Journal of Science in Sport and Exercise
https://doi.org/10.1007/s42978-023-00251-y

REVIEW ARTICLE

Risks and Recommendations for Resistance Training in Youth Athletes: A Narrative Review with Emphasis on Muscular Fitness and Hypertrophic Responses

Vitor de Salles Painelli[1,2]

Received: 19 February 2023 / Accepted: 29 August 2023

Abstract

Purpose The aim of this manuscript was to review the evidence regarding the risks, concerns, and efficacy of resistance training (RT) on measures related to muscular fitness and hypertrophic responses of youth athletes, while also establishing recommendations to assist the prescription of RT in this population.

Methods PubMed and Google Scholar databases were searched for studies that met the following inclusion criteria: (a) published in English as a full-text manuscript or thesis; (b) inclusion of RT protocols lasting > 6 weeks; (c) involvement of youth individuals (≤ 19 years) engaged in sport modalities.

Results Twenty-nine studies assessing muscle strength, power and/or endurance in young athletes were identified; only one of these studies did not show significant improvements with RT, specifically in muscle power, but improvements were substantially heterogeneous across the studies. The literature is still inconclusive regarding the occurrence of muscle hypertrophy in response to RT among youth athletic population, but this was drawn from just seven studies in non-athletic populations. Injury rates among youth participants were low and less concerning in well-designed, progressed, supervised and technique-oriented RT programs.

Conclusion RT is an effective method to improve muscular fitness-related measures in young athletes. The varying experimental designs across studies still represent an obstacle to the establishment of precise guidelines for RT prescription in this population. Nevertheless, some suggestions about RT frequency, resting interval, intensity and volume were elaborated in this review to assist coaches working with youth athletes to optimize muscular fitness-related measures gains.

Keywords Muscle strength · Hypertrophy · Exercise · Youth sports

Background

There is a growing trend of sport specialization (i.e., repetitive training for the purpose of skill acquisition and athlete development in a single main sport at the exclusion of all other sports) across many countries around the globe [34]. Despite the broadly known beneficial effects of regular physical activity for overall health [76], the intense practice generally associated with sports specialization may increase the risk of injury [66], psychological stress [8] and performance impairment [55], due to the high sport-related physiological demand and overtraining. Therefore, it is imperative for coaches and young athletes to include complementary strategies in their routine, aiming to support enhanced motor performance and body composition, to improve markers of health and well-being, and to reduce the risk of sustaining sports-related injuries. Among such strategies, resistance training (RT) stands out as a noteworthy option.

RT is a training strategy that involves the use of a wide range of resistive loads, movement velocities, and a variety of training modalities, including weight machines, free weights, elastic bands, medicine balls, and body weight [20]. RT has been extensively studied as a tool to improve injury recovery and/or prevention in sports, as well as performance and health in adults [45, 79], especially through

✉ Vitor de Salles Painelli
vitor.painelli@docente.unip.br

1 Institute of Health Sciences, Paulista University, R. Vergueiro 1211-Aclimação, São Paulo, SP 01533-000, Brazil

2 Exercise Psychophysiology Research Group, School of Arts, Sciences and Humanities, University of São Paulo, São Paulo, SP, Brazil

Published online: 30 October 2023

the development of muscle strength and mass. Over the past two decades, evidence-based reports [76, 77], meta-analyses [51] and position stands [5] have emerged, supporting the safety and efficacy of RT for children and adolescent in both clinical and non-clinical settings. This support extends to areas such as psychosocial well-being, bone mass, cardiovascular risk profile, motor performance skills, and sports performance [18] (Fig. 1). Consequently, RT has gained widespread acceptance in schools, medical and fitness centers [2]. However, data from these studies can only be partially translated to the athletic context, since the trainability, physiology, and motor performance proficiency markedly differ between non-athletic and athletic youth populations [3, 43]. Hence, in order to reduce the risk of injuries, enhance health-related indexes, and support motor performance and skill acquisition [21], coaches and instructors working with young athletes require an in-depth understanding of RT-induced adaptations, of which special attention has been given to muscle morphology (e.g., hypertrophy) and muscular fitness-related measures (e.g., muscle strength, muscle power and muscle endurance) response.

For instance, RT-induced strength improvements are typically related to an increase in muscle cross-sectional area [53], so that muscle hypertrophy-related strength gains may lead to sport performance enhancement and reduced injury risk [20, 79]. In turn, muscle strength consists in the ability to exert force or tension against a resistance at a given speed [2, 39]. High-velocity to overcome a resistance is usually required across several sport-specific contexts (e.g., own body mass, body mass of opponent, mass of object). Thus, maximal strength production should be an important capacity developed by conditioning programs to support sports performance, as it also enhances muscle power and muscle endurance performance [4, 39]. Muscle endurance, defined as the ability to consistently maintain force exertion against a given resistance over time [52], is an important capacity to sustain high velocities or to minimize the fatigue-related performance decrements. Hence, RT programs should promote the enhancement of this capacity to provide active muscles a higher endurance against fatigue and to maximize performance in sport modalities such as swimming, soccer, running and rowing. In addition, muscle power is defined as the amount of force/work/energy that can be produced in a given unit of time, and it is the product of the multiplication between two variables: force and velocity [15]. Consequently, muscle power is associated with explosive gestures/acts, and to be optimized, this capacity requires the training and enhancement of both force and velocity.

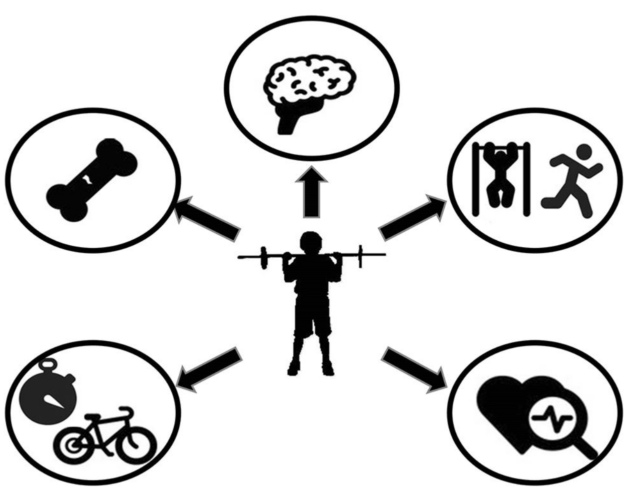

Fig. 1 RT offers multiple benefits for children and adolescents. To date, research has shown improvements in bone mass, psychosocial well-being, motor performance skills, sports performance, and cardiovascular risk profile in this population [13]

As more children and adolescents get specialized in sports and involved in RT throughout sport organizations and training centers, the aim of this review was to summarize the evidence regarding the risks, concerns and efficacy of RT on muscular fitness-related measures and hypertrophic responses of youth athletes, while also establishing recommendations and guidelines to assist RT application in this population. Despite the existence of distinct reviews published in the last years exploring RT impact for young athletes [10, 21, 27, 40, 41, 69], the vast majority of them were dedicated to examine the response of isolated parameters to RT programs (e.g. physical fitness; or injury risk; or muscle physiological adaptations; or health-related benefits), while none of these reviews were dedicated to compiling the main and lately findings, thereby highlighting the need to develop a more updated guideline and consensus for RT implementation in youth athletes. Considering the multiple important topics and wide scope of the current article, it was decided to concentrate the main information in the form of a narrative review.

Methodology

To counteract the subjective nature and probability of selection bias generally associated with narrative reviews, we conducted a search strategy using PubMed and Google Scholar databases without a specific set date, from February 2022 to June 2022 with an additional update in July 2023, using the following keywords combined with Boolean operators ("AND/OR"): "muscle hypertrophy", "injury", "sports injury", "resistance training", "muscle endurance", "strength training", "lean mass", "muscle thickness", "muscle power", "youth athletes", "young athletes", "sports", "sport specialisation" and "sport specialization". Studies were considered eligible for analysis based on the following inclusion criteria: (a) published in English as a full-text manuscript or thesis;

(b) involvement of youth individuals (≤ 19 years) engaged in sport modalities; (c) inclusion of RT protocols lasting a minimum of 6 weeks. Of note, this last criterion was adopted because the focus of this current review was to determine the influence of RT on muscle hypertrophy in youth individuals, and high-quality evidence [74] has demonstrated that increases in muscle cross-sectional area in response to RT lasting less than 6 weeks seem to be more related to muscle edema/swelling than actual protein accrual. Due to the difficulty in determining the total training load, studies using elastic bands or flywheels were not included in the review, as well as those failing to provide comprehensive information about RT methods. Moreover, even though plyometric training remains one of the most well-established methods to improve muscle power [46], because it differs slightly in nature and application from traditional RT, we limited our review to studies that assessed muscle power response solely through RT, without any other forms of training.

Results

Muscular Fitness-Related Measures

Muscle Strength

The literature pertaining the muscle strength response of youth athletes to RT is illustrated in Table 1, which includes data from 18 studies. In order to increase the practical applications of our observations, our review focused only on studies assessing muscle strength through the repetition maximum (RM) test. For example, Channell and Barfield [11], randomly allocated adolescent American football players to an 8-week traditional or Olympic RT program, three times a week. A control group of youth athletes, who engaged in regular training without RT, was also included. Both traditional and Olympic RT groups had similar exercise routines in terms of the number of exercises, sets, repetitions and intensity, with exception of two specific exercises in the Olympic RT group (‘power clean’ and ‘push jerk’). Importantly, a 4-week general RT period was employed before the experimental phase, in order to ensure that each participant conducted every lift with proper form. Results indicated that both traditional and Olympic RT groups experienced similar increases in their 1-RM in the squat exercise. However, only the Olympic RT group experienced improvements in the power clean exercise, probably due to the specificity principle. Interestingly, the relative increases observed by the authors were modest when compared to similar RT periods in other studies. It is possible that the initial 4-week familiarization period may have contributed to substantial strength increments from neural adaptations [4, 5, 27, 39], which tend to diminish with ongoing training, thereby limiting further gains during the experimental period.

In a subsequent investigation, Chelly et al. [12] recruited eleven junior soccer players and submitted them to an 8-week lower-body RT program, twice a week. A control group continued their soccer training, without RT. The primary exercise included in RT regimen was the back half squat, performed in four sets using in a pyramid model. Remarkably, this training protocol was sufficient to promote a ~ 35% increase in the participants' back half squat 1-RM, while the control group did not show significant differences. Similar findings were detected by Styles et al. [78], Hammani et al. [30], Harries et al. [31] and Contreras et al. [14], who employed a nearly identical RT protocol in terms of duration, intensity, and volume, as initially proposed by Chelly et al. [12]. Notably, Contreras et al. [14] made a noteworthy contribution by highlighting the importance of training and testing specificity in the context of increasing muscle strength of youth athletes through RT. The authors divided young rowers and rugby players to RT groups, performing either the hip thrust or the front squat exercise, for a duration of 6 weeks. Both training groups were assessed in both exercises before and after the RT period, despite performing just one of these exercises during the training sessions. On one hand, it was demonstrated that muscle strength increased in both exercises for both groups, suggesting some degree of transfer in the muscle strength gains between different exercises. On the other hand, the most significant improvements in muscle strength occurred in the exercises that were specifically trained during the RT period. This underscores the importance for coaches and athletes to select exercises that align with their specific goals.

The most comprehensive study was conducted by Sander et al. [70], who conducted a 80-week follow-up in 134 elite youth soccer players to examine the effect of RT on muscle strength performance while they continued with regular soccer training. Participants were divided in 3 categories according to age (under-13, under-15 and under-17 years old); and within each category, athletes were further divided into those who performed RT and those who did not (i.e. control group). The RT sessions were conducted twice a week and were focused on hypertrophy and intramuscular coordination throughout the study period. Participants were tested for their 1-RM in both the back and front squat exercises, which were part of the RT program along with other lower-body and upper-body exercises. The authors demonstrated a substantial relative increase in 1-RM strength among those who participated in the RT regimen, compared to those in the control group, with improvements ranging from ~ 100% in the oldest category to ~ 300% in the youngest category. These results align with those reported by Rodríguez-Rosell et al. [65] and are consistent with a recent quantitative review using the meta-analysis [41], both of which showed that younger age groups experienced more significant muscle strength gains with RT. While it remains difficult to explain these differences, bone plausible

Table 1 Studies assessing muscle strength response to RT in youth athletes

Reference	Participants			RT Characteristics	Results
	N	Age	Sex/modality		
DeRenne et al. [16]	T1: 7 T2: 8 C: 6	Prepubertal 13.3 years ears	M—Baseball	12 weeks dynamic upper- and lower-body training (1 × *vs*. 2 times/w, 3 sets, 10 RM, 75% 1-RM)	↑ BP 1-RM: 17.3%–22.9% ↑ LP 1-RM: 14.1%–26.3%
Kotzamanidis et al. [38]	T1: 23 C: 12	Adolescent 17.0 ± 1.1 years	M—Soccer	13 weeks lower-body training (3 times/w, 4 sets, 3–8-RM)	↑ BS 1-RM: 10%
Christou et al. [13]	T1: 9 C: 9	Adolescent 13–15 years	M—Soccer	16 weeks dynamic upper- and lower-body training (2 times/w, 2–3 sets, 8–15 RM, 55%–80% 1-RM)	↑ BP 1-RM: 68.4% ↑ LP 1-RM: 65.3%
Channell and Barfield [11]	T1: 11 T2: 10 C: 6	Adolescent 15.9 ± 1.2 years	M—Football	8 weeks dynamic upper- and lower-body training (3 times/w, 3–5 sets, 3–10 RM, 60%–90% 1-RM)	↑ BS 1-RM: 12.2%–16.1%
Chelly et al. [12]	T: 11 C: 11	Adolescent 17 ± 0.3 years	M—Soccer	8 weeks back half squat training (2 times/w, 4 sets, 2–7 reps, 70%–90% 1-RM)	↑ BS 1-RM: 35.2%
Sander et al. [70]	T1: 13 T2: 30 T3: 18 C1: 15 C2: 25 C3: 33	Adolescent 13–17 years	M—Soccer	80 weeks dynamic upper- and lower-body training (2 times/w, 4 × 20-week blocks—5 sets, 4–10 RM)	↑ BS 1-RM T1: 101.6%–106.2% ↑ BS 1-RM T2: 115.1%–123% ↑ BS 1-RM T3: 290.9%–312.5%
Harries et al. [31]	T: 16 C: 10	Adolescent 14–18 years	M—Rugby	12 weeks dynamic upper- and lower-body training (2 times/w, 4–6 sets, 3–10 RM)	↑ BS 1-RM: 33.9%–44.5% ↑ BP 1-RM: 7.0%–10.9%
Styles et al. [78]	T: 52 C: 47	Adolescent 18.3 ± 1.2 years	M—Soccer	6 weeks BS and Romanian deadlift training (2 times/w, 3–4 sets, 3–5 reps, 85%–90% 1-RM)	↑ BS 1-RM: 20%
Negra et al. [57]	T: 13 C: 11	Prepubertal 12.7 ± 0.8 years	M—Soccer	12 weeks BS training (2 times/w, 4 sets, 8–12 reps, 40%–60% 1-RM)	↑ BS 1-RM: 25.7%
Hammami et al. [30]	T: 19 C: 12	Adolescent 15.8–16.2 years	M—Soccer	8 weeks BS training (2 times/w, 3–5 sets, 3–8 reps, 70%–90% 1-RM)	↑ BS 1-RM: 25.3%
Contreras et al. [14]	T1: 14 T2: 14	Adolescent 15.5 years	M—Rugby/Rowing	6 weeks FS and HT training (2 times/w, 4 sets, 6–12 RM)	↑ FS 3-RM T1: 7.1% ↑ FS 3-RM T2: 12.85% ↑ HT 3-RM T1: 42.76% ↑ HT 3-RM T2: 21.06%
Weakley et al. [84]	T: 16	Adolescent 17.8 ± 0.9 years	M—Rugby	6 weeks dynamic upper- and lower-body training (2 times/w, 3 sets, 2–4 RM, 82%–92% 1-RM)	↑ BP 1-RM: 5%–7%

Table 1 (continued)

Reference	Participants			RT Characteristics	Results
	N	Age	Sex/modality		
Rodríguez-Rosell et al. [65]	T1: 15 T2: 14 T3: 14 C1: 15 C2: 14 C3: 14	Adolescent 13–17 years	M—Soccer	6 weeks free-weight full squat training (2 times/w, 2–3 sets, 4–8 reps, 45%–60% 1-RM)	↑ BS 1-RM T1: 48.2% ↑ BS 1-RM T2: 27.6% ↑ BS 1-RM T3: 13.5%
Huang et al. [33]	T1: 10 T2: 9	Adolescent 14.6 ± 0.96 years	F—Judo	6 weeks free-weight or pneumatic full squat training (2 times/w, 4 sets, 8 reps, 70% 1-RM)	↑ BS 1-RM T1: 4.9% ↑ BS 1-RM T2: 9.3%
Schneiker et al. [73]	T1: 8 T2: 8	Adolescent 19.0 ± 2.0 years	M—Australian Rules Football	6 weeks squat and deadlift training (2 times/w, 4 sets, 6 reps, 30%–85% 1-RM)	↑ BS 1-RM T1: 18.9% ↑ BS 1-RM T2: 20.1%
McQuilliam et al. [48]	T1: 8 T2: 7 C: 7	Adolescent 18.0 ± 1.0 years	M—Soccer	6 weeks half squat training (1 times/w, 3–4 sets, 3–8 reps, 80%–90% 1-RM)	↑ BS 1-RM T1: 17.1% ↑ BS 1-RM T2: 29.1% ↔ BS 1-RM C: 1.7%
Falch et al. [22]	T1: 11	Adolescent 17.5 ± 2.3 years	F—Handball	8 weeks bilateral, unilateral and lateral squat training (1–2 times/w, 3–6 sets, 3–12 reps, 75%–90% 1-RM)	↑ BS 1-RM T1: 20.1%
Mesfar et al. [50]	T1: 16 C: 15	Adolescent 14.5 ± 0.6 years	M—Volleyball	8 weeks dynamic upper- and lower-body training (2 times/w, 3–4 sets, 2–4 reps, 40%–80% 1-RM)	↑ BS 1-RM T1: 30.6% ↑ BS 1-RM C: 4.0%

T training group, *C* control group, *M* male, *1RM* one maximum repetition, *BP* bench press, *LP* leg press, *FS* front squat, *BS* back squat, *HT* hip thrust, *w* week; relative change values (%) are expressed in comparison to baseline values

explanation could be the increased neural plasticity observed in children as compared to adolescent athletes [60].

Muscle Endurance

There are fewer studies examining the impact of RT on the muscle endurance of youth athletes compared to those examining its effects on muscle strength ($N = 6$; Table 2). To our knowledge, DeRenne et al. [16] were the first to assess muscle endurance in response to RT in youth athletes. The authors employed a 12-week RT program for young baseball players, dividing them into experimental groups that either trained one or two times a week. Even though both trained groups improved their muscle endurance compared to the control group during the pull-ups test, the group that trained twice a week achieved greater improvements. Practical assessments conducted by Christou et al. [13], Klusemann et al. [37] and Weston et al. [87] revealed nearly identical enhancements in the lower-body, upper-body and core muscle endurance of young soccer, basketball and swimmers, respectively, in response to systematic RT programs, despite their variations in training duration, intensity and volume.

It is noteworthy that, following the principle of specificity, improvements in muscle endurance seem to most pronounced in the muscle groups that have been specifically trained and evaluated. In this direction, Moore et al. [54] recruited adolescent baseball players with 8–10 years of experience in the sport, and submitted them to a 20-week RT focused on strengthening the shoulder muscles, occurring three times a week. For this purpose, the authors employed a stair-step progression that prioritized endurance over strength, by increasing repetitions with proper technique before increasing resistive load through elastic bands and weight room exercises. A posterior shoulder endurance test was conducted before and after the intervention to assess the effects of RT. The authors observed a 166.5% improvement in posterior shoulder muscle endurance after the specific training.

The limited number of published investigations indicate RT as an effective method to improve muscle endurance in youth athletes. Additionally, it emphasizes the significance of two key factors: (1) training specificity, to improve muscle endurance in a given muscle group; and (2) testing specificity, to accurately confirm such improvement. Notwithstanding, the scarcity of examinations on this topic cast the need for additional studies involving various sports modalities and the utilization of RT protocols with distinct characteristics, to provide a clearer understanding of the true effect of RT on muscle endurance of child and adolescent athletes. Moreover, it's crucial to acknowledge the lack of information regarding well-conducted familiarization sessions for the exercise tests, which makes it difficult to differentiate the genuine effects of RT from the inherent learning process associated with the tests.

Muscle Power

Compared to muscle strength and muscle endurance, there is a greater number of studies that have investigated the effects of RT on muscle power of youth athletes (Table 3), in which 22 studies were identified. The vast majority was conducted on adolescents, and it was possible to detect some degree of heterogeneity in their RT protocols. To illustrate this argument, Gorostiaga et al. [26], Channell and Barfield [11] and Tran et al. [80] detected positive, but small improvements in muscle power, ranging from ~ 2.5% to 5.5% derived from RT protocols of similar characteristics. However, it's worth noting that some studies with similar durations and characteristics [12, 30, 42] detected 2 to 3 times greater improvements in muscle power.

It is challenging to reconcile the discrepancies among these findings, but as described in the 'muscle strength' topic, it's crucial to consider the potential interference of an individual's training level on the improvements induced by RT. For example, after a 26-week high-velocity squat training, González-Badillo et al. [25] observed that the most substantial improvements in the countermovement jump (CMJ) test performance were observed in the 'under-15' category compared to the 'under-21'. Similarly, Rodríguez-Rosell et al. [65] showed that the 'under-13' category demonstrated a 12% improvement in CMJ performance after 6 weeks of high-velocity squat training, while the 'under-17' category showed less than half of that improvement. Hence, superior gains in muscle power were more evident in the less experienced categories when compared to the more trained ones. On one hand, increased neural plasticity in child compared to adolescents is highlighted as a possible explanation for these results. On the other hand, the lack of adequate familiarization sessions for the exercise tests was a key feature among the different studies, hampering interpretations on the true extent of the effects of RT on muscle power.

Despite the heterogeneity underpinning their experimental designs, many studies reported enhancements in muscle powerin response to RT. In fact, with the exception of Prieske et al. [62], all other authors reported an improvement in muscle power, regardless of the magnitude. It might be speculated that the lack of change in muscle power in the study of Prieske et al. [62] is related to the use of unspecific testing (i.e., CMJ), especially considering that exercises targeting core muscles strengthening were employed. Therefore, RT is indeed an effective method to improve indicators of muscle power in youth athletes across different sport modalities. However, the current diversity in experimental designs still hampers the establishment of precise instructions and guidelines for optimizing muscle power improvement through RT in youth athletes.

Muscle Hypertrophy

There has been a long-standing paradigm supported by longitudinal studies that muscle hypertrophy either does not occur or occurs minimally in children and preadolescents in response to RT [42, 58, 68]. It is speculated that the low amount of circulating anabolic hormones [82] may contribute to morphological or architectural changes in this public, despite existing evidence showing that acute exercise-induced elevations in endogenous anabolic hormones does not enhance muscle hypertrophy [86].

Alternatively, the lack of gold-standard methods to assess and detect small but important changes in muscle hypertrophy could have had increased the chances of measurements-associated variation/error in most of the previous findings, thus hampering their interpretation. For example, no morphological changes were detected by Ozmun et al. [58] after an 8-week RT training program for elbow flexors in 16 male and female children aged between 9 and 12 years. Such changes were assessed through skinfolds, known for their poor accuracy and reliability [83]. Similar findings from anthropometric measures were demonstrated by Sadres et al. [68] and Lillegard et al. [42] after applying progressive RT over a 2-year and 12-week period, respectively, to prepubescent boys and girls.

Some of the studies conducted with more accurate, reliable and sensitive methods (i.e., magnetic resonance imaging; ultrasound), have shown results in the opposite direction (Table 4). For example, Mersch and Stoboy [49], with a small sample size (i.e., two sets of twins), demonstrated an increase in quadriceps cross-sectional area through magnetic resonance imaging in pre-adolescent boys after an RT program for the lower body. In another study [24], 1st–3rd grade Japanese boys and girls were assigned to a control or a RT group, with the latter being submitted to 12 weeks of RT for the elbow flexors. The RT group showed significant increases in muscle cross-sectional area using ultrasound technique, and such increment was significantly correlated with the skeletal age. However, contrary findings also exist; in the study by Ramsay et al. [63], no significant increases

Table 2 Studies assessing muscle endurance response to RT in youth athletes

Reference	Participants			RT Characteristics	Results
	N	Age	Sex/modality		
DeRenne et al. [16]	T1: 7 T2: 8 C: 6	Prepubertal 13.3 years	M—Baseball	12 weeks dynamic upper- and lower-body training (1 × vs. 2 times/w, 3 sets, 10 RM, 75% 1-RM)	↑ pull-ups: 27%–64%
Christou et al. [13]	T1: 9 C: 9	Adolescent 13–15 years	M—Soccer	16 weeks dynamic upper- and lower-body training (2 times/w, 2–3 sets, 8–15 RM, 55%–80% 1-RM)	↑ RJ: 15.8%
Klusemann et al. [37]	T1: 13 T2: 13 C3: 13	Adolescent 14 years	M/F—Basketball	6 weeks of supervised *vs*. video-oriented body-weight exercises	↑ push-ups: 20%–23%
Moore et al. [54]	T1: 14	Adolescent 16 years	M—Baseball	20-week shoulder training (2–3 times/w, 3 sets, 20RM)	↑ PSET: 166.5%
Sarabia et al. [72]	T: 11 C: 9	Adolescent 15 ± 1.0 years	M—Tennis	11 weeks BP and BS training (2 times/w, 3–6 sets, 60% 1-RM)	↑ BP reps to failure: 58% ↑ BS reps to failure: 56%
Weston et al. [87]	T1: 10 T2: 10	Adolescent 15.7–16.7 years	M/F—Swimming	12-week core training (3 times/w, 2–4 sets, 30–120 s hold/10–25 reps)	↑ prone-bridge: 7%

T training group, *C* control group, *M* male, F female, *1RM* one maximum repetition, *RJ* average height during 30-s repeated jump, *PSET* posterior shoulder endurance test, *BP* bench press, *BS* back squat, *w* week; relative change values (%) are expressed in comparison to baseline values

Table 3 Studies assessing muscle power response to RT in youth athletes

References	Participants			RT Characteristics	Results
	N	Age	Sex/modality		
Gorostiaga et al. [26]	T: 9 C: 10	Adolescent 15.1 ± 0.7 years	M—Handball	6 weeks of dynamic upper- and lower-body training (2 times/w, 4 sets, 3–12 reps, 40%–90% 1-RM)	↑ SJ: 3.4% ↑ CMJ: 3.2%
Kotzamanidis et al. [38]	T1: 23 C: 12	Adolescent 17.0 ± 1.1 years	M—Soccer	13 weeks lower-body training (3 times/w, 4 sets, 3–8 RM)	↑ SJ: 1.9%
Christou et al. [13]	T1: 9 C: 9	Adolescent 13–15 years	M—Soccer	16 weeks dynamic upper- and lower-body training (2 times/w, 2–3 sets, 8–15 RM, 55%–80% 1-RM)	↑ SJ: 31% ↑ CMJ: 25%
Channell and Barfield (11)	T1: 11 T2: 10 C: 6	Adolescent 15.9 ± 1.2 years	M—Football	8 weeks dynamic upper- and lower-body training (3 times/w, 3–5 sets, 3–10 RM, 60%–90% 1-RM)	↑ VJ: 2.3%–4.5%
Chelly et al. [12]	T: 11 C: 11	Adolescent 17 ± 0.3 years	M—Soccer	8 weeks back half squat training (2 times/w, 4 sets, 2–7 reps, 70%–90% 1-RM)	↑ SJ: 10%
Tsimahidis et al. [81]	T: 13 C: 13	Adolescent 18.0 ± 1.2 years	M—Basketball	10 weeks BS training (2 times/w, 5 sets, 5–8 RM)	↑ SJ: n/m ↑ DJ: n/m ↑ CMJ: n/m
Santos and Janeira [71]	T: 15 C: 10	Adolescent 14.5 ± 0.6 years	M—Basketball	10 weeks lower-body and upper-body training (2 times/w, 2–3 sets, 10–12RM)	↑ SJ: 12.5% ↑ DJ: 9.5% ↑ CMJ: 10.2% ↑ MBT: 7.6%
Ferrete et al. [23]	T: 11 C: 13	Prepubertal 8–9 years	M—Soccer	26 weeks BS training (2 times/w, 2–4 sets, 6–10 RM)	↑ CMJ: 6.7%
Piazza et al. [61]	T: 19	Prepubertal 12.0 ± 1.0 years	F—Gymnastics	6 weeks BS training (2 times/w, 3 sets, 12RM)	↑ SJ: 2.7% ↑ CMJ: 7.0%
González-Badillo et al. [25]	T1: 17 T2: 16 T3: 11	Adolescent 15–20 years	M—Soccer	26 weeks high-velocity squat training (2 times/w, 2–4 sets, 6–8 reps, 45%–60% 1-RM)	↑ CMJ T1: 10.5% ↑ CMJ T2: 7.5% ↑ CMJ T3: 2.7%
Tran et al. [80]	T: 10	Adolescent 14.0 ± 1.1 years	M—Surfers	7 weeks of lower- and upper-body exercises (2 times/w, 3 sets, 5–12RM)	↑ CMJ: 5.7%
Sarabia et al. [72]	T: 11 C: 9	Adolescent 15 ± 1.0 years	M—Tennis	11 weeks BP and BS training (2 times/w, 3–6 sets, 60% 1-RM)	↑ CMJ: 4.1% ↑ SJ: 9.6% ↑ MBT: 13.1%
Prieske et al. [62]	T1: 20 T2: 19	Adolescent 16.6 ± 1.0 years	M- Soccer	9 weeks of core strength training (2–3 times/w, 2–3 sets, 15–20 reps)	↔ CMJ T1: − 1.5% ↔ CMJ T2: 0.7%
Negra et al. [57]	T: 13 C: 11	Prepubertal 12.7 ± 0.8 years	M—Soccer	12 weeks BS training (2 times/w, 4 sets, 8–12 reps, 40%–60% 1-RM)	↑ CMJ: 23.5% ↑ LJ: 15.5%
Hammami et al. [30]	T: 19 C: 12	Adolescent 15.8–16.2 years	M—Soccer	8 weeks back half squat training (2 times/w, 3–5 sets, 3–8 reps, 70%–90% 1-RM)	↑ SJ: 19.4% ↑ CMJ: 14.5%

Table 3 (continued)

References	Participants			RT Characteristics	Results
	N	Age	Sex/modality		
Contreras et al. [14]	T1: 14 T2: 14	Adolescent 15.5 years	M—Rugby/Rowing	6 weeks FS and HT training (2 times/w, 4 sets, 6–12 RM)	↑ CMJ T1: 3.6% ↑ CMJ T2: 7.7% ↑ LJ T1: 16.3% ↑ LJ T2: 1.8%
Rodríguez-Rosell et al. [65]	T1: 15 T2: 14 T3: 14 C1: 15 C2: 14 C3: 14	Adolescent 13–17 years	M—Soccer	6 weeks free-weight full squat training (2 times/w, 2–3 sets, 4–8 reps, 45%–60% 1-RM)	↑ CMJ T1: 12% ↑ CMJ T2: 10% ↑ CMJ T3: 5.5%
Huang et al. [33]	T1: 10 T2: 9	Adolescent 14.6 ± 0.96 years	F—Judo	6 weeks free-weight or pneumatic full squat training (2 times/w, 4 sets, 8 reps, 70% 1-RM)	↑ CMJ T1: 14.0% ↑ CMJ T2: 4.2% ↑ SJ T1: 10.8% ↑ SJ T2: 3.4%
Schneiker et al. [73]	T1: 8 T2: 8	Adolescent 19.0 ± 2.0 years	M—Australian Rules Football	6 weeks squat and deadlift training (4 times/w, 4 sets, 6 reps, 30%–85% 1-RM)	↑ SJ T1: 8.9% ↑ SJ T2: 8.7%
McQuilliam et al. [48]	T1: 8 T2: 7 C: 7	Adolescent 18.0 ± 1.0 years	M—Soccer	6 weeks half squat training (1 times/w, 3–4 sets, 3–8 reps, 80%–90% 1-RM)	↑ CMJ T1: 8.8% ↑ CMJ T2: 10.0% ↓ CMJ C: − 4.0% ↑ SJ T1: 6.1% ↑ SJ T2: 10.8% ↓ SJ C: − 6.5%
Falch et al. [22]	T1: 11	Adolescent 17.5 ± 2.3 years	F—Handball	8 weeks bilateral, unilateral and lateral squat training (1–2 times/w, 3–6 sets, 3–12 reps, 75%–90% 1-RM)	↑ CMJ T1: 11.3% ↑ DJ T1: 11.9%
Mesfar et al. [50]	T1: 16 C: 15	Adolescent 14.5 ± 0.6 years	M—Volleyball	8 weeks dynamic upper- and lower-body training (2 times/w, 3–4 sets, 2–4 reps, 40%–80% 1-RM)	↑ CMJ T1: 19.1% ↑ CMJ C: 3.0%

T training group, *C* control group, *M* male, *F* female, *RM* repetition maximum, *DJ* drop jump, *SJ* squat jump, *CMJ* countermovement jump, *VJ* vertical jump (using Vertec), *MBT* medicine ball throw, *w* week, *n/m* change not mentioned; relative change values (%) are expressed in comparison to baseline values in the cross-sectional area of the elbow flexors and knee extensors muscles were observed (through computerized tomography) among prepubescent boys, who participated in a progressive RT program three times a week for 20 weeks. Similarly. using the magnetic resonance imaging technique, Granacher et al. [27] did not demonstrate significant differences in the quadriceps cross-sectional area among prepubertal boys and girls after a well-controlled 10-week progressive RT program. Of note, none of these studies [24, 27, 49, 63] was conducted with young athletes. In fact, to the best of our knowledge, there are no longitudinal studies that have assessed muscle hypertrophy among young athletes in response to a systematic and supervised RT program.

It is difficult to understand the nature of the limited availability of research on this topic, even though one potential reason could be the difficulty of accessing sophisticated and expensive gold-standard methods. Likewise, from an ethical standpoint, subjecting children and adolescents to other invasive methods, such as muscle biopsy, for the investigation of physiological adaptations raises concerns. In view of the mentioned, while some of the above mentioned studies [49, 63] do support for the possibility of muscle hypertrophy among children and adolescents, the contrary results of others [24, 27], associated with the scarcity of qualified investigations, make it premature to conclude that this adaptation indeed occurs in this population. This is especially important for the purposes of this short narrative report, the response of youth athletes to RT. Future investigations should involve large sample sizes, longer durations, and the utilization of accurate and reliable techniques to elucidate the actual effect of RT on muscle hypertrophy in young athletes.

Risks and Concerns

There has been a traditional/cultural concern that RT during childhood and adolescence may induce potential injuries to the epiphyseal plate or growth cartilage. This preconception was originated from several retrospective studies in the 70s and 80s, which reported damage to the growth cartilage in youth undertaking RT [6, 29, 35, 67, 85]. Data from the National Electronic Injury Surveillance System (NEISS) have indicated increasing trends of epiphyseal injuries in youth lifters, further reinforcing such concern. NEISS data also suggest that many of the reported injuries are muscle strains, with the hand, lower back, and upper trunk being the most commonly affected areas. Recent NEISS data even suggest that hand injuries are particularly common in children < 12 years old [36]. Indeed, caution merits to be exercised on this matter if we consider that (1) injuries to these structures could result in lost of training time, significant discomfort, and growth disturbances (in the case of epiphyseal plate or growth cartilage injuries) [9]; and (2) the growth plate may be less resistant to shear and tension forces [75]. However, an in-depth analysis of these retrospective studies reveals that most of the reported injuries were linked to improper lifting technique, poorly designed RT programs, and lack of qualified supervision, instruction or equipment [20].

In fact, the number of prospective studies reporting RT-related injuries in young lifters is scarce. For example, one study reported a participant who required 1 week of rest due to anterior shoulder pain [64]. Another participant experienced had a shoulder strain that led to missing a single training session [42]. However, other studies reported high rates of lower back/lumbar spine pain; with 29 out of 43 adolescents experiencing RT-related injuries in this region. While most of these injuries were minor, 4 were severe enough to necessitate surgery [7]. Although these data may initially raise concern, the relative high incidence of lower back injuries could be a result of insufficient focus on strengthening the trunk or posterior chain musculature, and once again, suboptimal program design. Additional factors such as inappropriate RT progression or incorrect technique could also increase the risk of soft-tissue injury. Supporting this notion, some authors found that there was no increased risk of injury when children were adequately supervised and submitted to one repetition maximum training with weight machines [19]. This finding is supported by other investigations employing similar RT designs but with free weights [32]. Of note, a review [20] of the above-mentioned findings revealed estimated injury rates of 0.176 [64] and 0.053 [42] per 100 participant hours, respectively. Importantly, these injury rates are lower than those exhibited by heavier contact sports such as rugby, which has reported injury rates approaching 0.800 per 100 participant hours [47], suggesting that well-designed and supervised RT protocols are relatively safe for youth.

Any type of sport carries some degree of injury. Although RT might present a risk of injury, this method does not seem to add any injury risk to the sports that youth athletes are already engaged. Furthermore, the risk of injury resulting from RT can be minimized with a number of procedures (see Table 5), which include safe exercise equipments, effective supervision, lifting form education, appropriate overload, gradual progression, careful selection of exercises, and adequate recovery between training sessions. It is important to remember that children and adolescents of the same age may differentially tolerate a given physical and mental stress, and therefore, an individual approach should be prioritized.

Recommendations

Adult training guidelines and philosophies should not be imposed on youth, since they are physically and psychologically less mature than adults. However, as confirmed throughout this report, the studies conducted with young athletes are reduced, and their characteristics differ substantially from each other in terms of sample size, participants-related sports modality, participants' training status, and RT duration and protocol (volume, intensity, frequency), making it difficult to establish accurate guidelines for RT prescription to this population. Therefore, suggestions regarding exercise intensity and volume, inter-set resting interval and frequency will be provided for young athletes engaged in RT to help optimize results and reduce the risk of injury (Table 6). Naturally, the first consideration should be working with qualified instructors having appropriate certifications, who understand youth RT principles and pediatric exercise science, enabling them to provide real-time feedback and ensure safe and correct development of movement.

RT Frequency

The training frequency refers to the number of workouts performed per week, and more specifically, how often a muscle group is worked in a weekly manner. It is an important variable to ensure sufficient recovery, avoid overtraining, and achieve maximal benefits of RT. Most previous research (Tables 1, 2, 3) employed 2 or 3 weekly RT sessions. This frequency is in agreement with established position statements [18] and recent meta-analysis [56], although information from these reviews was mainly based on physically active children and adolescent, but not athletes. The only meta-analysis published to date encompassing youth athletes did not uncover statistically significant differences in muscle strength or power between training with 2 or 3 sessions per week [41]. Hence, one might speculate that training twice per week might be sufficient and even preferable to achieve gains in muscle strength and power in youth athletes, while also minimizing the physical stress from higher exposures. It is worth mentioning that, to the best of the author's knowldege, there are no available studies directly comparing the effects of distinct RT frequencies (e.g., 1 time/week vs. 3 times/week vs. 5 times/week) for youth athletes, reinforcing the necessity of studies to address this issue.

RT Volume and Intensity

The relationship between volume and intensity is inverse in nature, and both of them require special consideration when prescribing RT to induce muscular fitness gains and reduce injury risk. While intensity most commonly refers to the magnitude of resistance that is required to be overcome during a repetition, volume refers to the total number of within a training session, the number of sets and repetitions within each set [4]. To prescribe training intensity, coaches typically specify a percentage of an athlete's 1 RM. While this approach is routinely used within a research environment or elite level sport, equipment constraints and time (for the test itself and for familiarization) may lead to the use of repetition-maximum ranges (e.g., 8–12 RM) or predictive equations that estimate 1RM values based on sub-maximal loads in youth populations.

A recent meta-analysis showed that conventional RT programs with average RT intensities of 80%–89% 1RM were most beneficial in terms of improving muscle strength in youth athletes [41]. These results are in accordance with previously published position stands [1] and meta-analysis [59] demonstrating that the most substantial muscle strength gains in adults, trained individuals and athletes were achieved when training at 80%–85% 1RM. Regarding the number of sets per exercise, the aforementioned meta-analysis [41] showed similar effects between single-set and multiple-set RT programs. Despite the time-efficiency of single-set programs, this result was extracted from only one study, thereby requiring precaution when interpreting this result. To date, there are no studies directly comparing the impact of RT volume in youth athletes. Evidence from adult athletes demonstrated that single-set RT programs may be appropriate during the initial phase of RT [88], whereas multiple-set should be used to promote additional gains in muscle strength [39]. Therefore, multiple-set RT may be necessary to elicit adequate stimuli during long-term youth athlete development.

Additionally, based on the current scientific knowledge, it seems that there is no significant difference in muscle strength and/or hypertrophy gains between non-failure training and training to failure [28]. Therefore, it would be unnecessary to systematically train to failure (i.e. on each set) to increase a youth athlete's strength to a greater extent than a workout where sets conclude with a few repetitions left in reserve. It is therefore quite possible, depending on individual preferences, to choose one or the other method, although minimizing failure might also be interesting to prevent overtraining.

In view of the mentioned, when introducing RT to a youth athlete's routine, especially given the already high demands associated with their respective sport modalities, it seems reasonable to prescribe an appropriate repetition range initially. This approach allows for the development of technical competency and the acquisition of a base level of adaptation. Over time, the external load can be increased as technique proficiency improves. In this sense, a beginner may be prescribed 1–2 sets of 15–20 repetitions with a light or moderate load (50%–70% 1RM or equivalent). As exposure to RT increases, the prescription may be augmented to 2–3 sets of 8–12 repetitions with a heavier load (70%–85% 1RM). When technical expertise is appropriate, lower volumes (3–5 sets of 3–8 repetitions) and higher loads (> 85% 1RM) can be introduced to optimize training adaptations.

Table 4 Studies assessing muscle hypertrophy response to RT in children and adolescents through gold-standard methods

Reference	Participants			RT Characteristics	Results
	N	Age	Sex		
Mersch and Stoboy [49]	T: 2	Prepubertal	M	10 weeks unilateral isometric leg training	↑ QCSA: 4.0%–9.2%
Ramsay et al. [63]	T: 13 C: 13	Prepubertal 10.5–11.4 years	M	20 weeks bilateral dynamic upper- and lower-body training (3 times/w, 3–5 sets, 5–12 RM, 70%–85% 1RM)	↔ QCSA ↔ EFCSA
Fukunaga et al. [24]	T: 52 C: 47	Prepubertal 6.9–11.2 years	M/F	12 weeks bilateral maximum isometric contractions of elbow flexors (3 times/w, 2 sets, 3 reps, 10 s)	↑ EFCSA: 7%–15%
Granacher et al. [27]	T: 17 C: 15	Prepubertal 8.6 ± 0.5 years	M/F	10 weeks bilateral dynamic lower-body training (2 times/w, 3 sets, 10–12 RM, 70%–80% 1RM)	↔ QCSA

T training group, *C* control group, *QCSA* quadriceps cross-sectional area, *EFCSA* elbow flexors cross-sectional area, *F* female, *M* male, *1RM* one maximum repetition, *w* week; relative change values (%) are expressed in comparison to baseline values

RT Inter-set Resting Interval

Due to the limited number of studies reporting the duration of rest between sets, this author has chosen not to include this information in Tables 1, 2 and 3. Nevertheless, the inter-set resting interval is another variable commonly manipulated in RT programs, it is worth briefly discussing what the literature may indicate regarding the most appropriate duration of rest between sets, which should be influenced by parameters like RT intensity and volume.

Although limited evidence regarding the optimal rest periods for youth-based RT, available research indicates that children can recover more rapidly from fatigue-inducing resistance exercise [89]. It has been suggested that children are less likely to suffer muscle damage following such exercise, owing to the increased pliability of their muscle tissue [17], thus rest periods of approximately 1 min may be sufficient for inexperienced children. However, a recent meta-analytic review revealed that long inter-set resting periods (i.e. 3–4 min) were most effective for improving muscle strength following RT in youth athletes. It is likely that longer resting periods allow athletes to maintain higher volumes and intensities during each set, thereby maximizing long-term muscle strength gains [44]. Hence, while beginners may cope with RT demands using shorter rest intervals (e.g. 1 min), it is reasonable to assume that these intervals should be extended as children enter adolescence and become more experienced, especially when exercises require high levels of skill, force or power production.

Final Considerations

There is a growing body of studies investigating the effects of RT programs on muscle strength, endurance and power of youth athletes. The present report attests the consistent positive effects of this method for this population, with most findings demonstrating improvements in muscle strength and power, and few in muscle endurance. Despite the promising prospects for in this field, the existing investigations suffer from the overlapping of diversified experimental designs, demonstrating that a need for further exploration. Presumably, the improvement in muscular fitness should be largely

Table 5 Potential procedures that can be employed to minimize RT-related injury factors in youth athletes

Injury factor	Adopted procedure
Preexisting injury	Communicate to clinician/modify and adapt RT design
Inadequate (use of) equipment	Education on safety use of equipment/adjustment or change of equipment
Insufficient recovery	Review RT design/employ subjective between-exercise or between-sessions resting scales/consider lifestyle factors (e.g. nutrition, sleep, overtraining)
Deficient exercise technique	Review and clear instructions/feedback on gesture
Unsafe environment	Move to an appropriate space/adequate equipment layout
Unpleasant workout	Consider changing some exercises or RT strategies (e.g. conventional training to a pyramid RT system) for a period/apply pleasure scales
Excessive exercise load and/or volume	Consider a slightly decrease in volume/consider the use of the 'Repetitions-in-Reserve' scale
Muscle and contralateral imbalance	Include training for both agonists and antagonists exercises/target a volume-matched from the weaker limb

Table 6 Suggested recommendations for youth athletes-based RT prescription

Variable	Beginner	Intermediate	Advanced
Frequency (RT sessions per week)	1–2	2–3	2–3
Intensity (%1RM)	50%–70%	70%–85%	≥ 85%
Volume (sets × repetitions)	1–2 × 12–15	2–3 × 8–12	3–5 × 3–8
Inter-set resting interval (min)	1–2	2–3	3–4

explained by the RT-induced muscle hypertrophy. The few and heterogeneous examinations up to date employing gold-standard methods for determining muscle hypertrophy, however, prevent definitive conclusions from being drawn. Future studies should aim to clarify the underpinning mechanisms contributing to the improvement in muscular fitness observed in youth athletes. Based on years of research, it appears that RT injury rates among youth participants are low and less concerning in well-designed, progressed, supervised and technique-oriented programs, which should be safely achieved through the guidance of experienced and certified professionals. Finally, to enhance RT-induced muscular fitness gains without increasing risk of injury, care must be taken to provide appropriate instruction and prescription for child and adolescent athletes. Although international consortia have disseminated RT recommendations for young participants, these guidelines do not necessarily apply to the athletic community. The suggestions on RT frequency, intensity volume and inter-set resting interval presented in this brief report are based on scientific evidence and represent an important starting point. However, it is imperative to establish more specific guidelines for youth athletes, encompassing other less investigated parameters, such as ideal warm-up, movement velocity, exercise selection, and order.

Funding The author is grateful to the Institutional Individual Research Program for his scholarship of productivity in research (#7-02-1166/2021).

Data availability Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The author has no conflicts of interest to declare.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

References

1. American College of Sports Medicine. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc. 2009;41(3):687–708.
2. American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. 8th ed. Baltimore: Lippincott, Williams and Wilkins; 2010.
3. Armstrong N, McManus AM. Physiology of elite young male athletes. In: Armstrong N, McManus AM, editors. The elite young athlete. Basel: Karger; 2011. pp. 1–22.
4. Baechle TR, Earle RW, Strength N, National Strength & Conditioning Association (US). Essentials of strength training and conditioning. 3rd ed. Champaign: Human Kinetics; 2008.
5. 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):547–61.
6. Benton JW. Epiphyseal fracture in sports. Phys Sports Med. 1982;10(11):62–71.
7. Brady TA, Cahill BR, Bodnar LM. Weight training-related injuries in the high school athlete. Am J Sports Med. 1982;10(1):1–5.
8. Rottensteiner C, Laakso L, Pihlaja T, Konttinen N. Personal reasons for withdrawal from team sports and the influence of significant others among youth athletes. Int J Sports Sci Coach. 2013;8(1):19–32.
9. Caine D, DiFiori J, Maffulli N. Physeal injuries in children's and youth sports: reasons for concern? Br J Sports Med. 2006;40(9):749–60.
10. Chaabene H, Lesinski M, Behm DG, Granacher U. Performance- and health-related benefits of youth resistance training. Sports Orthop Traumat. 2020;36(3):231–40.
11. Channell BT, Barfield JP. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. J Strength Cond Res. 2008;22(5):1522–7.
12. Chelly MS, Fathloun M, Cherif N, Ben Amar M, Tabka Z, Van Praagh E. Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. J Strength Cond Res. 2009;23(8):2241–9.
13. Christou M, Smilios I, Sotiropoulos K, Volaklis K, Pilianidis T, Tokmakidis SP. Effects of resistance training on the physical capacities of adolescent soccer players. J Strength Cond Res. 2006;20(4):783–91.
14. Contreras B, Vigotsky AD, Schoenfeld BJ, Beardsley C, McMaster DT, Reyneke JHT, Cronin JB. Effects of a six-week hip thrust vs. front squat resistance training program on performance in adolescent males: a randomized controlled trial. J Strength Cond Res. 2017;31(4):999–1008.
15. Cronin J, Sleivert G. Challenges in understanding the influence of maximal power training on improving athletic performance. Sports Med. 2005;35(3):213–34.
16. DeRenne C, Hetzler RK, Buxton BP, Ho KW. Effects of training frequency on strength maintenance in pubescent baseball players. J Strength Cond Res. 1996;10(1):8–14.

17. Eston R, Byrne C, Twist C. Muscle function after exercise-induced muscle damage: considerations for athletic performance in children and adults. J Exerc Sci Fit. 2003;1:85–96.
18. Faigenbaum A, Kraemer W, Blimkie C, Jeffreys I, Micheli LJ, Nitka M, Rowland TW. Youth resistance training: updated position statement paper from the National Strength and Conditioning Association. J Strength Cond Res. 2009;23(5):60–79.
19. Faigenbaum AD, Milliken LA, Westcott WL. Maximal strength testing in healthy children. J Strength Cond Res. 2003;17(1):162–6.
20. Faigenbaum AD, Myer GD. Resistance training among young athletes: safety, efficacy and injury prevention effects. Br J Sports Med. 2010;44(1):56–63.
21. Faigenbaum AD, Lloyd RS, MacDonald J, Myer GD. Citius, Altius, Fortius: beneficial effects of resistance training for young athletes. Br J Sports Med. 2016;50(1):3–7.
22. Falch HN, Haugen ME, Kristiansen EL, van den Tillaar R. Effect of strength vs. plyometric training upon change of direction performance in young female handball players. Int J Environ Res Public Health. 2022;19(11):6946.
23. Ferrete C, Requena B, Suarez-Arrones L, de Villarreal ES. Effect of strength and high-intensity training on jumping, sprinting, and intermittent endurance performance in prepubertal soccer players. J Strength Cond Res. 2014;28(2):413–22.
24. Fukunaga T, Funato K, Ikegawa S. The effects of resistance training on muscle area and strength in prepubescent age. Ann Physiol Anthropol. 1992;11(3):357–64.
25. González-Badillo JJ, Pareja-Blanco F, Rodríguez-Rosell D, Abad-Herencia JL, Del Ojo-López JJ, Sánchez-Medina L. Effects of velocity-based resistance training on young soccer players of different ages. J Strength Cond Res. 2015;29(5):1329–38.
26. Gorostiaga EM, Izquierdo M, Iturralde P, Ruesta M, Ibáñez J. Effects of heavy resistance training on maximal and explosive force production, endurance and serum hormones in adolescent handball players. Eur J Appl Physiol Occup Physiol. 1999;80(5):485–93.
27. Granacher U, Goesele A, Roggo K, Wischer T, Fischer S, Zuerny C, Gollhofer A, Kriemler S. Effects and mechanisms of strength training in children. Int J Sports Med. 2011;32(5):357–64.
28. Grgic J, Schoenfeld BJ, Orazem J, Sabol F. Effects of resistance training performed to repetition failure or non-failure on muscular strength and hypertrophy: a systematic review and meta-analysis. J Sport Health Sci. 2022;11(2):202–11.
29. Gumbs VL, Segal D, Halligan JB, Lower G. Bilateral distal radius and ulnar fractures in adolescent weight lifters. Am J Sports Med. 1982;10(6):375–9.
30. Hammami M, Negra Y, Shephard RJ, Chelly MS. The Effect of standard strength vs. contrast strength training on the development of sprint, agility, repeated change of direction, and jump in junior male soccer players. J Strength Cond Res. 2017;31(4):901–12.
31. Harries SK, Lubans DR, Callister R. Comparison of resistance training progression models on maximal strength in sub-elite adolescent rugby union players. J Sci Med Sport. 2016;19(2):163–9.
32. Hetzler R, DeRenne C, Buxton B, Ho KW, Chai DX, Seichi G. Effects of 12 weeks of strength training on anaerobic power in prepubescent male athletes. J Strength Cond Res. 1997;11(3):174–81.
33. Huang R, Zhang M, Huang L, Chen Z, Mo Y, Gao Y. Effects of lower-extremity explosive strength on youth judo athletes adopting different types of power-based resistance training. Front Physiol. 2023;14:1065036.
34. Jayanthi N, Pinkham C, Dugas L, Patrick B, Labella C. Sports specialization in young athletes: evidence-based recommendations. Sports Health. 2013;5(3):251–7.
35. Jenkins NH, Mintowt-Czyz WJ. Bilateral fracture-separations of the distal radial epiphyses during weight-lifting. Br J Sports Med. 1986;20(2):72–3.
36. Kerr ZY, Collins CL, Comstock RD. Epidemiology of weight training-related injuries presenting to United States emergency departments, 1990 to 2007. Am J Sports Med. 2010;38(4):765–71.
37. Klusemann MJ, Pyne DB, Fay TS, Drinkwater EJ. Online video-based resistance training improves the physical capacity of junior basketball athletes. J Strength Cond Res. 2012;26(10):2677–84.
38. Kotzamanidis C, Chatzopoulos D, Michailidis C, Papaiakovou G, Patikas D. The effect of a combined high-intensity strength and speed training program on the running and jumping ability of soccer players. J Strength Cond Res. 2005;19(2):369–75.
39. Kraemer WJ, Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. Med Sci Sports Exerc. 2004;36(4):674–88.
40. Legerlotz K, Marzilger R, Bohm S, Arampatzis A. Physiological adaptations following resistance training in youth athletes-a narrative review. Pediatr Exerc Sci. 2016;28(4):501–20.
41. Lesinski M, Prieske O, Granacher U. Effects and dose-response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. Br J Sports Med. 2016;50(13):781–95.
42. Lillegard WA, Brown EW, Wilson DJ, Henderson R, Lewis E. Efficacy of strength training in prepubescent to early postpubescent males and females: effects of gender and maturity. Pediatr Rehabil. 1997;1(3):147–57.
43. Lloyd RS, Oliver JL, Faigenbaum AD, Howard R, De Ste Croix MBA, WilliamsCA, Best TM, Alvar BA, Micheli LJ, Thomas DP, Hatfield DL, Cronin JB, Myer GD. Long-term athletic development- part1: a pathway for all youth. J Strength Cond Res. 2015;29(5):1439–50.
44. Longo AR, Silva-Batista C, Pedroso K, de Salles Painelli V, Lasevicius T, Schoenfeld BJ, Aihara AY, de Almeida Peres B, Tricoli V, Teixeira 1EL. Volume load rather than resting interval influences muscle hypertrophy during high-intensity resistance training. J Strength Cond Res. 2022;36(6):1554–9.
45. Maestroni L, Read P, Bishop C, Papadopoulos K, Suchomel TJ, Comfort P, Turner A. The benefits of strength training on musculoskeletal system health: practical applications for interdisciplinary care. Sports Med. 2020;50(8):1431–50.
46. Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. Br J Sports Med. 2007;41(6):349–55.
47. McIntosh AS. Rugby injuries. Med Sport Sci. 2005;49:120–39.
48. McQuilliam SJ, Clark DR, Erskine RM, Brownlee TE. Effect of high-intensity vs. moderate-intensity resistance training on strength, power, and muscle soreness in male academy soccer players. J Strength Cond Res. 2023;37(6):1250–8.
49. Mersch F, Stoboy H. Strength training and muscle hypertrophy in children. In: Oseid S, Carlsen KH, editors. Children and exercise XIII. Champaign: Human Kinetics; 1989. pp. 165–82.
50. Mesfar A, Hammami R, Selmi W, Gaied-Chortane S, Duncan M, Bowman TG, Nobari H, van den Tillaar R. Effects of 8-week in-season contrast strength training program on measures of athletic performance and lower-limb asymmetry in male youth volleyball players. Int J Environ Res Public Health. 2022;19(11):6547.
51. Michaleff ZA, Kamper SJ. Effects of resistance training in children and adolescents: a meta-analysis. Br J Sports Med. 2011;45(6):755.
52. Moir GL. Muscular endurance. In: Miller T, editor. NSCA's guide to tests & assessments. Champaign: Human Kinetics; 2012. pp. 193–216.
53. Moore DR, Young M, Phillips SM. Similar increases in muscle size and strength in young men after training with maximal

shortening or lengthening contractions when matched for total work. Eur J Appl Physiol. 2012;112(4):1587–92.
54. Moore SD, Uhl TL, Kibler WB. Improvements in shoulder endurance following a baseball-specific strengthening program in high school baseball players. Sports Health. 2013;5(3):233–8.
55. Myer GD, Jayanthi N, Difiori JP, Faigenbaum AD, Kiefer AW, Logerstedt D, Micheli LJ. Sport specialization, Part I: does early sports specialization increase negative outcomes and reduce the opportunity for success in young athletes? Sports Health. 2015;7(5):437–42.
56. Naimo MA, Gu JK. The relationship between resistance training frequency and muscle quality in adolescents. Int J Environ Res Public Health. 2022;19(13):8099.
57. Negra Y, Chaabene H, Hammami M, Hachana Y, Granacher U. Effects of high-velocity resistance training on athletic performance in prepuberal male soccer athletes. J Strength Cond Res. 2016;30(12):3290–7.
58. Ozmun JC, Mikesky AE, Surburg PR. Neuromuscular adaptations following prepubescent strength training. Med Sci Sports Exerc. 1994;26(4):510–4.
59. Peterson MD, Rhea MR, Alvar BA. Maximizing strength development in athletes: a meta-analysis to determine the dose-response relationship. J Strength Cond Res. 2004;18(2):377–82.
60. Pfeiffer RD, Francis RS. Effects of strength training on muscle development in prepubescent, pubescent and postpubescent males. Phys Sportsmed. 1986;14(9):134–43.
61. Piazza M, Battaglia C, Fiorilli G, Innocenti G, Iuliano E, Aquino G, Calcagno G, Giombini A, Cagno AD. Effects of resistance training on jumping performance in pre-adolescent rhythmic gymnasts: a randomized controlled study. Ital J Anat Embryol. 2014;119(1):10–9.
62. Prieske O, Muehlbauer T, Borde R, Gube M, Bruhn S, Behm DG, Granacher U. Neuromuscular and athletic performance following core strength training in elite youth soccer: role of instability. Scand J Med Sci Sports. 2016;26(1):48–56.
63. Ramsay JA, Blimkie CJ, Smith K, Garner S, MacDougall JD, Sale DG. Strength training effects in prepubescent boys. Med Sci Sports Exerc. 1990;22(5):605–14.
64. Rians CB, Weltman A, Cahill BR, Janney CA, Tippett SR, Katch FI. Strength training for prepubescent males: is it safe? Am J Sports Med. 1987;15(5):483–9.
65. Rodríguez-Rosell D, Franco-Márquez F, Mora-Custodio R, González-Badillo JJ. Effect of high-speed strength training on physical performance in young soccer players of different ages. J Strength Cond Res. 2017;31(9):2498–508.
66. Rose MS, Emery CA, Meeuwisse WH. Sociodemographic predictors of sport injury in adolescents. Med Sci Sports Exerc. 2008;40(3):444–50.
67. Ryan JR, Salciccioli GG. Fractures of the distal radial epiphysis in adolescent weight lifters. Am J Sports Med. 1976;4(1):26–7.
68. Sadres E, Eliakim A, Constantini NW, Lidor R, Falk B. The effect of long-term resistance training on anthropometric measures, muscle strength, and self concept in pre-pubertal boys. Ped Exerc Sci. 2007;13(4):357–72.
69. Sánchez Pastor A, García-Sánchez C, Marquina Nieto M, de la Rubia A. Influence of strength training variables on neuromuscular and morphological adaptations in prepubertal children: a systematic review. Int J Environ Res Public Health. 2023;20(6):4833.
70. Sander A, Keiner M, Wirth K, Schmidtbleicher D. Influence of a 2-year strength training programme on power performance in elite youth soccer players. Eur J Sport Sci. 2013;13(5):445–51.
71. Santos EJ, Janeira MA. The effects of resistance training on explosive strength indicators in adolescent basketball players. J Strength Cond Res. 2012;26(10):2641–7.
72. Sarabia JM, Fernandez-Fernandez J, Juan-Recio C, Hernández-Davó H, Urbán T, Moya M. Mechanical, hormonal and psychological effects of a non-failure short-term strength training program in young tennis players. J Hum Kinet. 2015;45:81–91.
73. Schneiker KT, Fyfe JJ, Teo SYM, Bishop DJ. Comparative effects of contrast training and progressive resistance training on strength and power-related measures in subelite Australian rules football players. J Strength Cond Res. 2023;37(7):1440–8.
74. Shiromaru FF, de Salles PV, Silva-Batista C, Longo AR, Lasevicius T, Schoenfeld BJ, Aihara AY, Tricoli V, de Almeida Peres B, Teixeira EL. Differential muscle hypertrophy and edema responses between high-load and low-load exercise with blood flow restriction. Scand J Med Sci Sports. 2019;29(11):1713–26.
75. Smith A, Loud K. Special populations. In: Chan K, Micheli L, Smith A, editors. F.I.M.S. team physical manual. 2nd ed. Hong Kong: CD Concept; 2006. pp. 206–34.
76. Sothern M, Loftin M, Suskind R, Udall JN, Blecker U. The health benefits of physical activity in children and adolescents: implications for chronic disease prevention. Eur J Pediatr. 1999;158(4):271–4.
77. Sothern MS, Loftin JM, Udall JN, Suskind RM, Ewing TL, Tang SC, Blecker U. Safety, feasibility, and efficacy of a resistance training program in preadolescent obese children. Am J Med Sci. 2000;319(6):370–5.
78. Styles WJ, Matthews MJ, Comfort P. Effects of strength training on squat and sprint performance in soccer players. J Strength Cond Res. 2016;30(6):1534–9.
79. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. Sports Med. 2016;46(10):1419–49.
80. Tran TT, Nimphius S, Lundgren L, Secomb JL, Farley OR, Haff GG, Newton RU, Brown LE, Sheppard JM. 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.
81. Tsimahidis K, Galazoulas C, Skoufas D, Papaiakovou G, Bassa E, Patikas D, Kotzamanidis C. The effect of sprinting after each set of heavy resistance training on the running speed and jumping performance of young basketball players. J Strength Cond Res. 2010;24(8):2102–8.
82. Vingren JL, Kraemer WJ, Ratamess NA, Anderson JM, Volek JS, Maresh CM. Testosterone physiology in resistance exercise and training: the up-stream regulatory elements. Sports Med. 2010;40(12):1037–53.
83. Walia BN, Bhalla AK, Suri S. Reliability of skinfold calipers as a tool for measuring body fat in human beings. Indian J Med Res. 1992;96:255–7.
84. Weakley JJS, Till K, Darrall-Jones J, Roe GAB, Phibbs PJ, Read DB, Jones BL. Strength and conditioning practices in adolescent rugby players: relationship with changes in physical qualities. J Strength Cond Res. 2019;33(9):2361–9.
85. Weiss AP, Sponseller PD. Team physician #5. Salter-Harris type I fracture of the distal radius due to weightlifting. Orthop Ver. 1989;18(2):233–5.
86. West DW, Burd NA, Tang JE, Moore DR, Staples AW, Holwerda AM, Baker SK, Phillips SM. Elevations in ostensibly anabolic hormones with resistance exercise enhance neither training-induced muscle hypertrophy nor strength of the elbow flexors. J Appl Physiol. 2010;108(1):60–7.
87. Weston M, Hibbs AE, Thompson KG, Spears IR. Isolated core training improves sprint performance in national-level junior swimmers. Int J Sports Physiol Perform. 2015;10(2):204–10.
88. Wolfe BL, LeMura LM, Cole PJ. Quantitative analysis of single- vs. multiple-set programs in resistance training. J Strength Cond Res. 2004;18(1):35–47.
89. Zafeiridis A, Dalamitros A, Dipla K, Manou V, Galanis N, Kellis S. Recovery during high-intensity intermittent

anaerobic exercise in boys, teens, and men. Med Sci Sports Exerc. 2005;37(3):505–12.