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Strength and conditioning programs in youth athletes: a systematic review

review paper
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ABSTRACT
Purpose. The relationship between strength, power, and sports performance may have long-term effects on the development pathways of youth athletes. This study systematically reviewed the current evidence of strength and conditioning interventions among youngsters in competitive sports.
Methods. The research was conducted following the Preferred Reporting Items for Systematic and Meta-Analyses (PRISMA) 2020 guidelines.
Results. A total of 415 articles were identified, and 20 remained for analysis. All studies reported resistance training (RT) and/or plyometric training (PT) interventions as beneficial to improving youngsters' overall physical fitness. The lower-body explosive strength, speed, and agility improvements were more evident in training plans that combined heavy RT and PT programs. The training frequency of twice a week was sufficient to induce strength gains. The results indicate that strength and conditioning programs positively influence sport-specific skills performance.
Conclusions. PT and RT should not be implemented as single exercise interventions but as complementary programs to optimise physical and game performance. This study contributes to creating awareness among sports agents and coaches for integrating planned strength and conditioning programs with qualified instruction at least two times per week to improve young athletes' physical development.
Key words: balance, speed, agility, power, periodisation

Introduction

The development of physical fitness in the youth is critical in building the qualities that support future elite athletic performance [1]. Strength stands out within physical fitness components due to its strong relationship with other functional capacities, such as speed and agility [2, 3], and its contribution to reducing the risk of sports-related injuries [4]. Despite the diversity of strength and conditioning interventions promoted in youth sports, the use of resistance training (RT) and plyometric training (PT) have become popular [5].

Both RT and PT programs have been described as beneficial in enhancing athletic performance in several sports contexts [6]. The main purpose of RT is to induce gains in strength using exercises performed with several resistive loads, such as free weights, weight machines, medicine balls, elastic tubing, and body weight [7, 8]. On the other hand, PT refers to exercises designed to enhance neuromuscular performance, and

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improve ballistic and maximal strength. Indeed, plyometric exercises are present in most sports movements since they involve jumping, hopping, and skipping [9].

The use of RT and/or PT interventions is well-documented in elite sports [10–12]. However, their effectiveness and safety considerations in youth sports have recently attracted scientific attention [13, 14]. Several prospective studies have been developed through RT interventions in children and adolescents [15–18]. Besides the benefits for athletes' physical attributes (e.g., strength, power, speed, and agility), RT has also been associated with improving the motor skills [6, 19]. Indeed, early childhood and adolescence are critical windows to developing physical literacy [20], which specific RT interventions may encourage. On the other hand, PT has been linked to athletic performance by enhancing maximal strength, power output, and coordination [9]. Although RT and PT alone have been proven effective in youngsters' muscular development [3], the literature suggests that the combination of RT and PT may optimise maximal strength development [21].

However, sports agents and coaches must be aware of the outlined principles, such as exercise selection, intensity, and volume, to promote healthy training [19, 22]. Nevertheless, to the best of our knowledge, the literature still makes claims of details regarding the characteristics of a training program that achieves better gains in youth that have so far not been systematically evaluated on a broad empirical basis. Therefore, to close this critical gap, the purpose of this study was to perform a systematic review of strength and conditioning interventions in youth athletes (aged between 8 and 17 years). Of particular interest were to: (1) identify which types of methods (e.g., weekly training frequency, exercise intensity, rest period) have been used among youngsters; and (2) identify the primary physiological outcomes of the applied programs.

Material and methods

This research was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [23]. The PRISMA checklist is presented in Figure 1.

Search strategy

Four comprehensive electronic databases (PubMed, Scopus, SPORTDiscus, and Web of Science) were searched for relevant records on the 20th of December 2021. The following search filter was applied to the title/abstract: children OR adolescent OR youth AND 'strength and conditioning' OR 'resistance training' OR 'plyometric training' AND intervention* OR program* OR protocol* OR RCT OR 'randomized controlled trial' OR experimental AND Sport* OR competitive.

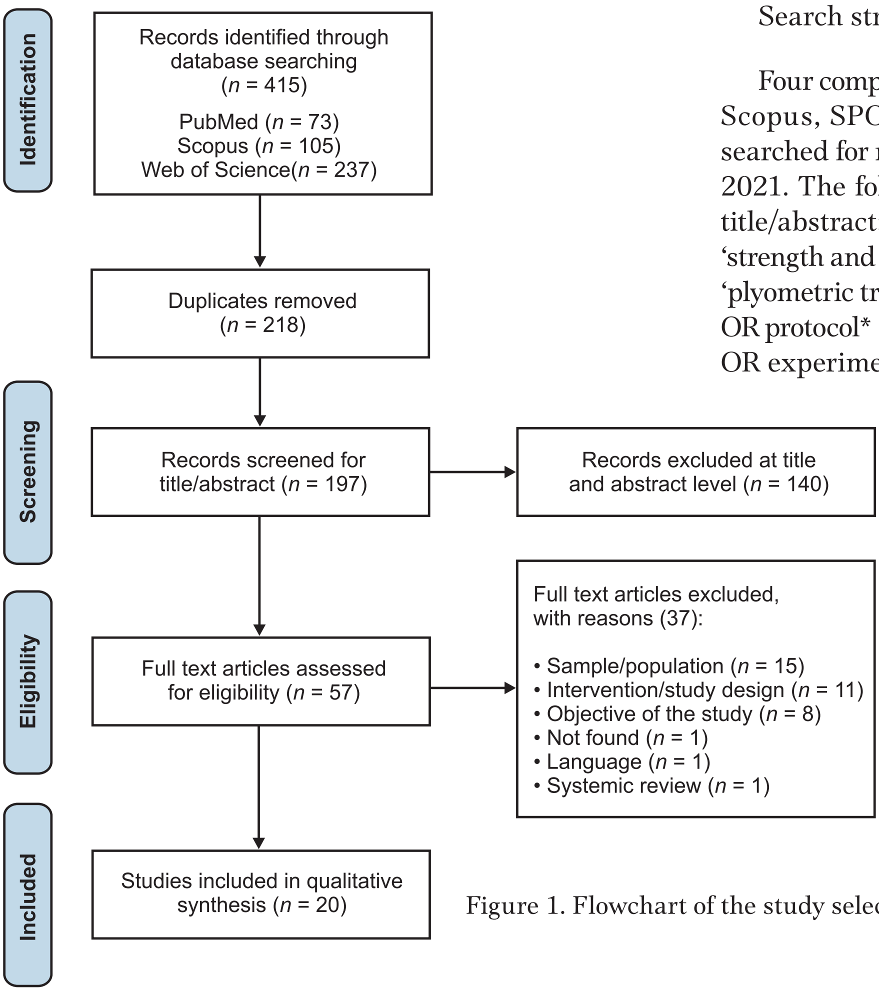

Figure 1. Flowchart of the study selection

Study selection

Study selection was conducted following the criteria defined in the PICOS (participants, intervention, comparison, outcome, study design) guidelines: (1) youth players from both sexes enrolled in any competitive sport, aged between 8 and 17 years; without injury or illness reported; (2) any type of strength and conditioning program implemented with the purpose of enhancing strength, endurance, or speed, for at least four weeks; (3) intervention programs compared with a control group or with another intervention group; intervention programs made in a single group with a test and re-test output reported; (4) studies that reported at least one post-acute response (i.e., immediate response of a physical or physiological parameter to the resistance training program), and/or chronic response (i.e., long-term adaptations promoted by the training intervention) following the intervention program; (5) articles that compared two groups (i.e., randomised, or non-randomised) or one group with a test and re-test output described. Only articles written in English and published in peer-reviewed journals were considered. After removing duplicate records from the search results, three authors independently screened the title and abstract for eligibility (FS, CF, RC). The same three authors read all eligible records before determining which studies should be included. In the case of discrepancies, the inclusion and exclusion decisions were reached by consensus by the research team.

Data extraction and harmonisation

Three authors (F.S., C.F., R.C.) performed data extraction and harmonisation using a standardised approach with a consensus. Relevant information is presented in Table 2 and Table 3. Table 2 includes the sample characteristics, purpose of the study, sports context, measures/instruments, and main results. Table 3 includes the intervention time, weekly training frequency, intensity, type of training, description of exercises, and the number of sets, reps, and rest time.

Study quality and risk of bias

Study quality and bias were evaluated using the Quality Assessment Tool for Quantitative Studies of the Effective Public Health Practice Project (EPHPP) [24]. The study design, confounding factors, data collection methods/instruments, whether the raters and participants were 'blinded', and reports of withdrawals and dropouts are the six components of this instrument that were used to assess selection bias. Each category was given a weak, moderate, or strong score based on the specified criteria (Table 1). Three investigators independently rated the study's quality (F.S., C.F., R.C.).

Table 1. Studies' methodological quality assessment using EPHPP [24]

Authors	Selection bias	Design	Confounders	Blinding	Data collection methods	Withdrawals and drop-outs	Overall
Arede et al. [25]	Moderate	Strong	Strong	Weak	Strong	Strong	Moderate
Batalha et al. [26]	Weak	Strong	Strong	Weak	Strong	Moderate	Weak
Bishop et al. [27]	Moderate	Strong	Weak	Weak	Strong	Moderate	Weak
Bluett et al. [28]	Weak	Moderate	Strong	Weak	Strong	Moderate	Weak
Chaouachi et al. [29]	Moderate	Strong	Strong	Weak	Strong	Moderate	Moderate
Dowse et al. [30]	Moderate	Moderate	Weak	Weak	Strong	Moderate	Weak
Escamilla et al. [31]	Weak	Strong	Strong	Weak	Strong	Moderate	Weak
Freeman et al. [32]	Weak	Strong	Strong	Weak	Strong	Moderate	Weak
Gabbett et al. [33]	Moderate	Moderate	Weak	Weak	Strong	Moderate	Weak
Hopper et al. [34]	Weak	Strong	Strong	Weak	Strong	Moderate	Weak
Karagianni et al. [35]	Weak	Strong	Strong	Weak	Strong	Moderate	Weak
Makhlouf et al. [36]	Moderate	Moderate	Strong	Weak	Strong	Strong	Weak
Marina and Jemni [37]	Weak	Moderate	Weak	Weak	Strong	Moderate	Weak
McKinlay et al. [38]	Moderate	Moderate	Strong	Weak	Strong	Moderate	Moderate
Moreno-Azze et al. [39]	Weak	Strong	Strong	Weak	Strong	Strong	Weak
Sadowski et al. [40]	Moderate	Strong	Strong	Weak	Strong	Moderate	Moderate
Santos and Janeira [41]	Weak	Strong	Weak	Weak	Strong	Moderate	Weak
Smart and Gill [42]	Moderate	Strong	Strong	Weak	Strong	Moderate	Moderate
Tillaar et al. [43]	Moderate	Moderate	Strong	Weak	Strong	Moderate	Moderate
Tran et al. [44]	Weak	Moderate	Weak	Weak	Strong	Moderate	Weak

The differences were discussed and resolved by consensus.

Ethical approval

The conducted research is not related to either human or animal use.

Results

Study selection

Figure 1 depicts the flowchart of the study selection process. A total of 415 articles were found after searching the databases. After deleting duplicates (*n* = 218), 197 studies were considered eligible. During the title and abstract screening process, 140 studies were removed. Finally, the whole text of 57 studies was reviewed, and 20 were chosen as relevant for inclusion.

Study quality and risk of bias

Table 1 shows a summary of the study's quality evaluation. None of the studies had a high level of methodological quality, six had a moderate level of methodological quality, and 14 had a low level of methodological quality. Regarding the parameters analysed, 10 studies were rated as moderate, and the other 10 as weak in selection bias. The design of the studies was the second parameter analysed. Most of the studies were classified as strong (*n* = 12), and the remaining were classified as moderate (*n* = 8) as they were cohort (i.e., one group pre + post) or cohort analytic (i.e., two groups pre + post) studies. At the cofounders' point, nine articles did not show baseline differences between groups, and five articles accounted for at least 80% of the relevant confounders. In the blinding part, none of the studies blinded the assessor and participants, so they were classified as weak. All the studies were carried out with valid and reliable data collection instruments. For the last parameter analysed, withdrawals and dropouts, the studies that reported dropouts and had a participant follow-up of > 80% were rated as strong (*n* = 3), while the studies that did not describe and present the dropouts were rated as moderate (*n* = 17).

Intervention characteristics

The characteristics of each study can be consulted in Table 2 and Table 3. The interventions included 575 young athletes (132 females and 443 males). The age range that covered the largest number of studies was 8 to 13 years (*n* = 8), followed by 13 to 15 years (*n* = 7), and > 15 years (*n* = 5). The intervention with the smallest sample was found in the study by Marina and Jemni [37] (*n* = 9), and the largest sample in the study by Chaouachi et al. [29] (*n* = 63).

Interventions covered a wide range of sports contexts and participants. Eleven studies were carried out among team sports [25, 31–34, 36, 38, 39, 41–43], and nine in individual sports [26–30, 35, 37, 40, 44]. Of those studies, 11 considered only male participants [26, 27, 29, 31, 33, 36, 38–40, 42], five used exclusively female participants [25, 30, 34, 35, 37], and four used both male and female participants [28, 32, 43, 44].

Most studies evaluated interventions of at least six weeks (*n* = 18), while the other two examined a four-week program. The training frequency mainly used was twice a week (*n* = 11). The training intensity was not clearly defined in most interventions (*n* = 13). However, different methods were used by the investigators to determine the exercise intensity, such as one-repetition maximum (1RM; *n* = 2) and rated perceived exertion (RPE; *n* = 4).

Main results

All interventions showed positive outcomes, which varied according to the objectives and data collection instruments. The most commonly evaluated functional capacity was strength/power (*n* = 17) [25, 26, 28–34, 36-39, 41–44], mainly related to the lower limbs (*n* = 14) [25, 28–30, 32–34, 37–39, 41–44], followed by speed (*n* = 10) [27, 29, 31, 33–36, 40, 42, 43], change of direction and/or agility (*n* = 4) [34–36, 43[, balance (*n* = 3) [30, 35, 36], and aerobic capacity (*n* = 2) [28, 33]. The outcomes of some programs were also reported regarding sports-specific skills performance [27, 31, 35, 40].

Regarding the training programs used in the various studies, RT and PT were the most frequently implemented. Individually, RT was applied in eight studies [25, 26, 30, 31, 33, 39, 40, 44]. From the RT interventions, two programs were based on isoinertial flywheel training [25, 39], and two studies combined this RT with speed training [32) and aerobic training [28]. On the other hand, PT was individually used in one study [27]. Other interventions combined PT and balance training (BT) [36] and explosive strength training (EST) [43]. Seven articles analysed the combined effects of RT and PT programs [29, 34, 35, 37, 38, 41, 42]. Also, the effects of Olympic-style weightlifting (OWL) [29] and speed training (ST) [42] interventions were studied in the sample considered.

Regarding the materials used in the interventions, the RT programs were implemented using elastic bands

Table 2. Characteristics and main results of the studies included in the analysis

Author (year)	*N*, Sex	Groups (age)	Sport	Purpose	Variables	Main results
Arede et al. [25]	19 F	15.0 ± 0.5 years	Basketball and volleyball	To study the effects of an inter-repetition variable rotational flywheel training program (variable) over standard rotational flywheel training (standard)	Anthropometry, self-reported patellar tendon condition questionnaire, jumping tests, *t*-test, sprint tests (5 and 10 m), maturity status	Both training programs applied were beneficial at the level of physical and patellar conditions. Substantial improvements were reported in jumping performance and patellar condition levels
Batalha et al. [26]	25 M	2 groups: water group (*n* = 12, 13.3 ± 1.0 years) and land goup (*n* = 13, 13.5 ± 0.9 years)	Swimming	To evaluate and compare the effects of two training programs (dry-land and water resistance programs) on strength, balance, and shoulder endurance	Isokinetic dynamometer to assess the strength of the shoulders' rotators	The dry-land training program was more effective than the water resistance program, particularly by reducing muscle imbalance and decreasing muscle fatigue
Bishop et al. [27]	22 M	2 groups: IG (*n* = 11, 13.1 ± 1.4 years) and CG (*n* = 11, 12.6 ± 1.9 years)	Swimming	To identify the effect of combined PT and habitual training programs on the swim start performance	Swimming block start performance is evaluated through videography in the sagittal plane of motion	Post-intervention swim performance time of 5.5 m and velocity of take-off during swimming block start were significantly better in the IG compared to the CG. Including PT and habitual training routines positively influenced the swim start performance
Bluett et al. [28]	12 M/F (6 +6)	2 groups: AT (*n* = 6, 10–13 years) and concurrent training (*n* = 6, 10–13 years)	Distance running	To examine the effect of a 10-week AT program compared to a concurrent AT and RT program	FVC, %FFM, leg strength using isokinetic concentric knee extension and flexion, 3 km running time trial	Significant correlations were found between 3 km running performance, leg strength, FVC, and %FFM. The CT increased 1RM for leg press, and although the mean 1RM for bench press increased, it was not statistically significant. 3 km running time increased in the CT compared with a decrease in the AT group
Chaouachi et al. [29]	64 M	4 groups: CG (*n* = 13, 11.1 ± 1.0 years); OWL (*n* = 17, 11.1 ± 1.0 years), PT (*n* = 17, 11.1 ± 1.0 years), and RT (*n* = 17, 11.1 ± 1.0 years)	Judo and wrestling	To evaluate the effectiveness of OWL, PT, and traditional RT programs in youth athletes	Anthropometry, CMJ, horizontal jump, sprint tests (5 and 20 m), isokinetic force, and power at 60 and 300°/s	All interventions promote substantial improvements compared to the CG. The OWL was 80% more likely to provide performance gains than the PT for CMJ, horizontal jump, and sprint times. The OWL group was 75% more likely to exceed the RT group for isokinetic power at 300°/s. PT was 78% likely to elicit substantially better training adaptations than RT for isokinetic power at 300°/s, and in sprint times. RT only exceeded PT for BMI and isokinetic power at 60°/s

Dowse et al. [30]	12 F	14.2 ± 1.9 years	Dance	To determine if an RT program could significantly affect adolescent dancers' maximum lower-body strength and power, dynamic balance, and dance performance	Anthropometry, subjective dancing performance questionnaire, dynamic balance (Biodex system), lower body strength and power (isometric mid-thigh pull, CMJ, SJ, and single-leg CMJ)	Significant improvements in balance, and lower body strength and power (peak force and peak power). Incorporating RT may enhance strength and power adaptations in adolescent dancers
Escamilla et al. [31]	34 M	2 groups: IG (*n* = 17) and CG (*n* = 17); 12.5 ± 1.5 years	Baseball	To examine the effects of a 4-week youth baseball conditioning program on maximum throwing velocity	Throwing velocity, and satisfaction questionnaire	Throwing velocity increased significantly in the IG. In contrast, the CG did not significantly improve the throwing velocity
Freeman et al. [32]	28 M/F (23 M + 5 F)	2 groups: eccentric training group and sprint training group (16.2 ± 1.3 years)	Australian football, soccer, cricket, baseball, and field hockey	To compare the effects of sprint training and the Nordic hamstring exercise on youth athletes' eccentric hamstring strength and sprint performance	40 m sprint time and eccentric hamstring strength	Both groups improved their eccentric hamstring strength significantly. The Eccentric training group showed trivial improvements in sprint performance, while the Sprint training group presented a moderate improvement in their maximum speed
Gabbett et al. [33]	14 M	14.1 ± 0.2 years	Rugby	To study the time course of adaptations to training in young (< 15 years) and older (> 18 years) junior rugby league players	Anthropometry, vertical jump, sprint tests (10, 20 and 40 m), agility 505 test, maximal aerobic power using multistage fitness test, 60 s push-up test, 60 s sit-up test, 60 s chin-up test	Maximal aerobic power and muscular endurance improved in both groups. The improvements in speed, muscular power, maximal aerobic power, and upper-body muscular endurance were more significant in the younger group. In contrast, gains in lower-body muscular endurance were superior in the older group
Hopper et al. [34]	23 F	2 groups: IG (*n* = 13, 12.1 ± 1.0 years) and CG (*n* = 10, 12.3 ± 1.0 years)	Netball	To examine the effects of a neuromuscular training program on the movement competency and physical performance of female netball players	Anthropometry, CMJ, 20 m sprint, 505 netball agility tests, NMST	The trained athletes significantly improved their times in sprinting and change of direction tests, and CMJ performance. NMST scores were also higher post-intervention in the IG. In contrast, the CG group did not exhibit any significant changes after the 6 weeks
Karagianni et al. [35]	23 F	2 groups: IG (*n* = 12, 13.2 ± 1.3 years) and CG (*n* = 11, 12.3 ± 1.3 years)	Gymnastics	To examine the effects of a short-duration strength/power training program on neuromuscular and sport-specific skills performance	Anthropometry, 10 m sprint, CMJ (one-leg and two-legs), DJ, single-leg jumping agility test, sport-specific skills test	IG improved in the CMJ tests, DJ, single-leg jumping agility and sport-specific skills performance, but not in the 10 m sprint time. No changes were observed in the CG in the variables considered

Makhlouf et al. [36]	57 M	3 groups: BPT (*n* = 21, 11.1 ± 0.8 years), APT (*n* = 20, 11.3 ± 0.9 years) and CG (*n* = 16, 11.0 ± 0.8 years)	Soccer	To evaluate the effect of 8 weeks of free-weight RT and PT on maximal strength, explosiveness, and jump performance in youth soccer players	Muscle power (CMJ and triple-hop-test), muscle strength reactive strength index (RSI), maximum voluntary isometric contraction (MVIC) of the handgrip, back extensors, and knee extensors), Illinois change of direction test with and without a ball, balance (standing stork and Y-balance), sprint tests (10 and 30 m)	BPT and APT showed significant improvements in sprinting, change of direction, agility, and the Y-balance test performance after the intervention. No differences were observed in the CG in the variables considered
Marina and Jemni [37]	9 F	11.7 ± 0.8 years	Gymnastics	To examine the effectiveness of combined strength and PT programs on the jumping performance of youth gymnasts	Jumping assessment (contact time, flight time, mechanical power, flight-contact ratio), maturity status	The results showed larger improvements in the jumping assessment during the experimental period. The combination of heavy RT with high-impact PT was effective in youth gymnasts, despite their initial level of physical conditioning
McKinlay et al. [38]	41 M	3 groups: RT (*n* = 14, 12.5 ± 0.7 years), PT (*n* = 13, 12.6 ± 0.7 years), and CG (*n* = 14, 12.5 ± 0.3 years)	Soccer	To examine the effect of free-weight RT and PT on maximal strength, explosiveness, and jump performance	Anthropometry, isometric and dynamic (240°/s) knee extensions pre- and post-training, jump performance, maturity status	Increases in isometric peak torque but not in the peak rate of toque development in both the RT and PT groups. Jumping performance increased in both groups, with only PT being significantly different from CG. PT was more effective in improving jump performance
Moreno-Azze et al. [39]	45 M	3 groups: SVW (*n* = 15), SVS (*n* = 15) DVW (*n* = 15); 15.6 ± 1.0 years	Soccer	To compare the effects of performing the lateral squat exercise in three different formats on concentric/eccentric, peak/mean power, and inter-limb asymmetries	Lateral squat test using a conical pulley for each leg, comparing the values obtained for the weaker and stronger leg (mean concentric power, mean eccentric power)	All groups improved power variables (concentric mean and peak power). Both SVW and DVW groups showed lower eccentric mean and peak power asymmetry. Greater enhancements and reductions in inter-limb asymmetries were seen in the groups that started the exercises with the weaker leg
Sadowski et al. [40]	26 M	2 groups: IG (*n* = 12, 15.8 ± 0.4 years) and CG (*n* = 14, 15.6 ± 0.6 years)	Swimming	To compare the effects of specific dry-land RT on an ergometer with traditional dry-land exercises, and to determine how much of the RT effects were transferred to specific swimming conditions	Swimming performance during the front crawl over 25 m, strength during tethered swimming (1.000 N load cell with 4 strain gauges attached with a commercial elastic cord), and isometric strength conducted on a 'hydroisokinetic' ergometer	The results show that the transfer rates were much higher in the IG than in the CG. This resulted in a significant increase in the swimming velocity of the IG

Santos and Janeira [41]	25 M	2 groups: IG (n = 15, 14.7 ± 0.5 years) and CG (n = 10, 14.2 ± 0.4 years)	Basketball	To evaluate the effects of a complex training program combined with weight and plyometric training on explosive strength development	Vertical jumps (SJ, CMJ, and Abalakov test), depth jump, medicine ball throw	The IG significantly improved the vertical jump performance, including the mechanical power values
Smart and Gill [42]	44 M	2 groups: supervised group (n = 27, 15.4 ± 1.4) and unsupervised group (n = 17, 15.1 ± 1.3 years)	Rugby	To evaluate if a supervised off-season conditioning program enhanced gains in physical characteristics compared with the same program performed in an unsupervised context	Anthropometry, vertical jumping, 1RM of bench press, box squat and chin-ups, 60 m sprint to test speed, 400 m sprint to test anaerobic performance, and 1.500 m running to test aerobic capacity	Supervised players realised more significant improvements in strength, body composition, and acceleration than the common unsupervised approach
Tillaar et al. [43]	42 (12 M + 30 F)	2 groups (14.9 ± 0.5 years): start explosive strength (6 M and 15 F) and start plyometric strength (6 M and 15 F)	Handball	To compare the effects of the training period where explosive strength training preceded plyometric training or vice versa	30 m sprint, change of direction test, CMJ with and without arm swing, load-velocity back squat assessment, overhead throwing velocity with and without preliminary steps, Yo-Yo IR1	Both groups improved their performance in the CMJ, change of direction tests, and load-velocity squat assessments. No improvements were observed in the Yo-Yo IR1, 30 m sprint, or throwing velocity tests. Training order did not play an essential role in the physical development of the young handball players
Tran et al. [44]	10 M/F	2 groups (14.0 ± 1.1 years): stable group (n = 5) and unstable group (n = 5)	Surf	To compare the effects of two resistance training interventions (unstable or stable) on strength, power, and sensorimotor abilities	Isometric mid-thigh pulls using a portable force plate and the CMJ. Dynamic postural control was measured by performing five drops and stick trials while barefoot from a pre-determined box height of 0.5 m	The Unstable group showed a significant decrease in power, in contrast to what was observed in the Stable group. Unstable and stable RT effectively developed strength, however, with little effect on the sensorimotor abilities. Overall, the unstable RT was less effective for developing lower-body strength

F – females, M – males, IG – intervention group, CG – control group, PT – plyometric training, RT – resistance training, AT – aerobic training, CT – concurrent training, FVC – forced vital capacity, %FFM – fat-free mass percentage, 1RM – one-repetition maximum, OWL – olympic-style weightlifting, BMI – body mass index, CMJ – countermovement jump, SJ – squat jump, DJ – drop jump, NWT – neuromuscular training, NMST – Netball Movement Screening Tool, BPT – balance plyometric group, APT – agility plyometric group, SVW – starting with the weak leg, SVS – starting with the stronger leg, DVW – double volume, Yo-Yo IR1 – Yo-Yo intermittent recovery test level 1

Table 3. Description of the methods used in the studies included in the analysis

Author, year	IT (number of weeks)	WTF (times/week)	TI	Type of training	Description of exercises	Sets (*n*)	Reps (*n*)	Rest
Arede et al. [25]	6	2	n/s	IFT	Using a portable isoinertial flywheel training device: backward lunges, defensive-like shuffling steps, side-steps (players were encouraged to perform the concentric phase as fast as possible while delaying braking action to the last third of the eccentric phase)	1	5–6	3 m
Batalha et al. [26]	10	3	n/s	RT	Land group training: exercises using an elastic band to perform exercises that involved upper limb abduction and external rotation Water group training: exercises using hand paddles that involved upper limb abduction and external rotation	3	20	30 s
Bishop et al. [27]	8	2	n/s	PT	SJ, split squat jump, multiple box-to-box jumps, hurdle hops, front cone hops, double leg hops, depth jumps, and standing long jumps	2–4	1–5	60 to 90 s
Bluett et al. [28]	10	2–3	60–75% 1RM	AT RT	AT: continuous running (25–30 m at 60, 65, and 70% effort) and interval training (4 sets of 800 m at 70, 75, and 85% effort with 800 m walking recovery; 2 sets of 3 reps of 300 m at 90–100% effort with 3 m of active recovery between reps and 5–10 m static recovery between sets) RT: two additional sessions per week for the participants in this group consisting of 3–4 sets of 10 reps with a load ranging between 60 to 75% of 1RM (preacher arm curl, double leg curl, double leg extension, leg press, bench press, lat pulldown, sit-ups)	3–4	10	n/s
Chaouachi et al. [29]	12	2	n/s	OWL PT RT	OWL: cleans, snatches, shoulder push press, kettlebell/dumbbell cross body pull PT: countermovement jumps, drop jumps, drop from a low platform and perform ballistic type push-ups or clapping push-ups, MB throws forward and behind the body RT: squats, lunges, alternate flat and incline chest press, unilateral shoulder flyes [sic] or presses	1–3	8–12	3 m
Dowse et al. [30]	9	2	n/s	RT	Phase 1 (2 sets × 15–20 reps): single-leg Romanian deadlift, Bulgarian split squat, bent over row, push up, squat walk with an elastic band, plank, dumbbell twist Phase 2 (3 sets × 8 reps): deadlift, bent over row, push up, split squat, hip thrusts, straight arm plank, dumbbell twist Phase 3 (4 sets × 6 reps): deadlift, explosive power bag pulls, clapping push-ups, depth jumps, split squat, lunge jump, plank complex	2–4	6–20	30 s to 3 m

Escamilla et al. [31]	4	3	n/s	RT	Using elastic tubing: elbow extension, arm extension, chest fly, reverse chest fly, rowing, internal rotation with shoulder flexed 90°, external rotation with shoulder flexed 90°, internal rotation with shoulder abducted 0°, internal rotation with shoulder abducted 0°, internal rotation with shoulder abducted 90°, external rotation with shoulder abducted 90°, shoulder abduction to 180°, diagonal pattern flexion, reverse throw, diagonal pattern extension, standard forward throw	1	20–25	n/s
Freeman et al. [32]	4	2	RPE	RT ST	RT: (2–3 sets × 4–6 sets at 100% PME): self-myofascial release, squat variations, barbell rows, Romanian deadlifts, single-leg squats, core exercises such as supine holds, and prone walks ST: 6–10 sets × 30–40 m at 100% PME)	variable	variable	3 m
Gabbett et al. [33]	10	3	Submaximal loads	RT	Bench press, shoulder press, wide grip pull-down, chin-ups, leg press	2–4	8–15	n/s
Hopper et al. [34]	6	3	RPE adjusted to each session's goals	PT RT	PT: MB squat jump, MB lateral bound, single-leg push-off, 180° spin jump RT: back squat, front squat, incline bench press, bench press, split squat (back foot elevated), spit squat (front foot high), chin-up, bent over row, forward alternating lunge, backward alternating lunge, Romanian deadlift	3	5–8	60 s
Karagianni et al. [35]	10	3	n/s	PT RT	PT: jumps variations using resistance bands (jumping lunges, squat jumps, squat abductor jumps, fast skipping, single-leg side jumping), Bulgarian split squat jump, pistol squat and jump, tuck jumps over 6 low hurdles, burpees, 3 kg MB throwing and catching while skipping RT: push-ups, plank variations, squat with a 5 kg kettlebell, single-arm row with a 5 kg kettlebell, Bulgarian split squats with kettlebells, pistol squats, and several exercises using elastic bands (leg scissors, hip thrust, squat side-kicks, rowing movement, push-press, and elbow extensions)	2	15–30	15 to 30 s
Makhlouf et al. [36]	8	2	n/s	BT PT	BT: standing with the knee on Swiss ball progressing to closed-eyed execution, unilateral and bilateral standing on inflated disk moving to squat, supine straight leg bridge on the Swiss ball, lunge on foam surface progressing to Bosu ball holding dumbbells, bilateral squat with elastic straps attached to bar placed on the shoulder on a foam surface progressing to Bosu PT: CMJs, drop jumps, horizontal line jumps, lateral hops, ankle jumps, single-leg cone jumps front to back and side to side, hurdle jumps, single-leg maximal rebounding hops	1–3	8–15	20 s
Marina and Jemni [37]	2 seasons	2	n/s	RT PT	RT: horizontal leg press, seated press, leg extension, leg curl, standing calf, seated calf PT: CMJ with and without arm swing, free 1 leg hops, hops above Swedish bench, SJ with and without arm swing, plinth jumps, frog jumps, reactive jumps	PT: 1–3 RT: 3	PT: 8–10 RT: 8–12	1.5 to 2 m

McKinlay et al. [38]	8	3	n/s	RT PT	RT: squats, lunges, step-ups, calf-raises, wide-stance-squats, raised-rear-foot lunge, 1-legged sit-to-stand raises, 1-legged squats PT: CMJ, drop jumps, knees-to-chest jumps, consecutive long jumps, jump lunges, straight-legged jumps w/toe-touch, side-to-side lateral hops, high-knee skips, hop and skip jumps, 1-legged CMJ, 1-legged knees-to-chest jumps, 1-legged consecutive long jumps	3	12	3 m
Moreno-Azze et al. [39]	10	1	n/s	IFT	Lateral squat using a portable conical pulley. Subjects were distributed into three unilateral eccentric overload groups. SVW group (executing the same training volume with both legs, beginning with the weaker leg), SVS group (same training volume with both legs, starting with the stronger leg), and DVW group (double training volume with the weaker leg and commenced with such leg)	2	6–10	1 to 3 m
Sadowski et al. [40]	12	3	50–60 strokes/min	RT	IG used a specialised ergometer. CG performed a traditional resistance exercise (bench press, backward arm press, horizontal row, supine straight-arm pullover, and dips)	10	30"	30 s
Santos and Janeira [41]	10	2	n/s	RT PT	RT: (week 1 to 10): leg extension, pullover, leg curl, decline press, leg press, and lat pull down; 2–3 min rest between sets and 45 and 60 s on exercises PT (week 1 and 2): rim jump, MB squat toss, MB chest pass, SJ, zigzag drill, 2-foot ankle hop; 60 s rest between sets and 15 s on exercises PT (week 3 and 4): tuck jump, alternate leg push-off, MB backward throw, lateral jump over cone, MB overhead throw, and single-arm alternate-leg bound; 60–90 s rest between sets and 15–30 s on exercises PT (week 5 to 7): side jump/sprint, MB seated chest pass, lateral box jump, MB seated backward throw, depth jump, and hurdle hops; 2–3 min rest between sets and 60 s on exercises PT (week 8 to 10): depth jump 180°, multiple box-to-box jumps, MB pullover pass, MB power drop, alternate lateral/frontal of hurdle hops, and sprint right/left of cone hops with the change of direction sprint; 2–3 min rest between sets and 60 s on exercises	RT: 2–3 PT: 2–4	RT: 10–12 PT: 5–15	RT: 45 to 60 s PT: 15 to 60 s
Smart and Gill [42]	15	4	RPE	RT PT ST	RT: box squat, bench press, chin-ups, seated hammer row, lat pull down, calf raises, dumbbell shoulder, dumbbell lateral raises, dumbbell bench press, single arms dumbbell row, leg press, single-leg step-ups, prone hip extension, single-leg, Bulgarian squat, and deadlift PT: vertical jump, broad jump, clap push-up, and single-leg broad jump Speed and conditioning ST: sprints at different distances (22 m, 40 m, 50 m, 100 m)	RT: 2–5 PT: 2–3 ST: 1–4	RT: 8–25 PT: 8–12 ST: 3–4	RT: 2 m PT: 1 m ST: 3 m

Tillaar et al. [43]	12	2	40–45% of 1RM	EST PT	PT (6 weeks): 2-legged jumps without bending knees; 2-legged jumps with bending knees; 2-legged jumps as far as possible with bending knees; hop with one leg short and quickly; 1-legged jumps as high as possible EST (6 weeks): squats; sprint from standing start position; sprint from lying start position; sprint from 5 m sideways start	PT: 2–5 EST: 3–6	PT: 8–25 EST: 1–3	n/s
Tran et al. [44]	7	2	RPE	RT	The exercises were performed on a Bosu by the unstable group and without a Bosu by the stable group. Session 1 of the week: double leg forward jump off the Bosu; MB slam; overhead squat and dumbbell squat; 1-arm row and push-up; MB rotation Session 2 of the week: vertical jump off the Bosu; MB chest throw; Dumbbell squat then shoulder press; 1-arm dumbbell row; assisted (straps) single-leg squat; push-up and MB woodchop	3	5–12	1 m

IT – intervention time, WTF – weekly training frequency, TI – training intensity, n/s – not-specific, 1RM – one-repetition maximum, IFT – isoinertial flywheel training, RT – resistance training, PT – plyometric training, SJ – squat jump, AT – aerobic training, OWL – olympic-style weightlifting, ST – speed training, PME – perceived maximum effort, MB – medicine ball, BT – balance training, CMJ – countermovement jump, SVW – starting with the weak leg, SVS – starting with the stronger leg, DVW – double volume, IG – intervention group, CG – control group, EST – explosive strength training, RPE – rate of perceived exertion

[26, 31, 35], medicine balls [44], isoinertial flywheels [25, 36), bodyweight exercises [28, 30, 32–35, 38, 40, 42–44), free-weights exercises [28–30, 32–35, 37, 38, 40–44], and weight machines [28, 33, 37, 41]. The PT programs were mainly based on bodyweight exercises, particularly through jumping variations [27, 29, 34, 37, 38, 41–43]. The PT interventions also included medicine ball throwing exercises [29, 34–36, 41], and elastic bands [35].

When relating the type of intervention with the outcomes obtained, we verified that the programs that used RT individually presented positive results in terms of strength, whether in the upper or lower limbs. On the other hand, those who used PT showed positive effects on the strength of the lower limbs, change of direction/agility, and speed. Two studies compared the effectiveness of PT with RT [29, 38]. The first showed that although both groups improved in outcomes, PT was more likely to elicit substantially better training adaptations than RT regarding isokinetic power in the lower limbs at 300°/s, and in sprint times [29]. The second study also showed improvements in both groups, however, PT was more effective in improving lower limb strength [38].

Regarding age ranges, most interventions performed between 8 and 13 years considered athletes in individual sports (n = 5), particularly in swimming [27], judo and wrestling [29], distance running [28], and gymnastics [35, 37]. Two studies were performed in soccer [36, 38] and one in netball [34]. The program's duration varied between six weeks and two seasons, primarily focused on improving strength, speed, and sport-specific skills through body weight exercises [27–29, 34–37], medicine ball throws [29, 34], weight machines and free-weights [28, 29, 34, 35, 37], and elastic bands [35]. Of note, across interventions, most of the bodyweight exercises were focused on abdominal strength and endurance (e.g., sit-ups and plank variations) and lower-body explosive strength (e.g., jumps).

Among 13 and 15 years, four studies were developed in individual sports, namely, swimming [26], dance [30], handball [43], and surfing [44]. On the other hand, three investigations were conducted in team sports: baseball [31], basketball [41] and rugby [33]. The program's duration ranged from 4 to 12 weeks. One study relied exclusively on elastic band exercises to improve the throwing ability in baseball [31], while two studies integrated medicine ball throws into their programs [41, 44]. Other interventions used privileged bodyweight exercises [30, 41, 43, 44], and weight machines and free weights exercises [30, 33, 41, 43, 44] to develop the strength, speed, change of direction, and balance capacities.

Finally, in participants over 15 years, four interventions were performed in team sports [25, 32, 39, 42], while one considered swimmers [40]. Two studies used a portable isoinertial flywheel device to perform exercises that improved jumping performance in basketball and volleyball players [25], and in soccer players [39]. Bodyweight, machines, and free weights exercises were used to promote lower-body strength and speed ability [32, 42], and crawl velocity over 25 m [40].

Discussion

This study aimed to provide a comprehensive overview of the current evidence on strength and conditioning interventions among youngsters involved in competitive sports. All the studies included in this analysis described the effectiveness of RT or PT interventions in increasing a range of physical fitness outcomes in youth sports, particularly in body composition, jumping, sprinting, and change of direction capacities. Most of the interventions considered participants aged 8 to 13 years, mainly involved in individual sports. In contrast, the studies developed with participants over 15 years favoured athletes involved in team sports.

Independent of the age group or the type of sport, training-induced gains in strength and power were consistently reported in youth following participation in RT and/or PT programs, including different durations, intensities, and loading schemes [18, 45]. Regarding lower-body explosive strength, the authors observed significant improvements in training groups submitted to RT combined with PT programs in netball [34], gymnastics [35, 37], basketball [41], rugby [42], and handball [43]. The programs' durations varied between 6 and 15 weeks, with a training frequency ranging between two and four times a week. The RT interventions often considered free weights, weight machines, and bodyweight exercises to target the major muscle groups, while the PT designs were frequently based on jumps and their variations [34, 35, 37, 41–43]. Similar to the conclusions of a previous review on this topic, PT interventions integrated CMJ, squats, and other jumps involved in bilateral take-offs and landings [3].

According to our analysis, several studies reported significant improvements in athletes' lower-body strength, speed, and agility tests [3, 32–34]. Indeed, previous research conducted to evaluate the relationship between lower-body explosive strength, sprinting, and change of direction performance in youth athletes showed that greater lower-body explosive strength was significantly and negatively correlated to speed and agility tests [46, 47]. Behm et al. [3] reported that strength training provided greater benefits to sprint ability due to the development of greater strength that allows the individuals to absorb and react to the ground reaction forces more efficiently. Empirical research among youth male handball players described a significant relationship between the t-test and vertical jumping scores (CMJ: $r = -0.69$, $p \leq 0.01$, SJ: $r = -0.60$, $p \leq 0.01$) [46]. In another study on youth male football players, the authors also described a strong correlation between vertical jumping and sprint times ($29 > r < 65$, $p \leq 0.01$) [47]. Further, after controlling for chronological age and body composition, SJ persisted as the most powerful predictor of speed and agility tests, explaining nearly 37% of the variance observed in the 35 m linear sprint and *t*-test time [47]. Therefore, better scores in lower-body explosive strength have been associated with lower times spent on speed and agility tests [46].

Meanwhile, the literature showed that using RT or PT programs alone is also beneficial for developing the physical attributes of youth athletes [26, 27, 29, 30, 38]. PT programs seemed more focused on enhancing power and were frequently implemented to promote sprinting and jumping [3, 29, 38]. On the other hand, RT programs aim to increase power, reduce fatigue, and improve body composition [26, 29]. However, the literature advocates that combining the RT and PT programs is more effective than using one of those training regimes alone [45]. Indeed, according to our analysis, the improvements in lower-body explosive strength, speed, and agility were more evident in training plans that combined heavy RT and PT programs [34, 37, 41, 43].

The development of youngsters' physical attributes is crucial for sport-specific skills performance. Strength is associated with force-time characteristics, and enhanced force-time features should transfer to the ability to perform general sport-specific skills [45]. In our analysis, several studies described benefits in sport-specific skills performance as an outcome of RT and/or PT programs [26, 27, 31]. In youth baseball, four weeks of RT focused on upper-body strength was proven to increase throwing velocity [31]. Past literature has advocated that young athletes consistently involved in well-designed conditioning programs can improve their muscular strength, power, body composition, and ability to perform motor skills [2, 19, 48]. Therefore, it is crucial to create awareness among youth sports agents and coaches about the influence of strength on game performance, providing enhanced muscular fitness and improving skill competency.

A training frequency of two times per week is sufficient to induce strength gains in youth athletes. In contrast, the optimal exercise duration and intensity are not precise. Our study's strength is capturing the overall differences between the variables and methods used in the selected intervention programs. Moreover, this analysis included studies on athletes of several ages and both sexes. The relationship between age, sexes, and training prescription was not debated. Besides this, the possible effects of biological maturation were only considered in three of the studies retained for analysis [25, 37, 38]. Indeed, the mature state could be an important confounder in youth sports, particularly concerning strength [49]. Although our analysis covered different age ranges, no pattern was found in the type of program used according to athletes' age. Future work to assess the interrelationship between age, sexes, biological maturation, and training prescription would be more informative.

The results of this study underline the crucial role of strength and conditioning programs in enhancing physical fitness, body composition, and skill competency among youth athletes. The key to safe and effective training interventions in youth is supervision by qualified professionals to ensure the program is properly designed and performed [19]. PT, mainly through jumping and sprinting tasks, is related to speed and agility improvements. Moreover, strength development using heavy RT may also be beneficial to enhance sprint and change of direction times. Therefore, PT and RT should not be implemented as single-exercise interventions but as complementary programs to optimise physical and game performance. This study contributes to creating awareness among sports agents and coaches for integrating planned strength and conditioning programs with qualified instruction at least two times per week to improve young athletes' physical development.

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Conflict of interest

The authors state no conflict of interest.

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References

1. Ford P, De Ste Croix M, Lloyd R, Meyers R, Moosavi M, Oliver J, et al. The long-term athlete development model: physiological evidence and application. J Sports Sci. 2011;29(4):389–402; doi: 10.1080/02640414.2010.536849.
2. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, et al. National Strength and Conditioning Association position statement on long-term athletic development. J Strength Cond Res. 2016;30(6): 1491–1509; doi: 10.1519/JSC.0000000000001387.
3. Behm DG, Young JD, Whitten JHD, Reid JC, Quigley PJ, Low J, et al. Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: a systematic review and meta-analysis. Front Physiol. 2017;8:423; doi: 10.3389/fphys.2017.00423.
4. Zwolski C, Quatman-Yates C, Paterno MV. Resistance training in youth: laying the foundation for injury prevention and physical literacy. Sports Health. 2017;9(5): 436–443; doi: 10.1177/1941738117704153.
5. Peitz M, Behringer M, Granacher U. A systematic review on the effects of resistance and plyometric training on physical fitness in youth-What do comparative studies tell us? PLoS One. 2018;13(10):e0205525; doi: 10.1371/journal.pone.0205525.
6. Faigenbaum AD, Kraemer WJ, Blimkie CJ, Jeffreys I, Micheli LJ, Nitka M, et al. Youth resistance training: updated position statement paper from the national strength and conditioning association. J Strength Cond Res. 2009;23:60–79; doi: 10.1519/JSC.0b013e31819df407.
7. Stricker PR, Faigenbaum AD, McCambridge TM. Resistance training for children and adolescents. Pediatrics. 2020;145(6):e20201011; doi: 10.1542/peds.2020-1011.
8. Keiner M, Sander A, Wirth K, Caruso O, Immesberger P, Zawieja M. Strength performance in youth: Trainability of adolescents and children in the back and front squats. J Strength Cond Res. 2013;27(2):357–62; doi: 10.1519/JSC.0b013e3182576fbf.
9. De Villarreal ES-S, Requena B, Newton RU. Does plyometric training improve strength performance? A meta-analysis. J Sci Med Sport. 2010;13(5):513–522; doi: 10.1016/j.jsams.2009.08.005.
10. Pareja-Blanco F, Sanchez-Medina L, Suarez-Arrones L, Gonzalez-Badillo JJ. Effects of velocity loss during resistance training on performance in professional soccer players. Int J Sports Physiol Perform. 2017;12(4):512–519; doi: 10.1123/ijspp.2016-0170.

11. Maroto-Izquierdo S, McBride JM, Gonzalez-Diez N, García-López D, González-Gallego J, de Paz JA. Comparison of flywheel and pneumatic training on hypertrophy, strength, and power in professional handball players. Res Q Exerc Sport. 2020;93(1):1–15; doi: 10.1080/02701367.2020.1762836.
12. de Villarreal ES, Suarez-Arrones L, Requena B, Haff GG, Ramos-Veliz R. Effects of dry-land vs. in-water specific strength training on professional male water polo players' performance. J Strength Cond Res. 2014;28(11): 3179–3187; doi: 10.1519/jsc.0000000000000514.
13. Falk B, Eliakim A. Resistance training, skeletal muscle and growth. Pediatr Endocrinol Rev. 2003;1(2):120–127.
14. Behm DG, Faigenbaum AD, Falk B, Klentrou P. Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents. Appl Physiol Nutr Metab. 2008;33(3):547–561; doi: 10.1139/H08-020.
15. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res. 2005;19(1):51–60; doi: 10.1519/13643.1.
16. Myer GD, Faigenbaum AD, Chu DA, Falkel J, Ford KR, Best TM, et al. Integrative training for children and adolescents: techniques and practices for reducing sports-related injuries and enhancing athletic performance. Phys Sportsmed. 2011;39(1):74–84. doi: 10.3810/psm.2011.02.1864.
17. Pichardo AW, Oliver JL, Harrison CB, Maulder PS, Lloyd RS, Kandoi R. Effects of Combined Resistance Training and Weightlifting on Injury Risk Factors and Resistance Training Skill of Adolescent Males. J Strength Cond Res. 2021;35(12):3370–3377; doi: 10.1519/jsc.0000000000003341.
18. Faigenbaum AD, Schram J. Can resistance training reduce injuries in youth sports? Strength Cond J. 2004; 26(3):16–21; doi:10.1519/00126548-200406000-00004.
19. Faigenbaum AD, Lloyd RS, MacDonald J, Myer GD. Citius, altius, fortius: beneficial effects of resistance training for young athletes: narrative review. Br J Sports Med. 2016;50(1):3–7; doi: 10.1136/bjsports-2015-094621.
20. Balyi I, Way R, Higgs C. Long-term athlete development. Human Kinetics; 2013.
21. Berryman N, Maurel DB, Bosquet L. Effect of plyometric vs. dynamic weight training on the energy cost of running. J Strength Cond Res. 2010;24(7):1818–1825; doi: 10.1519/JSC.0b013e3181def1f5.
22. Walters BK, Read CR, Estes AR. The effects of resistance training, overtraining, and early specialization on youth athlete injury and development. J Sports Med Phys Fitness. 2018;58(9):1339–1348. doi: 10.23736/s0022-4707.17.07409-6.
23. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Int J Surg. 2021;88:105906; doi: 10.1016/j.ijsu.2021.105906.
24. Thomas B, Ciliska D, Dobbins M, Micucci S. Quality assessment tool for quantitative studies dictionary: the Effective Public Health Practice Project (EPHPP). McMaster University; 2008.
25. Arede J, Gonzalo-Skok O, Bishop C, Schollhorn WI, Leite N. Rotational flywheel training in youth female team sport athletes: could inter-repetition movement variability be beneficial? J Sports Med Phys Fitness. 2020;60(11):1444–1452; doi: 10.23736/s0022-4707.20.10962-9.
26. Batalha N, Dias S, Marinho DA, Parraca JA. The effectiveness of land and water based resistance training on shoulder rotator cuff strength and balance of youth swimmers. J Hum Kinet. 2018;62:91–102. doi: 10.1515/hukin-2017-0161.
27. Bishop DC, Smith RJ, Smith MF, Rigby HE. Effect of plyometric training on swimming block start performance in adolescents. J Strength Cond Res. 2009;23(7): 2137–2143; doi: 10.1519/JSC.0b013e3181b866d0.
28. Bluett KA, Croix MBADS, Lloyd RS. A preliminary investigation into concurrent aerobic and resistance training in youth runners. Isokinet Exerc Sci. 2015;23(2): 77–85; doi: 10.3233/IES-150567.
29. Chaouachi A, Hammami R, Kaabi S, Chamari K, Drinkwater EJ, Behm DG. Olympic weightlifting and plyometric training with children provides similar or greater performance improvements than traditional resistance training. J Strength Cond Res. 2014;28(6): 1483–1496; doi: 10.1519/jsc.0000000000000305.
30. Dowse RA, McGuigan MR, Harrison C. Effects of a resistance training intervention on strength, power, and performance in adolescent dancers. J Strength Cond Res. 2020;34(12):3446–3453; doi: 10.1519/jsc.0000000000002288.
31. Escamilla RF, Fleisig GS, Yamashiro K, Mikla T, Dunning R, Paulos L, et al. Effects of a 4-week youth baseball conditioning program on throwing velocity. J Strength Cond Res. 2010;24(12):3247–3254; doi: 10.1519/JSC.0b013e3181db9f59.
32. Freeman BW, Young WB, Talpey SW, Smyth AM, Pane CL, Carlon TA. The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. J Sports Med Phys Fitness. 2019;59(7):1119–1125; doi: 10.23736/s0022-4707.18.08703-0.
33. Gabbett TJ, Johns J, Riemann M. Performance changes following training in junior rugby league players. J Strength Cond Res. 2008;22(3):910–917; doi: 10.1519/JSC.0b013e31816a5fa5.
34. Hopper A, Haff EE, Barley OR, Joyce C, Lloyd RS, Haff GG. Neuromuscular training improves movement competency and physical performance measures in 11–13-year-old female netball athletes. J Strength Cond Res. 2017;31(5):1165–1176; doi: 10.1519/jsc.0000000000001794.
35. Karagianni K, Donti O, Katsikas C, Bogdanis GC. Effects of supplementary strength-power training on

neuromuscular performance in young female athletes. Sports. 2020;8(8):104; doi: 10.3390/sports8080104.
36. Makhlouf I, Chaouachi A, Chaouachi M, Ben Othman A, Granacher U, Behm DG. Combination of agility and plyometric training provides similar training benefits as combined balance and plyometric training in young soccer players. Front Physiol. 2018;9:1611; doi: 10.3389/fphys.2018.01611.
37. Marina M, Jemni M. Plyometric training performance in elite-oriented prepubertal female gymnasts. J Strength Cond Res. 2014;28(4):1015–1025; doi: 10.1519/jsc.0000000000000247.
38. McKinlay BJ, Wallace P, Dotan R, Long D, Tokuno C, Gabriel DA, et al. Effects of plyometric and resistance training on muscle strength, explosiveness, and neuromuscular function in young adolescent soccer players. J Strength Cond Res. 2018;32(11):3039–3050; doi: 10.1519/jsc.0000000000002428.
39. Moreno-Azze A, Arjol-Serrano JL, Falcon-Miguel D, Bishop C, Gonzalo-Skok O. Comparison of three eccentric overload training strategies on power output and interlimb asymmetry in youth soccer players. Int J Environ Res Public Health. 2021;18(16)8270; doi: 10.3390/ijerph18168270.
40. Sadowski J, Mastalerz A, Gromisz W. Transfer of dryland resistance training modalities to swimming performance. J Hum Kinet. 2020;74(1):195–203; doi: 10.2478/hukin-2020-0025.
41. Santos E, Janeira M. Effects of complex training on explosive strength in adolescent male basketball players. J Strength Cond Res. 2008;22(3):903–909; doi: 10.1519/JSC.0b013e31816a59f2.
42. Smart DJ, Gill ND. Effects of an off-season conditioning program on the physical characteristics of adolescent rugby union players. J Strength Cond Res. 2013;27(3):708–717; doi: 10.1519/JSC.0b013e31825d99b0.
43. Tillaar RVD, Roaas TV, Oranchuk D. Comparison of effects of training order of explosive strength and plyometrics training on different physical abilities in adolescent handball players. Biol Sport. 2020;37(3):239–246; doi: 10.5114/biolsport.2020.95634.
44. Tran TT, Nimphius S, Lundgren LE, Secomb JL, Farley ORL, Haff GG, et al. Effects of unstable and stable resistance training on strength, power, and sensorimotor abilities in adolescent surfers. Int J Sports Sci Coach. 2015;10(5):899–910; doi: 10.1260/1747-9541.10.5.899.
45. Faigenbaum AD, McFarland JE, Keiper FB, Tevlin W, Ratamess NA, Kang J, et al. Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. J Sports Sci Med. 2007;6(4):519–525.
46. Negra Y, Chaabene H, Hammami M, Amara S, Sammoud S, Mkaouer B, et al. Agility in young athletes: is it a different ability from speed and power? J Strength Cond Res. 2017;31(3):727–735; doi: 10.1519/JSC.0000000000001543.
47. França C, Gouveia É, Caldeira R, Marques A, Martins J, Lopes H, et al. Speed and Agility Predictors among Adolescent Male Football Players. Int J Environ Res Public Health. 2022;19(5):2856; doi: 10.3390/ijerph19052856.
48. Behringer M, Vom Heede A, Yue Z, Mester J. Effects of resistance training in children and adolescents: a meta-analysis. Pediatrics. 2010;126(5):1199–1210; doi: 10.1542/peds.2010-0445.
49. Malina RM, Bouchard C, Bar-Or O. Growth, Maturation, and Physical Activity. Champaign: Human Kinetics; 2004.