

# The Youth Physical Development Model: A New Approach to Long-Term Athletic Development

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## SUMMARY

THE DEVELOPMENT OF PHYSICAL FITNESS IN YOUNG ATHLETES IS A RAPIDLY EXPANDING FIELD OF INTEREST FOR STRENGTH AND CONDITIONING COACHES, PHYSICAL EDUCATORS, SPORTS COACHES, AND PARENTS. PREVIOUS LONG-TERM ATHLETE DEVELOPMENT MODELS HAVE CLASSIFIED YOUTH-BASED TRAINING METHODOLOGIES IN RELATION TO CHRONOLOGIC AGE GROUPS, AN APPROACH THAT HAS DISTINCT LIMITATIONS. MORE RECENT MODELS HAVE ATTEMPTED TO BRIDGE MATURATION AND PERIODS OF TRAINABILITY FOR A LIMITED NUMBER OF FITNESS QUALITIES, ALTHOUGH SUCH MODELS APPEAR TO BE BASED ON SUBJECTIVE ANALYSIS. THE YOUTH PHYSICAL DEVELOPMENT MODEL PROVIDES A LOGICAL AND EVIDENCE-BASED APPROACH TO THE SYSTEMATIC DEVELOPMENT OF PHYSICAL PERFORMANCE IN YOUNG ATHLETES.

## INTRODUCTION

In recent times, scientists and coaches have shown an increasing interest in the long-term development of young

athletes (7,23,30,44,63,65,80,100,102). Enhancing the physical abilities of children throughout childhood and adolescence to maximize athletic success at an adult age is not a novel concept, as evidenced by earlier youth-based training programs (20). Researchers have previously documented the importance of not treating children like “miniature adults” owing to clear differences in physical growth and stature (39). Therefore, the content and delivery of youth strength and conditioning provision should be markedly different from that of fully matured adults.

The long-term athlete development (LTAD) model (7) takes into consideration the maturational status of the child and offers a more strategic approach to the athletic development of youth. The LTAD model suggests that there exist critical “windows of opportunity” during the developmental years, whereby children and adolescents are more sensitive to training-induced adaptation (7). The model also states that a failure to use these windows will result in the limitation of future athletic potential (7). However, this concept is largely theoretical and lacks supporting longitudinal empirical evidence (4,44,84).

This article will present a new model, which provides a more considered and evidence-based approach to the long-term development of young athletes. The model will demonstrate that most, if not all, components of fitness are trainable throughout childhood and will question some preconceptions of current LTAD theory.

## THE EVOLUTION OF LTAD THEORY

Early attempts at objectifying the process of LTAD were based on research that highlighted distinct phases of learning that characterized the development of elite performers: the early years, the middle years, and the later years (18). This early work was extended by Cote (32) who, after interviewing elite junior athletes, identified 3 distinct sport-specific stages of development: the sampling years (ages 6–12), the specializing years (ages 13–15), and the investment years (ages 16+). A common problem with these models is that they are classified in accordance with chronologic age, an approach that has previously been deemed flawed (44),

## KEY WORDS:

pediatrics; maturation; long-term athlete development

owing to differential rates of development of chronologic age and biologic maturity (57,68,108).

Consequently, a more comprehensive LTAD model was introduced that attempted to address the interaction between growth, maturation, and training (7). The model suggests that measures of height and weight are routinely collected to be able to identify peak height velocity (PHV) and peak weight velocity (PWV), which reflect individual maturation rates (68). PHV refers to the maximum velocity of growth in stature and has been used to characterize developments in performance relative to the adolescent growth spurt (68). PWV is a phase of development characterized by rapid increases in muscle mass as a result of increasing sex hormone concentrations (44). By objectively measuring the rates of change in height and body mass, it is suggested that children can be trained according to biologic status as opposed to chronologic age (7).

### **WINDOWS OF OPPORTUNITY**

A review article by Viru et al. (110) examined developmental literature and identified the existence of naturally occurring periods of accelerated adaptation for a range of biomotor qualities. A preadolescent spurt was highlighted for strength, speed, explosive strength, and endurance, in both boys and girls (110). It was suggested that age-related developments in neural properties were responsible for the prepubertal window, characterized by increased intramuscular and intermuscular coordination and improvements in motor control programs (110). An adolescent spurt was also identified in the review, but this differentiated between biomotor qualities (110). Maturity-related adaptations are typically the result of increased androgen concentrations, fiber-type differentiation, resting adenosine triphosphate, and creatine phosphate levels and further architectural development of musculotendon units (73).

Viru et al. (110) identified that spurts in speed and endurance occurred before

and around PHV, respectively, whereas accelerated gains in strength qualities occurred after PHV (110). Using PHV as a key reference marker of maturation, the LTAD model proposes that these periods of accelerated adaptation offer windows of opportunity where training responses will be maximized (7). In the LTAD model, it is assumed that these periods of rapid natural development represent a time of increased sensitivity to training, although empirical evidence supporting this suggestion is lacking (44). Furthermore, according to the LTAD model, should a child not engage in the appropriate training during the specific window, then their ceiling potential may never be reached. This concept would appear to be too simplistic and has recently been questioned by researchers (4,44,85). Conversely, research would suggest that most fitness components are trainable throughout childhood and should not be restricted to specific “windows” at various stages of development (3,44,94). Another weakness of the current LTAD model (7) is that its inclusion of stamina, suppleness, speed, strength, and skill presents a somewhat limited approach to the holistic development of young athletes. Despite the importance of power, agility, and hypertrophy to human performance (56,98,120), no guidance is offered as to when and why these qualities should be trained throughout childhood and adolescence.

### **THE YOUTH PHYSICAL DEVELOPMENT MODEL**

Given the limitations of previous athletic development models, the present article introduces a new alternative model that encompasses athletic development from early childhood (2 years of age) up to adulthood (21+ years of age). The model has been titled the Youth Physical Development (YPD) model and offers a comprehensive approach to the development of young males (Figure 1) and females (Figure 2), respectively. It is expected that the new model will provide strength and conditioning coaches,

sports coaches, physical educators, and parents with an overview of total physical development, while identifying when and why the training of each fitness component should be emphasized.

Within the model, training emphasis is highlighted by increasing font size (i.e., the greater the font size, the more important it is to train for that fitness quality). For example, the model shows that a 12- to 13-year-old boy should primarily focus their training on strength, power, speed, agility, and sport-specific skill (SSS) development, with a reduced focus on hypertrophy, mobility, fundamental movement skill (FMS), endurance, and metabolic conditioning. Discussion of how maturational status, sex, and initial training level affect the application of the model will be discussed later in the article. Below is a detailed overview of the rationale behind the emphasis of targeting various fitness components at different stages of a child's development.

### **FUNDAMENTAL MOVEMENT SKILLS AND SPORT-SPECIFIC SKILLS**

The topic of FMS development has received considerable interest owing to the close association between FMS competency, health and well-being, physical activity, and to a lesser degree physical performance (29,38,66,82,83,103). Previous research has indicated that FMS development is essential to ensure that correct movement patterns are mastered in a safe and fun environment to ensure safe and effective performance of more complex sports movements at a later stage (85). FMSs have been viewed as the building blocks for sport-specific movement patterns and should typically be the focus of physical development programs for children from early childhood to develop gross motor skills (35). From the onset of puberty, adolescents can then be introduced to more SSSs, whereby FMSs are tested within more competitive scenarios.

YOUTH PHYSICAL DEVELOPMENT (YPD) MODEL FOR MALES																				
CHRONOLOGICAL AGE (YEARS)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21+
AGE PERIODS	EARLY CHILDHOOD			MIDDLE CHILDHOOD						ADOLESCENCE						ADULTHOOD				
GROWTH RATE	RAPID GROWTH			STeady GROWTH						ADOLESCENT SPURT						DECLINE IN GROWTH RATE				
MATURATIONAL STATUS	YEARS PRE-PHV										PHV				YEARS POST-PHV					
TRAINING ADAPTATION	PREDOMINANTLY NEURAL (AGE-RELATED)										COMBINATION OF NEURAL AND HORMONAL (MATURITY-RELATED)									
PHYSICAL QUALITIES	FMS	FMS			FMS			FMS												
	SSS	SSS			SSS			SSS												
	Mobility	Mobility						Mobility												
	Agility	Agility						Agility			Agility									
	Speed	Speed						Speed			Speed									
	Power	Power						Power			Power									
	Strength	Strength						Strength			Strength									
		Hypertrophy						Hypertrophy		Hypertrophy				Hypertrophy						
	Endurance & MC	Endurance & MC						Endurance & MC			Endurance & MC									
TRAINING STRUCTURE	UNSTRUCTURED			LOW STRUCTURE						MODERATE STRUCTURE			HIGH STRUCTURE			VERY HIGH STRUCTURE				

Figure 1. The YPD model for males. Font size refers to importance; light blue boxes refer to preadolescent periods of adaptation, dark blue boxes refer to adolescent periods of adaptation. FMS = fundamental movement skills; MC = metabolic conditioning; PHV = peak height velocity; SSS = sport-specific skills; YPD = youth physical development.

However, it must be noted that FMS should always be present within any strength and conditioning program, for any athlete, of any age (65). For example, the main emphasis of a training session for an inexperienced 7-year-old boy may revolve around a series of FMS development exercises, whereas a young, elite, 21-year-old man may integrate FMS maintenance exercises within a dynamic warm-up. This logical approach is reflected in the YPD model (Figures 1 and 2), where an emphasis is placed on FMS development up to the onset of puberty, and subsequently, focus is given to SSS from adolescence onward. However,

the YPD model also shows that both FMS and SSS are present at all times throughout childhood and adolescence, but the emphasis placed on both components varies according to developmental stage.

### STRENGTH

Despite previous concerns, it is now accepted that children can safely and effectively participate in strength training, when prescribed and supervised by appropriately qualified personnel (6,11,39,62,88,105). The LTAD model (7) suggests that a “window of opportunity” for strength development in youths occurs 12–18 months after PHV, which is typically commensurate

with PWV (14,15). The rationale behind this window is that around the time of PWV, adolescents will undergo periods of rapid gains in muscle mass resulting from increased circulating androgen concentrations (110).

However, by limiting the period of trainability to coincide with maturity-related increases in muscle mass would suggest that children can only become stronger as a consequence of muscle fiber hypertrophy and subsequent increases in muscle cross-sectional area. Despite this, it has previously been established that strength development is multifaceted and results from a combination of muscular,

# Youth Physical Development Model

YOUTH PHYSICAL DEVELOPMENT (YPD) MODEL FOR FEMALES																					
CHRONOLOGICAL AGE (YEARS)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21+	
AGE PERIODS	EARLY CHILDHOOD			MIDDLE CHILDHOOD					ADOLESCENCE							ADULTHOOD					
GROWTH RATE	RAPID GROWTH			↔ STEADY GROWTH ↔					↔ ADOLESCENT SPURT ↔				↔ DECLINE IN GROWTH RATE								
MATURATIONAL STATUS	← YEARS PRE-PHV ←							PHV			→ YEARS POST-PHV →										
TRAINING ADAPTATION	PREDOMINANTLY NEURAL (AGE-RELATED)										↔ COMBINATION OF NEURAL AND HORMONAL (MATURITY-RELATED)										
PHYSICAL QUALITIES	FMS	FMS		FMS		FMS															
	SSS	SSS		SSS		SSS															
	Mobility	Mobility					Mobility														
	Agility	Agility					Agility					Agility									
	Speed	Speed					Speed					Speed									
	Power	Power					Power					Power									
	Strength	Strength					Strength					Strength									
		Hypertrophy					Hypertrophy		Hypertrophy							Hypertrophy					
	Endurance & MC	Endurance & MC					Endurance & MC					Endurance & MC					Endurance & MC				
TRAINING STRUCTURE	UNSTRUCTURED			LOW STRUCTURE					MODERATE STRUCTURE			HIGH STRUCTURE				VERY HIGH STRUCTURE					

Figure 2. The YPD model for females. Font size refers to importance; light pink boxes refer to preadolescent periods of adaptation, dark pink boxes refer to adolescent periods of adaptation. FMS = fundamental movement skills; MC = metabolic conditioning; PHV = peak height velocity; SSS = sport-specific skills; YPD = youth physical development.

neural, and mechanical factors (1,34). Owing to the neural plasticity associated with the prepubertal years, where development of the neuromuscular system naturally accelerates (21), it is suggested that strength development should be targeted during childhood in addition to after the adolescent spurt. This notion is reinforced by research and meta-analytical reviews that have proven that both prepubertal children and adolescents can achieve training-induced improvements in muscular strength (12,13,40,42,48).

The YPD model shows that the development of muscular strength should be a priority at all stages of development for both males and females (Figures 1

and 2). This notion is based on previous research that has revealed close associations between muscular strength and running speed (114), muscular power (104,116), change of direction speed (78), plyometric ability (71), and endurance (53). Additionally, it has been speculated that muscular strength is indeed critical for successful FMS development (12). Consequently, it is reasonable to suggest that developing levels of muscular strength should be a priority of any athlete development program, as strength would appear to transcend all other fitness components. Although not all these relationships have been validated in pediatric populations, early research

has indicated that muscular strength (in addition to stature) could account for up to 70% of the variability in a range of motor skills including throwing, jumping, and sprinting in 7- to 12-year-old boys (106).

The development of muscular strength should also be viewed as an integral component of youth strength and conditioning programs not only for performance enhancement but also for reducing the risk of sport-related injuries (39). It has been reported that high aerobic fitness and low levels of muscle strength heighten the risk of fracture in children participating in exercise protocols (26), highlighting the importance of strength within an



athletic development program. It is now accepted that the risk of sports-related injuries in youths can be reduced by regularly engaging in an appropriately designed strength training program that is supervised by appropriately qualified personnel (42,73). In 2011, the National Athletic Trainers' Association suggested that approximately 50% of overuse injuries within youth sports could be preventable in part with appropriate preparatory conditioning (109). However, it must be stressed that strength development sessions should not simply be viewed as an addition to a young athletes' development program but as a replacement for another form of training (e.g., endurance training or skill development session).

#### **HYPERTROPHY**

The YPD model depicts that an emphasis on training for hypertrophy may begin around the ages of 14 years in male and 12 years in female athletes. As mentioned previously, these phases of development will typically occur after PHV, at a time where levels of circulating testosterone and growth hormone rapidly increase in accordance with the adolescent growth spurt (68,110). Increases in serum concentrations of testosterone, estradiol, and progesterone have been directly linked with the stimulation of protein synthesizing pathways (45) and are responsible for the pubertal growth spurt and adaptations to muscle and skeletal tissue (19). Although not proven with direct evidence, it is reasonable to assume that because of a lack of circulating androgens, significant training-induced increases in muscle size before adolescence would appear limited. Consequently, within the YPD model, it is suggested in terms of resistance training that a focus should be geared toward strength development before adolescence, and after the adolescent spurt, strength training should be interspersed with bouts of hypertrophy training to make further gains in muscular strength and overall performance.

#### **POWER**

The ability to generate high levels of power is essential for sporting success (119); however, power is omitted from the current LTAD model (7). Vertical jump height is an indirect measure of muscular power, and owing to its simplicity, most developmental literature has used the test modality to assess pediatric lower limb muscular power (50,55).

The YPD model shows that the key period of power development starts at the onset of adolescence and continues throughout adulthood, largely because of rapid improvements in muscle power during adolescence being attributed to maturational influences (15). However, although power development is emphasized primarily after the onset of puberty, the YPD model does suggest that some training focus should also be given to developing power during the prepubertal phase. This is in response to research that shows that both children and adolescents can make worthwhile training-induced improvements in measures of muscular power (25,41,64,69,92,97,118). As is the case with muscular strength, the research would therefore suggest that muscular power is trainable throughout childhood, although the magnitude and rate of development may differ before and after the onset of puberty.

#### **SPEED**

Currently, the LTAD model advocates that windows of opportunity for speed development are entirely age related (7). According to the model, any training effects will therefore result from neural adaptations, which have previously been highlighted as significant factors in speed gains (21). However, alternative research has indicated that speed development in young athletes might also be influenced by maturation (94), which suggests that as is the case with many fitness components, speed is indeed trainable throughout childhood and adolescence. Interestingly, the review of Rumpf et al. (94) revealed that prepubescents

benefited most from training requiring high levels of neural activation (plyometrics and sprint training), whereas adolescents responded more favorably to training modes that targeted both neural and structural development (strength and plyometrics). This might support the concept of windows when different training adaptations predominate reflecting natural development; however, trainability per se remains throughout childhood. From a practical perspective, this would suggest that prepubescent children should focus their speed development around plyometrics, technical competency, and sprint work to develop existing physical qualities, whereas adolescents should focus more on strength training, plyometrics, and sprint training, to maximize overall speed gains.

#### **AGILITY**

Agility is arguably one of the most underresearched fitness components within the pediatric literature, despite the acknowledgment that a high degree of agility is required for optimal performance in the majority of sports (56). Furthermore, a window of opportunity is not present within the current LTAD model (7). Consequently, it is difficult to determine whether age, maturation, or both are determinants of agility performance. There is a lack of research that identifies appropriate time frames to target agility-specific training. Therefore, the YPD model makes inferences in relation to the development of the subcomponents of agility, as defined previously (99,120): *change of direction speed* (inclusive of technique, straight sprinting speed, lower limb strength, and anthropometry) and *cognitive function* (perceptual and decision-making processes).

*Change of direction speed.* When examining the literature surrounding these components, the YPD model suggests that agility should be targeted during both prepubescence and adolescence. As lower limb strength and straight running speed are components of agility (120), it is logical to look to develop agility and reinforce

coordination and movement pattern accuracy during the early years. The prepubertal years have already been shown to represent an opportunity for children to enhance strength (12,48) and speed (94), resulting from enhanced neural contribution to rate of force development (110). Once a child reaches adolescence, they will typically experience further gains in strength through continued neural maturation and also significant increases in lean muscle mass, owing to increased serum androgen concentrations (110). It is reasonable to suggest that adolescence will therefore serve as an opportune time to further develop agility, as peak force and peak rate of force development are likely to increase because of the adaptation in muscle structure. Prepubescence has also been identified as a period that sees children undergo rapid developments in the neuromuscular system (21), with the rates of brain maturation peaking between 6 and 8 and 10 and 12 years (90). Naturally, owing to the neural plasticity associated with prepubescence, this would seem an ideal opportunity to develop motor control programs inclusive of basic change of direction techniques in the first instance and then progressing to more sport-specific agility movements as the child approaches adolescence.

*Cognitive function.* According to Sheppard and Young (99), a number of perceptual variables influence agility. Specifically, the authors state that visual scanning, knowledge of situations, pattern recognition, and anticipatory qualities influence individual agility performance (99). Minimal literature exists examining the influence of growth and maturation on these components and their subsequent effects on agility performance. Outside sporting situations, research suggests that cognitive capacities increase during late childhood and adolescence and that throughout these phases of development, repeated exposure to a given stimulus will result in faster response times because of an apparent

strengthening of existing synaptic pathways (24). Whether these theories translate to actual sporting situations, in which athletes will need to react rapidly to fluctuating stimuli (e.g. body position, bounce of ball, opposition movement), remains to be seen.

It is expected that the locomotive vocabulary developed during the prepubertal phase will continuously be enhanced as the child progresses through adolescence and into adulthood, through an increase in experiential learning opportunities within sports-specific environments. Given the lack of existing developmental literature, it is suggested that the training focus of agility should be made more challenging as the individual progresses through childhood and into adulthood, with the use of more open and unplanned training methods to continually overload the training stimulus. Additionally, with an increase in training demands within an overall athletic schedule, it is expected that agility development (and maintenance) will be garnered from specific sports skill-based sessions, where movement demands replicate the exact locomotive demands of the sport.

As per speed development, a caveat should be noted for agility development during adolescence, as children learn to move with longer limbs. The rapid gains in limb length during the adolescent growth spurt can lead to decrements in motor control performance, a concept commonly referred to as “adolescent awkwardness” (87). During this stage of development, researchers have suggested that many of the previously acquired movement patterns will need to be reperfected (37). Through regular monitoring of growth rates, periods of adolescent awkwardness can potentially be identified and strength and conditioning coaches should be aware of the underlying processes attributable to such disruptions in motor control and adjust the content of training sessions accordingly.

## **MOBILITY**

Despite highlighting “suppleness” as one of the key components to develop

through training (7), the LTAD model fails to suggest an appropriate window of opportunity for its development. The YPD model purports that at no stage is mobility the main emphasis of a training program during childhood or adolescence. However, it should be noted that as authors, we recommend that mobility development and maintenance should be an essential part of any athletic program to ensure athletes are capable of reaching the requisite ranges of motion required for their sports.

Specifically, the YPD model proposes that middle childhood (ages 5–11) serves as the most important time frame for an individual to incorporate flexibility and mobility training. The rationale for this selection is that it incorporates a period that has previously been termed a critical period of development for flexibility (67,96). Sex differences are apparent within the research, suggesting that boys show a reduction in trunk forward flexibility between 9 and 12 years (16), whereas girls demonstrate accelerated improvement beginning at 11 years of age (22). It is therefore suggested that prepubescence serves as an opportunity to develop mobility, whereas maintenance of the acquired levels should be the focus for adolescents and adults.

## **ENDURANCE AND METABOLIC CONDITIONING**

Early research produced conflicting results with respect to the trainability of youths, with studies suggesting that children who were circa-PHV possessed greater training responsiveness (113) or, conversely, that large training gains were possible for children who were pre-PHV (93). It is suggested that inconsistencies in research design have been attributable to these confounding results and that a lack of longitudinal empirical evidence refutes the claims of the existence of a window of opportunity as defined in the LTAD model (44). Regardless of the lack of evidence, growth-related changes in central and peripheral cardiovascular systems, neuromuscular function, and metabolic

capacities are expected to influence endurance and metabolic conditioning development throughout childhood (93). As physiological components are continually developed throughout childhood and adolescence, it is not surprising that prepubertal, circumpubertal, and postpubertal children have all been reported as being able to make worthwhile improvements in endurance performance as indicated by  $\dot{V}O_2\text{max}$  responses (3).

The YPD model proposes that more attention is given to endurance and metabolic conditioning as the child approaches adulthood, and at no stage, it is seen as the main focus of an individual's training. Although this may appear controversial, the rationale is based on the assumption that an individual will be exposed to sport-specific endurance development while participating in organized matches or competitions and potentially within a technical skill session of their given sport. Additionally, remarkable levels of endurance are not necessarily required in the majority of sports, and endurance appears to remain trainable in adulthood. Within the education sector, cardiovascular endurance is inadvertently the most commonly developed fitness component, as asking a child to perform some form of submaximal locomotion would appear safer to teachers than asking them to participate in some form of resistance training. This is especially the case within the primary school setting in the United Kingdom, where not only have strength levels in children diminished in the last decade (31) but also it is recognized that teachers are inappropriately prepared through their teacher training to teach physical education and that statutory requirements for physical education are routinely not achieved (59).

### **THE NEED TO INDIVIDUALIZE LONG-TERM ATHLETIC DEVELOPMENT PROGRAMS**

The YPD model is presented for both males (Figure 1) and females (Figure 2) displaying what would be classified as an average maturing child (i.e., not an early or late maturer). However,

strength and conditioning coaches will habitually come into contact with athletes of varying stages of maturation, age, sex, and training history. Although previous models have alluded to these variables (7), it is not apparent that the impact of the individual variables on training prescription has been addressed. Consequently, the following section will examine how the YPD model should be manipulated when considering sex-dependent factors, timing and rates of maturation, and the training history associated with different athletes.

### **SEX DIFFERENCES**

Despite more boys engaging in youth sports than girls, there has been an increase in the overall number of children and adolescents actively participating in organized youth sports over the past decade (77). With participation numbers increasing, it is imperative that any strength and conditioning coach is aware of the physiological and maturational differences that exist between males and females and design-specific programs accordingly.

During the prepubertal years, boys and girls will follow similar rates of development in growth and maturation, and despite consistent sex differences, strength, speed, power, endurance, and coordination will develop at similar rates for both sexes throughout childhood (14). Consequently, from a training perspective, both boys and girls can follow similar training programs during the prepubertal years. The YPD model advocates a prepubertal focus of training for both boys and girls that centers on FMS, strength speed, and agility development.

The prepubertal years are a period where children will experience rapid gains in bone mass because of modeling and remodeling (9). Exposure to appropriately designed weight-bearing exercise of moderate- to high-load intensity (with appropriate technical competency) is an osteogenic stimulus (60,61,111,115). Such training can result in large increases in bone mass and

density (5,10,17,46,117), and research has suggested that this adaptive response is most sensitive during the prepubertal years (8). Due to women possessing a greater risk of osteoporosis in later life (58) and that strength training has previously been deemed to offer the potential of reducing osteoporotic fractures in older women (79), the importance of strength training for women at all stages of development should not be underestimated.

Upon the onset of the adolescent growth spurt, clear maturational differences are apparent for nearly all components of fitness, with men making greater improvements in most physical qualities, with the exception of flexibility (14,68). Typically, the onset of the adolescent growth spurt occurs around 2 years earlier in girls (about 10 years of age) than in boys (approximately 12 years of age) (14), and in the majority of instances, girls experience PHV at an earlier age than boys (12 years versus 14 years) (15). Despite an earlier attainment of PHV in girls, the magnitude of the growth spurt is greater in boys (15).

During the adolescent spurt, female athletes will undergo sex-specific physiological processes that may affect performance: increased fat mass, differential rates of development of neuromuscular strength, and height and weight; commencement of menstrual cycle, increased joint laxity, increased knee valgus angle; and increased reliance on quadriceps-dominant landing strategies, all of which have been associated with an increased risk of noncontact anterior cruciate ligament injury (2,43,51,52,72,75,86,89).

Consequently, the YPD model suggests that training strategies designed to reduce the risk of noncontact anterior cruciate ligament injuries, such as plyometrics, core strengthening, strength training, and balance and perturbation training (74), should be implemented within the strength and conditioning program



of female athletes and maintained into adulthood.

## **EARLY VERSUS LATE MATURING INDIVIDUALS**

Because of the highly individual timing of maturation, it is imperative that any LTAD model contains a degree of flexibility (65). An early maturing child has previously been defined as a girl or boy who starts their adolescent growth spurt approximately 1.5 or 2 years earlier than a late maturing child (47).

Although research has indicated that eventual adult height is not affected by early or late maturation (49), strength and conditioning coaches must appreciate that an early or late maturing child will need to be treated somewhat differently than an “average” maturing child, when prescribing long-term athletic development programs. For example, if a child is routinely monitored for stature and body mass every 3–6 months throughout childhood, growth rates, percentage of adult height, and predictions of age from PHV can be calculated (70). Using these measurements, the maturational status of a child can be approximated, thus providing a more robust estimate of their biological age.

In relation to the YPD model, if a child is deemed to be an early maturer, then the components of the model will need to be moved to the left, thus enabling the child to commence more advanced training techniques at an earlier chronological age. In contrast, a strength and conditioning coach must allow the components of the YPD model to be moved to the right for a child who is deemed a late maturer, thereby introducing them to more advanced training at a later chronological age, when they are physiologically ready to cope with the increased training stimulus. In either of these instances, although training prescription will vary according to chronological age, it should allow greater consistency and more accuracy in terms of the child’s biological age.

## **INITIAL TRAINING STATUS**

Irrespective of chronological or biological age, a strength and conditioning coach must give thought to the training age of any athlete that they start working with. Training age can be defined as the number of years an athlete has been participating in formalized training and is an important factor to consider when designing long-term athletic development programs. Such an approach is particularly pertinent when a strength and conditioning coach begins to work with an athlete who is approaching adulthood that has missed the initial stages of the YPD model.

In such an instance, the athletes should begin with early development of FMS and muscular strength before embarking on the training content that is commensurate with their chronological age. Conversely, should a strength and conditioning coach begin working with an early maturing 10-year-old boy who can display exceptional strength, speed, and power while maintaining the requisite technical competency, then they should not be restricted to the introductory training methods more akin to his chronological age. This concept has previously been discussed in relation to both plyometric (63) and weightlifting (65) development models.

## **THE YPD MODEL AS A VEHICLE FOR ATHLETE WELL-BEING**

Well-being has been defined as a positive and sustainable state that allows individuals, groups, or nations to thrive and flourish (54). The philosophy of the YPD model is that it permits individualization, is athlete centered, and promotes the development of the child over performance outcomes. This may sacrifice short-term performance success but should maximize the opportunity to foster a sense of well-being and provide long-term gains. This philosophy will help the child to appreciate the benefits of training and develop intrinsic motivation for participating in training, which is a strong predictor of well-being (95) and is associated with positive behaviors (112). Additionally, provided the coach

can deliver the content of the model in a positive manner the child should recognize the gains they are achieving (e.g., technical, physical, developmental), leading to increased perceived competence, which is a primary determinant of a sense of well-being in child athletes (91). This will increase the likelihood of the child being able to persist in the face of adversity and to sustain continued interest in sport (4,36).

The YPD model advocates the development of FMS from a young age, which are associated with physical and psychologic health benefits in children (66). Furthermore, the progression provided throughout the YPD model will enable the children to experience continued mastery of new tasks throughout their developmental years.

Task mastery is associated with increased enjoyment, perceived competence, satisfaction, and beliefs that effort causes success (81,101,107). Such positive experiences should also provide valuable and highly transferable life skills (33). The continued and overlapping development of a number of fitness components in the YPD model should also provide the strength and conditioning coach with the ability to develop training programs containing a high degree of variation, something that has been suggested to be important in maintaining the interest of and promoting the well-being of child athletes (85).

## **DESIRED CREDENTIALS FOR STRENGTH AND CONDITIONING COACHES WORKING WITH YOUTH ATHLETES**

It is important to realize that the success of any long-term development program will be dependent largely on the level of education and quality of instruction received by the athlete from the responsible coach (73). Within the literature, cases of training-induced injury in children and adolescents are reported only in instances where a young athlete has been exposed to excessive, unfamiliar, and poorly prescribed training, which in both cases have led to exertional rhabdomyolysis



and hospitalization (27,28). Research suggests that outside these isolated cases, most incidences of resistance training-related injuries tend to be accidental in nature, with the number of accidental injuries decreasing with age (76). However, to minimize the chances of such isolated instances occurring, it is imperative that those coaches who actively coach young athletes possess the appropriate credentials.

First, a coach must hold a relevant strength and conditioning qualification (e.g., Certified Strength and Conditioning Specialist in the United States or Accredited Strength and Conditioning Coach in the United Kingdom). Second, a coach must have a sound underpinning knowledge of pediatric exercise science, ideally at an undergraduate or postgraduate level. Finally, a coach should have a strong pedagogical background to ensure they have an appreciation of the different styles of communication and interaction that they will need to adopt with athletes, who might range from early prepubescent to late adolescent. Satisfaction of these criteria will hopefully ensure that young athlete development models are delivered in a safe and effective manner, underpinned by appropriate individual program design (inclusive of exercise selection and progressions, volume loads, rest, and recovery), realistic goal setting, and a coaching philosophy that is tailored toward the holistic development of the young athlete.

### SUMMARY

The present article has provided a sound rationale for the YPD model. This approach to the development of young athletes appears to be more realistic in terms of acknowledging that most fitness components are trainable throughout childhood. Central to the YPD model is that during prepubescence, strength, FMS, speed, and agility should be the main physical qualities targeted and that adaptive responses to the appropriate training methods will be neural in nature. Once the child reaches adolescence, additional components (SSS, power, and hypertrophy) become

more important owing to the increased androgenic internal environment associated with this stage of development. The need for individualization of the model should not be underestimated when dealing with athletes of different sex, maturity status, and training history. Crucially, appropriately qualified personnel should always be responsible for the implementation of the YPD model, to ensure the holistic development of children and adolescents.



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### REFERENCES

1. Aagaard P. Training-induced changes in neural function. *Sports Med* 31: 61–67, 2003.
2. Arendt E and Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of the literature. *Am J Sports Med* 23: 694–701, 1995.
3. Bacquet G, van Praagh E, and Berthoin S. Endurance training and aerobic fitness in young people. *Sports Med* 33: 1127–1143, 2003.
4. Bailey R, Collins D, Ford P, MacNamara A, Toms M, and Pearce G. Participant development in sport: An academic review. *Sports Coach UK* 4: 1–134, 2010.
5. Bailey DA, Faulkner RA, and McKay HA. Growth, physical activity and bone mineral acquisition. In: *Exercise and Sports Science Review. American College of Sports Medicine Series.*

- Holloszy JO, ed. Vol. 24. Baltimore, MD: Williams & Wilkins, 1996. pp. 233–266.
6. Baker D, Mitchell J, Boyle D, Currell S, Wilson G, Bird SP, O'Connor D, and Jones J. Resistance training for children and youth: A position stand from the Australian Strength and Conditioning Association (ASCA). 2007. Available at: <http://www.strengthandconditioning.org>. Accessed July 13, 2011.
7. Balyi I and Hamilton A. *Long-Term Athlete Development: Trainability in Childhood and Adolescence—Windows of Opportunity—Optimal Trainability.* Victoria, Canada: National Coaching Institute British Columbia & Advanced Training and Performance Ltd, 2004.
8. Bass SL. The prepubertal years—A unique opportune stage of growth when the skeleton is most responsive to exercise? *Sports Med* 30: 73–78, 2000.
9. Bass S, Delmas PD, Pearce G, Hendrich E, Tabensky A, and Seeman E. The differing tempo of growth in bone size, mass and density in girls is region-specific. *J Clin Invest* 104: 795–804, 1999.
10. Bass SL and Myburg K. The effect of exercise on peak bone mass and bone strength. In: *Sports Endocrinology.* Warren M and Constantini N, eds. Totowa, NJ: Humana Press Inc, 2000. pp. 253–280.
11. Behm DG, Faigenbaum AD, Flak B, and Klentrou P. Canadian Society for Exercise Physiology position paper: Resistance training in children and adolescents. *Appl Physiol Nutr Metab* 33: 547–561, 2008.
12. Behringer M, vom Heede A, Matthews M, and Mester J. Effects of strength training on motor performance skills in children and adolescents: A meta-analysis. *Pediatr Exerc Sci* 23: 186–206, 2011.
13. Behringer M, vom Heede A, Yue Z, and Mester J. Effects of resistance training in children and adolescents: A meta-analysis. *Pediatrics* 126: 1199–1210, 2010.
14. Beunen GP and Malina RM. Growth and biological maturation: Relevance to athletic performance. In: *The Child and Adolescent Athlete.* Bar-Or O, ed. Oxford, United Kingdom: Blackwell Publishing, 2005. pp. 3–17.
15. Beunen GP and Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev* 16: 503–540, 1988.
16. Beunen GP, Malina RM, Van't Hof MA, Simons J, Ostyn M, Renson R, and

- Van Gerven D. *Adolescent Growth and Motor Performance*. Champaign, IL: Human Kinetics, 1988. pp. 6–9.
17. Blimkie CJ, Rice S, Webber CE, Martin J, Levy D, and Gordon CL. Effects of resistance training on bone mineral content and density in adolescent females. *Can J Physiol Pharmacol* 74: 1025–1033, 1996.
  18. Bloom BS. *Developing Talent in Young People*. New York, NY: Ballantine Books, 1985. pp. 139–211.
  19. Boisseau N and Delamarche P. Metabolic and hormonal responses to exercise in children and adolescents. *Sports Med* 30: 405–422, 2000.
  20. Bompá TO. *Total Training for Young Champions*. Champaign, IL: Human Kinetics, 2000. pp. 21–31.
  21. Borms J. The child and exercise: An overview. *J Sports Sci* 4: 4–20, 1986.
  22. Branta C, Haubenstricker J, and Seefeldt V. Age changes in motor skills during childhood and adolescence. *Exerc Sport Sci Rev* 12: 467–520, 1984.
  23. Burgess DJ and Naughton GA. Talent development in adolescent team sports: A review. *Int J Sports Physiol Perform* 5: 103–116, 2010.
  24. Casey BJ, Giedd JN, and Thomas KM. Structural and functional brain development and its relation to cognitive development. *Biol Psychol* 54: 241–257, 2000.
  25. Chioldera P, Volta E, Gobbi G, Milioli MA, Mirandola P, Bonetti A, Deisignore R, Bernasconi S, Anedda A, and Vitale M. Specifically designed physical exercise programs improve children's motor abilities. *Scand J Med Sci Sports* 18: 179–187, 2008.
  26. Clark EM, Tobias JH, Murray L, and Boreham C. Children with low muscle strength are at an increased risk of fracture with exposure to exercise. *J Musculoskelet Neuronal Interact* 11: 196–202, 2011.
  27. Clarkson PM. Case report of exertional rhabdomyolysis in a 12-year-old boy. *Med Sci Sports Exerc* 38: 197–200, 2006.
  28. Cleary MA, Sadowski KA, Lee SY, Miller GL, and Nichols AW. Exertional rhabdomyolysis in an adolescent athlete during preseason conditioning: A perfect storm. *J Strength Cond Res* 25: 3506–3513, 2011.
  29. Cliff DP, Okely AD, Smith LM, and McKeen K. Relationships between fundamental movement skills and objectively measured physical activity in preschool children. *Pediatr Exerc Sci* 21: 436–449, 2009.
  30. Cogley S, Baker J, Wattie N, and McKenna J. Annual age-grouping and athlete development: A meta-analytical review of relative age effects in sport. *Sports Med* 39: 235–256, 2009.
  31. Cohen DD, Voss C, Taylor MJ, Delextrat A, Ogunleye AA, and Sandercock GR. Ten-year secular changes in muscular fitness in English children. *Acta Paediatr* 100: e175–e177, 2011.
  32. Cote J. The influence of the family in the development of talent in sport. *Sport Psychol* 13: 395–417, 1999.
  33. Danish S, Forneris T, Hodge K, and Heke I. Enhancing youth development through sport. *World Leisure J* 46: 38–49, 2004.
  34. De Ste Croix M. Advances in paediatric strength assessment: Changing our perspective on strength development. *J Sports Sci Med* 6: 292–304, 2007.
  35. Deli E, Bakle I, and Zachopoulou E. Implementing intervention movement programs for kindergarten children. *J Early Child Res* 4: 5–18, 2006.
  36. Donaldson SJ and Ronan KR. The effects of sports participation on young adolescents' emotional wellbeing. *Adolescence* 41: 369–388, 2006.
  37. Drabik J. *Children & Sports Training: How Your Future Champions Should Exercise to be Healthy, Fit, and Happy*. Island Pond, VT: Stadion Publishing Co, 1996.
  38. Faigenbaum AD, Farrell A, Fabiano M, Radler T, Nacierio F, Ratamess NA, Kang J, and Myer GD. Effects of integrative neuromuscular training on fitness performance in children. *Pediatr Exerc Sci* 23: 573–584, 2011.
  39. Faigenbaum AD, Kraemer WJ, Blimkie CJ, Jeffreys I, Micheli LJ, Nitka M, and Rowland TW. Youth resistance training: Updated position statement paper from the National Strength and Conditioning Association. *J Strength Cond Res* 23: S60–S79, 2009.
  40. Faigenbaum AD, Loud RL, O'Connell J, Glover S, O'Connell J, and Westcott W. Effects of different resistance training protocols on upper-body strength and endurance development in children. *J Strength Cond Res* 15: 459–465, 2001.
  41. Faigenbaum A and Mediate P. Medicine ball for all: A novel program that enhances physical fitness in school-age youths. *J Phys Educ Recreation Dance* 77: 25–30, 2006.
  42. Faigenbaum AD and Myer GD. Resistance training among young athletes: Safety, efficacy and injury prevention effects. *Br J Sports Med* 44: 56–63, 2010.
  43. Fischer DV. Neuromuscular training to prevent anterior cruciate ligament injury in the female athlete. *Strength Cond J* 28: 44–54, 2006.
  44. Ford PA, De Ste Croix MBA, Lloyd RS, Meyers R, Moosavi M, Oliver J, Till K, and Williams CA. The long-term athlete development model: Physiological evidence and application. *J Sports Sci* 29: 389–402, 2011.
  45. Fragala MS, Kraemer WJ, Denegar CR, Maresh CM, Mastro AM, and Volek JS. Neuroendocrine-immune interactions and responses to exercise. *Sports Med* 41: 621–639, 2011.
  46. Fuchs RK, Bauer JJ, and Snow CM. Jumping improves hip and lumbar spine bone mass in prepubescent children: A randomized controlled trial. *J Bone Miner Res* 16: 148–156, 2001.
  47. Gasser T, Sheehy A, Molinari L, and Largo RH. Growth of early and late maturers. *Ann Hum Biol* 28: 328–336, 2001.
  48. Granacher U, Goesele A, Roggo K, Wischer T, Fischer S, Zuerny C, Gollhofer A, and Kriemler S. Effects and mechanisms of strength training in children. *Int J Sports Med* 32: 357–364, 2011.
  49. Hägg U and Taranger J. Height and height velocity in early, average and late maturers followed to the age of 25: A prospective longitudinal study of Swedish urban children from birth to adulthood. *Ann Hum Biol* 18: 47–56, 1991.
  50. Harrison AJ and Gaffney S. Motor development and gender effects on SSC performance. *J Sci Med Sport* 4: 406–415, 2001.
  51. Hewett TE, Myer GD, and Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am* 86: 1601–1608, 2004.
  52. Hewett TE, Zazulak BT, and Myer GD. Effects of the menstrual cycle on anterior cruciate ligament injury risk: A systematic review. *Am J Sports Med* 35: 659–668, 2007.
  53. Hoff J, Helgerud J, and Wisloff U. Maximal strength training improves work economy in trained female cross-country skiers.

- Med Sci Sports Exerc* 31: 870–877, 1999.
54. Huppert FA, Baylis N, and Keverne B. Introduction: Why do we need a science of well-being? *Philos Trans R Soc Lond B Biol Sci* 359: 1331–1332, 2004.
  55. Isaacs LD. Comparison of the vertec and just jump systems for measuring height of vertical jump by young children. *Percept Mot Skills* 86: 659–663, 1998.
  56. Jeffreys I. Motor learning—Applications for agility, part 1. *Strength Cond J* 28: 72–76, 2006.
  57. Katzmarzyk PT, Malina RM, and Beunen GP. The contribution of biological maturation to the strength and motor fitness of children. *Ann Hum Biol* 24: 493–505, 1997.
  58. Kelly PJ, Twomey L, Sambrook PN, and Eisman JA. Sex differences in peak adult bone mineral density. *J Bone Miner Res* 5: 1169–1175, 1990.
  59. Kirk D. Physical education, youth sport and lifelong participation: The importance of early learning experiences. *Eur Phys Edu Rev* 11: 239–255, 2005.
  60. Lanyon LE. Functional strain in bone tissue as the objective and controlling stimulus for adaptive bone remodeling. *J Biomech* 20: 1083–1095, 1987.
  61. Lanyon LE and Rubin CT. Static versus dynamic loads as an influence on bone remodeling. *J Biomech* 12: 897–907, 1984.
  62. Lloyd RS, Brewer C, Faigenbaum AD, Jeffreys I, Moody J, Myer GD, Oliver JL, Pierce K, and Stone MH. United Kingdom Strength and Conditioning Association position statement on youth resistance training. *Prof Strength Cond J* In press.
  63. Lloyd RS, Meyers RW, and Oliver JL. The natural development and trainability of plyometric ability during childhood. *Strength Cond J* 33: 23–32, 2011.
  64. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Effects of 4-weeks plyometric training on reactive strength index and leg stiffness in male youths. *J Strength Cond Res* 2012, in press. DOI: 10.1519/JSC.0b013e318242d-2ec.
  65. Lloyd RS, Oliver JL, Meyers RW, Moody J, and Stone MH. Long-term athletic development and its application to youth weightlifting. *Strength Cond J* 2012, in press. DOI: 10.1519/SSC.0b013e31825ab4bb.
  66. Lubans DR, Morgan PJ, Cliff DP, Barnett LM, and Okely AD. Fundamental movement skills in children and adolescents. *Sports Med* 40: 1019–1035, 2010.
  67. Malina RM. Growth, maturation and development: Applications to young athletes and in particular to divers. In: *USA Diving Coach Development Reference Manual*. Malina RM and Gabriel JL, eds. Indianapolis, IN: USA Diving, 2007. pp. 3–29.
  68. Malina RM, Bouchard C, and Bar-Or O. *Growth, Maturation, and Physical Activity*. Champaign, IL: Human Kinetics, 2004. pp. 41–77.
  69. McGuigan MR, Tataschiere M, Newton RU, and Pettigrew S. Eight weeks of resistance training can significantly alter body composition in children who are overweight or obese. *J Strength Cond Res* 23: 80–85, 2009.
  70. Mirwald RL, Baxter-Jones AD, Bailey DA, and Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc* 33: 689–694, 2002.
  71. Miyaguchi K and Demura S. Relationships between muscle power output using the stretch-shortening cycle eccentric maximum strength. *J Strength Cond Res* 22: 1735–1741, 2008.
  72. Murphy DF, Connolly DAI, and Beynon BD. Risk factors for lower extremity injury: A review of the literature. *Br J Sports Med* 37: 13–29, 2003.
  73. Myer GD, Faigenbaum AD, Ford KR, Best TM, Bergeron MF, and Hewett TE. When to initiate integrative neuromuscular training to reduce sport-related injuries and enhance health in youth. *Curr Sports Med Rep* 10: 157–166, 2011.
  74. Myer GD, Ford KR, Palum-Bo JP, and Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res* 19: 51–60, 2005.
  75. Myer GD, Ford KR, Paterno MV, Nick TG, and Hewett TE. The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med* 36: 1073–1080, 2008.
  76. Myer GD, Quatman C, Khoury J, Wall E, and Hewett T. Youth vs. adult “weightlifting” injuries presenting to United States emergency rooms: Accidental vs. non-accidental injury mechanisms. *J Strength Cond Res* 23: 2054–2060, 2009.
  77. National Council on Youth Sports. NCYS report on trends and participation in organized youth sports (2008 Edition). Available at: <http://www.ncys.org/pdfs/2008/2008-ncys-market-research-report.pdf>. Accessed December 23, 2011.
  78. Negrete R and Brophy J. The relationship between isokinetic open and closed kinetic chain lower extremity strength and functional performance. *J Sports Rehab* 9: 46–61, 2000.
  79. Nelson ME, Fiatarone MA, Morganti CM, Trice I, Greenberg RA, and Evans WJ. Effects of high-intensity strength training on multiple risk factors for osteoporotic fractures. *J Am Med Assoc* 272: 1909–1914, 1994.
  80. Norris SR. Long-term athlete development Canada: Attempting system change and multi-agency cooperation. *Curr Sports Med Rep* 9: 379–382, 2010.
  81. Ntoumanis N and Biddle SJH. A review of motivational climate in physical activity. *J Sports Sci* 17: 643–665, 1999.
  82. Okely AD, Booth ML, and Patterson JW. Relationship of physical activity to fundamental movement skills among adolescents. *Med Sci Sports Exerc* 33: 1899–1904, 2001.
  83. Okely AD, Booth ML, and Patterson JW. Relationship of cardiorespiratory endurance to fundamental movement skill proficiency among adolescents. *Pediatr Exerc Sci* 13: 380–391, 2001.
  84. Oliver JL and Lloyd RS. Long-term athlete development and trainability during childhood. *Prof Strength Cond J*. In press.
  85. Oliver JL, Lloyd RS, and Meyers RW. Training elite child athletes: Welfare and well-being. *Strength Cond J* 33: 73–79, 2011.
  86. Padua DA, Arnold BL, Perrin DH, Gansneder BM, Carcia CR, and Granata KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train* 41: 294–304, 2006.
  87. Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, Bourgeois J, Vrijens J, Beunen GP, and Malina RM. The relationship between peak height velocity and physical performance in youth soccer players. *J Sports Sci* 24: 221–230, 2006.
  88. Pierce KC, Brewer C, Ramsey MW, Byrd R, Sands WA, Stone ME, and Stone MH. Youth resistance training. *Prof Strength Cond J* 10: 9–23, 2008.
  89. Quatman CE, Ford KR, Myer GD, and Hewett TE. Maturation leads to gender differences in landing force and vertical jump performance: A longitudinal study. *Am J Sports Med* 34: 806–813, 2006.



90. Rabinowickz T. The differentiated maturation of the cerebral cortex. In: *Human Growth: A Comprehensive Treatise, Postnatal Growth: Neurobiology*. Falkner F and Tanner J, eds. Vol. 2. New York, NY: Plenum, 1986.
91. Reinboth M, Duda JL, and Ntoumanis N. Dimensions of coaching behavior, need satisfaction, and the psychological and physical welfare of young athletes. *Motiv Emot* 28: 297–313, 2004.
92. Rhea MR, Peterson MD, Lunt KT, and Ayllón FN. The effectiveness of resisted jump training on the VertiMax in high school athletes. *J Strength Cond Res* 22: 731–734, 2008.
93. Rowland TW. Aerobic response to endurance training in prepubescent children: A critical analysis. *Med Sci Sports Exerc* 17: 493–497, 1985.
94. Rumpf MC, Cronin JB, Oliver JL, and Hughes MG. Effect of different training methods on running sprint times in male youth. *Pediatr Exerc Sci* In press.
95. Ryan RM and Deci EL. Self-determination theory and the facilitation of intrinsic motivation, social development, and wellbeing. *Am Psychol* 55: 68–78, 2000.
96. Sands WA. Physiology. In: *Scientific Aspects of Women's Gymnastics*. Sands WA, Caine DJ, and Borms J, eds. Basel, Switzerland: Karger, 2002. pp. 128–161.
97. Santos E and Janeira MA. Effects of complex training on explosive strength in adolescent male basketball players. *J Strength Cond Res* 22: 903–909, 2008.
98. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res* 24: 2857–2872, 2010.
99. Sheppard JM and Young WB. Agility literature review: Classifications, training and testing. *J Sports Sci* 24: 919–932, 2006.
100. Smith DJ. A framework for understanding the training process leading to elite performance. *Sports Med* 33: 1103–1126, 2003.
101. Smith RE, Smoll FL, and Cumming SP. Motivational climate and changes in young athletes' achievement goal orientations. *Motiv Emot* 33: 173–183, 2009.
102. Stafford I. *Coaching for Long-Term Athlete Development: To Improve Participation and Performance in Sport*. Leeds, United Kingdom: Sports Coach UK, 2005.
103. Stodden DF, Goodway JD, Langendorfer SJ, Robertson MA, Rudisill ME, Garcia C, and Garcia LE. A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship. *Quest* 60: 290–306, 2008.
104. Stone MH, Sanborn K, O'Bryant HS, Hartman M, Stone ME, Proulx C, Ward B, and Hruby J. Maximum strength-power-performance relationships in collegiate throwers. *J Strength Cond Res* 17: 739–745, 2003.
105. Stratton G, Jones M, Fox KR, Tolfrey K, Harris J, Maffulli N, Lee M, and Frosotick SP. BASES position statement on guidelines for resistance exercise in young people. *J Sports Sci* 22: 383–390, 2004.
106. Teeple JB, Lohman TG, Misner JE, Boileau RA, and Massey BH. Contribution of physical development and muscular strength to the motor performance capacity of 7 to 12 year old boys. *Br J Sports Med* 9: 122–129, 1975.
107. Theeboom M, De Knop P, and Weiss MR. Motivational climate, psychological responses, and motor skill development in children's sport: A field-based intervention study. *J Sport Exerc Psychol* 17: 294–311, 1995.
108. Vaeyens R, Lenoir M, Williams MA, and Philippaerts RM. Talent identification and development programmes in sport. *Sports Med* 38: 703–714, 2008.
109. Valovich-McLeod TC, Decoster LC, Loud KJ, Micheli L, Parker JT, Sandrey MA, and White C. National Athletic Trainers' Association position statement: Prevention of pediatric overuse injuries. *J Athl Train* 46: 206–220, 2011.
110. Viru A, Loko J, Harro M, Volver A, Laaneaots L, and Viru M. Critical periods in the development of performance capacity during childhood and adolescence. *Eur J Phys Educ* 4: 75–119, 1999.
111. Vuori I, Heinonen A, Sievanen H, Kannus P, Pasanen M, and Oja P. Effects of unilateral strength training and detraining on BMD and content in young women: A study of mechanical loading and deloading in human bones. *Calcif Tissue Int* 55: 59–67, 1994.
112. Wang CKJ and Biddle SJH. Understanding young people's motivation towards exercise. In: *Intrinsic Motivation and Self-Determination in Exercise and Sport*. Hagger MS and Chatzisarantis NLD, eds. Champaign, IL: Human Kinetics, 2007. pp. 193–208.
113. Weber G, Kartodiharjo W, and Klissouras V. Growth and physical training with reference to heredity. *J Appl Physiol* 40: 211–215, 1976.
114. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991–1999, 2000.
115. Whalen RT and Carter DR. Influence of physical activity on the regulation of bone density. *J Biomech* 21: 825–837, 1988.
116. Wisloff U, Castagna C, Helgerud J, Jones R, and Hoff J. Strong correlations of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 38: 285–288, 2004.
117. Witzke KA and Snow CM. Effects of plyometric jump training on bone mass in adolescent girls. *Med Sci Sports Exerc* 32: 1051–1057, 2000.
118. Wong P, Chamari K, and Wisloff U. Effects of 12-week on-field combined strength and power training on physical performance among U-14 young soccer players. *J Strength Cond Res* 24: 644–652, 2010.
119. Young WB. Transfer of strength and power training to sports performance. *Int J Sports Physiol Perform* 1: 74–78, 2006.
120. Young WB, James R, and Montgomery I. Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness* 43: 282–288, 2002.