

POSITION STAND / PRISE DE POSITION

Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents

David G. Behm, Avery D. Faigenbaum, Baraket Falk, and Panagiota Klentrou

Abstract: Many position stands and review papers have refuted the myths associated with resistance training (RT) in children and adolescents. With proper training methods, RT for children and adolescents can be relatively safe and improve overall health. The objective of this position paper and review is to highlight research and provide recommendations in aspects of RT that have not been extensively reported in the pediatric literature. In addition to the well-documented increases in muscular strength and endurance, RT has been used to improve function in pediatric patients with cystic fibrosis and cerebral palsy, as well as pediatric burn victims. Increases in children's muscular strength have been attributed primarily to neurological adaptations due to the disproportionately higher increase in muscle strength than in muscle size. Although most studies using anthropometric measures have not shown significant muscle hypertrophy in children, more sensitive measures such as magnetic resonance imaging and ultrasound have suggested hypertrophy may occur. There is no minimum age for RT for children. However, the training and instruction must be appropriate for children and adolescents, involving a proper warm-up, cool-down, and appropriate choice of exercises. It is recommended that low- to moderate-intensity resistance exercise should be done 2–3 times/week on non-consecutive days, with 1–2 sets initially, progressing to 4 sets of 8–15 repetitions for 8–12 exercises. These exercises can include more advanced movements such as Olympic-style lifting, plyometrics, and balance training, which can enhance strength, power, co-ordination, and balance. However, specific guidelines for these more advanced techniques need to be established for youth. In conclusion, an RT program that is within a child's or adolescent's capacity and involves gradual progression under qualified instruction and supervision with appropriately sized equipment can involve more advanced or intense RT exercises, which can lead to functional (i.e., muscular strength, endurance, power, balance, and co-ordination) and health benefits.

Key words: youth, pediatric, exercise, health, strength.

Résumé : Selon de nombreux énoncés de principe et des articles de synthèse, il n'y a pas lieu d'interdire l'entraînement à la force (RT) chez les enfants et les adolescents. Si les méthodes sont ajustées à ces groupes de sujets, l'entraînement à la force s'avère sécuritaire et améliore la santé globale de l'individu. Le but de cet article-synthèse est d'arriver à un énoncé de principe après avoir analysé les textes de la littérature scientifique et de formuler des recommandations relatives à l'entraînement à la force n'ayant pas fait l'objet d'études poussées dans la recherche pédiatrique. En plus de susciter l'amélioration de la force et de l'endurance musculaires, comme le rapportent de nombreuses études, l'entraînement à la force améliore les fonctions chez les enfants souffrant de fibrose kystique, de paralysie cérébrale et de brûlures. D'après les études, l'augmentation de la force observée chez les enfants serait surtout due aux adaptations du système nerveux plus qu'à l'hypertrophie, car les gains observés sont démesurément importants. Bien que dans la plupart des études portant sur les caractéristiques anthropométriques, on n'a pas observé un degré significatif d'hypertrophie, les études faisant appel à la résonance magnétique et à l'ultrasonographie indiquent que l'hypertrophie est possible. Il n'y a pas d'âge minimal pour s'entraîner à la force quand on est jeune. Ceci étant dit, il faut ajuster le programme d'entraînement et les directives aux enfants et aux adolescents concernant l'échauffement, le retour au calme et le choix d'exercices. On recommande un entraînement au moyen de charges légères et modérées à raison de 2 à 3 fois par semaine en sautant des jours et en commençant par 1 à 2 séries d'exercices pour en arriver à 4 séries constituées de 8 à 15 répétitions d'un ensemble de 8 à 12 exercices. Parmi ces exercices, on peut inclure des mouvements avancés qu'on observe en haltérophilie aux Jeux olympiques, des exercices pliométriques et des exercices d'équilibre, tous contribuant à l'amélioration de la force, de la puis-

Received 30 October 2007. Accepted 24 January 2008. Published on the NRC Research Press Web site at apnm.nrc.ca on 10 April 2008.

D.G. Behm.¹ School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NL A1C 5S7, Canada.

A.D. Faigenbaum. Department of Health and Exercise Science, The College of New Jersey, P.O. Box 7718, Ewing, NJ 08628-0718, USA.

B. Falk and P. Klentrou. Department of Physical Education & Kinesiology, Brock University, St. Catharines, ON L2S 3A1, Canada.

¹Corresponding author (e-mail: dbehm@mun.ca).

sance, de la coordination et de l'équilibre. En ce qui concerne ces derniers mouvements, il est important d'élaborer des directives spécifiques à ce groupe de sujets. En conclusion, les enfants et les adolescents peuvent s'entraîner à la force au moyen d'exercices standards et de niveau avancé pourvu que la progression de l'entraînement soit graduelle et bien supervisée par du personnel qualifié et que l'équipement soit adapté aussi à ce groupe de sujets. Le bilan est positif aux plans fonctionnels (force musculaire, endurance, puissance, équilibre et coordination) et de la santé.

Mots-clés : jeunesse, pédiatrie, exercice physique, santé, force musculaire.

[Traduit par la Rédaction]

Definition of terms

For the purpose of this paper, the term "children" refers to boys and girls who have not yet developed secondary sex characteristics (approximately up to age 11 in girls and 13 in boys; Tanner stages 1 and 2 of sexual maturation). This period of development is often referred to as pre-adolescence. The term "adolescence" refers to the period of time between childhood and adulthood and includes girls aged 12–18 years and boys aged 14–18 years (Tanner stages 3 and 4 of sexual maturation). The term "youth" is broadly defined in this paper to include the years of childhood and adolescence. The term "resistance training" refers to a specialized method of conditioning that involves the progressive use of a wide range of resistive loads, including body mass, and a variety of training modalities designed to enhance health, fitness, and sports performance. Although the terms "resistance training", "strength training", and "weight training" are sometimes used synonymously, resistance training encompasses a broader range of training modalities and a wider variety of training goals. The term "weightlifting" refers to a competitive sport that involves the snatch and clean and jerk lifts.

Introduction

The conclusions regarding the beneficial effects of resistance training (RT) for pre-adolescent children and adolescents has been consistently positive in the scientific literature. The concerns and myths that were pervasive throughout the general population have been persistently refuted in the scientific literature. Some of these myths purported that RT for children would result in stunted growth, epiphyseal plate damage, lack of strength increases due to a lack of testosterone, and a variety of safety issues (Blimkie 1993). There has been a universal acceptance in various association position papers (American Academy of Pediatrics 2001; American College of Sports Medicine 2006; British Association of Sport and Exercise Science 2004; Faigenbaum et al. 1996b; Golan et al. 1998; Smith et al. 1993) and review articles (Blimkie 1993, 1992; Faigenbaum 2000; Falk and Eliakim 2003; Falk and Tenenbaum 1996; Hass et al. 2001; Malina 2006; McNeely and Armstrong 2002; Payne et al. 1997; Sale 1989; Webb 1990) that RT for children will improve muscular strength and muscular endurance if performed under the supervision of a qualified instructor, using proper technique, gradual training progressions, and proper warm-up and cool-down periods. These strength gains are relatively comparable with adolescent or adult strength gains, but do not typically provide substantial gains in muscle size (Blimkie 1993, 1992). Falk and

Tenenbaum (1996) conducted a meta-analysis and reported RT-induced strength increases of 13%–30% in pre-adolescent children following RT programs of 8–20 weeks.

Rather than contributing to injuries as was previously thought, RT has been reported to be safe (when supervised and with proper technique) for children and to potentially decrease the incidence and severity of sport injuries (Faigenbaum et al. 1996b; Falk and Eliakim 2003; Hamill 1994; McNeely and Armstrong 2002; Smith et al. 1993; Webb 1990). Furthermore, RT has been reported to increase bone mineral density (Nichols et al. 2001) while not adversely affecting maturational growth (Sadres et al. 2001), cardiorespiratory fitness, or resting blood pressure (Blimkie 1993), and either has no effect on or improves body composition (Faigenbaum et al. 1993; Hass et al. 2001; Lillegard et al. 1997; Sadres et al. 2001; Siegal et al. 1989; Sothorn et al. 2000). In addition, RT can have a positive effect on other health- and fitness-related measures (Faigenbaum 2000) including the blood lipid profile (Hass et al. 2001). Psychosocial skills and measures of well being can be enhanced with RT (Faigenbaum et al. 1996b; Falk and Eliakim 2003; Hass et al. 2001), as can motor control skills or performance (Faigenbaum 2000; Falk and Eliakim 2003; Hass et al. 2001) and co-ordination (Blimkie 1993). Although there is some diversity of opinion on whether sports performance is directly improved with RT, it appears that regular participation in a sport-specific resistance-training program can result in some degree of improvement in athletic performance in young athletes (Faigenbaum et al. 1996b; Falk and Eliakim 2003; McNeely and Armstrong 2002; Webb 1990). The current literature generally agrees that low- to moderate-intensity resistance should be conducted (Golan et al. 1998; Hass et al. 2001) 2–3 times/week on non-consecutive days, with 1–4 sets of 6–20 repetitions for 6–12 exercises and generally through a full range of motion (Faigenbaum et al. 1996b; Golan et al. 1998; Malina 2006; McNeely and Armstrong 2002; Webb 1990). Thus, if it is now well accepted among sports and medical associations that RT is effective and beneficial for children and adolescents, is there any necessity for another position paper or review on this matter?

Although the benefits and prescriptions for standard RT programs are well established, there are a number of relatively new or more advanced RT concepts that have not been comprehensively addressed in the pediatric literature. More advanced training concepts such as plyometrics, instability RT, periodization, Olympic-style weightlifting, testing methods, and others have been well documented in the adult literature but have received much less exposure or research in the pediatric literature and may be somewhat controver-

sial. It is important to highlight new knowledge in these areas or alert the professionals to the lack of information and the possibility of future research directions in the area of pediatric RT. Thus, it is the objective of this position paper to highlight the major findings related to new trends in pediatric RT and the benefits and the mechanisms underlying the training adaptations in children, to provide training recommendations, and to illustrate areas that need more research.

Health benefits

In the past, RT was not recommended for children as it was believed to be ineffective in terms of strength improvements, while at the same time thought to lead to injuries and long-term health consequences such as damage of growth plates and premature closure of epiphyses. However, recent studies are finding positive results with such practice and have proven RT to actually be beneficial to this population (Steinberger 2003). There is actually an increasing amount of evidence suggesting that RT has the potential to increase bone mineral density, develop greater muscle strength and endurance, and maintain lean body mass, as well as provide a rehabilitation vehicle for various other conditions that impair growth such as cystic fibrosis and osteopenia in both pre- and post-adolescent youth. RT can also lead to improvements in motor skills and performance while helping resist injury and building up a positive attitude by increasing confidence levels and self-esteem (Faigenbaum 2007; Hass et al. 2001; Suman et al. 2001). Accordingly, strong emphasis relies upon ensuring proper technique and considering confounding variables, such as the type and length of the training program. For optimal outcome, the RT program should be designed specifically in conjunction with the age, gender, health status, and physical fitness of the child involved. Table 1 presents a summary of studies on the health-related effects of RT in children and adolescents.

Muscular strength and endurance of children and adolescents have been shown to significantly improve beyond normal growth and maturation when practicing a specifically designed RT program (Benson et al. 2007; Faigenbaum et al. 1999; Falk and Mor 1996; Ramsay et al. 1990). To control for growth and maturation effects, the majority of RT studies included an age-matched control group and have shown that over a period of 6–20 weeks, muscle strength and performance increased to a greater extent in children who participated in RT compared with those who did not. More specifically, it has been reported that moderate loads (e.g. 50%–60% of one repetition maximum (1RM)) and higher repetitions (e.g. 15–20 repetitions) may be most beneficial for enhancing muscular strength and endurance in youth during the initial adaptation period (Benson et al. 2007; Christou et al. 2006; Faigenbaum et al. 1999, 2005b; Lillegard et al. 1997; Pfeiffer and Francis 1986). Overall, in a recent summary by Malina (2006), the 22 reviewed studies agreed that RT twice or three times per week resulted in significant improvements in muscle strength during childhood and adolescence, and that minimal injuries were reported. Significant gains have been reported in isometric and isokinetic strength, muscular endurance, and flexibility with RT protocols of different frequencies and duration, and

across maturity levels (Blimkie et al. 1989; Faigenbaum et al. 1993, 1999, 2001, 2005b; Rians et al. 1987; Ramsay et al. 1990; Sailors and Berg 1987; Weltman et al. 1986). These training-induced improvements were in some cases more evident in older boys and greater in lower- than in upper-body strength, and with 2 days/week compared to 1 day/week (Pikosky et al. 2002; Vrijens 1978; Faigenbaum et al. 2002). A 12-week school-based RT program also resulted in significant improvements of strength, endurance, and flexibility in pre-pubertal boys and girls as compared with their control counterparts (Siegal et al. 1989). In addition, an injury-free 12-week combined program of resistance and martial arts exercises showed improvements in physical performance tasks reflecting muscle strength, endurance, power, and coordination (Falk and Mor 1996). Strength training can also augment the muscle enlargement that normally occurs with pubertal growth in males and females (Kraemer et al. 1989; Webb 1990), but the magnitude of changes in children's cross-sectional muscle area is smaller than that found in adults (Fukunaga et al. 1992; Mersch and Stoboy 1989). It should also be noted that gains in muscle strength and power begin to regress towards untrained values if RT is discontinued (Faigenbaum et al. 1996a; Tsolakis et al. 2004).

Bone health is another area of study when considering health benefits of RT (Table 1). Bass et al. (1998) have reported that pre-pubertal female gymnasts, whose training mainly involves high-impact and resistance training, had significantly higher bone mineral density (BMD) than age-matched controls. Lumbar spine bone mass, volume, and volumetric BMD were also higher in the gymnasts than those found in the control group. They also showed that endocortical diameter was lower in the control group, suggesting an increased cortical thickness in the gymnasts. The gymnasts, however, were growing at a slower rate than the controls when comparing sitting height, femur height and length, and tibia length. This does not seem to be related to the training but is rather a result of selection because of an advantage of shorter athletes in the sport (Daly et al. 2000; Erlandson et al. 2008; Gurd and Klentrou 2003). In a more recent study, Ward et al. (2005) also compared the bone size of the peripheral and axial skeleton among pre-pubertal gymnasts, swimmers, and controls. After adjustment for age and gender, they found that male pre-pubertal gymnasts had significantly thicker cortical bone at the tibia and radius than the controls (Ward et al. 2005). Adolescent male weightlifters have also been found to have significantly greater BMD or bone mineral content (BMC) than age-matched controls (Conroy et al. 1993; Virvidakis et al. 1990). Conroy et al. (1993) have shown a significant relationship between BMD and muscle strength in this group of junior weightlifters, with strength accounting for 30%–65% of variance, whereas in the Virvidakis et al. (1990) study, BMC was highly correlated with weight record. Furthermore, Nichols et al. (2001) compared a group of 13–17 years old females assigned to an RT intervention group 3 times/week for 15 months with a control group of age-matched females. They reported no significant changes in the lumbar BMD and BMC in their RT group as compared with the control group. The only difference between the groups was an increased leg strength and femoral neck BMD in the RT

Table 1. Summary of the effects of resistance training (RT) in children and adolescents.

Effect	Children	Adolescents	Sample references	Notes
Muscle strength	+++	+++	Blimkie et al. 1989, 1996; Christou et al. 2006; Faigenbaum et al. 1993, 1996a, 2001, 2002, 2005b; Fukunaga et al. 1992; Lillegard et al. 1997; Nichols et al. 2001; Ozmun et al. 1994; Pfeiffer and Francis 1986; Pikosky et al. 2002; Ramsay et al. 1990; Sadres et al. 2001; Sailors and Berg 1987; Siegal et al. 1989; Tsolakis et al. 2004; Weltman et al. 1986	Smaller absolute strength gains in children compared with adults, but comparable relative gains
Muscle power	?	+	Christou et al. 2006; Faigenbaum et al. 1993, 1996a, 2002, 2005b; Lillegard et al. 1997; Weltman et al. 1986	Small if any changes in children; limited data in adolescents
Muscular endurance	++	+	Faigenbaum et al. 1999, 2001, 2005b; Ramsay et al. 1990; Sailors and Berg 1987	Limited data in adolescents
Bone strength, BMD, BMC	?	?	Blimkie et al. 1996; Nichols et al. 2001	Limited number of studies using RT alone to examine effect on bone
Flexibility	+	?	Christou et al. 2006; Faigenbaum et al. 2002, 2005b; Siegal et al. 1989; Weltman et al. 1986	Small if any changes in children; limited data in adolescents
Agility and physical performance	?	?	Christou et al. 2006; Falk and Mor 1996	Changes only shown when RT was combined with specific sports training
Body composition	—	?	Faigenbaum et al. 1993; Lillegard et al. 1997; Sadres et al. 2001; Siegal et al. 1989; Sothorn et al. 2000; Siegal et al. 1989	Some data suggesting reduced adiposity in overweight children; no data in adolescents

Note: +++, clear effect in numerous studies; ++, some effect in limited number of studies; +, small effect in limited number of studies; ?, unclear effect; —, no effect. BMD, bone mineral density; BMC, bone mineral content.

group. Based on the skeletal benefits described (Table 1), RT beginning at a young age is also associated with a decreased risk of osteoporotic fractures later in life (Heinonen et al. 2000). Childhood through late adolescence is a crucial period in bone formation, with about 50% of the peak bone mass being acquired during this period (Bonjour et al. 1991; Matkovic et al. 1994). Peak bone mass is defined as the amount of bony tissue present at the end of skeletal maturation. Because a low peak bone mass is a significant risk factor for osteoporosis and associated fractures, the attainment of an ample peak bone mass during childhood and adolescence is an effective method to reduce the risk for the later development of osteoporosis (Hansen et al. 1991).

As the prevalence of childhood obesity continues to increase, the positive impact of RT on body composition in obese youths should be considered. A number of studies have been reported that regular participation in RT programs resulted in an improvement of body composition in obese children and adolescents (Sothorn et al. 2000; Treuth et al. 1998; Watts et al. 2004). RT has also been used as a rehabilitation strategy in children with other chronic conditions. Selvadurai et al. (2002) studied 3 groups of children suffering from cystic fibrosis with pulmonary exacerbation: a group who participated in an aerobic-training program, an RT group, and a control group. They found that both the aerobic and RT groups had positive results compared with the control group. More specifically, the RT group had improved lung function, leg muscle strength, and fat-free mass. Research studies also suggest that strength-training programs for children with cerebral palsy may help to increase muscle strength and improve daily activities and quality of life

(Damiano et al. 1995; Dodd et al. 2002; McBurney et al. 2003; Morton et al. 2005). Furthermore, Suman et al. (2001) conducted an intervention study in a group of children who had a total of greater than 40% of their body surface area burned. Patients were required to complete a 12-week exercise program at home or in the hospital's rehabilitation center. They were divided into two groups: the RT group, which participated in an individualized training program supervised by personal trainers, and a control group who were asked to complete a home-based rehabilitation program without exercise. The results of this study showed significant increases in muscle strength, total work resistance, and lean body mass in the RT group compared with the control home group.

Based on anecdotal evidence, it was believed that RT lead to injury of epiphyseal plates, cartilage, ligaments, or muscles. However, prospective studies in children do not support this belief. Faigenbaum et al. (2003) examined the safety and efficacy of maximal strength testing in healthy children between the ages of 6 and 12 years in a controlled environment. During the intervention, the researchers asked the children about muscle pain, soreness, and difficulty of movements at the end of each testing session and over a period of time. The study concluded that during supervised strength testing no injuries had occurred and no complaints were reported in either the boys or the girls. In a previous study, Weltman et al. (1986) examined the effectiveness and safety of a 14-week hydraulic resistance-training program in 26 pre-pubertal males using musculoskeletal scintigraphy to assess tissue damage. They found no evidence of damage to epiphyses, bone, or muscle as a result of strength

training and concluded that in the short term, supervised concentric strength training using hydraulic resistance equipment is safe and effective in pre-pubertal boys (Weltman et al. 1986). The safety of a resistance-training program in pre-pubescent to early post-pubescent males and females was also examined by Lillegard et al. (1997). Only one injury had been recorded during the 12-week training session. The injury, a minor strain of the shoulder muscle, was considered incidental due to the low exercise to injury ratio and the severity of this one injury (Lillegard et al. 1997). Injuries of the epiphyseal plates have been suggested to be less likely to occur during childhood than during adolescence, because the growth plates of children may actually be stronger and more resistant to various forces than those of adolescents (Micheli 1988). Further, although elite RT sports such as gymnastics have also been associated in the past with delayed growth and skeletal maturity, recent research has shown that the shorter stature found in young gymnasts when compared with age-matched controls is a result of selection rather than an effect of training on physical growth, because of an advantage of shorter athletes in the sport (Daly et al. 2000; Erlandson et al. 2008; Gurd and Klentrou 2003).

Recent studies appear to have come to a consensus regarding the beneficial effects of RT in young populations. Not only has it been found to be beneficial to healthy growing muscles and bones, but it has also been found to help children suffering from various diseases or health conditions. On the other hand, there are many precautions that must be considered when practicing RT with children, the most important being proper technique and appropriate volume. As pointed out by Selvadurai et al. (2002), one must remember that even though RT aims at improving muscle strength, other forms of physical activity such as cardio-respiratory activities should be practiced on a regular basis to maintain a balanced and healthy lifestyle, optimize recovery time, and improve cardiovascular growth and function.

Thus, there are numerous beneficial effects of RT in general, and in children in particular. Most notably these include an increase in muscle strength (Blimkie 1992, 1993; Falk and Tenenbaum 1996; Payne et al. 1997; Sale 1989). Other beneficial effects include a potential increase in bone strength, a desirable change in body composition, and an improvement in motor skills and sports performance. The next section focuses on the physiological mechanisms explaining the increase in muscle strength, highlighting the available evidence in children and the known differences between children and adults.

Physiological mechanisms

There are two generally acceptable types of adaptations that may occur in response to RT and may explain the observed strength gains: morphological and neurological. The relative contribution of these adaptations may be different in children, adolescents, and adults.

Morphological adaptations

Morphological changes following RT include an increase in muscle size, primarily due to an increase in fibre size, potential hyperplasia, and changes in fibre-type composition

and connective tissue, as well as structural changes in the muscle. Commonly, morphological changes imply that muscle mass has increased or hypertrophy has occurred. This has been a common observation in adults, but not so children or adolescents. Although RT has been shown effective in increasing muscle strength in children and adolescents the reported increases in muscle size have been relatively small among studies. RT programs do not seem to influence growth in height and weights of pre- and early adolescent youth, whereas changes in body composition, considering both fat and muscle mass, are minimal (Malina 2006; Falk and Eliakim 2003; Sadres et al. 2001). Studies examining whole-muscle hypertrophy in children and adolescents have usually used anthropometric techniques and have provided very limited evidence of hypertrophy in adolescents (Lillegard et al. 1997), and no evidence of muscle hypertrophy in children (Blimkie 1989; Ozmun et al. 1994; Ramsay et al. 1990; Sailors and Berg 1987; McGovern 1984; Siegel et al. 1989), as a result of RT. However, two studies in which more sensitive methods of measurements were used (magnetic resonance imaging and ultrasound) have suggested that muscle hypertrophy may indeed occur among children following RT. Mersch and Stoboy (1989) used magnetic resonance imaging and were the first to demonstrate an increase in quadriceps cross-sectional area, together with increases in knee-extension isometric strength, in pre-adolescent boys. However, only two sets of twins participated in this study. Later, Fukunaga et al. (1992) used ultrasound to demonstrate increases in lean (muscle and bone) cross-sectional area among 1st–3rd grade Japanese boys and girls who engaged in RT (elbow flexion) over 12 weeks, whereas little change was observed in those children who did not train. Elbow flexors' cross-sectional area significantly increased, but interestingly, the extensor's cross-sectional area increased to a similar extent. Given the small sample size in the study by Mersch and Stoboy (1989) and the somewhat inconsistent results of the study by Fukunaga et al. (1992), it may be premature to conclude that whole-muscle hypertrophy does indeed occur in children as a response to RT. However, these two studies do present the prospect that muscle hypertrophy is possible among children, although these small potential changes may be difficult to measure.

In the above studies, the anatomical cross-sectional area was measured. In both of the studies that suggested hypertrophy in children (Mersch and Stoboy 1989; Fukunaga et al. 1992), as is the case in most studies examining hypertrophy in adults, the increases in muscle cross-sectional area were much smaller than the increases in muscle strength. In other words, there was an increase in strength per whole muscle area, sometimes referred to as muscle-specific tension. Theoretically, cross-sectional area should be measured perpendicular to the line of pull of the fibres, called the physiological cross-sectional area. However, this measurement is problematic and has not been attempted in children or adolescents following RT.

The increase in the cross-sectional area of muscle as a result of RT in adults is primarily due to the hypertrophy of individual muscle fibres (McDonagh and Davies 1984; Jones et al. 1989). Changes in fibre cross-sectional area in humans can only be examined using muscle biopsies. Given ethical

considerations, it is understandable why such training-induced data do not exist in healthy children and adolescents. Nevertheless, if muscle hypertrophy does occur in children, it is likely due primarily to fibre hypertrophy. The latter is a result of myofibrillar growth (an increase in contractile proteins) and proliferation (an increase in the number of myofibrils), as well as satellite cell activation in the early stages of RT (Folland and Williams 2007). These mechanisms have not been investigated in children or adolescents.

The occurrence of hyperplasia as a result of RT remains controversial, but it has been suggested to take place in adults following such training (Appell et al. 1988; Kadi and Thornell 2000). However, this potential hyperplasia is argued to occur at a very slow rate and its contribution to strength gains is argued to be minimal (Appell 1990). In view of the need for muscle biopsy samples to investigate this issue, hyperplasia has not been examined in children.

Other potential morphological effects of RT, which may explain increases in muscle strength, include changes in myosin heavy-chain and fibre-type composition, increased tendinous stiffness, and an increase in the angle of muscle pennation. Several studies have reported an increase in the number of type IIa fibres and a concomitant decrease in type IIx fibres in adults (Campos et al. 2002; Hakkinen et al. 1998; Hather et al. 1991; Staron et al. 1990), suggesting subtle fibre-type changes. These have not been examined in children or adolescents. Tendinous stiffness has been demonstrated to increase following RT in adults (Kubo et al. 2001, 2002; Reeves et al. 2003), reducing the electromechanical delay in the muscle and increasing the rate of force development. Although musculo-tendinous stiffness has been reported as lower in children than in adults in some (Lambertz et al. 2003) but not all studies (Cornu and Goubel 2001), the effect of RT on tendinous stiffness in children and adolescents has not been investigated. Finally, recent studies in adults have provided strong evidence for an increase in the angle of pennation following RT (Aagaard et al. 2001; Kanehisa et al. 2002; Kawakami et al. 1995; Reeves et al. 2004), allowing for more myofibrillar packing and effectively increasing the physiological cross-sectional area. An increase in the angle of pennation by itself is not necessarily advantageous. However, an increase in myofibrillar packing would, in effect, increase muscle strength, since most muscles in humans have an angle of pennation substantially lower than the optimal 45°. Although tendinous stiffness and angle of pennation can be examined using non-invasive techniques, the effects of RT on these characteristics have not been examined in children.

Regardless of their potential existence in children, adolescents or adults, the morphological adaptations described above explain only a small portion of the increases observed in muscle strength among children and adolescents. More studies using sensitive techniques are needed to clarify the contribution of the various morphological adaptations to the strength gains observed in children following RT.

Neurological adaptations

In view of the limited evidence of muscle hypertrophy and its small potential contribution, strength gains among children have been attributed mainly to neurological adaptations. These adaptations are difficult to define but can be

viewed as modifications in coordination and learning that facilitate better recruitment and activation of muscles involved in specific strength tasks (Folland and Williams 2007; Sale et al. 1983). Measurement of such adaptation is elusive, and therefore neurological adaptations are mainly based on indirect evidence.

In adults, indirect evidence of neural adaptations includes the disproportionately greater increase in muscle strength compared with the observed increases in muscle size. The case is similar in adolescents, where some hypertrophy has been demonstrated, but not sufficient to explain the increase in muscle strength. In children, since there is minimal evidence of an increase in muscle size, the neurological adaptations are inferred from strength gains that are not accompanied by muscle hypertrophy. In most cases, whether children, adolescents, or adults, there is an increase in the specific tension (torque/size) of the muscle. However, as pointed out recently by Folland and Williams (2007), this increase in specific tension can be explained not only by neurological adaptations, but also by some morphological adaptations, such as increases in tendinous stiffness or in the angle of pennation.

No studies have specifically examined neurological adaptations in adolescents. There are only two studies that attempted to directly demonstrate neurological changes in children following RT. Using the interpolated twitch technique, Ramsay et al. (1990) demonstrated an increase of 9% and 12% in motor unit activation of the elbow flexors and knee extensors, respectively, following 10 weeks of RT and an additional 3% and 2%, respectively, following another 10 weeks of training. Nevertheless, the training-induced increases in strength were much greater than the concurrent increases in neuromotor activation. Likewise, Ozmun et al. (1994) used integrated electromyography amplitude (IEMG) to demonstrate an increase in neuromuscular activation in agonist muscles following 8 weeks of RT in pre-pubertal boys and girls. As with the interpolated twitch technique, the increase in IEMG was smaller than the increases in strength (16.8% vs. 27.8%, respectively).

An increase in agonist's activation is likely to result in enhanced force production. However, the latter would also be a result of a decrease in antagonist activation, or improved inter-muscular coordination. Several studies have demonstrated lower antagonist co-activation in strength and (or) power in adult athletes compared with non-athletes (Baratta et al. 1988; Osternig et al. 1986). Similarly, some studies have indicated lower antagonist co-activation in adults compared with children (Frost et al. 1997; Lambertz et al. 2003). Isometric training has been shown to decrease antagonistic co-activation during knee extension in adults (Carolan and Cafarelli 1992), but there are no comparative studies in children or adolescents. This type of adaptation likely has a greater influence on strength improvements in complex multi-joint movements, rather than in simple single-joint tasks.

Neurological adaptations are believed to occur predominantly in the early phases of training (Moritani 1992; Sale 1989). This is supported by the findings of Ramsay et al. (1990) of greater increase in motor unit activation in children in the first 10 weeks of training, compared with the second 10 weeks, as cited previously. In fact, the earliest

phase of training likely involves the learning or optimization of inter-muscular coordination (agonists, synergists, stabilizers). Folland and Williams (2007) propose that the magnitude of this learning depends on prior physical activity level and experience in the specific task. This would suggest that children, being younger and generally less experienced or skillful in most tasks than adults, would exhibit greater neurological adaptations in response to RT. Indeed, based on the lack of observed morphological changes in children, this notion has been indicated in the past (Blimkie 1989; Sale and Spriet 1996). The specificity of training has not been investigated in children. In adults, a low-repetition – high-load RT program is recommended to increase maximal strength. However, in 5- to 12-year-old children, Faigenbaum et al. (1999) demonstrated that high-repetition – low-load and low-repetition – high-load RT programs resulted in a similar enhancement of maximal strength. It is therefore unclear whether the neurological adaptations to RT in children are specific to the training parameters, as would be expected in adults.

Thus, training-induced strength gains in children and adolescents may possibly be explained in part by muscle hypertrophy, but especially in children, are largely explained by neurological adaptations such as increased motor unit activation or other changes such as improved inter-muscle coordination or neuromuscular learning (Kraemer et al. 1989; Ozmun et al. 1994; Ramsay et al. 1990). The latter probably has a higher relative contribution in more complex, multi-joint actions (e.g., squat) than in single isometric contractions (e.g., of the knee extensors). The muscle learns to be more efficient due to this stimulus and it is not until puberty that the learned adaptation becomes permanent in the hypertrophic muscle (Malina 2006).

In view of the scarcity of findings, more research is required to elucidate the effect of different modes of training, different training parameters (volume, intensity, frequency, duration), and the status of maturity on the neurological adaptations to RT in children and adolescents, along with the morphological changes that possibly accompany these adaptations.

Training guidelines and considerations

Youth RT programs need to be carefully prescribed and progressed due to inter-individual differences in physical maturation, training experience, and stress tolerance. Although there is no minimal age requirement for participation in a youth RT program, all participants should have a desire to resistance train and should be able to follow coaching instructions and comply with safety rules. In general, if a child is ready for sports participation (generally age 7 or 8 years), then he or she may be ready for some type of RT. A pre-participation medical exam is not required for apparently healthy children, but is recommended for youth with known or suspected health problems (e.g., diabetes, obesity, orthopedic ailments).

With age-appropriate instruction and competent supervision, regular participation in a youth RT program can offer observable health and fitness value to boys and girls and may foster favorable attitudes towards lifelong physical activity. However, over-prescription of RT and excessive pres-

sure from coaches and parents to perform at a level beyond one's capabilities may result in overtraining, injury, or burn-out (American Academy of Pediatrics 2000; International Federation of Sports Medicine 1998). The prescription of RT programs should take into consideration the maturational status of the youth, training mode, and extent and intensity of other activities. It is not uncommon for some youth to be involved in a number of sports or activities, which may limit the possible positive training adaptations that could be accrued from additional RT. The training and participation in multiple sports and activities highlight the need for periodized youth RT programs, which vary in volume and intensity throughout the season and year. For that reason, adult exercise guidelines and training philosophies should not be imposed on youth, since they are physically and psychologically less mature than adults.

Participation in a youth RT program should provide all participants with an opportunity to learn about their bodies, experience the benefits of resistance exercise, embrace self-improvement, and feel good about their performances. In addition, youth RT programs can include basic education on proper nutrition, adequate sleep, fitness conditioning, and, if age-appropriate, performance-enhancing drug abuse. As such, the cognitive and physical maturity of each participant along with individual needs, goals, and abilities must be carefully considered. Since enjoyment has been shown to mediate the effects of youth physical activity programs (Dishman et al. 2005), the importance of creating an enjoyable exercise experience for all participants should not be overlooked.

A key factor in the design of any youth RT program is appropriate program design, which includes instruction on proper lifting techniques, correct prescription of the program variables, and specific methods of progression. Since the act of RT itself does not ensure that optimal gains in health and fitness will be realized, youth RT programs need to be individually prescribed and sensibly progressed over time. Several specific areas of concern are important to consider when designing youth RT programs; the quality of instruction, type of warm-up, choice of exercise, training intensity and volume, and method of testing. The following is a summary of general RT guidelines for children and adolescents:

- qualified professionals (e.g., Certified Exercise Physiologists or Certified Strength and Conditioning Specialists) should provide instruction and attentive supervision;
- consider each participant's cognitive development, physical maturity, and training experience;
- ensure the exercise environment is safe and free of hazards;
- begin each session with a 5 to 10 min dynamic warm-up period.
- start resistance training 2 or 3 nonconsecutive days/week;
- begin with 8–12 exercises that strengthen the upper body, lower body, and midsection;
- initially perform 1 or 2 sets of 8–15 repetitions with a light to moderate load (about 60% 1RM) to learn proper form and technique;
- focus on learning the correct exercise technique and safe training procedures instead of the amount of resistance or weight lifted;

- include specific exercises that require balance and coordination;
- gradually progress to more advanced movements that enhance power production;
- cool down with less-intense activities and static stretching;
- systematically vary the training program over time to optimize gains and reduce boredom.

Quality of instruction

Health and fitness professionals who have a thorough understanding of youth RT guidelines and safety procedures should provide instruction and supervision for all participants. In addition, professionals should genuinely appreciate the developmental uniqueness of youth and should be able to present information to children and adolescents in a way that is appropriate for their level of understanding. Qualified instruction not only enhances participant safety, but direct supervision of youth RT programs can result in greater program adherence and increased strength gains as compared with unsupervised training (Coutts et al. 2004). Although adults with less experience may assist professionals in the organization and administration of youth RT programs, it is unlikely that they will be able to provide the level of instruction and supervision that is needed for safe and effective training. Professional certification in the area of strength and conditioning (e.g., Certified Exercise Physiologists or Certified Strength and Conditioning Specialists) is highly desirable.

Professionals need to be aware of the inherent risks associated with RT and should attempt to decrease this risk by matching the RT program to the needs and abilities of each participant. This is particularly important for untrained children who often overestimate their physical abilities (Plumert and Schwebel 1997). An advanced RT program for an adolescent athlete would be inappropriate for an untrained child who should be provided with an opportunity to learn basic training procedures and experience the mere enjoyment of resistance exercise. It is always better to underestimate the physical abilities of a child rather than overestimate them and risk negative consequences such as an injury.

Type of warm-up

All participants should warm up prior to RT. While a general warm up of low-intensity aerobic exercise and static stretching is a common practice prior to participation in recreational activities and athletic events (Martens 2004; Shehab et al. 2006; Virgilio 1997), long-held beliefs regarding the routine practice of pre-event static stretching have been questioned (Rubini et al. 2007; Shrier 2004; Thacker et al. 2004). Recently, the effects of warm-up procedures that involve the performance of dynamic movements (e.g., lunges, skips, twists, and throws) designed to elevate core body temperature, enhance motor unit excitability, improve kinesthetic awareness, and maximize active ranges of motion have received increased attention (Faigenbaum and McFarland 2007; Verstegen and Williams 2004). Of note, a dynamic warm up does not involve bouncing-type ballistic movements, but rather a controlled elongation of specific muscle groups.

Dynamic warm-up protocols that require balance, coordi-

nation, power, and speed have been shown to enhance performance in children and adolescents (Faigenbaum et al. 2005a; 2006a; 2006b; Siatras et al. 2003), whereas pre-event static stretching has been shown to reduce lower-extremity power and isokinetic peak torque in youth (McNeal and Sands 2003; Zakas et al. 2006). Furthermore, dynamic warm-up procedures require participants to become immediately engaged in class activities and ready to listen to instruction (Graham 2001). Since chronic static stretching is still recognized as a health-related component of physical fitness in physical education programs (National Association of Sport and Physical Education 2005), a reasonable recommendation is to perform dynamic activities during the warm-up period and static stretching exercises that are relaxing and less intense during the cool-down session. These recommendations are consistent with others who suggest that static stretching should be performed after exercise (Fields et al. 2007; Shrier 2004).

Choice of exercise

A limitless number of exercises can be used to enhance muscular fitness provided that the exercises are appropriate for a child's body size, fitness level, and exercise technique experience. Weight machines (both child- and adult-sized), free weights (barbells and dumbbells), elastic bands, medicine balls, and body mass exercises have been shown to be safe and effective for children and adolescents (Annesi et al. 2005; Faigenbaum and Mediate 2006; Faigenbaum et al. 2005b; Falk and Mor 1996; Ramsay et al. 1990; Sadres et al. 2001; Siegel et al. 1989). When deciding on equipment, realize that adolescents may be able to use adult-size weight machines, but that small children will not be able to position themselves properly on these large machines. Since children's smaller body size usually precludes the use of adult-sized equipment, child-size machines or other modes of training (e.g., dumbbells or medicine balls) are most appropriate for small children. Single-joint exercises (e.g., biceps curl and leg extension), which target specific muscle groups, and multi-joint exercises (e.g., bench press and back squat), which involve the coordinated action of many muscle groups, can be incorporated into a youth RT program. Regardless of the choice of exercise, the concentric and eccentric phases of each lift should be performed in a controlled manner with proper technique.

For youth beginning RT, it is important to choose exercises that match abilities. As such, it is reasonable to start RT with simple exercises and gradually progress to more complex exercises as competence and confidence improve. Advanced multi-joint exercises including Olympic-style lifts (e.g., snatch and clean and jerk) and modified cleans, pulls, and presses may be incorporated into a youth RT program (Faigenbaum et al. 2007a; Sadres et al. 2001). With qualified coaching and safety measures in place (e.g., safe lifting environment, appropriate loads), data indicate that risk of injury during the performance of Olympic-style lifts during training and weightlifting competition is relatively low (Byrd et al. 2003; Hamill 1994; Pierce et al. 1999). Nevertheless, Olympic-style lifts involve a more complex neural activation pattern and therefore participants need to learn how to perform these lifts early in the workout with a relatively light load (e.g., wooden dowel or unloaded barbell) to

develop coordination and skill technique without undue fatigue. As neural or learning adaptations are generally accepted as the major contributor to strength gains during preadolescence, the progression to more complex coordinated movements including Olympic-style lifts may be permitted during this developmental period to potentially enhance neuromuscular organization.

Plyometric training or stretch–shortening cycle exercise can be safe and effective for enhancing muscle power in children and adolescents provided that appropriate training and guidelines are followed (Brown et al. 1986; Kotzamanidis 2006; Lephart et al. 2005; Marginson et al. 2005; Matavulj et al. 2001; Diallo et al. 2001). Past recommendations for adult plyometric training (i.e., the athlete should be able to squat at least 1.5 times his or her body weight before performing lower-body plyometrics (Potach and Chu 2000) may have inhibited the implementation of plyometric training for youth. Although these adult recommendations may be appropriate for high-intensity or high-amplitude plyometrics, children and adolescents regularly perform plyometrics when they skip, hop, run, bound, and jump.

Typically, plyometric training involves body mass jumping exercises and medicine ball throws that are performed quickly and explosively. With plyometric training, the neuromuscular system is conditioned to react more quickly to the stretch–shortening cycle. Thus, this type of training may enhance a young athlete's ability to increase speed of movement and improve power production (Chu et al. 2006).

Youth should begin plyometric training with less-intense drills (e.g., double-leg jumps) and gradually progress to more advanced drills (e.g., single-leg hops) as competence and confidence to perform this type of training improve. Studies indicate that relatively few repetitions (i.e., ≤ 10) of each plyometric drill are needed to bring about significant training-induced gains in performance (Lephart et al. 2005; Myer et al. 2005; Matavulj et al. 2001). Plyometric training should take place on yielding surfaces (e.g., gymnasium floor or playing field) and the focus of early training should be on proper athletic positioning and landing. Since plyometric training is not intended to be a stand-alone exercise program, the best approach is to incorporate this type of training into a well-rounded program that also includes other types of strength and conditioning (Faigenbaum et al. 2007b; Ingle et al. 2006; Myer et al. 2005).

Exercises that require balance should also be incorporated into youth RT programs, since balance is essential for optimal performance and the prevention of athletic injuries (Verhagen et al. 2005). In adults, balance is related to the ability to exert force and power and therefore the ability to maintain and (or) control a body position can enhance the neuromuscular adaptations to RT (Anderson and Behm 2004). Typically, a stiffening strategy that decreases the magnitude and rate of voluntary movements is adopted when adult participants are presented with a threat of instability (Adkin et al. 2002; Carpenter et al. 2001). Thus, an RT program that includes exercises, which could improve stability or balance, could subsequently enhance force output, power, and coordination. In support of these observations, significant correlations between skating performance and the static wobble board balance test have been reported in youth under 19 years of age (Behm et al. 2005b).

Given that balance and coordination are not fully developed in children (Payne and Isaacs 2005), balance training may be particularly beneficial for reducing the risk of injury while performing RT, particularly to the lower back. A number of studies in adults have demonstrated increased muscle activation of trunk muscles when performing activities on an unstable versus a stable surface (Anderson and Behm 2005; Behm et al. 2005a). The advantage of training on an unstable surface is that high activation can be achieved without the imposition of high resistive loads (Anderson and Behm 2004; Behm et al. 2005a). When incorporating balance training into a child's or adolescent's RT program, exercises should progress from simple static balance activities on stable surfaces to more complex static instability training using devices such as wobble boards, BOSU ("both sides up") balls, and stability balls (Behm and Anderson 2006). Over time, the program can be made more challenging by changing the base of support, the moment or lever arm of the body segment, the movement pattern, or the speed of motion.

Training intensity and volume

RT intensity refers to the amount of weight lifted during the performance of an exercise, whereas training volume is typically estimated from the number of exercises performed per session, the repetitions performed per set, and the number of sets performed per exercise. Training intensity and training volume have a direct impact on training adaptations and are dependent upon other factors including exercise order, repetition speed, and rest interval length (Kraemer and Ratamess 2004).

Different combinations of sets and repetitions from single-set protocols with a moderate load (Westcott 1992) to progressive training regimens consisting of 3–5 sets with loads ranging from 70% to 85% of 1RM have proven safe and effective for youth (Ramsay et al. 1990). Although there is not one combination of sets and repetitions that will be optimal for all participants, a reasonable approach is to begin RT with 1 or 2 sets of 8–15 repetitions with a light to moderate load (30%–60% 1 RM) on 8 to 12 exercises. A training frequency of at least 2 nonconsecutive days/week is recommended, as RT only once per week may result in suboptimal adaptations (Faigenbaum et al. 2002). This type of program will provide an opportunity for beginners to learn proper lifting techniques while maximizing gains in muscular strength (Faigenbaum 2000; Kraemer and Fleck 2005).

Youth with RT experience can gradually progress to more intense or voluminous workouts to target specific training objectives (i.e., strength, power, hypertrophy, and (or) muscular endurance). For example, the performance of 3 sets with heavier loads (e.g., 6–10RM) performed to volitional fatigue can be used to increase maximal strength on large muscle group exercises (e.g., leg or bench press). Depending on program goals and individual abilities, progression can also be achieved by enhancing movement speed during the performance of selected exercises (i.e., plyometric drills and Olympic-style lifts). It is important to note that not all exercises need to be performed for the same number of sets and repetitions and that in some cases less-intense training can provide needed variation during long-term athletic-training programs.

Although additional long-term training studies are needed to explore the effects of different RT programs on youth, the best approach is to vary the RT program over time to keep the training stimulus challenging and effective. This does not mean that every training session needs to be more intense or voluminous than the previous session, but over time the RT program needs to be systematically varied to stimulate further adaptations and maximize gains (Kraemer et al. 2002). In the long term, program variation with adequate recovery between training sessions will allow children and adolescents to make even greater gains because their body will be able to adapt to even greater demands (Bompa 2000; Kraemer and Fleck 2005).

Method of testing

Strength testing provides an opportunity for professionals to assess initial strength levels, identify muscle imbalances, develop individualized programs, and monitor progress. In addition, if presented and administered properly, strength testing can provide an incentive for young participants to resistance train regularly to improve their strength performance. Although there are a variety of methods for evaluating muscular strength in children and adolescents (Gaul 1996), researchers typically used maximal load lifting (e.g., 1RM), relatively high RM lifting (e.g., 10RM), and maximal isokinetic tests to assess muscle strength in youth (Benson et al. 2007; Faigenbaum et al. 2003; Lillegard et al. 1997; Pfeiffer and Francis 1986; Ramsay et al. 1990). No injuries have been reported in any prospective youth RT study that involved strength testing procedures. It should be underscored that strength testing in the aforementioned reports involved adequate warm-up, gradual progression of testing loads, and close and competent supervision and instruction.

Although strength testing is not a prerequisite for participation in a youth RT program, professionals who have experience testing youth can administer strength tests to evaluate training-induced gains in muscular strength and muscular endurance. While field-based measures (e.g., push-up or modified pull-up) are appropriate for testing a large group of children (e.g., a physical education class), the use of RM strength testing procedures may provide more useful information for professionals who need to assess strength performance in trained youth (e.g., a youth sports program). Of note, RM testing procedures are labor intensive, time consuming, and require close, qualified supervision. Unsupervised and poorly performed strength tests should not be carried out under any circumstances because of the potential for injury.

Risks and concerns

A traditional concern associated with youth RT involves the potential for injury to the epiphyseal plate or growth cartilage. Although this type of injury is possible if proper training guidelines are not followed (Gumbs et al. 1982; Jenkins and Mintowt-Czyz 1986), an epiphyseal plate fracture has not been reported in any prospective youth RT study that was competently supervised and appropriately progressed. If children and adolescents are taught how to resistance train properly, it seems that the risk of injury to the growth cartilage is minimal. Moreover, data suggest that regular participation in a well-designed RT program does

not negatively impact growth or maturation of youth (Falk and Eliakim 2003; Malina 2006). Traditional fears associated with youth RT have been replaced with more recent findings that indicate that regular participation in weight-bearing physical activities is essential for normal bone growth and development (Bass 2000; Vicente-Rodriguez 2006).

It seems the greatest concern for children and adolescents who resistance train is the risk of an overuse soft-tissue injury, particularly to the lower back (Brady et al. 1982; Brown and Kimball 1983; Risser et al. 1990). These observations are consistent with other data, which suggest lower back pain is the number one musculoskeletal problem in North American adults (Coyte and Ashe 1998). Since weak musculature, improper lifting techniques, or improperly designed RT programs may explain, at least in part, these observations, professionals need to be aware of the inherent risks associated with RT and should attempt to decrease this risk with proper instruction and program design. As such, professionals should include progressive strengthening exercises for the hips, abdomen, and lower back in youth RT programs as part of a preventative health measure.

All types of physical activity carry some degree of risk of musculoskeletal injury, but the risk of injury resulting from RT can be minimized with appropriate overload, gradual progression, careful selection of exercises, and adequate recovery between training sessions. Of note, youth should not resistance train on their own without guidance from qualified professionals and, when appropriate, a spotter should be nearby in case of a failed repetition. Each participant must be treated as an individual due to the variability in children and adolescents of the same age to tolerate stress. Prescribing an RT program that exceeds a child's ability may undermine enjoyment of the training experience and may increase the risk of an acute or overuse injury. Qualified supervision, age-appropriate program design, safe exercise equipment, and a clean training environment are paramount.

Conclusions

In summary, a properly supervised and instructed RT program using appropriately sized equipment, involving exercises within the child's or adolescent's capability, and employing gradual progression can be implemented for youth. It has been well documented that optimal growth and development of the musculoskeletal system is achieved when progressive overload stresses are placed on the system. RT is one activity that can provide these results, whereas other sport and play activities that involve dynamic movement of body mass over extended periods can also provide positive adaptations. RT exercises can range in complexity from simple body mass, dumbbell, or machine-type resistance exercises to more advanced techniques such as plyometrics, instability RT devices, and Olympic-style lifting. Training-related physiological adaptations include neurological adaptations with an emphasis on learning and co-ordination, with limited evidence of muscle hypertrophy. However, more research is necessary regarding the physiological mechanisms of strength gains in children and adolescents as a result of RT. These mecha-

nisms include, but are not limited to, muscle hypertrophy, hyperplasia, fibre-type transformation, changes in tendinous stiffness, angle of pennation, motor unit recruitment, muscle activation, and antagonist co-contractions. Implementing an RT program for children and adolescents may not only improve muscular strength, endurance, power, and balance; there is evidence for improvements in body composition and motor skills, as well as functional performance improvements for individuals coping with cystic fibrosis, cerebral palsy, and burns.

Acknowledgement

Writing of this Position Stand was made possible by an unrestricted education grant to the Canadian Society for Exercise Physiology by Merck Frosst.

References

- Aagaard, P., Andersen, J.L., Dyhre-Poulsen, P., Leffers, A.M., Wagner, A., Magnusson, S.P., Halkjaer-Kristensen, J., and Simonsen, E.B. 2001. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J. Physiol.* **534**: 613–623. doi:10.1111/j.1469-7793.2001.t01-1-00613.x. PMID:11454977.
- Adkin, A.L., Frank, J.S., Carpenter, M.G., and Peysar, G.W. 2002. Fear of falling modifies anticipatory postural control. *Exp. Brain Res.* **143**: 160–170. doi:10.1007/s00221-001-0974-8. PMID:11880892.
- American Academy of Pediatrics. 2000. Intensive training and specialization in young athletes. *Pediatrics*, **106**: 154–157. doi:10.1542/peds.106.1.154. PMID:10878168.
- American Academy of Pediatrics. 2001. Strength training by children and adolescents. *Pediatrics*, **107**: 1470–1472.
- American College of Sports Medicine. 2006. ACSM's guidelines for exercise testing and prescription. 7th ed. Lippincott, Williams & Wilkins, Philadelphia, Penn.
- Anderson, K.G., and Behm, D.G. 2004. Maintenance of EMG activity and loss of force output with instability. *J. Strength Cond. Res.* **18**: 637–640. doi:10.1519/1533-4287(2004)18<637:MOEAAL>2.0.CO;2. PMID:15320684.
- Anderson, K., and Behm, D.G. 2005. Trunk muscle activity increases with unstable squat movements. *Can. J. Appl. Physiol.* **30**: 33–45. PMID:15855681.
- Annesi, J.J., Westcott, W.L., Faigenbaum, A.D., and Unruh, J. 2005. Effects of a 12-week physical activity protocol delivered by YMCA after-school counselors (Youth Fit for Life) on fitness and self-efficacy changes in 5–12 year old boys and girls. *Res. Q. Exerc. Sport*, **76**: 468–476. PMID:16739685.
- Appell, H.J. 1990. Muscular atrophy following immobilisation. A review. *Sports Med.* **10**: 42–58. PMID:2197699.
- Appell, H.J., Forsberg, S., and Hollmann, W. 1988. Satellite cell activation in human skeletal muscle after training: evidence for muscle fiber neof ormation. *Int. J. Sports Med.* **9**: 297–299. PMID:3182162.
- Baratta, R., Solomonow, M., Zhou, B.H., Letson, D., Chuinard, R., and D'Ambrosia, R. 1988. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *Am. J. Sports Med.* **16**: 113–122. doi:10.1177/036354658801600205. PMID:3377094.
- Bass, S.L. 2000. The prepubertal years: a uniquely opportune stage of growth when the skeleton is most responsive to exercise? *Sports Med.* **30**: 73–78. doi:10.2165/00007256-200030020-00001.
- Bass, S., Pearce, G., Bradley, M., Hendrich, E., Delmas, P.D., Harding, A., and Seeman, E. 1998. Exercise before puberty may confer Residual benefits in bone density in adulthood: studies in active prepubertal and retired female gymnasts. *J. Bone Miner. Res.* **13**: 500–507. doi:10.1359/jbmr.1998.13.3.500. PMID:9525351.
- Behm, D.G., and Anderson, K. 2006. The role of instability with resistance training. *J. Strength Cond. Res.* **20**: 716–722. doi:10.1519/R-18475.1. PMID:16937988.
- Behm, D.G., Leonard, A., Young, W., Bonsey, A., and MacKinnon, S. 2005a. Trunk muscle EMG activity with unstable and unilateral exercises. *J. Strength Cond. Res.* **19**: 193–201. doi:10.1519/1533-4287(2005)19<193:TMEAWU>2.0.CO;2. PMID:15705034.
- Behm, D.G., Wahl, M.J., Button, D.C., Power, K.E., and Anderson, K.G. 2005b. Relationship between hockey skating speed and selected performance measures. *J. Strength Cond. Res.* **19**: 326–331. doi:10.1519/R-14043.1. PMID:15903370.
- Benson, A.C., Torode, M.E., and Fiatarone Singh, M.A. 2007. A rational and method for high-intensity progressive resistance training with children and adolescents. *Contemp. Clin. Trials*, **28**: 442–450. doi:10.1016/j.cct.2006.11.004. PMID:17185043.
- Blimkie, C.J. 1989. Age- and sex-associated variation in strength during childhood: anthropometric, morphologic, neurologic, biomechanical, endocrinologic, genetic, and physical activity correlates. *In Perspectives in exercise science and sports medicine: youth, exercise and sports*. Vol. 2. Edited by C.V. Gisolfi. Benchmark Press, Indianapolis, Ind. pp. 99–163.
- Blimkie, C.J. 1992. Resistance training during pre- and early puberty: efficacy, trainability, mechanisms, and persistence. *Can. J. Sport Sci.* **17**: 264–279. PMID:1330264.
- Blimkie, C.J. 1993. Resistance training during preadolescence. *Sports Med.* **15**: 389–407. doi:10.2165/00007256-199315060-00004. PMID:8341873.
- Blimkie, C.J.R., Martin, J., Ramsay, J., Sale, D., and MacDougall, D. 1989. The effects of detraining and maintenance weight training on strength development in prepubertal boys. *Can. J. Sport Sci.* **14**: 104P.
- Blimkie, C.J.R., Rice, S., Webber, C.E., Martin, J., Levy, D., and Gordon, C.L. 1996. Effects of resistance training on bone mineral content and density in adolescent females. *Can. J. Physiol. Pharmacol.* **74**: 1025–1033. doi:10.1139/cjpp-74-9-1025. PMID:8960394.
- Bompa, T. 2000. Total training for young champions. Human Kinetics, Champaign, Ill.
- Bonjour, J.P., Theintz, G., Buchs, B., Slosman, D., and Rizzoli, R. 1991. Critical years and stages of puberty for spinal and femoral bone mass accumulation during adolescence. *J. Clin. Endocrinol. Metab.* **73**: 555–563. PMID:1874933.
- Brady, T.A., Cahill, B.R., and Bodnar, L.M. 1982. Weight training-related injuries in the high school athlete. *Am. J. Sports Med.* **10**: 1–5. doi:10.1177/036354658201000101. PMID:6459035.
- British Association of Sport and Exercise Science. 2004. BASES position statement on guidelines for resistance exercise in young people. *J. Sport Sci.* **22**: 383–390. doi:10.1080/02640410310001641629.
- Brown, E.W., and Kimball, R.G. 1983. Medical history associated with adolescent powerlifting. *Pediatrics*, **72**: 636–644. PMID:6634267.
- Brown, M., Mayhew, J., and Boleach, L. 1986. Effect of plyometric training on vertical jump performance in high school basketball players. *J. Sports Med.* **26**: 1–4.
- Byrd, R., Pierce, K., Rielly, L., and Brady, J. 2003. Young weightlifters' performance across time. *Sports Biomech.* **2**: 133–140. doi:10.1080/14763140308522812. PMID:14658250.
- Campos, G.E., Luecke, T.J., Wendeln, H.K., Toma, K., Hagerman, F.C., Murray, T.F., et al. 2002. Muscular adaptations in response

- to three different resistance-training regimens: specificity of repetition maximum training zones. *Eur. J. Appl. Physiol.* **88**: 50–60. doi:10.1007/s00421-002-0681-6. PMID:12436270.
- Carolan, B., and Cafarelli, E. 1992. Adaptations in coactivation after isometric resistance training. *J. Appl. Physiol.* **73**: 911–917. PMID:1400055.
- Carpenter, M.G., Frank, J.G., Silcher, C.P., and Peysar, G.W. 2001. The influence of postural threat on the control of upright stance. *Exp. Brain Res.* **138**: 210–218. doi:10.1007/s002210100681. PMID:11417462.
- Christou, M., Smiliou, I., Sotiropoulos, K., Volaklis, K., Piliandis, T., and Tokmakidis, S. 2006. Effects of resistance training on the physical capacities of adolescent soccer players. *J. Strength Cond. Res.* **20**: 783–791. doi:10.1519/R-17254.1. PMID:17194231.
- Chu, D., Faigenbaum, A., and Falkel, J. 2006. Progressive plyometrics for kids. Healthy Learning, Monterey, Calif.
- Conroy, B.P., Kraemer, W.J., Maresh, C.M., Fleck, S.J., Stone, M.H., Fry, A.C., et al. 1993. Bone mineral density in elite junior Olympic weightlifters. *Med. Sci. Sports Exerc.* **25**: 1103–1109. PMID:8231753.
- Cornu, C., and Goubel, F. 2001. Musculo-tendinous and joint elastic characteristics during elbow flexion in children. *Clin. Biomech. (Bristol, Avon)*, **16**: 758–764. doi:10.1016/S0268-0033(01)00076-6. PMID:11714553.
- Coutts, A.J., Murphy, A.J., and Dascombe, B.J. 2004. Effect of direct supervision of a strength coach on measures of muscular strength and power in young rugby league players. *J. Strength Cond. Res.* **18**: 316–323. doi:10.1519/R-12972.1. PMID:15142000.
- Coyte, P.C., and Ashe, C.V. 1998. The economic cost of musculoskeletal disorders in Canada. *Arthritis Care Res.* **11**: 315–325. doi:10.1002/art.1790110503. PMID:9830876.
- Daly, R.M., Rich, P.A., Klein, R., and Bass, S.L. 2000. Short stature in competitive prepubertal and early pubertal male gymnasts: the result of selection bias or intense training? *J. Pediatr.* **137**: 510–516. doi:10.1067/mpd.2000.109004. PMID:11035830.
- Damiano, D.L., Vaughan, C.L., and Abel, M.F. 1995. Muscle response to heavy resistance exercise in children with spastic cerebral palsy. *Dev. Med. Child Neurol.* **37**: 731–739. PMID:7672470.
- Diallo, O., Dore, E., Duche, P., and Van Praagh, E. 2001. Effects of plyometric training followed by a reduced training programme on physical performance in prepubescent soccer players. *J. Sports Med. Phys. Fitness*, **41**: 342–348. PMID:11533565.
- Dishman, R.K., Motl, R.W., Saunders, R., Felton, G., Ward, D.S., Dowda, M., and Pate, R.R. 2005. Enjoyment mediates effects of a school-based physical-activity intervention. *Med. Sci. Sports Exerc.* **37**: 478–487. doi:10.1249/01.MSS.0000155391.62733.A7. PMID:15741848.
- Dodd, K.J., Taylor, N.F., and Graham, H.K. 2003. A randomized clinical trial of strength training in young people with cerebral palsy. *Dev. Med. Child Neurol.* **45**: 652–657. doi:10.1017/S0012162203001221. PMID:14515935.
- Erlanson, M.C., Sherar, L.B., Mirwald, R.L., Maffulli, N., and Baxter-Jones, A.D. 2008. Growth and maturation of adolescent female gymnasts, swimmers, and tennis players. *Med. Sci. Sports Exerc.* **40**: 34–42. PMID:18182934.
- Faigenbaum, A.D. 2000. Strength training for children and adolescents. *Clin. Sports Med.* **19**: 593–619. doi:10.1016/S0278-5919(05)70228-3. PMID:11019731.
- Faigenbaum, A. 2007. Resistance training for children and adolescents: Are there health outcomes? *Am. J. Lifestyle Med.* **1**: 190–200. doi:10.1177/1559827606296814.
- Faigenbaum, A., and McFarland, J. 2007. Guidelines for implementing a dynamic warm-up for physical education. *J. Phys. Ed. Rec. Dance*, **78**: 25–28.
- Faigenbaum, A., and Mediate, P. 2006. The effects of medicine ball training on fitness performance of high school physical education students. *Phys. Ed.* **63**: 160–167.
- Faigenbaum, A., Zaichkowsky, L., Westcott, W., Micheli, L., and Fehlandt, A. 1993. The effects of twice-per-week strength training program on children. *Pediatr. Exerc. Sci.* **5**: 339–346.
- Faigenbaum, A.D., Westcott, W.L., and Micheli, L.J. 1996a. The effects of strength training and detraining on children. *J. Strength Cond. Res.* **10**: 109–114. doi:10.1519/1533-4287(1996)010<0109:TEOSTA>2.3.CO;2.
- Faigenbaum, A.D., Kraemer, W.J., Cahill, B., Chandler, J., Dziados, J., Elfrink, L.D., et al. 1996b. Youth resistance training: position statement paper and literature review. *Strength & Conditioning Journal*, **18**(Dec.): 62–75.
- Faigenbaum, A.D., Westcott, W.L., Loud, R.L., and Long, C. 1999. The effects of different resistance training protocols on muscular strength and endurance development in children. *Pediatrics*, **104**: e5. doi:10.1542/peds.104.1.e5. PMID:10390291.
- Faigenbaum, A.D., Loud, R.L., O'Connell, J., Glover, S., O'Connell, J., and Westcott, W. 2001. Effects of different resistance training protocols on upper body strength and endurance development in children. *J. Strength Cond. Res.* **15**: 459–465. doi:10.1519/1533-4287(2001)015<0459:EODRTP>2.0.CO;2. PMID:11726257.
- Faigenbaum, A.D., Milliken, L.A., Loud, R.L., Burak, B.T., Doherty, C.L., and Westcott, W.L. 2002. Comparison of 1 and 2 days per week of strength training in children. *Res. Q. Exerc. Sport*, **73**: 416–424. PMID:12495243.
- Faigenbaum, A.D., Milliken, L.A., and Westcott, W.L. 2003. Maximal strength testing in healthy children. *J. Strength Cond. Res.* **17**: 162–166. doi:10.1519/1533-4287(2003)017<0162:MSTIHC>2.0.CO;2. PMID:12580672.
- Faigenbaum, A.D., Bellucci, M., Bernieri, A., Bakker, B., and Hoorens, K. 2005a. Acute effects of different warm-up protocols on fitness performance in children. *J. Strength Cond. Res.* **19**: 376–381. doi:10.1519/R-15344.1. PMID:15903378.
- Faigenbaum, A., Milliken, L., Moulton, L., and Westcott, W. 2005b. Early muscular fitness adaptations in children in response to two different resistance training regimens. *Pediatr. Exerc. Sci.* **17**: 237–248.
- Faigenbaum, A., Kang, J., McFarland, J., Bloom, J., Magnatta, J., Ratamess, N., and Hoffman, J. 2006a. Acute effects of different warm-up protocols on anaerobic performance in teenage athletes. *Pediatr. Exerc. Sci.* **17**: 64–75.
- Faigenbaum, A.D., McFarland, J.E., Schwerdtman, J.A., Ratamess, N.A., Kang, J., and Hoffman, J.R. 2006b. Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. *J. Athl. Train.* **41**: 357–363. PMID:17273458.
- Faigenbaum, A., McFarland, J., Johnson, L., Kang, J., Bloom, J., Ratamess, N., and Hoffman, J. 2007a. Preliminary evaluation of an after-school resistance training program for improving physical fitness in middle-school-aged boys. *Percept. Motor Skill.* **104**: 407–415.
- Faigenbaum, A., McFarland, J., Keiper, F., Tevlin, W., Kang, J., Ratamess, N., and Hoffman, J. 2007b. Effects of a short term plyometric and resistance training program on fitness performance in children age 12 to 15 years. *J. Sports Sci. Med.* **6**: 519–525.
- Falk, B., and Eliakim, A. 2003. Resistance training, skeletal muscle and growth. *Pediatr. Endocrinol Rev.* **1**: 120–127. PMID:16437017.

- Falk, B., and Mor, G. 1996. The effects of resistance and martial arts training in 6- to 8-year old boys. *Pediatr. Exerc. Sci.* **8**: 48–56.
- Falk, B., and Tenenbaum, G. 1996. The effectiveness of resistance training in children. A meta-analysis. *Sports Med.* **22**: 176–186. PMID:8883214.
- Fields, K., Burnworth, C., and Delaney, M. 2007. Should athletes stretch before exercise? *Gatorade Sports Sci. Inst. Sports Sci. Exchange*, **20**: 1–6.
- Folland, J.P., and Williams, A.G. 2007. The adaptations to strength training: morphological and neurological contributions to increased strength. *Sports Med.* **37**: 145–168. doi:10.2165/00007256-200737020-00004. PMID:17241104.
- Frost, G., Dowling, J., Dyson, K., and Bar-Or, O. 1997. Cocontraction in three age groups of children during treadmill locomotion. *J. Electromyogr. Kinesiol.* **7**: 179–186. doi:10.1016/S1050-6411(97)84626-3.
- Fukunaga, T., Funato, K., and Ikegawa, S. 1992. The effects of resistance training on muscle area and strength in prepubescent age. *Ann. Physiol. Anthropol.* **11**: 357–364. PMID:1642736.
- Gaul, C. 1996. Muscular strength and endurance. In *Measurement in pediatric exercise science*. Edited by D. Docherty. Human Kinetics, Champaign, Ill. pp. 225–254.
- Golan, R., Falk, B., Hoffman, J., Hochberg, Z., Ben-Sira, D., and Barak, Y. 1998. Resistance training for children and adolescents. Position statement by the International Federation of Sports Medicine (FIMS). In *Sports and Children*. Edited by K.M. Chan and L.J. Micheli. Williams & Wilkins Asia-Pacific Ltd., Hong Kong. pp. 265–270.
- Graham, G. 2001. Teaching children physical education. 2nd ed. Human Kinetics, Champaign, Ill.
- Gumbs, V.L., Segal, D., Hallihan, J.B., and Lower, G. 1982. Bilateral distal radius and ulnar fractures in adolescent weight lifters. *Am. J. Sports Med.* **10**: 375–379. doi:10.1177/036354658201000612. PMID:7180959.
- Gurd, B., and Klentrou, P. 2003. Physical and pubertal development in young male gymnasts. *J. Appl. Physiol.* **95**: 1011–1015. PMID:12807895.
- Hakkinen, K., Newton, R.U., Gordon, S.E., McCormick, M., Volek, J.S., Nindl, B.C., et al. 1998. Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. *J. Gerontol. A Biol. Sci. Med. Sci.* **53**: B415–B423. PMID:9823737.
- Hamill, B. 1994. Relative safety of weight lifting and weight training. *J. Strength Cond. Res.* **8**: 53–57. doi:10.1519/1533-4287(1994)008<0053:RSOWAW>2.3.CO;2.
- Hansen, M.A., Overgaard, K., Riis, B.J., and Christiansen, C. 1991. Role of peak bone mass and bone loss in postmenopausal osteoporosis: 12 year study. *BMJ*, **303**: 961–964. PMID:1954420.
- Hass, C.J., Feigenbaum, M.S., and Franklin, B.A. 2001. Prescription of resistance training for healthy populations. *Sports Med.* **31**: 953–964. doi:10.2165/00007256-200131140-00001. PMID:11735680.
- Hather, B.M., Tesch, P.A., Buchanan, P., and Dudley, G.A. 1991. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol. Scand.* **143**: 177–185. PMID:1835816.
- Heinonen, A., Sievänen, H., Kannus, P., Oja, P., Pasanen, M., and Vouri, I. 2000. High-impact exercise and bones of growing girls: a 9-month control trial. *Osteoporos. Int.* **11**: 1010–1017. doi:10.1007/s001980070021. PMID:11256891.
- Ingle, L., Sleaf, M., and Tolfrey, K. 2006. The effect of a complex training and detraining programme on selected strength and power variables in early prepubertal boys. *J. Sports Sci.* **24**: 987–997. doi:10.1080/02640410500457117. PMID:16882633.
- International Federation of Sports Medicine. 1998. Excessive physical training in children and adolescents. In *Sports and children*. Edited by K. Chan and L. Micheli. Williams and Wilkins Asia-Pacific, Ltd., Hong Kong. pp. 271–275.
- Jenkins, N.H., and Mintowt-Czyz, W.J. 1986. Bilateral fracture separations of the distal radial epiphyses during weight lifting. *Br. J. Sports Med.* **20**: 72–73. PMID:3730760.
- Jones, D.A., Rutherford, O.M., and Parker, D.F. 1989. Physiological changes in skeletal muscle as a result of strength training. *Q. J. Exp. Physiol.* **74**: 233–256. PMID:2664854.
- Kadi, F., and Thornell, L.E. 2000. Concomitant increases in myonuclear and satellite cell content in female trapezius muscle following strength training. *Histochem. Cell Biol.* **113**: 99–103. doi:10.1007/s004180050012. PMID:10766262.
- Kanehisa, H., Nagareda, H., Kawakami, Y., Akima, H., Masani, K., Kouzaki, M., and Fukunaga, T. 2002. Effects of equivolume isometric training programs comprising medium or high resistance on muscle size and strength. *Eur. J. Appl. Physiol.* **87**: 112–119. doi:10.1007/s00421-002-0604-6. PMID:12070620.
- Kawakami, Y., Abe, T., Kuno, S.Y., and Fukunaga, T. 1995. Training-induced changes in muscle architecture and specific tension. *Eur. J. Appl. Physiol. Occup. Physiol.* **72**: 37–43. doi:10.1007/BF00964112. PMID:8789568.
- Kotzamanidis, C. 2006. Effect of plyometric training on running performance and vertical jumping in prepubertal boys. *J. Strength Cond. Res.* **20**: 441–445. doi:10.1519/R-16194.1. PMID:16686577.
- Kraemer, W., and Fleck, S. 2005. Strength training for young athletes. 2nd ed. Human Kinetics, Champaign, Ill.
- Kraemer, W.J., and Ratamess, N.A. 2004. Fundamentals of resistance training: Progression and exercise prescription. *Med. Sci. Sports Exerc.* **36**: 674–688. doi:10.1249/01.MSS.0000121945.36635.61. PMID:15064596.
- Kraemer, W.J., Fry, A.C., Frykman, P.N., Conroy, B., and Hoffman, J. 1989. Resistance training and youth. *Pediatr. Exerc. Sci.* **1**: 336–350.
- Kraemer, W.J., Adams, K., Cafarelli, E., Dudley, G.A., Dooly, C., Feigenbaum, M.S., et al. 2002. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med. Sci. Sports Exerc.* **34**: 364–380. doi:10.1097/00005768-200205001-00389. PMID:11828249.
- Kubo, K., Kanehisa, H., and Fukunaga, T. 2001. Effects of different duration isometric contractions on tendon elasticity in human quadriceps muscles. *J. Physiol.* **536**: 649–655. doi:10.1111/j.1469-7793.2001.0649c.xd. PMID:11600697.
- Kubo, K., Kanehisa, H., and Fukunaga, T. 2002. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J. Physiol.* **538**: 219–226. doi:10.1113/jphysiol.2001.012703. PMID:11773330.
- Lambertz, D., Mora, I., Grosset, J.F., and Perot, C. 2003. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *J. Appl. Physiol.* **95**: 64–72. PMID:12626487.
- Lephart, S.M., Abt, J.P., Ferris, C.M., Sell, T.C., Nagai, T., Myers, J.B., and Irrgang, J.J. 2005. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br. J. Sports Med.* **39**: 932–938. doi:10.1136/bjism.2005.019083. PMID:16306502.
- Lillegard, W.A., Brown, E.W., Wilson, D.J., Henderson, R., and Lewis, E. 1997. Efficacy of strength training in prepubescent to early postpubescent males and females: effects of gender and maturity. *Pediatr. Rehabil.* **1**: 147–157. PMID:9689250.
- Malina, R.M. 2006. Weight training in youth – growth, maturation, and safety: An evidence-based review. *Clin. J. Sport Med.* **16**: 478–487. doi:10.1097/01.jsm.0000248843.31874.be. PMID:17119361.

- Marginson, V., Rowlands, A., Gleeson, N., and Eston, R. 2005. Comparison of the symptoms of exercise-induced muscle damage after and initial and repeated bout of plyometric exercise in men and boys. *J. Appl. Physiol.* **99**: 1174–1181. doi:10.1152/jappphysiol.01193.2004. PMID:15817716.
- Martens, R. 2004. Successful coaching. 3rd ed. Human Kinetics, Champaign, Ill.
- Matavulj, D., Kukulj, M., Ugarkovic, J., Tihanyi, J., and Jaric, S. 2001. Effects of plyometric training on jumping performance in junior basketball players. *J. Sports Med. Phys. Fitness*, **41**: 159–164. PMID:11447356.
- Matkovic, V., Jelic, T., Wardlaw, G.M., Ilich, J.Z., Goel, P.K., Wright, J.K., et al. 1994. Timing of peak bone mass in Caucasian females and its implication for the prevention of osteoporosis. Inference from a cross-sectional model. *J. Clin. Invest.* **93**: 799–808. doi:10.1172/JCI117034. PMID:8113412.
- McBurney, H., Taylor, N.F., Dodd, K.J., and Graham, H.K. 2003. 2003. A qualitative analysis of the benefits of strength training for young people with cerebral palsy. *Dev. Med. Child Neurol.* **45**: 658–663. doi:10.1017/S0012162203001233. PMID:14515936.
- McDonagh, M.J., and Davies, C.T. 1984. Adaptive response of mammalian skeletal muscle to exercise with high loads. *Eur. J. Appl. Physiol. Occup. Physiol.* **52**: 139–155. doi:10.1007/BF00433384. PMID:6370691.
- McGovern, M. 1984. Effects of circuit weight training on the physical fitness of prepubescent children. *Diss. Abstr. Int.* **45**: 452A–453A.
- McNeal, J., and Sands, W. 2003. Acute static stretching reduces lower extremity power in trained children. *Pediatr. Exerc. Sci.* **15**: 139–145.
- McNeely, E., and Armstrong, L. 2002. Strength training for children: a review and recommendations. *Physical Health Educ. J.* **68**: 1–6.
- Mersch, F., and Stoboy, H. 1989. Strength training and muscle hypertrophy in children. *In International series on sports sciences. Children and exercise XIII. Edited by S. Oseid and K.H. Carlsson.* Human Kinetics, Champaign, Ill. pp. 165–192.
- Micheli, L. 1988. Strength training in the young athlete. *In Competitive sports for children and youth. Edited by E. Brown and C. Branta.* Human Kinetics, Champaign, Ill. pp. 99–105.
- Moritani, T. 1992. Time course of adaptations during strength and power training. *In Strength and power in sport. The encyclopedia of sports medicine. Vol. III. Edited by P.V. Komi.* Blackwell Scientific Publications, Oxford, UK. pp. 266–278.
- Morton, J.F., Brownlee, M., and McFadyen, A.K. 2005. The effects of progressive resistance training for children with cerebral palsy. *Clin. Rehabil.* **19**: 283–289. doi:10.1191/0269215505cr804oa. PMID:15859529.
- Myer, G.D., Ford, K.K., Palumbo, J.P., and Hewett, T.E. 2005. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J. Strength Cond. Res.* **19**: 51–60. doi:10.1519/13643.1. PMID:15705045.
- National Association of Sport and Physical Education. 2005. Physical education for lifelong fitness. 2nd ed. Human Kinetics, Champaign, Ill.
- Nichols, D.L., Sanborn, C.F., and Love, A.M. 2001. Resistance training and bone mineral density in adolescent females. *J. Pediatr.* **139**: 494–500. doi:10.1067/mpd.2001.118420. PMID:11598594.
- Osternig, L.R., Hamill, J., Lander, J.E., and Robertson, R. 1986. Co-activation of sprinter and distance runner muscles in isokinetic exercise. *Med. Sci. Sports Exerc.* **18**: 431–435. PMID:3747804.
- Ozmun, J.C., Mikesky, A.E., and Surburg, P.R. 1994. Neuromuscular adaptations following prepubescent strength training. *Med. Sci. Sports Exerc.* **26**: 510–514. PMID:8201908.
- Payne, V.G., and Isaacs, L.D. 2005. Human motor development. A lifespan approach. 6th ed. McGraw-Hill, Whitby, Ont. pp. 78–80.
- Payne, V.G., Morrow, J.R., Jr., Johnson, L., and Dalton, S.N. 1997. Resistance training in children and youth: a meta-analysis. *Res. Q. Exerc. Sport*, **68**: 80–88. PMID:9094766.
- Pfeiffer, R., and Francis, R. 1986. Effects of strength training on muscle development in prepubescent, pubescent and postpubescent males. *Phys. Sportsmed.* **14**: 134–143.
- Pierce, K., Byrd, R., and Stone, M. 1999. Youth weightlifting – is it safe? *Weightlifting U. S. A.* **17**: 5.
- Pikosky, M., Faigenbaum, A., Westcott, W., and Rodriguez, N. 2002. Effects of resistance training on protein utilization in healthy children. *Med. Sci. Sports Exerc.* **34**: 820–827. doi:10.1097/00005768-200205000-00015. PMID:11984301.
- Plumert, J.M., and Schwebel, D.C. 1997. Social and temperamental influences on children's overestimation of their physical abilities: links to accidental injuries. *J. Exp. Child Psychol.* **67**: 317–337. doi:10.1006/jecp.1997.2411. PMID:9440296.
- Potach, D., and Chu, D. 2000. Plyometric training. *In Essentials of strength training and conditioning. 2nd ed. Edited by T. Baechle and R. Earle.* Human Kinetics, Champaign, Ill. pp. 427–470.
- Ramsay, J.A., Blimkie, C.J.R., Smith, K., Garner, S., MacDougall, J.D., and Sale, D.G. 1990. Strength training effects in prepubescent boys. *Med. Sci. Sports Exerc.* **22**: 605–614. doi:10.1249/00005768-199010000-00011. PMID:2233199.
- Reeves, N.D., Maganaris, C.N., and Narici, M.V. 2003. Effect of strength training on human patella tendon mechanical properties of older individuals. *J. Physiol.* **548**: 971–981. doi:10.1113/jphysiol.2002.035576. PMID:12626673.
- Reeves, N.D., Narici, M.V., and Maganaris, C.N. 2004. Effect of resistance training on skeletal muscle-specific force in elderly humans. *J. Appl. Physiol.* **96**: 885–892. doi:10.1152/jappphysiol.00688.2003. PMID:14578365.
- Rians, C.B., Weltman, A., Cahill, B.R., Janney, C.A., Tippet, S.R., and Katch, F.I. 1987. Strength training for prepubescent males: is it safe? *Am. J. Sports Med.* **15**: 483–489. doi:10.1177/036354658701500510. PMID:3674272.
- Risser, W.L., Risser, J.M., and Preston, D. 1990. Weight training injuries in adolescents. *Am. J. Dis. Child.* **144**: 1015–1017. PMID:2396614.
- Rubini, E.C., Costa, A.L., and Gomes, P.S. 2007. The effects of stretching on strength performance. *Sports Med.* **37**: 213–224. doi:10.2165/00007256-200737030-00003. PMID:17326697.
- Sadras, E., Eliakim, A., Constantini, N., Lidor, R., and Falk, B. 2001. The effect of long-term resistance training on anthropometric measures, muscle strength, and self-concept in pre-pubertal boys. *Pediatr. Exerc. Sci.* **13**: 357–372.
- Sailors, M., and Berg, K. 1987. Comparison of responses to weight training in pubescent boys and men. *J. Sports Med. Phys. Fitness*, **27**: 30–37. PMID:3599970.
- Sale, D.G. 1989. Strength training in children. *In Youth, exercise and sports. Perspectives in exercise science and sports medicine. Vol. 2. Edited by C.V. Gisolfi and D.R. Lamb.* Benchmark Press, Carmel, Ind. pp. 165–222.
- Sale, D.G., and Spriet, L.L. 1996. Skeletal muscle function and energy metabolism. *In Exercise and the female – a life span approach. Perspectives in exercise science and sports medicine. Vol. 19. Edited by O. Bar-Or, D.R.L., and P.M. Clarkson.* Cooper Publishing Group, Carmel, Ind. pp. 289–359.
- Sale, D.G., MacDougall, J.D., Upton, A.R., and McComas, A.J. 1983. Effect of strength training upon motoneuron excitability in man. *Med. Sci. Sports Exerc.* **15**: 57–62. PMID:6843320.

- Selvadurai, C., Blimkie, C., Meyers, N., Mellis, C., Cooper, J., and Asperen, V. 2002. Randomized controlled study of in-hospital exercise training programs in children with cystic fibrosis. *Pediatr. Pulm.* **33**: 194–200. doi:10.1002/ppul.10015.
- Shehab, R., Mirabelli, M., Gorenflo, D., and Fetters, M. 2006. Pre-exercise stretching and sports-related injuries: Knowledge, attitudes and practices. *Clin. J. Sport Med.* **16**: 228–231. doi:10.1097/00042752-200605000-00007. PMID:16778543.
- Shrier, I. 2004. Does stretching improve performance? A systematic and critical review of the literature. *Clin. J. Sport Med.* **14**: 267–273. doi:10.1097/00042752-200409000-00004. PMID:15377965.
- Siatras, T., Papadopoulos, G., Mameletzi, D., Gerodimos, V., and Kellis, S. 2003. Static and dynamic acute stretching effect on gymnasts' speed in vaulting. *Pediatr. Exerc. Sci.* **15**: 383–391.
- Siegel, J.A., Camaione, D.N., and Manfredi, T.G. 1989. The effects of upper body resistance training on prepubescent children. *Pediatr. Exerc. Sci.* **1**: 145–154.
- Smith, A.D., Andrish, J.T., and Micheli, L.J. 1993. The prevention of sport injuries of children and adolescents. *Med. Sci. Sports Exerc.* **25**(8 Suppl.): 1–7. doi:10.1249/00005768-199301000-00001. PMID:8371662.
- Sothern, M.S., Loftin, J.M., Udall, J.N., Suskind, R.M., Ewing, T.L., Tang, S.C., and Blecker, U. 2000. Safety, feasibility, and efficacy of a resistance training program in preadolescent obese children. *Am. J. Med. Sci.* **319**: 370–375. doi:10.1097/0000441-200006000-00005. PMID:10875292.
- Staron, R.S., Malicky, E.S., Leonardi, M.J., Falkel, J.E., Hagerman, F.C., and Dudley, G.A. 1990. Muscle hypertrophy and fast fiber type conversions in heavy resistance-trained women. *Eur. J. Appl. Physiol. Occup. Physiol.* **60**: 71–79. doi:10.1007/BF00572189. PMID:2311599.
- Steinberger, J. 2003. Diagnosis of the metabolic syndrome in children. *Curr. Opin. Lipidol.* **14**(6): 555–559. doi:10.1097/00041433-200312000-00002. PMID:14624131.
- Suman, O.E., Ricarda, R.J., Celis, M.M., Mlcek, R.P., and Herndon, D.N. 2001. Effect of a 12-week resistance exercise program on skeletal muscle strength in children with burn injuries. *J. Appl. Physiol.* **91**: 1168–1175. PMID:11509512.
- Thacker, S.B., Gilchrist, J., Stroup, D.F., and Kimsey, C.D., Jr. 2004. The impact of stretching on sports injury risk: a systematic review of the literature. *Med. Sci. Sports Exerc.* **36**: 371–378.
- Treuth, M.S., Hunter, G.R., Pichon, C., Figueroa-Colon, R., and Goran, M.I. 1998. Fitness and energy expenditure after strength training in obese prepubertal girls. *Med. Sci. Sports Exerc.* **30**: 1130–1136. doi:10.1097/00005768-199807000-00017. PMID:9662684.
- Tsolakis, C.K., Vagenas, G.K., and Dessypris, A.G. 2004. Strength adaptations and hormonal responses to resistance training and detraining in preadolescent males. *J. Strength Cond. Res.* **18**: 625–629. doi:10.1519/1533-4287(2004)18<625:SAAHRT>2.0.CO;2. PMID:15320685.
- Verhagen, E.A., van Tulder, M., van der Beek, A.J., Bouter, L.M., and van Mechelen, W. 2005. An economic evaluation of a proprioceptive balance board training programme for the prevention of ankle sprains in volleyball. *Br. J. Sports Med.* **39**: 111–115. doi:10.1136/bjism.2003.011031. PMID:15665210.
- Verstegen, M., and Williams, P. 2004. Core performance. Rodale, Emmaus, Pa. pp. 33–52.
- Vicente-Rodriguez, G. 2006. How does exercise affect bone development during growth? *Sports Med.* **36**: 561–569. doi:10.2165/00007256-200636070-00002. PMID:16796394.
- Virgilio, S. 1997. Fitness education for children. Human Kinetics, Champaign, Ill.
- Virvidakis, K., Georgiou, E., Korkotsidis, A., Ntalles, K., and Proukakis, C. 1990. Bone mineral content of junior competitive weightlifters. *Int. J. Sports Med.* **11**: 244–246. PMID:2373585.
- Vrijens, J. 1978. Muscle strength development in the pre- and post-pubescent age. *In Pediatric Work Physiology. Edited by J. Borms and M. Hebbelink.* Karger, Basel, Switzerland. pp. 152–158.
- Ward, K.A., Roberts, S.A., Adams, J.E., and Mughal, M.Z. 2005. Bone geometry and density in the skeleton of prepubertal gymnasts and school children. *Bone*, **36**: 1012–1018. doi:10.1016/j.bone.2005.03.001.
- Watts, K., Beye, P., Siafarikas, A., O'Driscoll, G., Jones, T.W., Davis, E.A., and Green, D.J. 2004. Effects of exercise training on vascular function in obese children. *J. Pediatr.* **144**: 620–625. doi:10.1016/j.jpeds.2004.02.027. PMID:15126996.
- Webb, D.R. 1990. Strength training in children and adolescents. *Pediatr. Clin. North Am.* **37**: 1187–1210. PMID:2216562.
- Weltman, A., Janney, C., Rians, C.B., Strand, K., Berg, B., Tippitt, S., et al. 1986. The effects of hydraulic resistance strength training in prepubertal males. *Med. Sci. Sports Exerc.* **18**: 629–689. PMID:2946921.
- Westcott, W. 1992. A look at youth fitness. *Am. Fitness Quart.* **11**: 16–19.
- Zakas, A., Doganis, G., Galazoulas, C., and Vamvakoudis, E. 2006. Effect of static stretching duration on isokinetic peak torque in pubescent soccer players. *Pediatr. Exerc. Sci.* **18**: 252–261.