

Citius, Altius, Fortius: beneficial effects of resistance training for young athletes: Narrative review

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ABSTRACT

The motto of the Olympic Games is *Citius, Altius, Fortius* which is Latin for 'Faster, Higher, Stronger'. It is a clarion call to all competitors, including the youngest, to engage in training strategies that prepare athletes to be the best in the world. Existing research indicates that various forms of resistance training can elicit performance improvements in young athletes. Stronger young athletes will be better prepared to learn complex movements, master sport tactics, and sustain the demands of training and competition. An integrative training programme grounded in resistance training and motor skill development can optimise a young athlete's potential to maximise their athletic and sporting performance, while reducing the risk of a sports-related injury. Resistance training may be especially important for modern-day young athletes who are more likely to specialise in one sport at an early age at the expense of enhancing general physical fitness and learning diversified sport skills. Structured interventions that include qualified instruction; targeted movement practice; and strength and conditioning activities that are developmentally appropriate, progressive and technique driven are needed to attain a level of athleticism that is consistent with the Olympic motto.

Pierre de Coubertin adopted the Latin phrase *Citius, Altius, Fortius* as the Olympic motto after the formation of the International Olympic Committee in 1894. The spirit of the motto—*Faster, Higher, Stronger*—captures the significance of an athlete's physical prowess as well as the holistic aspirations of the Olympic movement. The motto calls on all competitors, including the youngest, to engage in training methods that are designed to prepare Olympic athletes to be the best in the world. The enduring impact of enhancing athleticism early in life on successful and sustainable sport participation later in life continues to be advanced in the study of paediatric exercise science and sports medicine.^{1–3} A systematic approach to long-term athletic development grounded in resistance training principles is needed to better prepare aspiring Olympic athletes for the long-term demands of sports training.⁴

Regular participation in a developmentally-appropriate resistance training programme that is purposely designed to enhance neuromuscular fitness and function (eg, agility, balance, coordination, reaction time and speed) is the foundation of athletic development for all aspiring young athletes.^{5–7} Existing research indicates that various forms of resistance training can elicit performance improvements in muscular strength,⁸ power production,⁹ running velocity,¹⁰ tennis serve velocity,¹¹

ball shooting speed,¹² change of direction speed,¹³ aerobic endurance,¹² dynamic balance,¹⁴ flexibility¹⁵ and general motor performance¹⁶ in children and adolescents. Leading professional organisations within the fields of paediatrics, sports medicine and exercise science advocate participation in youth resistance training programmes that are consistent with the individual needs and abilities of young athletes.⁴

From a sports performance perspective, stronger young athletes will be better prepared to learn complex movements, master sport tactics and withstand the demands of long-term sports training and competition.^{6 7 9 17} A developmental approach to physical conditioning can also enhance the health of youth and data indicate that young athletes who engage in multifaceted strength and conditioning programmes are more resistant to sports-related injuries.^{5 18 19} Moreover, young athletes who resistance train are more likely to achieve a level of physical performance which is consistent with optimising their potential to run faster, jump higher and be stronger.^{1 6 20} This review synthesises the current research related to resistance training for young athletes and provides evidence for incorporating resistance training into long-term athletic development programmes.

By definition, the term *resistance training* refers to a specialised method of conditioning which involves the progressive use of a wide range of resistive loads and a variety of training modalities designed to enhance health, fitness and athletic performance.⁴ While different resistance training programmes can be used to accomplish training goals that are associated with improvements in musculoskeletal health and athletic performance, the design of the programme (eg, training intensity, training volume and exercise choice) will influence the specific adaptations that take place. Young athletes who consistently participate in well-designed resistance training programmes can expect to achieve gains in muscular strength, power and motor skill prowess provided the training programme is routinely periodised in line with their individual needs, goals and abilities.

SLOWER, LOWER, AND WEAKER

While the potential physical and psychosocial advantages of youth sports participation are well known,^{21–23} these pleiotrophic benefits will only be realised if aspiring young athletes have a level of muscular fitness that prepares them for the demands of sports practice and competition. Ten year secular trends in muscular fitness in English children indicate declines in bent arm hang, sit up

performance and handgrip strength over the study period.²⁴ Similar trends were observed in selected measures of motor fitness (eg, shuttle run and plate tapping) in Dutch primary school children and muscular power (eg, long jump and vertical jump) in Spanish adolescents.^{25 26} Australian researchers reported low levels of motor skill competence in school-age youth, and noted a clear and consistent association between low competency in motor skills and inadequate levels of cardio-respiratory fitness.²⁷ These data illustrate the physical *illiteracy* of the next generation of aspiring Olympic athletes. In support of this contention, a 2-year investigation of 501 children between 6 and 10 years of age found that low motor competent children participated less in sports and had fewer opportunities for developing motor abilities and physical fitness.²⁸ Consequently, the growing number of children with low muscle strength and poor motor skills within the general population is likely to reduce the talent pool from which national governing bodies and professional sports organisations can recruit their next generation of elite athletes.

The divergence in performance between young athletes with low and high levels of muscular fitness may persist into adolescence and speculatively, this may prevent relatively weaker young athletes from catching up with their peers who possess average or high levels of relative strength.²⁹ Participation in organised youth sports alone does not ensure that young athletes will attain a level of muscular fitness that will optimise performance and limit injury risk. For example, reports indicate that many youth sports practices do not provide a sufficient amount of moderate to vigorous physical activity to meet daily recommendations because a large proportion of time is spent in sedentary or light physical activities.^{30 31} An integrative training programme grounded in resistance training combined with sport participation may help fill the critical need for young athletes to maximise athletic performance and maintain injury free competition.

Foundational strength

A high level of muscular fitness contributes to effective performance ability in young athletes, and a multidimensional strength and conditioning programme can improve performance on a wide range of physiological and skill assessments.^{20 32} Regardless of sporting success, young athletes who do not address neuromuscular deficits early in life are less likely to sustain high-level performance and more likely to suffer a 'preventable' sports injury. For example, weakness in the hamstrings,³³ supraspinatus³⁴ and middle trapezius³⁵ was associated with an increased risk of injury in, retrospectively, young female athletes, adolescent baseball pitchers and age-group swimmers.

A certain level of force-production and force-attenuation is required to perform all athletic movements, and therefore the importance of enhancing muscular fitness should be considered foundational to athletic development.^{7 20 36} Consequently, young athletes need qualified instruction, targeted movement practice and a progression of strength and conditioning activities that are developmentally appropriate, progressive and technique driven.³⁷⁻³⁹ This type of intervention may be particularly valuable for modern-day young athletes who may specialise in one sport at an early age at the expense of enhancing general physical fitness and learning diversified sport skills.^{40 41} Also, young athletes who engage in strength and conditioning activities without qualified instruction may have some resistance training experience, but their development is typically isolated to specific muscle-groups (eg, pectoral development from the bench press) and does not include technically proficient multijoint exercise

competency. Enhancing muscular strength should be a priority in any athletic development programme, as strength would appear to transcend all other fitness components.⁷ With the understanding that many factors can influence training adaptations and athletic performance, the driving impact of strength and conditioning on performance parameters is illustrated in figure 1.

SURVIVAL OF THE STRONGEST

New insights into the design of physical development programmes and periodisation strategies for young athletes have highlighted the importance of general physical preparation (ie, conditioning to develop fundamental performance characteristics) early in life.^{1 7 42} Adolescent athletes with muscle imbalances and relatively poor levels of muscular fitness are often unwilling and at times unable to perform desired movements, complete training sessions and finish competitive matches. The observable impact of poor muscular fitness on athletic performance has resulted in the development of long-term physical developmental models that are designed to improve the health, fitness and performance of young athletes.^{1 7 43}

Enhancing the physical literacy of youth to improve athletic prowess is not a novel concept.⁴⁴ However, an evidence-based approach to long-term physical development must include resistance training given its proven performance enhancing benefits.^{1 4 43} In addition to enhancing muscular strength, regular participation in a progressive resistance training programme for 2 years improved sprint speed up to 6% in elite youth soccer players compared to a group of age-matched players who participated only in regular soccer training.⁴⁵ Others reported favourable changes in performance measures in age-group swimmers,⁴⁶ preadolescent rhythmic gymnasts,⁴⁷ and adolescent basketball,⁴⁸ handball⁴⁹ and tennis players¹¹ following resistance training. Of potential relevance is that researchers monitored strength performance on the front and back squat exercises in 141 elite youth soccer players over 2 years and determined possible reference values in strength performance for these athletes.⁵⁰ These researchers suggested that relative strength (ie, 1 repetition maximum (RM)/body weight) in parallel squat performance for young soccer players and other athletes with resistance training experience should range from 0.7 for 11 to 12-year olds, 1.5 for 13 to 15-year olds, and 2.0 for 16 to



Figure 1 The driving influence of strength and power on parameters of athletic performance.

19-year olds.⁵⁰ Although these values are based on the performance of young soccer players and are only a starting point for referencing strength performance benchmarks, these do highlight the high degree of trainability in youth and the potential differences in strength performance between subelite and elite young athletes.

Trainability of youth

The ability of young athletes to adapt to resistance training is influenced by a nexus of anatomical and physiological processes at each stage of development in addition to the design of the training programme. The first few years of life are characterised by rapid changes in myelination of the central nervous system,⁵¹ and the effects of a well-designed resistance training programme that is designed to enhance neuromuscular fitness and stimulate intermuscular coordination may be most propitious and enduring.^{6 8 16} For example, weightlifting exercises, such as the snatch and clean and jerk, are explosive but highly controlled movements that require a high degree of technical skill. Significant gains in power performance have been reported in U-14 soccer players and adolescent American football players who performed weightlifting movements as part of a strength and conditioning programme.^{12 52}

Similar to learning a language or a musical instrument, education and instruction on proper resistance training techniques and procedures should start early in life and utilise age-related strategies to enhance learning, optimise outcomes and stimulate an ongoing interest in this type of training. Without early interventions, coaches at all levels will eventually need to address technical flaws and neuromuscular limitations which become harder to 'fix' when ingrained motor control patterns have developed over time. Owing to neuromuscular plasticity during the growing years, there is an unparalleled opportunity to target strength development early in life to set the stage for enhanced athletic prowess later in life.⁷

Meta-analytical findings indicate that children show greater training-induced gains in motor skill performance (eg, jumping, running and throwing) following structured resistance training than adolescents,¹⁶ and that injury prevention training programmes are more effective with earlier intervention before the onset of altered mechanics that may increase injury risk.^{19 53} Conversely, research shows that adolescents typically make greater absolute gains in muscular strength than their less mature peers.^{8 54} Of interest is that researchers examined the effects of different training methods on running sprint times in male youth.⁵⁵ They reported that plyometric training had the greatest effect on sprint times in children who were pre-peak height velocity children (≤ 12 years) and mid-peak height velocity youth (13–15 years), although combined training methods were most effective in post-peak height velocity adolescents.⁵⁵

Cumulatively, these findings underline a potential synergistic adaptation whereby the prescribed training stimulus complements naturally occurring adaptations. Since motor performance skills are essential components of sport movements, there is an opportunity during childhood to develop a basal level of strength and power in order to provide a strong foundation that can then be augmented with more advanced training strategies as confidence and competence to perform resistance exercise develops over time. Indeed, Van Praagh⁵⁶ suggested that neuromuscular training methods designed to improve the movement efficiency and muscular coordination of young athletes should begin early in life (5–9 years of age). However, regardless of the starting age, participation in a youth resistance training programme needs to be an ongoing commitment because

training-induced gains in strength and power are impermanent and tend to regress towards untrained control group values during the detraining period.^{57–59}

Resistance training skill competency

Well-designed resistance training programmes provide a needed opportunity for young athletes to enhance muscular fitness and improve resistance training skill competency (RTSC). In addition to evaluating the 'quantity' of resistance training performance (ie, how much weight was lifted), it is equally important to provide specific feedback on the 'quality' of the movement. As such, the term RTSC refers to the technical ability of performing a resistance-based exercise. This type of 'process' assessment involves the evaluation of movement patterns that are considered essential for mastery of a particular exercise.^{60 61} If qualified coaches assess RTSC during the performance of a multijoint exercise, young athletes should receive constructive feedback on the technical performance of every exercise during a training session. This concept has been applied to the assessment of maximum muscular strength in young athletes with an approach called criterion RM testing that focuses on the technical performance of a lift using accepted commonalities of resistance exercise technique.⁶² This type of coaching, training and testing can form the foundation for enduring participation in context-specific sports by maximising a child's athletic prowess and reducing the risk of training-related injuries.^{4 29 63}

While it is important to consider an athlete's training age (ie, amount of time accumulated from participation in formalised training), the critical importance of assessing movement mechanics during the performance of resistance training exercises should be considered.⁶¹ Resistance training programmes characterised by age-related education and instruction provide a unique opportunity for all young athletes—especially those with deficient muscle strength or neuromuscular control—to learn task-related activities and perform resistance exercise movements with proper technique in a progressively challenging environment. For young athletes with poor technical competency (low RTSC), qualified coaches should prescribe a range of basic exercises which enhance muscular strength while developing an athlete's competence and confidence to perform a variety of resistance exercises. For technically competent young athletes (high RTSC), dynamic qualities can be enhanced with more advanced resistance training as part of a structured training paradigm that is designed to optimise specific physiological and performance outcomes in accordance with an athlete's needs.⁴²

The concept of RTSC not only relates to one's physical development, but also to one's cognitive abilities to focus, take direction and execute a task properly. To optimise training-induced adaptations, a child's cognitive-perceptive-motor interactions must be considered when designing training programmes.⁶⁴ To develop motoric competence, young athletes should display mastery of learned motor skills on basic exercises and gain new knowledge by performing novel movements on other exercises that require more complex movement capacities. In some instances, young athletes can create new exercises which can contribute to a mastery oriented climate as they control the type of task engagement and overcome challenges that are self-determined.⁶⁵ For example, young athletes can create new strength exercises with medicine balls or find a solution on their own to a challenging task that requires speed and agility (ie, a modified game of tag). There is some evidence that creative thinking may be declining in children,⁶⁶ and therefore, efforts to encourage creativity in youth sport programmes are needed to reclaim opportunities for young athletes to use their

imagination, collaborate with peers and release their creative energy. Combining developmentally-appropriate training activities with instruction and interaction from a qualified teacher or coach is likely to yield the highest physical, cognitive and affective benefits for youth.⁶⁷

Regular exposure to resistance training during preadolescence will increase the RTSC of young athletes and set the stage for even greater gains in muscular fitness during the postpubertal years, provided the training programme is well designed and focuses on enhancing a young athlete's competence and confidence to perform advanced resistance training exercises.⁶⁸ The concept of RTSC does not imply that all children will achieve a high level of technical competence on all exercises, but rather suggests young athletes should have the opportunity to learn and practice the desired skills in a controlled environment. There is, in fact, no evidence-based minimum age for participation in a supervised resistance training programme. Participants should be able to follow instructions and handle the demands of a training programme. Although participants as young as 5 and 6 years of age have benefitted from participation in a resistance training programme,^{69 70} an age of 7–8 years is when most young athletes are ready for some type of structured resistance training.⁴

Conceptually, young athletes who are not exposed to resistance training early in life may not be able to capitalise on the high degree of neuromuscular plasticity during this developmental period.^{29 50} The ability to execute athletic movements with style, grace and precision requires the coordinated integration of cognitive, sensory, emotional, perceptual and motor control subsystems that evolve during childhood.⁶⁴ With regular exposure to environments that enhance muscular fitness and motor skill performance, young athletes will learn to organise and control these subsystems as described in classic motor development theory.⁷¹ Brain development during the growing years likely corresponds to this developmental period when these subsystems are developing optimally,^{64 72} and therefore children can learn advanced resistance training skills (eg, weightlifting movements or advanced plyometrics) at an earlier age more efficiently than older populations because they can employ developing pathways that control coordination, control and proficiency.

The intricate design of the resistance training programme and use of feedback systems (visual or verbal) can influence the acquisition of desired movement patterns and the development of training-induced gains in muscular fitness.^{4 73} While most children are able to learn basic movements that require squatting, pushing, and pulling, their ability to progress to more complex movements over time will be influenced by the amount of time they have practiced these skills with a knowledgeable coach who can address neuromuscular deficiencies and target specific outcomes.⁷⁴ Young athletes who have not participated in a resistance training programme will be ill-prepared for advanced training and will need to begin conditioning with more basic, developmentally-appropriate skills and exercises. Moreover, adolescent athletes with low RTSC will have greater difficulty mastering complex movements and will not be able to build on an existing foundation of muscular fitness. In addition, early development of RTSC can help assure that aspiring Olympians take advantage of alterations in the hormonal milieu associated with the adolescence.^{1 6}

Importance of qualified professionals

Participation in a resistance training programme with a qualified professional who is well-versed in kinesiology, physical development, and paediatric exercise science, and who is skilled at

teaching and communicating with young athletes is needed to optimise resistance training adaptations and enhance exercise adherence in youth. Poor lifting technique and inappropriate pedagogical approaches (eg, unrealistic progression of training loads or inappropriate cueing) are potentially injurious.⁷⁵ Extreme conditioning protocols which include exhaustive metabolic resistance training programmes have been found to alter barbell back squat biomechanics and injury risk in trained adults⁷⁶ and therefore this type of training would not be expected to favour optimal strength development in youth with limited resistance training experience. The development of a standard certification related to youth strength and conditioning is warranted.^{74 77}

While resistance training should provide an opportunity for participants to engage in an activity that is physically challenging and mentally engaging, the quality of the training experience must also be considered when designing youth programmes.⁷⁸ This is where the art of youth resistance training comes into play: the physical demands of training must be balanced with effective coaching to enhance a child's emotional, social and cognitive well-being. Children cite 'fun' as the number one reason for participation in organised sport and its absence as the number one reason for attrition from sport.⁷⁹ Notwithstanding the potential value of *deliberate play* which characterises sporting activities that are unstructured, play-like and enjoyable,^{80 81} a strategy of *deliberate preparation* characterised by planned training and qualified instruction is needed to improve a young athlete's skill competency and prevent the accrual of neuromuscular deficits during the growing years. The primary goal of any physical development programme should be to improve holistically the physiological and performance attributes that enhance athleticism while promoting welfare and well-being.⁸²

RESISTANCE EXERCISE /S SPORTS MEDICINE

Since sports medicine professionals focus on athletic performance as well as the prevention and treatment of injuries related to exercise and sport, the prescription of resistance exercise for young athletes is fundamental to the scope and practice of this subspecialty of medicine. Traditional fears and misinformed concerns regarding the effects of resistance training on the immature skeleton have been replaced by scientific evidence that indicates childhood and adolescence may be the opportune time for the bone remodelling process to respond to the tensile and compressive forces associated with resistance training.^{5 83} Weight-bearing activities, particularly resistance training, may actually be most beneficial during the growing years because the mechanical stress from this type of training may act synergistically with growth-related increases in bone mass.^{18 83 84} Adolescent weightlifters who regularly train with heavy loads have been found to have levels of bone mineral density and bone mineral content significantly greater than age-matched control participants.^{85 86}

The dose response

Although youth resistance training guidelines are available,^{87–89} specific details of the programme need to be individually prescribed and the 'dose' of exercise must be safe, efficacious and enjoyable. An 'overdose' of training can result in non-functional overreaching, overtraining, injury or burnout.^{41 90 91} An examination of the training profiles of, and injuries suffered by, elite youth track and field athletes between the ages 13–17 years showed that injured athletes trained at a higher intensity at 13–14 years, completed more high-intensity training sessions at 13–

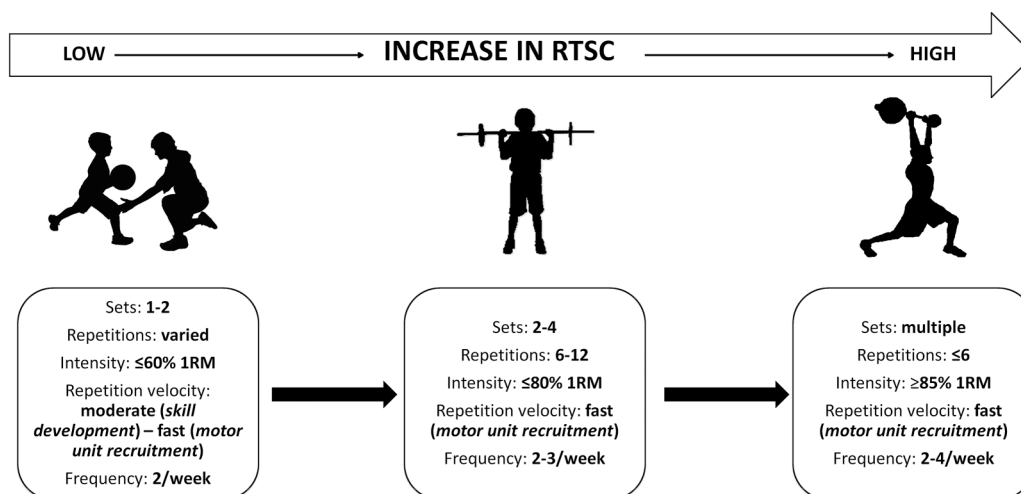


Figure 2 Youth resistance training guidelines with progression based on each athlete's resistance training skill competency (RTSC) to perform the desired movements.

14 years and 15–16 years, and had a higher yearly training load at 13–14 years.⁹² These observations are supported by others who noted that the capacity of adolescent athletes to adapt to the training stimulus and improve physical performance must be balanced with the risk of overuse injury or illness associated with high training loads and longer training durations.^{32 93}

Different combinations of sets and repetitions may be effective, although the average resistance training programme in a meta-analysis on youth resistance training consisted of 2–3 sets of 8–15 repetitions with loads between 60% and 80% of the 1 RM on 6–8 exercises.⁸ Of note, the minimal dose of resistance exercise required to elicit the desired effect is different in untrained youth and young athletes. A significant positive correlation was found between gains in motor performance skills (running, jumping and throwing) and the mean intensity (% 1 RM) of the resistance training programme.¹⁶ Therefore, once young athletes develop proper exercise technique using light and moderate loads, the training programme should be advanced based on each athlete's RTSC to perform the desired movements. Resistance training guidelines from the International Consensus Statement on youth resistance training are outlined in [figure 2](#).⁴

SUMMARY

Protecting the health of the athlete is the primary goal of the International Olympic Committee's Medical Commission,⁹⁴ and therefore coaches, parents and sport administrators need to ensure that young athletes are prepared for the demand of sports training and competition. A compelling body of data indicates that regular participation in a youth resistance training programme that is well designed, developmentally appropriate, and supervised by qualified professionals can offer observable health, fitness and performance value to young athletes.^{1 4 17} Stronger young athletes will be better prepared to withstand the demands of sports training and competition, and will be less likely to suffer a sports-related injury.^{6 7} A systematic approach to physical conditioning that includes resistance training and begins during childhood is needed to attain a level of athleticism that is consistent with the Olympic motto. The development of Olympic athletes should be viewed as a long-term project, and scientific evidence supports the premise that training-induced gains in muscular fitness during the growing years are vital for building young athletes who can run faster, jump higher and be stronger.

What are the new findings?

- ▶ New insights into the design of physical development programmes for young athletes have highlighted the importance of general physical preparation and the multiple health, fitness and performance benefits of structured resistance training.
- ▶ Young athletes who engage in resistance training are more likely to sustain elite-level performance and less likely to suffer a sports-related injury.
- ▶ A strategy of *deliberate preparation*, characterised by athlete-centred training and qualified instruction, is needed to improve a young athlete's resistance training skill competency, enhance muscular fitness and help facilitate the continued development of elite athletic prowess.

How might it impact clinical practice in the near future?

- ▶ Structured interventions are needed to target deficits in muscular fitness early in life so weaker young athletes will be more likely to reach their genetic potential and less likely to suffer a sports-related injury than their stronger counterparts.
- ▶ Without early interventions, coaches at all levels will more likely need to address technical flaws and neuromuscular limitations which become harder to 'fix' when ingrained motor control patterns have developed over time.
- ▶ Owing to the heightened neuromuscular plasticity associated with the growing years, there is an unparalleled opportunity to target strength development early in life to set the stage for future Olympians later in life.

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