterogeneity was considered negligible; when I^2 was between 25 % and 75 %, the heterogeneity was considered moderate; when I^2 was greater than 75 %, the heterogeneity was considered high [37]. For studies with heterogeneity less than 25 %, a fixed-effects model was used to analyze the outcome measures. For studies with heterogeneity greater than 25 %, a random-effects

Table 2
Meta-Analysis eligibility: inclusion and exclusion standards.

Category	Inclusion criteria	Exclusion criteria
Population	Adolescent soccer players aged 10–19 years, categorized according to the World Health Organization (WHO) maturation classification (10–12.99 years as PRE-PHV, 13–15.99 years as MID-PHV, and 16–18.99 years as POST-PHV [35].	(1) Study participants not belonging to the soccer player population; (2) Age of study participants exceeding or not meeting the adolescent stage
Intervention	After undergoing the plyometric training intervention, the experimental group engaged in soccer-specific drills that were consistent with the exercises performed by the control group.	The experimental group participated in plyometric training and also received other forms of training outside of soccer-specific drills.
Control	The control group either served as a blank control or engaged in identical soccer-specific drills as those performed by the experimental group.	(1) Absence of control group; (2) The control group participated in training modalities other than soccer-specific drills.
Outcome	CMJ and 20-m sprint	(1) Unable to obtain study data; (2) Studies for which full text remained inaccessible even after attempting to contact the authors
Study design	Randomized controlled trials (RCTs)	Non-randomized controlled trials, self-controlled experiments, or randomized crossover experiments

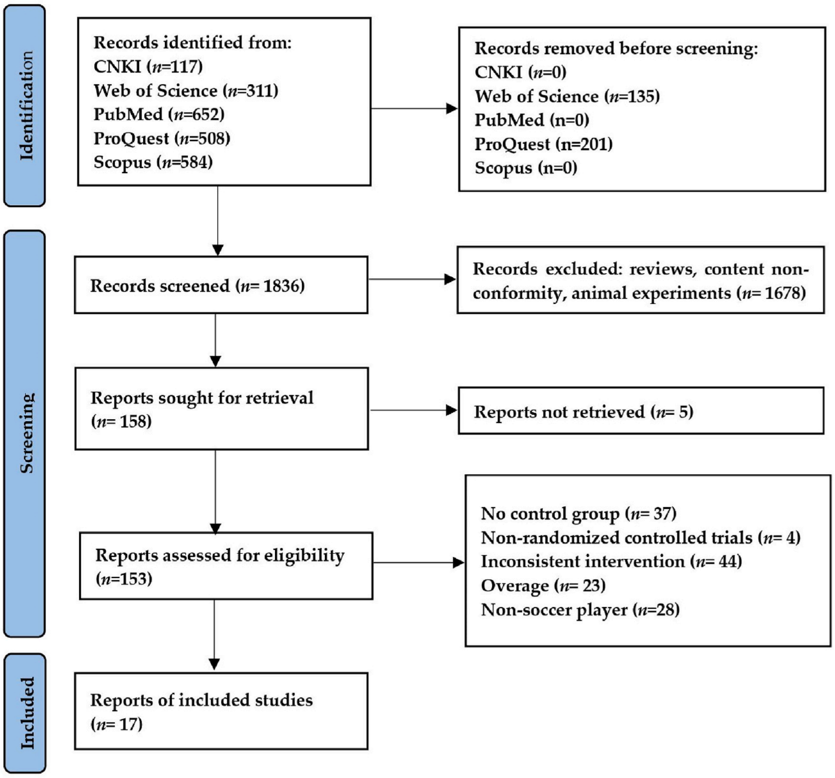

Fig. 1. Flowchart of the inclusion and exclusion criteria following PRISMA standards.

model was used for the analysis. A P value of less than 0.05 was considered statistically significant.

3. Results

3.1. Study characteristics

This meta-analysis included 17 studies encompassing 24 randomized controlled trials. The total sample size was 681 participants, all of whom were adolescent soccer players ranging from 10 to 19 years of age. The intervention group received plyometric training. In contrast, the control group performed sport-specific training without any other training interventions. Most studies employed 20–40 min training sessions, 2 times per week, over a 6–12 weeks intervention period (Table 3).

3.2. Risk of bias in the included articles

The quality of all included studies was evaluated using the Cochrane risk of bias assessment tool. Allocation concealment was applied in 5 studies, and among these, 3 also employed comprehensive blinding for researchers and participants. All such trials were randomized and rated as low risk of bias (Fig. 2).

4. Meta-analysis results

4.1. Jumping performance

The meta-analysis encompassed 14 studies with 21 groups of trials and 605 participants were included to assess the impact of plyometric training on CMJ performance in adolescent soccer players (Fig. 3). The result showed an overall positive effect of plyometric training on CMJ performance in adolescent soccer players (MD = 3.23, 95%CI (2.32, 4.14)), with moderate heterogeneity (I^2 = 58 %) and statistical significance ($P < 0.01$). Subgroup analysis revealed positive effects of plyometric training on CMJ performance in adolescent soccer players at all three different maturations stages: PRE-PHV (MD = 3.00, 95%CI (1.63, 4.37), $P < 0.01$, I^2 = 65 %); MID-PHV (MD = 2.79, 95%CI (1.16,4.41, P = 0.08, I^2 = 49 %); POST-PHV(MD = 4.35, 95%CI (2.11,6.8859), $P < 0.01$, I^2 = 60 %).

Table 3
Comprehensive characteristics of participants.

Studies	Genders	Number of Participants		Maturation Characteristics			Exercise Parameters		
		PT	CON	PT	CON	Maturation	Session Duration	Frequency	Period
Asadi 2018(Pre-PHV) [31]	M	10	10	11.5 ± 0.8	11.7 ± 0.4	PRE	30–40 min	2/weeks	6 weeks
Asadi 2018 (Mid-PHV) [31]	M	10	10	14.0 ± 0.7	14.2 ± 0.6	MID	30–40 min	2/weeks	6 weeks
Asadi 2018(Post-PHV) [31]	M	10	10	16.6 ± 0.6	16.2 ± 0.3	POST	30–40 min	2/weeks	6 weeks
Drouzas 2020 [38]	M	23	22	10.0 ± 0.5	10.2 ± 1.6	PRE	15 min	2/weeks	10 weeks
Hammami 2016 [39]	M	15	13	15.7 ± 0.2	15.8 ± 0.2	MID	35 min	2/weeks	8 weeks
Hammami 2019 [40]	M	14	12	15.7 ± 0.2	15.8 ± 0.2	MID	35 min	2/weeks	8 weeks
Jlid 2019 [41]	M	14	14	11.8 ± 0.4	11.6 ± 0.5	PRE	20–25 min	2/weeks	8 weeks
Michailidis 2013 [42]	M	24	21	10.6 ± 0.6	10.6 ± 0.5	PRE	20–25 min	2/weeks	12 weeks
Negra 2020 (4weeks) [43]	M	11	11	12.7 ± 0.3	12.8 ± 0.3	PRE	20–25 min	2/weeks	4 weeks
Negra 2020 (8weeks) [43]	M	11	11	12.7 ± 0.1	12.8 ± 0.1	PRE	20–25 min	2/weeks	8 weeks
Negra 2020 (12weeks) [43]	M	11	11	12.7 ± 0.1	12.8 ± 0.1	PRE	20–25 min	2/weeks	12 weeks
Negra 2020 [44]	M	13	11	12.7 ± 0.2	12.7 ± 0.2	PRE	25–35 min	2/weeks	8 weeks
Nurper 2014 [45]	F	9	9	18.3 ± 2.6	18.0 ± 2.0	POST	60 min	1/weeks	8 weeks
Padrón-Cabo 2021 [46]	M	10	10	12.6 ± 0.7	12.4 ± 0.5	PRE	20–35 min	2/weeks	6 weeks
Vera-Assaoka2019 (T1-3) [12]	M	16	16	11.2 ± 0.8	11.5 ± 0.9	PRE	21 min	2/weeks	7 weeks
Vera-Assaoka 2019 (T4-5) [12]	M	22	22	14.4 ± 1.0	14.5 ± 1.1	MID	21 min	2/weeks	7 weeks
Ramirez-Campillo 2019 [47]	M	19	20	13.2 ± 1.8	13.5 ± 1.9	MID	20 min	2/weeks	7 weeks
Ramirez-Campillo 2020 [48]	M	8	7	12.9 ± 1.9	12.6 ± 1.8	PRE	10–15 min	2/weeks	8 weeks
Ramirez-Campillo 2018 (IDE) [49]	M	24	24	13.1 ± 1.7	13.7 ± 1.6	MID	13 min	2/weeks	7 weeks
Ramirez-Campillo 2018 (CST) [49]	M	25	24	13.9 ± 1.9	13.7 ± 1.6	MID	13 min	2/weeks	7 weeks
Sammoud 2022 [50]	M	11	11	12.7 ± 0.3	12.8 ± 0.3	PRE	35–40 min	3/weeks	12 weeks
Sedano 2011 [51]	/	11	11	18.4 ± 1.1	18.2 ± 0.9	POST	/	3/weeks	10 weeks
Ramirez-Campillo 2020 (Pre-soccer) [52]	M	14	12	17.1 ± 0.3	17.1 ± 0.5	POST	20 min	2/weeks	7 weeks
Ramirez-Campillo 2020 (Post-soccer) [52]	M	12	12	16.9 ± 0.7	17.1 ± 0.5	POST	20 min	2/weeks	7 weeks

Note: M: male; F: female; T1-3: the Tanner stages that mark early adolescence are 1 through 3; T4-5: the Tanner stages that indicate late adolescence are 4 through 5; CST: maintained a constant drop-box height; IDE: ideal drop-box height achieved; Pre-soccer: plyometric training occurs prior to the soccer drill; Post-soccer: plyometric training takes place after soccer drill; PT: plyometric training; CON: control group.

4.2. Sprint performance

The meta-analysis encompassed 13 studies with 20 groups of trials and 590 participants were included to assess the impact of plyometric training on 20-m sprint performance in adolescent soccer players (Fig. 4). The result showed an overall positive effect of plyometric training on 20-m sprint performance in adolescent soccer players (MD = −0.12, 95%CI(-0.18,-0.05)), with no heterogeneity (I^2 = 38 %) and statistical significance (P < 0.01). Subgroup analysis showed that plyometric training significantly enhanced sprint performance in both the PRE-PHV [MD = −0.06, 95 % CI: (−0.12, 0), P < 0.01, I^2 = 0 %] and MID-PHV stages [MD = −0.18, 95 % CI: (−0.27, −0.08), P < 0.01, I^2 = 0 %]; however, the improvement was not significant in the POST-PHV stage [MD = −0.36, 95 % CI: (−0.73, −0.05), P = 0.06, I^2 = 79 %].

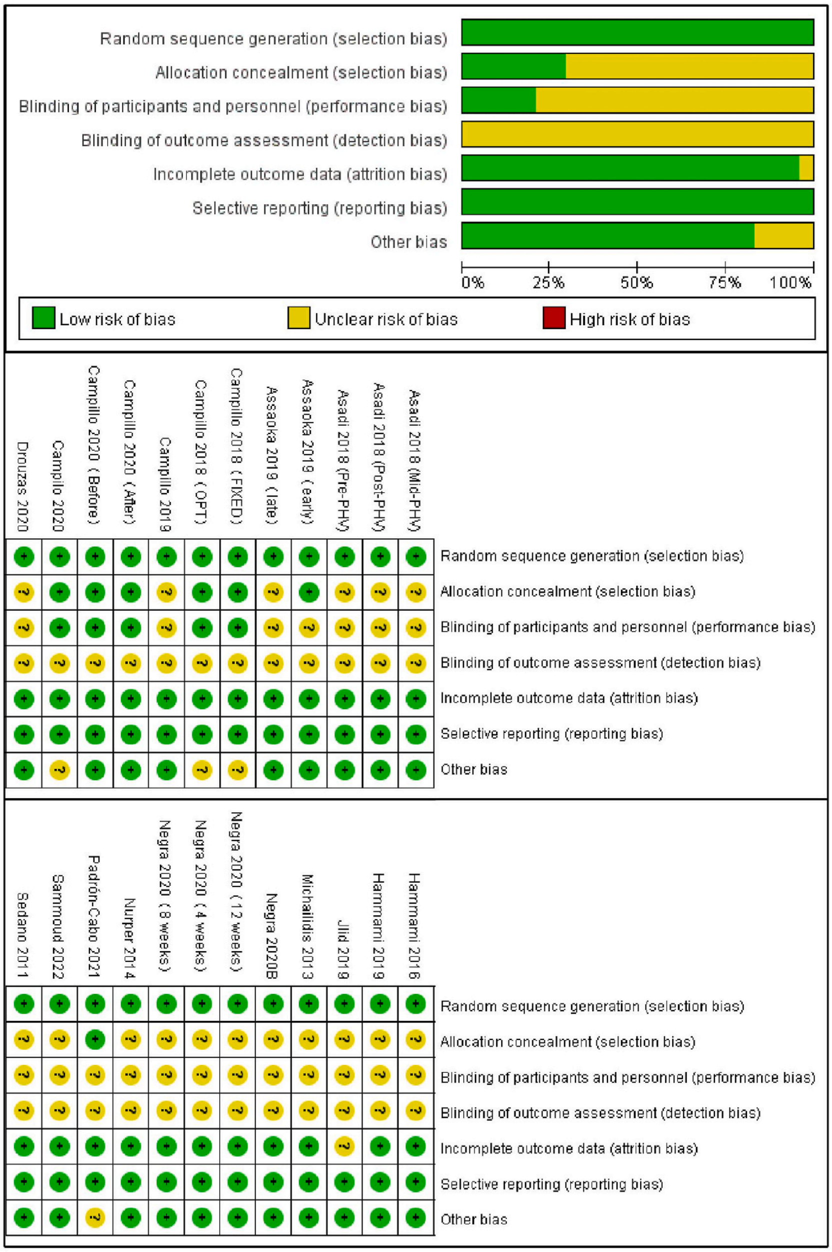

Fig. 2. Assessments of risk-of-bias aspects within each study, with the prevalence of each bias item depicted as a percentage among all studies.

4.3. Reporting bias

A symmetrical distribution in the funnel plot indicates that the study has low risk of publication bias (Fig. 5).

5. Discussion

The primary objective of this research was to investigate the maturation-dependent effects of plyometric training on lower-extremity explosive power capabilities in adolescent soccer players, as evaluated through CMJ performance and 20-m sprint times. The current systematic review and meta-analysis, which synthesized findings from 17 relevant studies, revealed that plyometric training interventions elicited significant improvements in CMJ performance across all stages of PHV within the adolescent soccer player population. Notably, the positive trend of training was most pronounced in the POST-PHV stage, while the improvements were relatively weaker in the MID-PHV stage. Furthermore, 20-m sprint ability was enhanced in the PRE-PHV and MID-PHV stages, but no significant improvements were found in the POST-PHV stage.

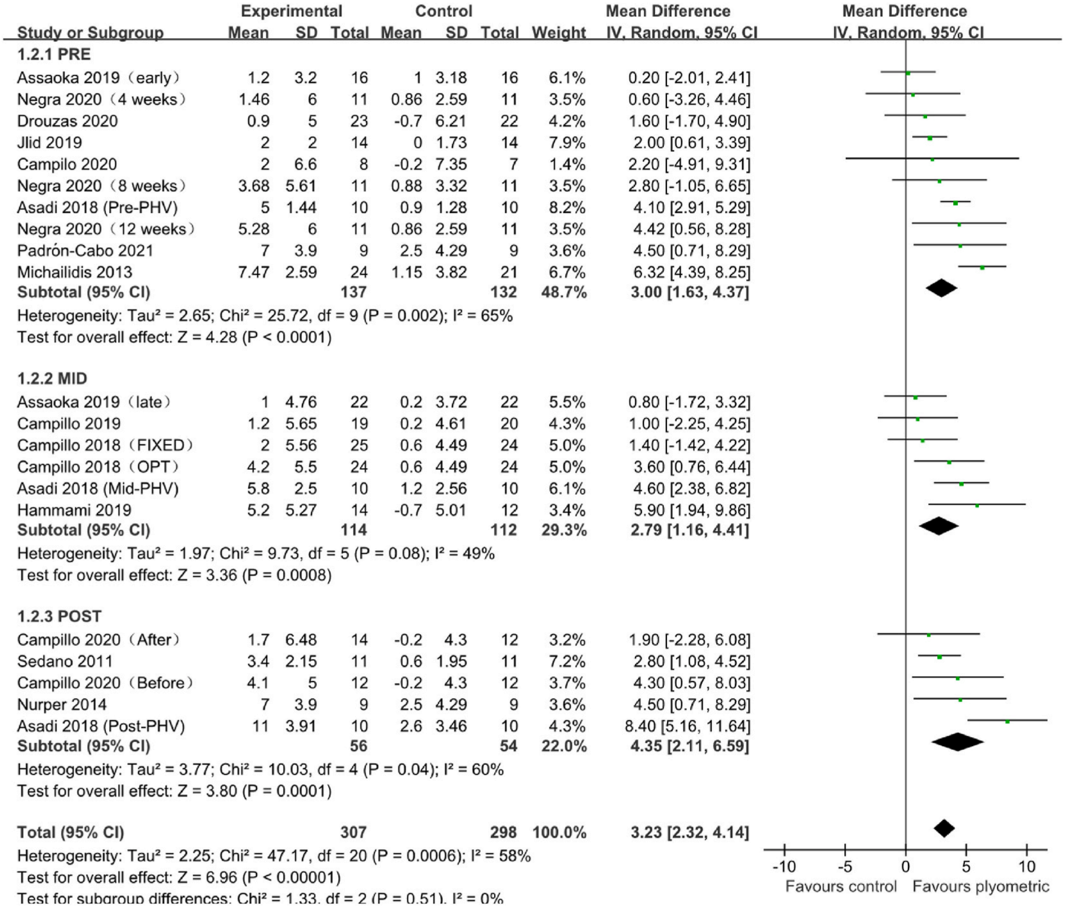

Fig. 3. Visual representation of CMJ results based on a forest plot analysis.

These findings highlight the crucial influence of biological maturity on training adaptations in adolescent soccer players. The results provide a theoretical foundation for tailoring training programs to the specific maturity levels of adolescent athletes. This research may hold important implications for the design and implementation of training regimens targeting adolescent soccer players, particularly when accounting for their stage of biological maturation.

6. Jumping performance

The present systematic review and meta-analysis indicate that, overall, plyometric training has a significant positive effect on jump performance in youth. This finding is consistent with the conclusions of many previous meta-analyses examining the impact of plyometric training on jumping abilities in young athletes [53,54]. Subgroup analysis results demonstrate that the CMJ performance among adolescent soccer players through plyometric training varies with maturation, with a tendency for higher values in the POST-PHV stage [MD = 4.35 (2.11, 6.59), $P < 0.01$], followed by the PRE-PHV stage [MD = 3.00 (1.63, 4.37), $P < 0.01$], and the lowest tendency observed in the MID-PHV stage [MD = 2.79 (1.16, 4.41), $P < 0.01$]. This pattern aligns with the findings of Moran et al. [54], indicating a trend where adolescents in the POST-PHV stage show the greatest improvement in inducing jumping ability, followed by those in the PRE-PHV stage, while the improvement during the MID-PHV stage is less pronounced.

The augmentation of the SSC is identified as a pivotal mechanism by which plyometric training elevates jumping capabilities. This enhancement is linked to a range of neuromuscular improvements, including heightened neural stimulation to the muscles engaged, refined muscle coordination due to optimized muscle activation sequences, and an overall increase in the excitability of the SSC [55,56]. Furthermore, Plyometric training can also induce adaptations within the plantar flexor muscle-tendon complex, including increased stiffness of the elastic components, as well as alterations in muscle size and structure, which directly lead to improvements in jumping performance [57]. However, in plyometric training, the improvement in SSC shows a nonlinear increase with maturation [58]. Research indicates that there may be two key windows of opportunity in the development of lower limb SSC [59]. During these periods of natural accelerated adaptation, adolescents are more responsive to plyometric training, suggesting that the specific physiological adaptations induced by training are synergistic with the natural adaptations occurring during the maturation process [34]. This study suggests that individuals in the PRE-PHV and POST-PHV stages exhibit better training adaptations during plyometric

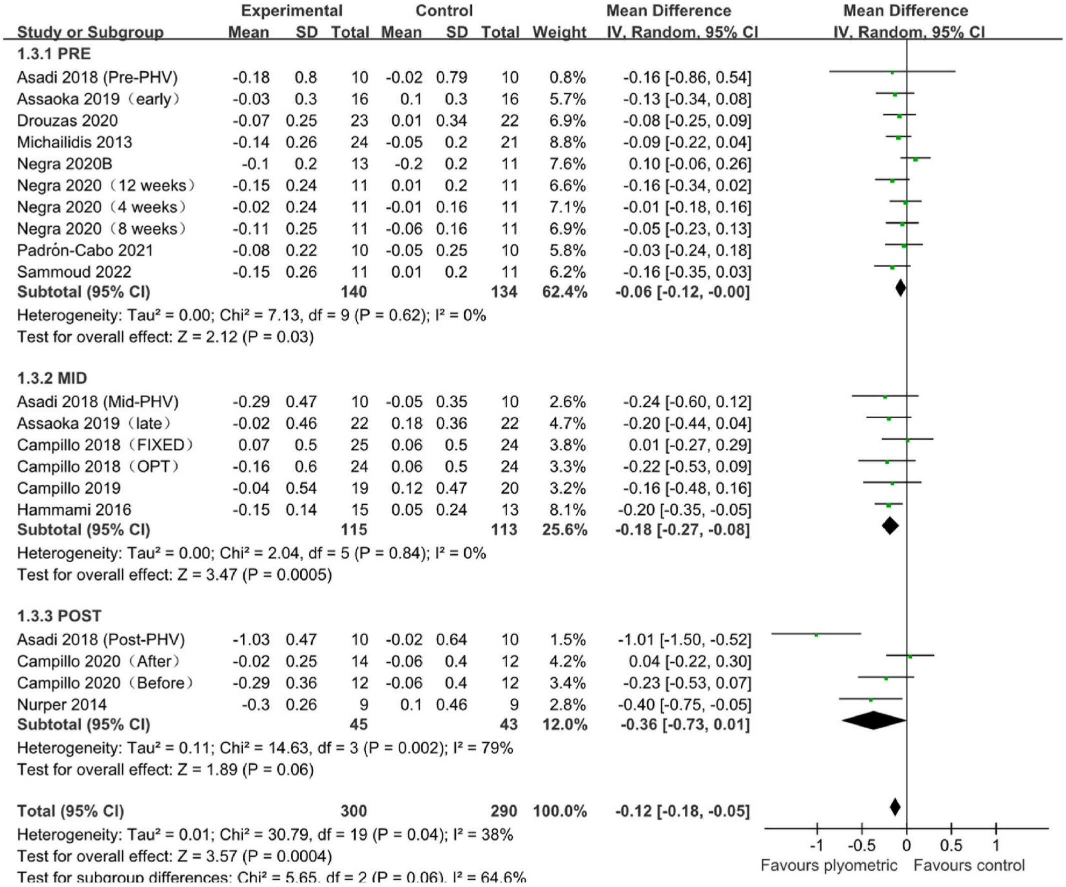

Fig. 4. Visual representation of 20-m sprint results based on a forest plot analysis.

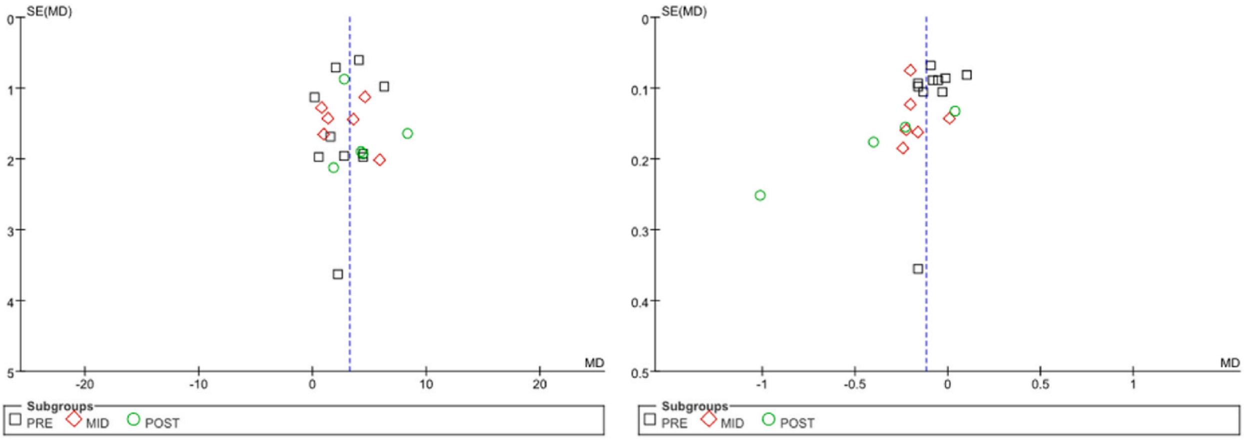

Fig. 5. Visual presentation of publication bias for CMJ and 20-m sprint indicators in included studies.

training compared to those in the MID-PHV stage. This disparity may stem from the accelerated adaptation period observed in adolescent SSC performance [60].

(1) The first accelerated adaptation period occurs in the PRE-PHV stage and is mainly associated with age-related improvements in neuromuscular efficiency because PRE-PHV is a stage of rapid development of neuromuscular coordination and the central nervous system [61,62]. The neural adaptations induced by plyometric training coincide with the natural adaptations caused by growth and maturation during PRE-PHV, and this synergy may enhance the adaptability of PRE-PHV to plyometric training

[62]. This synergistic relationship is likely not a mere coincidence, but rather the result of an interaction between specific training demands and the natural physiological changes occurring during growth and developmental stages. Overall, in adolescents in the pre-PHV stage, the synergistic effects of training and natural growth could amplify their response to age-related training adaptations, a point that is supported by existing literature [63]. Furthermore, Adolescents in the PRE-PHV stage demonstrate relatively higher efficiency in storing and utilizing elastic energy during slow SSC. The SSC is controlled by neuromuscular function and requires interaction between the neuromuscular system and the muscle-tendon unit structure [64]. During adolescence, tendon stiffness increases with age [65], At the age of 10, children possess tendons that are significantly less stiff than those of their counterparts at 13 years of age and adults. This disparity narrows as they mature, with tendon stiffness at 15 years of age closely mirroring that observed in adults, indicating a developmental convergence in musculoskeletal properties [66]. Therefore, tendon flexibility in adolescents during the PRE-PHV stage facilitates the more efficient storage and utilization of elastic energy under identical loading conditions [67,68]. During the slow SSC (CMJ) phase, the muscle-tendon complex in PRE-PHV adolescents undergoes more pronounced elongation, thereby accumulating a higher amount of elastic energy [69].

(2) The second accelerated adaptation period of the SSC in adolescents occurs in the POST-PHV stage and is primarily associated with significant increases in anabolic hormone levels, muscle fiber type transitions, and muscle mass [60]. Peak muscular strength gains usually occur during the POST-PHV stage [70]. Compared to the PRE-PHV stage, adolescents in the POST-PHV stage have higher levels of hormones such as testosterone, growth hormone, and insulin-like growth factor. Plyometric training promotes the discharge of growth factors similar to insulin [71], leading to greater muscle hypertrophy effects and promoting increased muscle mass in adolescents [72]. Additionally, the central nervous system of adolescents approaches maturity, making it easier to recruit high-threshold motor units. As adolescents age, muscle activation strategies also evolve; the co-contraction of agonist-antagonist muscle pairs may decrease owing to desensitization of the Golgi tendon organs, thereby improving neuromuscular coordination, reducing energy loss during movements, and resulting in greater net force output [27,55]. These adaptations can positively influence the performance of the SSC, allowing for more effective utilization of the SSC and generating greater training adaptations in CMJ.

However, during the MID-PHV stage, the improvement in CMJ performance among adolescents diminishes, which may be related to poor posture control abilities in this stage [73]. As adolescents rapidly grow in height and weight, the body's center of mass gradually rises, while the growth rates of the legs and trunk are not synchronized [70], making it more difficult for adolescents to maintain trunk stability during SSC. Therefore, in this stage, the neural pathways of adolescents need time to adapt to these growth changes [74], and their coordination may temporarily decline, thereby limiting the training adaptations related to plyometric training".

7. Sprint performance

The present systematic review and meta-analysis suggests that the impacts of plyometric training on young soccer players across maturation stages. Specifically, players in the PRE-PHV [MD = −0.06 (−0.12, −0.00), p = 0.03] and MID-PHV [MD = −0.18 (−0.27,0.08), p = 0.0005] stages exhibited significant performance improvements. However, for players in the POST-PHV [MD = −0.36 (−0.73,0.01), p = 0.06] stage, similar improvements were not observed. This finding emphasizes that training effects may vary with the degree of physiological maturation, suggesting the specific characteristics of the maturation stage warrant consideration when designing training programs for adolescent athletes.

Consistent with most studies on the effects of plyometric training on sprinting performance, this meta-analysis concludes that plyometric training can improve sprinting performance in adolescents [13,75,76]. Ramirez-Campillo et al. [76] performed a systematic review and meta-analysis examining the effects of plyometric training on sprint performance in young male soccer players, concluding that plyometric training is an effective method for enhancing sprint capacity in this population. However, It is crucial to recognize that their study focused on a population of young male soccer players, which is different from adolescent soccer players, and did not specifically explore the maturation effects of plyometric training on adolescent soccer players. Silva et al. [77], on the other hand, conducted a systematic review and meta-analysis examining the maturation effects of plyometric training on youth male team sports players. However, their results suggested that plyometric training does not significantly improve sprinting performance in adolescent soccer players, and the changes across each maturation stage were similar. This observed inconsistency in results potentially arises from the relatively small sample of studies that comprised their evaluation.

Contrary to the findings of Silva et al. [77], the present systematic review and meta-analysis demonstrate a significant improvement in sprinting performance among adolescent soccer players through plyometric training, with the existence of maturation effects. The movement characteristics of plyometric training can reduce ground contact time during sprinting, thereby enhancing sprinting performance [78]; Additionally, the training-induced enhancements associated with plyometric training involve peripheral, central nervous system, and neuromuscular factors, which can improve joint proprioception and kinematics, ultimately leading to improved sprinting performance [79,80]. Interestingly, a trend of gradual improvement in sprinting performance was observed during the PRE-PHV and MID-PHV stages, while no significant improvement was observed during the POST-PHV stage. Several factors may contribute to the increasing trend in sprinting performance during the PRE-PHV and MID-PHV stages, including:

(1) As adolescents undergo natural growth and development, changes occur in muscle dimensions, lower limb segment lengths, and muscle-tendon properties due to individual maturation and growth. These changes lead to improved movement quality and positively impact sprinting performance [27,77,81].
(2) With accumulated experience in various movements and sports, adolescents further develop their neuromuscular coordination abilities. This development enables them to more effectively utilize SSC capabilities, resulting in greater kinetic output and enhanced energy utilization efficiency during movement [82].

However, the expected training effects of plyometric training were not observed in adolescent soccer players during the POST-PHV stage. During the PRE-PHV and MID-PHV stages, the nervous system is still undergoing development, and there is a higher capacity for neuromuscular coordination and motor skill learning [83]. Plyometric training can stimulate the nervous system, improve neuromuscular coordination, and enhance motor skills, thereby improving 20-m sprint performance [55,56]. However, in the POST-PHV stage, the nervous system of adolescents may have reached a certain level of maturity, and further training may not lead to significant improvements [84].

8. Conclusion

Plyometric training can effectively enhance the lower limb explosive strength of adolescent soccer players, but there are maturation-related effects among players at different stages of maturation. Plyometric training can effectively enhance the CMJ performance of adolescent soccer players, with the greatest adaptations observed in those who undergo training during the POST-PHV and PRE-PHV stages, followed by the MID-PHV stage. However, when it comes to the 20-m sprint, the improvements in sprint performance are more significant during the MID-PHV stage compared to the PRE-PHV stage, while no significant improvements were observed in adolescent soccer players during the POST-PHV stage.

9. Practical application

Plyometric training is an effective method that can be incorporated into the daily training routines of adolescent soccer players to enhance their lower limb performance. It is crucial, however, to consider the different stages of development when implementing plyometric training in this population, as our results have demonstrated. By tailoring the training protocols to align with specific developmental stages, coaches and trainers can optimize training adaptations and outcomes.

10. Limitations

In this study, we have utilized the maturation categorization standards established by the WHO to delineate the stages of maturation in adolescents. Although this strategy indicates a robust link to an individual's biological maturity, it is essential to be aware of the inherent risk of bias. To enhance the accuracy and reliability of future research, it is recommended to incorporate more precise tools for assessing biological maturity.

Ethics approval

The study has been registered in the International Prospective Register of Systematic Reviews (PROSPERO: CRD42023485762).

Consent for publication

All authors agreed to the published version of the manuscript.

Funding

Digital Physical Fitness Training Scientific Research Innovation Team (2023WCXTD012).

Data availability statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Lunxin Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruixiang Yan:** Writing – original draft, Visualization, Conceptualization. **Lin Xie:** Investigation, Data curation. **Zhiyong Zhang:** Software, Investigation, Data curation. **Wenfeng Zhang:** Methodology, Conceptualization. **Hengtong Wang:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

Hengtong Wang reports financial support was provided by Guangzhou Sport University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

SSC Stretch-shortening cycle
CMJ Countermovement jump
20 m 20-m sprint
RCTs Randomized controlled trial studies
PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses
MD mean difference
PT Plyometric training
CON Control group
PRE-PHV Pre-peak height velocity
MID-PHV Middle-peak height velocity
POST-PHV Post-peak height velocity
PPT Progressed plyometric training
NPPT Non-progressed plyometric training

References

[1] R.M. Malina, M.P. Reyes, J. Eisenmann, et al., Height, mass and skeletal maturity of elite Portuguese soccer players aged 11–16 years, J. Sports Sci. 18 (9) (2000) 685–693.
[2] T. Reilly, J. Bangsbo, A. Franks, Anthropometric and physiological predispositions for elite soccer, J. Sports Sci. 18 (9) (2000) 669–683.
[3] R.M. Malina, J.C. Eisenmann, S.P. Cumming, et al., Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years, Eur. J. Appl. Physiol. 91 (2004) 555–562.
[4] T. Pavillon, C. Tourny, A.B. Aabderrahman, et al., Sprint and jump performances in highly trained young soccer players of different chronological age: effects of linear VS. CHANGE–OF–DIRECTION sprint training, Journal of Exercise Science and Fitness 19 (2) (2021) 81–90.
[5] J. Bangsbo, M. Mohr, P. Krustrup, Physical and metabolic demands of training and match-play in the elite football player, J. Sports Sci. 24 (7) (2006) 665–674.
[6] B.R. Ronnestad, N.H. Kvamme, A. Sunde, et al., Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players, J. Strength Condit Res. 22 (3) (2008) 773–780.
[7] J. Bangsbo, L. Nørregaard, F. Thorsø, Activity profile of competition soccer, Can. J. Sport Sci. 16 (2) (1991) 110–116.
[8] T. Reilly, A motion analysis of work-rate in different positional roles in professional football match-play, Hum. Move. Stud. 2 (1976) 87–97.
[9] T. Stølen, K. Chamari, C. Castagna, et al., Physiology of soccer: an update, Sports Med. 35 (2005) 501–536.
[10] T. Reilly, Motion analysis and physiological demands, Sci. Soccer 2 (2003) 59–72.
[11] F.M. Impellizzeri, E. Rampinini, C. Castagna, et al., Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players, Br. J. Sports Med. 42 (1) (2008) 42–46.
[12] T. Vera-Assaoka, R. Ramirez-Campillo, C. Alvarez, et al., Effects of maturation on physical fitness adaptations to plyometric drop jump training in male youth soccer players, 34(10), 2020, pp. 2760–2768.
[13] L. Chen, Z. Zhang, Z. Huang, et al., Meta-analysis of the effects of plyometric training on lower limb explosive strength in adolescent athletes 20 (3) (2023) 1849.
[14] E.S.-S. De Villarreal, B. Requena, R.U. Newton, et al., Does plyometric training improve strength performance? A meta-analysis, 13(5), 2010, pp. 513–522.
[15] E.S.-S. de Villarreal, E. Kellis, W.J. Kraemer, et al., Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis, 23(2), 2009, pp. 495–506.
[16] E.S. de Villarreal, B. Requena, J.B.J.S. Cronin, et al., The effects of plyometric training on sprint performance: A meta-analysis, 26(2), 2012, pp. 575–584.
[17] R. Ramírez-Campillo, C.H. Burgos, C. Henríquez-Olguín, et al., Effect of unilateral, bilateral, and combined plyometric training on explosive and endurance performance of young soccer players, 29(5), 2015, pp. 1317–1328.
[18] Y.-C. Wang, N. Zhang, Effects of plyometric training on soccer players, Exp. Ther. Med. 12 (2) (2016) 550–554.
[19] K.E. Wilk, M.L. Voight, M.A. Keirns, et al., Stretch-shortening drills for the upper extremities: theory and clinical application, 17(5), 1993, pp. 225–239.
[20] R.S. Lloyd, R.W. Meyers, J.L.J.S. Oliver, et al., The natural development and trainability of plyometric ability during childhood, 33(2), 2011, pp. 23–32.
[21] P.J.I.J. Komi, Training of muscle strength and power: interaction of neuromotoric, hypertrophic, and mechanical factors, 7(S 1), 1986, pp. S10–S15.
[22] G.A. Cavagna, B. Dusman, R.J.J. Margaria, Positive work done by a previously stretched muscle, 24(1), 1968, pp. 21–32.
[23] P.V. Komi, A.J.J. Gollhofer, Stretch reflexes can have an important role in force enhancement during SSC exercise, 13(4), 1997, pp. 451–460.
[24] J.M. Radnor, R.S. Lloyd, J.L.J. Oliver, et al., Individual response to different forms of resistance training in school-aged boys, 31(3), 2017, pp. 787–797.
[25] J.J. Moran, G.R. Sandercock, R. Ramírez-Campillo, et al., Age-related variation in male youth athletes' countermovement jump after plyometric training: a meta-analysis of controlled trials, 31(2), 2017, pp. 552–565.
[26] G. Beunen, R.M. Malina, Growth and biologic maturation: relevance to athletic performance, Young Athlete 1 (2008) 3–17.
[27] J.M. Radnor, J.L. Oliver, C.M. Waugh, et al., The influence of growth and maturation on stretch-shortening cycle function in youth, Sports Med. 48 (2018) 57–71.
[28] B.J. Casey, S. Getz, A. Galvan, The adolescent brain, Dev. Rev. 28 (1) (2008) 62–77.
[29] B. Ullrich, T. Pelzer, M.J.T.J. Pfeiffer, et al., Neuromuscular effects to 6 weeks of loaded countermovement jumping with traditional and daily undulating periodization, 32(3), 2018, pp. 660–674.
[30] A.J. Blazevich, N.D. Gill, R. Bronks, et al., Training-specific muscle architecture adaptation after 5-wk training in athletes, 35(12), 2003, pp. 2013–2022.
[31] A. Asadi, R. Ramirez-Campillo, H. Arazi, et al., The effects of maturation on jumping ability and sprint adaptations to plyometric training in youth soccer players, 36(21), 2018, pp. 2405–2411.
[32] R.M. Malina, C. Bouchard, Growth, maturation, and physical activity, Med. Sci. Sports Exerc. 24 (7) (1992) 841.

[33] R.S. Lloyd, J.L. Oliver, A.D. Faigenbaum, et al., Chronological age vs. biological maturation: implications for exercise programming in youth, J. Strength Condit Res. 28 (5) (2014) 1454–1464.
[34] I. Balyi, A. Hamilton, Long-term athlete development: trainability in childhood and adolescence, Olympic Coach 16 (1) (2004) 4–9.
[35] M.L. Plummer, V. Baltag, K. Strong, et al., Global accelerated action for the health of adolescents (AA-HA!): guidance to support country implementation, in: Global Accelerated Action for the Health of Adolescents (AA-HA!): Guidance to Support Country Implementation, 2017.
[36] C. Zheng, E.T.-C. Poon, K. Wan, et al., Effects of wearing A mask during exercise on physiological and psychological outcomes in healthy individuals: A Systematic Review and Meta-Analysis, 53(1), 2023, pp. 125–150.
[37] J.P. Higgins, S.G. Thompson, J.J. Deeks, et al., Measuring inconsistency in meta-analyses, 327(7414), 2003, pp. 557–560.
[38] V. Drouzas, C. Katsikas, A. Zafeiridis, et al., Unilateral plyometric training is superior to volume-matched bilateral training for improving strength, speed and power of lower limbs in preadolescent soccer athletes, J. Hum. Kinet. 74 (1) (2020) 161–176.
[39] M. Hammami, Y. Negra, R. Aouadi, et al., Effects of an in-season plyometric training program on repeated change of direction and sprint performance in the junior soccer player, J. Strength Condit Res. 30 (12) (2016) 3312–3320.
[40] M. Hammami, N. Gaamouri, R.J. Shephard, et al., Effects of contrast strength vs. plyometric training on lower-limb explosive performance, ability to change direction and neuromuscular adaptation in soccer players, J. Strength Condit Res. 33 (8) (2019) 2094–2103.
[41] M.C. Jlid, G. Racil, J. Coquart, et al., Multidirectional plyometric training: very efficient way to improve vertical jump performance, change of direction performance and dynamic postural control in young soccer players, Front. Physiol. 10 (2019) 1462.
[42] Y. Michailidis, I.G. Fatouros, E. Primpa, et al., Plyometrics' trainability in preadolescent soccer athletes, J. Strength Condit Res. 27 (1) (2013) 38–49.
[43] Y. Negra, H. Chaabene, T. Stöggl, et al., Effectiveness and time-course adaptation of resistance training vs. plyometric training in prepubertal soccer players, J. Sport Health Sci. 9 (6) (2020) 620–627.
[44] Y. Negra, H. Chaabene, J. Fernandez-Fernandez, et al., Short-term plyometric jump training improves repeated-sprint ability in prepuberal male soccer players, J. Strength Condit Res. 34 (11) (2020) 3241–3249.
[45] N. Ozbar, S. Ates, A. Agopyan, The effect of 8-week plyometric training on leg power, jump and sprint performance in female soccer players, J. Strength Condit Res. 28 (10) (2014) 2888–2894.
[46] A. Padrón-Cabo, M. Lorenzo-Martínez, A. Pérez-Ferreirós, et al., Effects of plyometric training with agility ladder on physical fitness in youth soccer players, Int. J. Sports Med. 42 (10) (2021) 896–904.
[47] R. Ramirez-Campillo, C. Alvarez, F. García-Pinillos, et al., Effects of plyometric training on physical performance of young male soccer players: potential effects of different drop jump heights, Pediatr. Exerc. Sci. 31 (3) (2019) 306–313.
[48] R. Ramirez-Campillo, C. Álvarez, F. García-Pinillos, et al., Effects of combined surfaces vs. single-surface plyometric training on soccer players' physical fitness, J. Strength Condit Res. 34 (9) (2020) 2644–2653.
[49] R. Ramirez-Campillo, C. Alvarez, F. García-Pinillos, et al., Optimal reactive strength index: is it an accurate variable to optimize plyometric training effects on measures of physical fitness in young soccer players? J. Strength Condit Res. 32 (4) (2018) 885–893.
[50] S. Sammoud, R. Bouguezzi, R. Ramirez-Campillo, et al., Effects of plyometric jump training versus power training using free weights on measures of physical fitness in youth male soccer players, J. Sports Sci. 40 (2) (2022) 130–137.
[51] S. Sedano, A. Matheu, J. Redondo, et al., Effects of plyometric training on explosive strength, acceleration capacity and kicking speed in young elite soccer players, J. Sports Med. Phys. Fit. 51 (1) (2011) 50.
[52] R. Ramirez-Campillo, C. Alvarez, P. Gentil, et al., Sequencing effects of plyometric training applied before or after regular soccer training on measures of physical fitness in young players, J. Strength Condit Res. 34 (7) (2020) 1959–1966.
[53] L. Chen, Z. Zhang, Z. Huang, et al., Meta-analysis of the effects of plyometric training on lower limb explosive strength in adolescent athletes, Int. J. Environ. Res. Publ. Health 20 (3) (2023) 1849.
[54] J.J. Moran, G.R. Sandercock, R. Ramírez-Campillo, et al., Age-related variation in male youth athletes' countermovement jump after plyometric training: a meta-analysis of controlled trials, J. Strength Condit Res. 31 (2) (2017) 552–565.
[55] W. Taube, N. Kullmann, C. Leukel, et al., Differential reflex adaptations following sensorimotor and strength training in young elite athletes, Int. J. Sports Med. 28 (12) (2007) 999–1005.
[56] G. Markovic, P. Mikulic, Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training, Sports Med. 40 (2010) 859–895.
[57] G. Markovic, P. Mikulic, Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training, Sports Med. 40 (10) (2010) 859–895.
[58] G. Laffaye, M.A. Choukou, N. Benguigui, et al., Age- and gender-related development of stretch shortening cycle during a sub-maximal hopping task, Biol. Sport 33 (1) (2016) 29–35.
[59] R.S. Lloyd, J.L. Oliver, M.G. Hughes, et al., The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys, J. Strength Condit Res. 25 (7) (2011) 1889–1897.
[60] R.S. Lloyd, J.L. Oliver, M.G. Hughes, et al., The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys, J. Strength Condit Res. 25 (7) (2011) 1889–1897.
[61] E.R. Sowell, P.M. Thompson, C.M. Leonard, et al., Longitudinal mapping of cortical thickness and brain growth in normal children, J. Neurosci. 24 (38) (2004) 8223–8231.
[62] G.D. Myer, A.M. Kushner, A.D. Faigenbaum, et al., Training the developing brain, part I: cognitive developmental considerations for training youth, Curr. Sports Med. Rep. 12 (5) (2013) 304–310.
[63] R.S. Lloyd, J.M. Radnor, M.B.D.S. Croix, et al., Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre-and post-peak height velocity, J. Strength Condit Res. 30 (5) (2016) 1239–1247.
[64] C. Nicol, J. Avela, P.V. Komi, The stretch-shortening cycle : a model to study naturally occurring neuromuscular fatigue, Sports Med. 36 (11) (2006) 977–999.
[65] D. Lambertz, I. Mora, J.F. Grosset, et al., Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity, J. Appl. Physiol. 95 (1) (2003) 64–72.
[66] K. Kubo, H. Kanehisa, Y. Kawakami, et al., Growth changes in the elastic properties of human tendon structures, Int. J. Sports Med. 22 (2) (2001) 138–143.
[67] K. Kubo, M. Morimoto, T. Komuro, et al., Influences of tendon stiffness, joint stiffness, and electromyographic activity on jump performances using single joint, Eur. J. Appl. Physiol. 99 (3) (2007) 235–243.
[68] M.F. Bobbert, Dependence of human squat jump performance on the series elastic compliance of the triceps surae: a simulation study, J. Exp. Biol. 204 (Pt 3) (2001) 533–542.
[69] T. Korff, S.L. Horne, S.J. Cullen, et al., Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence, J. Exp. Biol. 212 (Pt 22) (2009) 3737–3742.
[70] R.M. Philippaerts, R. Vaeyens, M. Janssens, et al., The relationship between peak height velocity and physical performance in youth soccer players, J. Sports Sci. 24 (3) (2006) 221–230.
[71] J.R. Florini, D.Z. Ewton, S.A. Coolican, Growth hormone and the insulin-like growth factor system in myogenesis, Endocr. Rev. 17 (5) (1996) 481–517.
[72] F. Arntz, B. Mkaouer, A. Markov, et al., Effect of plyometric jump training on skeletal muscle hypertrophy in healthy individuals: a systematic review with multilevel meta-analysis, Front. Physiol. 13 (2022) 888464.
[73] R. Hammami, A. Chaouachi, I. Makhlouf, et al., Associations between balance and muscle strength, power performance in male youth athletes of different maturity status, Pediatr. Exerc. Sci. 28 (4) (2016) 521–534.
[74] C.C. Quatman-Yates, C.E. Quatman, A.J. Meszaros, et al., A systematic review of sensorimotor function during adolescence: a developmental stage of increased motor awkwardness? Br. J. Sports Med. 46 (9) (2012) 649–655.
[75] M. Oxfeldt, K. Overgaard, L.G. Hvid, et al., Effects of plyometric training on jumping, sprint performance, and lower body muscle strength in healthy adults: a systematic review and meta-analyses 29 (10) (2019) 1453–1465.

[76] R. Ramirez-Campillo, D. Castillo, J. Raya-González, et al., Effects of plyometric jump training on jump and sprint performance in young male soccer players: a systematic review and meta-analysis, Sports Med. 50 (2020) 2125–2143.
[77] A.F. Silva, R. Ramirez-Campillo, H.İ. Ceylan, et al., Effects of maturation stage on sprinting speed adaptations to plyometric jump training in youth male team sports players: a systematic review and meta-analysis, Open Access J. Sports Med. (2022) 41–54.
[78] E. Rimmer, G.J.T.J. Sleivert, C. Research, Effects of a plyometrics intervention program on sprint performance, 14(3), 2000, pp. 295–301.
[79] P.J.J.R. Grigg, Peripheral neural mechanisms in proprioception, 3(1), 1994, pp. 2–17.
[80] A.J.S.S. Asadi, Effects of in-season plyometric training on sprint and balance performance in basketball players, 6(1), 2013, pp. 24–27.
[81] R.S. Lloyd, J.L. Oliver, Strength and Conditioning for Young Athletes: Science and Application, Routledge, 2019.
[82] A. Fort-Vanmeerhaeghe, D. Romero-Rodriguez, R.S. Lloyd, et al., Integrative neuromuscular training in youth athletes. Part II: Strategies to prevent injuries and improve performance, 38(4), 2016, pp. 9–27.
[83] Żurek G. MOTOR ABILITIES AND SOMATIC INDICATORS IN 12-YEAR OLD STUDENTS AND THEIR SKILL OF REASONING [J]. AN TRO PO MO TO RY KA.
[84] S. Sahrom, Understanding Stretch Shorten Cycle Capability in Adolescence across the Different Maturational Stages, Auckland University of Technology, 2013.