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REVIEW / SPECIAL ISSUE

Performance- and health-related benefits of youth resistance training

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Summary

There is ample evidence that youth resistance training (RT) is safe, joyful, and effective for different markers of performance (e.g., muscle strength, power, linear sprint speed) and health (e.g., injury prevention). Accordingly, the first aim of this narrative review is to present and discuss the relevance of muscle strength for youth physical development. The second purpose is to report evidence on the effectiveness of RT on muscular fitness (muscle strength, power, muscle endurance), on movement skill performance and injury prevention in youth. There is evidence that RT is effective in enhancing measures of muscle fitness in children and adolescents, irrespective of sex. Additionally, numerous studies indicate that RT has positive effects on fundamental movement skills (e.g., jumping, running, throwing) in youth regardless of age, maturity, training status, and sex. Further, irrespective of age, sex, and training status, regular exposure to RT (e.g., plyometric training) decreases the risk of sustaining injuries in youth. This implies that RT should be a meaningful element of youths' exercise programming. This has been acknowledged by global (e.g., World Health Organization) and national (e.g., National Strength and Conditioning Association) health- and performance-related organizations which is why they recommended to perform RT as an integral part of weekly exercise programs to promote muscular strength, fundamental movement skills, and to resist injuries in youth.

Keywords
Muscle strength – muscle power – strength training – children – adolescents

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Leistungs- und gesundheitsbezogene Wirkungen von Krafttraining mit Heranwachsenden

Zusammenfassung

Die aktuelle Literatur zum Krafttraining mit Kindern und Jugendlichen zeigt

Introduction

It is well-known that physical activity is vital to maintain and/or promote health, irrespective of age, maturation status, and sex [52,64]. Sufficient amounts of daily physical activity are particularly important for a healthy upbringing of children and adolescents [45,59]. There is evidence from observational and experimental studies that different intervention programs have the potential to improve markers of health (e.g., improved blood lipid profile, increased bone density) [64]. Accordingly, the world health organization (WHO) propagates that youth aged 5-17 years should accumulate a minimum of 60 minutes of moderate-to-vigorous physical activity (MVPA) daily to achieve health benefits [64]. Accompanying to the rather general physical activity guidelines, WHO recommends youth to perform resistance training (RT) at least three times per week to strengthen muscles and bones [54,64].

Unfortunately, many children around the globe are not sufficiently physically active [64]. In fact, 81% of youth aged 11 to 17 years do not meet WHO guidelines [66]. In addition, there appears to be a significant and large effect with adolescents being less active than children and girls showing lower physical activity levels than boys [65]. Faigenbaum and colleagues introduced a specific term for youth who do not meet WHO physical activity guidelines [22,24]. This phenomenon has been denoted as "exercise deficit disorder" (EDD). These authors suggested that deficits in muscle strength could be the starting point for sedentary behavior [22,24]. More specifically, children with insufficient levels of muscle strength may lack an important prerequisite to develop fundamental movement skills such as running, jumping, and throwing. Accordingly, they suffer from poor movement skill competency which leads to low movement confidence and may subsequently cause sedentary behavior [22]. Taken together, deficits in muscle strength may act as a trigger to start a negative spiral leading to adverse health outcomes such as overweight or obesity (Fig. 1) [19,22].

The term "*dynapenia*" (Greek translation for poverty of strength,

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eindrücklich, dass ein altersgerechtes und fachlich angeleitetes Krafttraining eine sichere, freudvolle und effektive Maßnahme für die Leistungsentwicklung (z. B. Muskelkraft, Schnellkraft, Sprintgeschwindigkeit) und Gesundheitserhaltung (z. B. Verletzungsprävention) von Heranwachsenden darstellt. Einerseits ist es das Ziel dieses narrativen Übersichtsartikels, die Relevanz der Muskelkraft für die körperliche Entwicklung von Heranwachsenden zu diskutieren. Andererseits sollen aktuelle Befunde zur Effektivität von Krafttraining auf die muskuläre Fitness (Maximal-/Schnellkraft, Kraftausdauer), elementare Bewegungsfertigkeiten (z.B. Springen, Rennen, Werfen) sowie die Verletzungsprävention bei Kindern und Jugendlichen beschrieben werden. Die aktuelle Literatur belegt, dass Krafttraining die Muskelkraft, die Schnellkraft und die Kraftausdauer von Kindern und Jugendlichen unabhängig vom Geschlecht verbessern kann. Weiterhin zeigen Studien, dass trainingsbedingte Verbesserungen der muskulären Fitness auf elementare Bewegungsfertigkeiten transferieren. Diese Wirkungen sind unabhängig vom Alter, der biologischen Reife, dem Trainingsstatus und dem Geschlecht der Trainierenden. Zudem verringert regelmäßiges Krafttraining das Verletzungsrisiko der Heranwachsenden unabhängig von Alter, Geschlecht und Trainingsstatus. Aufgrund dieses breiten Wirkungsspektrums sollte Krafttraining ein elementarer Bestandteil des Trainings von Heranwachsenden darstellen. Nationale (National Strength and Conditioning Association) sowie internationale (Weltgesundheitsorganisation) gesundheits- und leistungsorientierte Standesgesellschaften haben die positiven Wirkungen von Krafttraining erkannt und in ihre Bewegungsempfehlungen für Kinder und Jugendliche übernommen.

Schlagwörter
Maximalkraft- Schnellkraft- Widerstandstraining- Kinder- Jugendliche

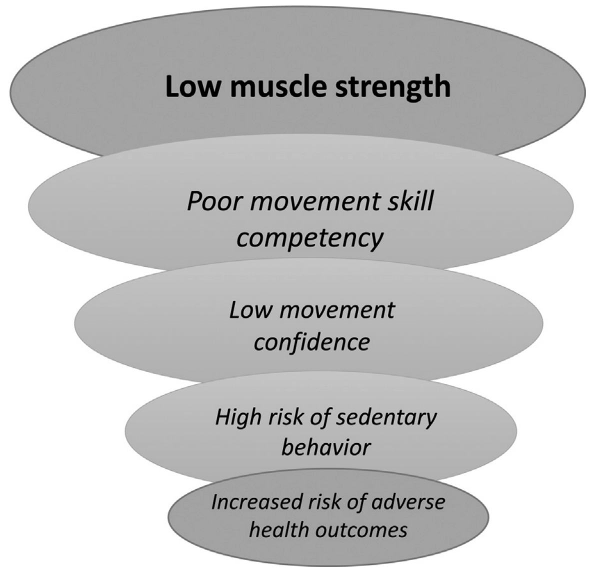

Figure 1
Adverse health outcomes caused by low muscle strength during childhood (modified from Faigenbaum et al. [19]).

power, or force) has originally been used in a geriatric context and it describes poor levels of muscular strength and power not related to neurological or muscular disease [16,23]. Today, it also characterizes abnormally low levels of muscular strength that limit a child's ability to perform activities of daily living, such as climbing stairs [16,23]. The introduction of the term "*dynapenia*" in a pediatric context originates from the observation of secular declines in youths' muscle strength and power. In fact, data from a 10-year longitudinal study [11] with 10-year-olds from Great Britain indicated a performance decline in bent arm hang, sit-up, and hand-grip strength by 25.9%, 27.1%, and 6.3%, respectively. More recently, Fraser et al. [27] studied secular changes between 1985 and 2015 in standing long jump performance of Australian children aged 11-12 years. These authors demonstrated that in 1985 children jumped on average 16.4 cm (11.2%) longer compared with children in 2015. Moreover, results from a longitudinal study in which the same subjects were tracked over 20 years indicate that youth suffering from *dynapenia* are at increased risk of becoming *dynapenic* adults (relative risk = 4.70 and 4.06 for muscle strength and power, respectively) [28].

An effective means to counteract pediatric *dynapenia* is the application of youth resistance training in different settings (e.g., sports clubs, schools, etc). Of note, RT involves the progressive use of a variety of loads and movement velocities as well as different training modalities (e.g., weight training machines, free weights, elastic bands, plyometrics) [21]. Today, it is well-established that RT in youth is safe, effective and joyful if it is adequately designed and supervised [18]. For instance, Hamill [33] studied injury rates in youth aged 13-16 years while performing different sports. These authors revealed that RT resulted in markedly lower injury rates (0.0035 injuries per 100 participation hours) compared with soccer (0.014 injuries per 100 participation hours) and rugby (0.8000 injuries per 100 participation hours). Accordingly and compared with other sports (e.g., rugby, soccer), RT can be considered safe [33]. Unfortunately, many coaches and physical education (PE) teachers are still hesitant in applying RT in sports clubs or schools due to misconceptions from the 1970-1980s that was primarily reported in the form of anecdotal evidence. For instance, it has been postulated that RT induces damage to the growth plates. Today, a plethora of literature indicates the positive effects of RT on markers of performance and health in youth [29,39]. Therefore, it is timely to summarize these findings in an attempt to provide strength and conditioning specialists, PE teachers, and decision-makers with evidence-based information on the relevance and effectiveness of youth RT on variables of performance and health (i.e., injury prevention). Accordingly, the first aim of this narrative review is to present and discuss the relevance of muscle strength for youth physical development. The second objective is to report evidence-based information on the effectiveness of RT on muscular fitness, movement skill performance, and injury prevention in youth.

Methods

Given that the scope of this review article is large and addresses many relevant topics within youth RT, we decided to summarize the main findings in the form of a narrative review [26]. A typical characteristic of narrative review articles is a comprehensive literature overview on a topic with a rather broad scope [3]. As such, this review presents findings on the relevance of muscle strength for physical development. It further illustrates performance-related effects of RT on muscular fitness and movement skill performance in youth. Health-related aspects of RT will be discussed with regards to injury prevention in young healthy populations. A literature search in the electronic databases PubMed and Google Scholar was conducted. The following keywords were used either separately or in combination: children, adolescents, youth, strength training, resistance training, physical activity, muscular fitness, muscle strength, muscle power, muscle endurance, physical development, movement skill development, injury prevention. Only studies were included that addressed a research question related to the main purposes of this narrative review article.

The relevance of muscle strength for youth physical development

It is well-known that timing and tempo of youth physical development follow a non-linear pathway due to growth and maturation [44]. An important component of physical fitness is muscular fitness which is an umbrella term for muscle strength, muscle power, and local muscular endurance. Catley and Tomkinson [10] studied the development of strength using the handgrip test in a large sample of male and female 9 to 15 year olds. These authors reported an almost linear increase up to the adolescent age. Thereafter, a marked acceleration in strength development was observed, especially in males. Specifically, males outperformed females with small differences before puberty (approximately 10%), becoming more apparent around and after puberty (up to approximately 30%) [10]. Likewise, a 10% difference in jump performance (standing long jump test) can be found at the age of 9 years (prepuberal) in favor of boys [10]. However, this sex-related difference increases to >15% after puberty (14-15 years). Similar observations were reported for proxies of local muscular endurance (i.e., number of sit-ups during 180 s) [10].

The increase in performance differences between boys and girls in muscle strength at the onset of puberty is primarily due to elevated levels of circulating testosterone in boys [7]. In fact, the increased secretion of anabolic hormones (e.g., testosterone) triggers a considerable increase in lean mass and muscle strength [7]. It is noteworthy that inter-individual differences in biological maturation influence muscle strength development, particularly during the adolescent years with early-maturers displaying greater strength development than late-maturers [44].

It is well-known that the neuromuscular system displays large adaptive capacities (i.e., plasticity) over the growing years [36]. For instance, a rapid change in myelination of the central nervous system is a main characteristic during the growing years [55]. Indeed, this period represents an unparalleled opportunity to develop muscle strength and fundamental movement skills [41]. It has been demonstrated that the size of muscle fibers increases 4-to-5 fold from early childhood to adolescence [50]. This gain in muscle mass occurs without structured training and it leads to increased muscle strength [44].

Lloyd et al.[42] proposed the Composite Youth Physical Development (CYPD) model as a guideline to promote physical fitness development according to age, sex and maturational status in healthy children and adolescents (Tables 1 and 2).

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Table 1. Composite youth physical development model for males (adapted from Lloyd et al. [42]). Note: The number of dots displays the importance of the respective component of physical fitness during the different developmental stages. FMS: fundamental movement skills; SSS: sport-specific skills; PHV: peak height velocity.

Chronological age (years)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21+
Age periods	Early childhood			Middle childhood					Adolescence										Adulthood	
Maturational status	Pre-PHV									PHV			Post-PHV							
Adaptations	*Mostly neural*									*Combined neural and structural/hormonal*										
FMS	••••			••••			••		••											
SSS	•			••			•••		••••											
Mobility	••			•••					••											
Agility	••			••••					••••						•••					
Speed	••			••••					••••						•••					
Power	••			••••					••••						••••					
Strength	••••			••••					••••						••••					
Hypertrophy	•								•		••••								•••	
Endurance	•			•						•							•••			

Table 2. Composite youth physical development model for females (adapted from Lloyd et al. [42]). Note: The number of dots displays the importance of the respective component of physical fitness during the different developmental stages. FMS: fundamental movement skills; SSS: sport-specific skills; PHV: peak height velocity.

Chronological age (years)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21+
Age periods	Early childhood			Middle childhood							Adolescence									Adulthood
Maturational status	Pre-PHV											PHV			Post-PHV					
Adaptations	*Mostly neural*											*Combined neural and structural/hormonal*								
FMS	••••			••••				••			••									
SSS	•			••				•••			••••									
Mobility	••			••••							••									
Agility	••			••••							••••						•••			
Speed	••			••••							••••						•••			
Power	••			••••							••••						••••			
Strength	••••			••••							••••						••••			
Hypertrophy	•										•			••••						•••
Endurance	•			•								•						•••		

The CYPD model is based on experimental data related to the development of individual measures and it places an emphasis on the long-term development of physical fitness for athletes and the general youth population. More specifically, the CYPD model questions the concept of "windows of opportunity" (i.e., periods of optimal trainability) and acknowledges that all components of physical fitness are trainable, irrespective of the stage of development in males and females. Notably, the development and promotion of muscular strength during all stages of physical development is a central tenet of the model.

Effects of resistance training on fundamental movement skills in youth

Fundamental movement skills (FMS) include basic locomotor (e.g., running, jumping, hopping) and object control skills (throwing, catching, and kicking) [2,14]. Most of the locomotor and object control skills should be mastered at the end of childhood [38]. Current evidence indicates that RT is key for FMS development. Lloyd et al. [43] investigated the effects of different types of RT (i.e., traditional RT, plyometric training, combined traditional RT with plyometric training) over a period of six weeks on FMS (i.e., vertical jump, linear sprint) in

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untrained pre- and post-puberal boys. Irrespective of the type of RT and maturity status, all training groups but not control showed significant training-related improvements in measures of sprint and jump performances. Further, Hammami et al. [34] examined the effects of eight weeks of RT vs. complex training vs. control on FMS (e.g., vertical jump, linear sprint) in young male soccer players aged 16±0.5 years. They found that both RT programs showed significant improvements in vertical jump, linear sprint, and change-of-direction speed performances at post compared with the control group. Behringer et al. [5] conducted a systematic review with meta-analysis on the effects of RT on FMS in healthy trained and untrained children and adolescents aged 13.2 years. They found moderate effects of RT on running (standardized mean difference [SMD] = 0.53) and jumping (SMD = 0.54) performances as well as large effects on throwing (SMD = 0.99) performances. The same authors revealed no significant differences in performance gains between trained and untrained youth. They also showed that the type, time, and frequency of RT did not significantly moderate the effects of RT on FMS. Notably, Behringer et al. [5] reported that RT induced larger effects on FMS in younger compared with older individuals. In addition, RT using higher intensities was more effective compared with lower intensities on FMS. More recently, Collins and colleagues [13] conducted a systematic literature search with meta-analysis on the effects of RT on FMS in healthy trained and untrained children and adolescents. They demonstrated small-to-moderate effects of RT on vertical jump (e.g., countermovement jump), standing long jump, linear speed, squat jump, and throwing performances ($0.29 \leq$ SMD $\leq 0.0.73$). Unlike Behringer et al. [5], Collins et al. [13] could not find significant age effects. However, they revealed that training status and sex moderated RT-related effects on jump performances. More precisely, these authors showed that trained youth experienced larger RT-related improvements in their squat and standing long jump performances ($0.95 \leq$ SMD ≤ 1.66) compared with untrained youth ($0.23 \leq$ SMD ≤ 0.25). Further, their analyses indicated that boys improved their squat jump performance (SMD = 0.84) significantly more than girls (SMD = 0.21) following RT. Moreover, Peitz et al. [53] conducted a systematic review with comparative studies only and examined the effects of traditional RT and plyometric training on FMS (e.g., jumping, running) in healthy youth. Their findings showed that training-related adaptations appear to be moderated by the maturity status. Specifically, the authors revealed that traditional RT induced small and plyometric training large effects on FMS outcomes in prepuberals. Further, Peitz and colleagues revealed that the factor sex appeared not to have an impact following RT. With plyometric training, the situation appears to be more complex. While similar effects were found for prepuberal boys and girls, boys appear to show larger adaptive potential compared with girls during mid- and post-puberty.

The observed differences in outcomes between the above-cited systematic review using comparative studies and the previously reported meta-analyses could be due to methodological disparities such as the date of literature search or different inclusion criteria. The publication type could also play a prominent role (meta-analyses vs. comparative studies). Comparative studies assess the effects of different training descriptors while holding other variables constant. Meta-analyses synthesize results from different studies while ignoring important differences across the included original studies. Taken together, RT has positive effects on FMS in youth, irrespective of age, maturity, training status, and sex.

Effects of resistance training on muscular fitness in youth

Alongside its positive effects on FMS, RT is crucial for the development of muscular fitness. There is compelling evidence that RT generates positive effects on muscular fitness in youth, irrespective of age, maturation, and sex [17,21,31,40]. In terms of muscle strength, Granacher et al. [30] investigated the effects of ten weeks of machine-based high-intensity RT integrated into physical education classes on peak torque of the knee extensors/flexors in prepuberal children aged 9 years. These authors reported a significantly higher increase in peak torque in the intervention (12-19%) compared with the control group (0-6%). Moreover, Faigenbaum et al. [20] examined the effects of eight weeks of RT with one versus two training sessions per week on muscle strength in young boys and girls aged 7-12 years. These authors reported that both RT interventions were effective. However, significantly greater gains in 1-RM leg press performance were found following two (24.7%) compared with one (14.2%) weekly RT sessions. The control group showed hardly any changes over the experimental period (2.4%). Over the past years, findings from original studies have been statistically aggregated in the form of meta-analyses. Of note, many meta-analyses proved the effectiveness of RT on measures of muscular fitness in children and

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adolescents [5,25,37,46,51]. For example, Behringer et al. [6] investigated the effects of RT on muscle strength in trained and untrained children and adolescents. They included 42 original studies and revealed that RT produced large effects (SMD = 1.12) on measures of muscle strength. Likewise, Lesinski et al. [37] conducted a systematic review with meta-analyses on the effects of RT on muscle strength in trained youth. They included 43 original studies and revealed that RT showed large effects (SMD = 1.09) on proxies of muscle strength. Most importantly, a number of key stakeholders (e.g., National Strength and Conditioning Association, United Kingdom Strength and Conditioning Association, and The British Association of Sport and Exercises Sciences) have developed evidence-based position statements on the effects of RT on muscular fitness in youth [17,40,61]. All of these position papers concluded that RT has positive effects on muscular fitness in youth, irrespective of sex.

To achieve performance and health-related effects of RT in youth, adequate RT dosage has to be applied according to age, maturity level, and resistance training skill competency (RTSK). Faigenbaum et al. [18] reported dose-response relationships for youth RT if the goal is to enhance muscle strength. These authors considered RTSK (i. e., technical mastery when performing resistance-based exercises) of youth as the decisive factor with regards to the line of progression in terms of exercise prescription and programming. Children with low RTSK should perform 2 sessions per week with 1-2 sets per exercise at ≤60% of the 1-RM and performing moderate-to-fast movement velocities. For youth with medium RTSK, 2-3 weekly sessions should be applied with 2-4 sets per exercise and 6-12 repetitions per set at an intensity of ≤80% of the 1-RM and performing fast movement velocities. In terms of expert youth with high RTSK, 2-3 weekly sessions should be carried out with multiple sets (e.g., 5) per exercise and ≤6 repetitions per set at an intensity ≥85% 1-RM and performing fast movement velocities [18].

In summary, there is strong evidence indicating that RT has the potential to improve muscular fitness in youth (Fig. 2). Therefore, it is recommended to include RT as a fundamental element of youth fitness programming.

Effects of neuromuscular training on injury prevention in youth

Most research on injury preventive effects in youth sports have been conducted using neuromuscular training (NT). NT is an umbrella term that covers general (e.g., FMS) and specific (e.g., sport-specific actions) strength and conditioning activities like resistance, balance, core strength, plyometric, and agility exercises [48]. Therefore, we will focus in the following on the effects of NT on injury rate reduction in youth sports. Thereafter, we will report study outcomes on the effects of NT on lowering risk and rate of injuries in the general youth population.

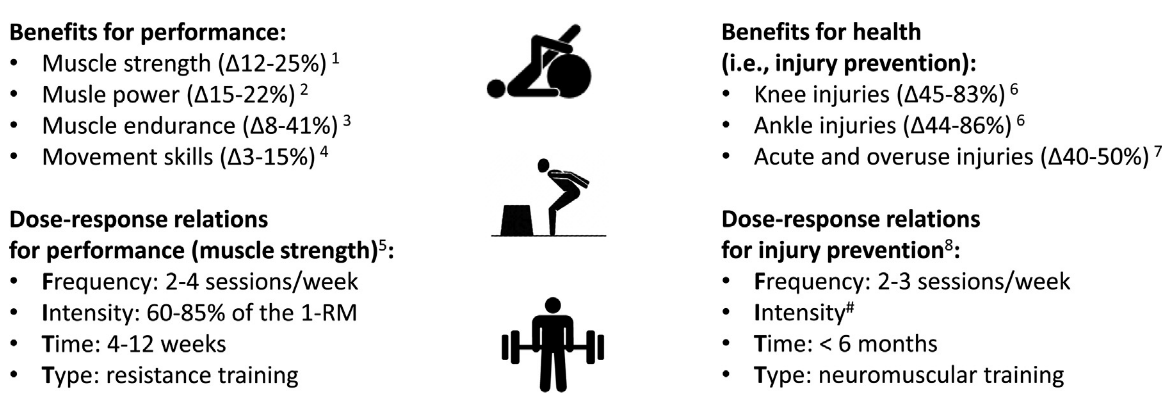

Figure 2
Benefits of youth resistance and/or neuromuscular training on markers of performance and health (i.e., injury prevention) as well as established dose-response relations according to the FITT principle. FITT stands for Frequency, Intensity, Time, Type.
References used in figure 2: [1] [20,30], [2] [49], [3] [32], [4] [4], [5] [18,37], [6] [15], [7] [35], [8] [60].
 # Training intensity is difficult to specify in multicomponent neuromuscular training programs which is why no information can be provided due to a lack of reported data.
RM: repetition maximum.

A meta-analysis of Emery et al. [15] included 25 studies on the effects of NT on injury rate ratio in youth team sport. Findings were promising and showed an average 36% reduction in lower limbs incidence rate ratio (IRR=0.64). These authors concluded that NT has a substantial overall injury protective effect in youth athletes which is in line with previous reviews on injury preventive effects in youth sports [1,35,57,58]. Another meta-analysis on the preventive effects of NT on anterior cruciate ligament (ACL) injuries in female athletes showed up to 68% risk reduction after training [62]. Recently, Steib et al. [60] conducted a meta-analysis and they examined the effects and dose-response relations of NT for injury prevention in youth athletes. These authors revealed that on average NT resulted in a 42% injury rate reduction. They additionally computed dose-response relations and showed that a training frequency of 2-3 weekly sessions with 10-to-15 minutes training time per session, and a total training volume of 30-to-60 minutes per week induced the largest preventive effects for lower extremity injuries in youth athletes. According to the same authors, these effects can be achieved after a total of 20-to-60 training sessions with training times <6 months. Taken together, NT should be included in youth strength and conditioning programs to lower injury rates [45].

Most research on NT and injury preventive effects has been conducted in youth athletes. However, it appears to be relevant for the general youth population as well (e.g., school PE classes). There is evidence that children with low movement competency and low levels of physical fitness are more vulnerable to injuries [12,47,63]. In fact, physical inactivity *per se* has been shown to represent a risk factor for physical activity-related injuries in children aged 10-12 years [8]. Of note, Collard et al. [12] studied the effects of a school-based physical activity program (i.e., strength, speed, flexibility, and coordination exercises) on injuries during PE in primary school children aged 10-12 years. The results of this study showed a substantial and relevant reduction in physical activity-related injury rate, particularly, in the least physically active children (~50% reduction in total injuries; hazard ratio = 0.47). Richmond et al. [56] investigated the effects of a 12 weeks high-intensity NT program delivered as a warm-up during the first 15 min of PE classes in students aged between 11-15 years. These authors reported a significant reduction in the rate of sustaining injuries following training (IRR = 0.30).

In sum, there is compelling evidence that neuromuscular training is an effective means to lower risk and rate of lower limbs injuries in young athletes and the general youth population.

Limitations

This narrative review has inherent methodological limitations that warrant discussion. First, in contrast to systematic reviews, narrative reviews do not cover all available scientific literature on a specific topic. Moreover, the reported literature in narrative reviews is usually subjectively selected by the authors which implies that the literature search is of less rigour [9]. Therefore, conclusions from narrative reviews could be limited by the pre-selected and included studies. However, an advantage of narrative compared with systematic reviews is the broader scope [9]. In our case, the effects of RT in youth on markers of performance and health (i.e., injury prevention). This rather broad scope could not be addressed in a systematic literature review. The second limitation of this research article that warrants discussion is the correct interpretation of dose-response relationships following resistance training in youth. In fact, dose-response relations are helpful for practitioners and coaches but from a scientific standpoint they should be viewed with caution and as a first crude estimate for exercise prescription according to a specific training goal (e.g., increases in muscle strength). Of note, some dose-response recommendations for youth RT appear to be based on anecdotal evidence or expert opinion [18] others were statistically aggregated [37,60]. In any case, they are methodologically limited. The reported dose-response relations (Fig. 2) are a good starting point for the design of youth resistance or NT programs. However, the reported dose-response relations should always be modified according to the individual needs (e.g., RTSC, maturational status, sex, major training goal).

Conclusions

RT should be integrated during all developmental stages to enhance muscular fitness and movement skill performance with the goal to promote physical development and to lower the rate of injuries in children and adolescents. There is evidence that youth RT is safe when properly designed, administered, and supervised. One might even dare to say that it could be harmful for youth not to regularly apply RT during the developmental stages. Future studies should particularly examine the role of potential moderating variables such as maturation and sex on RT-related effects on muscular fitness, FMS as well as injury risk and rate.

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Conflict of interest

All authors declare that they have no conflict of interest.

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