Review

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# Integrating models of long-term athletic development to maximize the physical development of youth

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## Abstract

Long-term athletic development is important to prepare youth for sport and an active lifestyle. Several models have provided general frameworks for long-term athletic development from different perspectives that consider factors such as when to sample and specialize and what physical qualities to train and when. More recently more specific models of long-term athletic development have emerged that focus on both specific modes of training and specific fitness qualities. This includes models focused on the development of speed, agility, power and endurance as well as models devoted to resistance training, plyometric training and weightlifting. These models incorporate factors such as technical competency, developmental stage, maturation and training age to describe the long-term progression of athletic development. A challenge for the coach is to understand how these models inform one another and how they integrate into practice to allow the use of multiple modes of training to develop multiple components of fitness simultaneously throughout childhood and adolescence. This review will examine how information from various models can be integrated to maximize the physical long-term athletic development of youth.

## Key Words

Long-Term Athletic Development, Evidence-Based Model, Resistance Training, Plyometrics, Weightlifting

# Introduction

In recent years, there has been a growing interest in long-term athletic development (LTAD), with a need to properly prepare youth for both sport and a physically active life [1]. Over the last two decades, academics have proposed a number of LTAD models, with early general models structuring athletic development into stages based on participation, chronological age or maturation [2-4]. These general LTAD models provided frameworks for subsequent athletic development models specific to different types of physical training [5-7] and fitness, including aerobic fitness [8], muscular power [9], speed [10] and agility [11]. Identifying links between common themes of various models may provide coaches and practitioners valuable insight into components of a successful LTAD program. The purpose of this review is to examine existing models of LTAD regarding the physical preparation of youth.

# General long-term athletic development models

Sport participation and athletic development models originated from basic models of talent development, such as the Differentiated Model of Giftedness and Talent [12]. The key concept that gifts are essentially innate and youth can develop talent through practice remains integral in subsequent models of athletic development. Three models that have arguably had the largest influence on how youth athletes are physically developed are the Developmental Model of Sports Participation (DMSP) of Côté [2], the LTAD model popularized by Balyi and Hamilton [3] and the Youth Physical Development (YPD) model proposed by Lloyd and Oliver [4]. While each of those models provide a unique perspective, they each provide a pathway for the development of athleticism based on either chronological age and/or maturation. According to the NSCA's position statement on LTAD [1], athleticism refers to the ability to repeatedly perform a range of movements which require competent levels of motor skills, strength, power, speed, agility, balance, coordination and endurance. Figure 1 provides an overview of how these three models align to each other. The figure shows that the foci in each model shifts with advancing age and maturity as youth progress towards adulthood.

[Insert Figure 1.]

Figure 1. Composite diagram of three popular general models of long-term athletic development; the Developmental Model of Sports Participation (DMSP, top, redrawn and adapted from Côté [2]), the Long-Term Athlete Development Model (LTAD, middle, (redrawn and adapted from Balyi and Hamilton [3]) and the Youth Physical Development model (YPD, bottom, redrawn and adapted from Lloyd and Oliver [4]). In the LTAD model, closed boxes align to chronological age and dashed boxes to maturation. In the YPD, FMS = fundamental movement skills, SSS = sport-specific skills, MC = metabolic conditioning, font size represents the importance of a given fitness component at a given stage, shaded boxes identify interactions between training adaptations and maturation: bold box = prepuberty (predominantly neural adaptations), dashed box = pubertal (hormonal and neural adaptations).

The DMSP demonstrates the different pathways a child may take through their sporting career. Although titled a participation model, Côté [2] originally developed the DMSP following 15 individual interviews with four elite sporting families (three rowing, one tennis) and thus arguably better reflects a model of sporting excellence. Nonetheless, the DMSP identifies three developmental stages: the sampling years, the specializing years and the investment years. The sampling years (age 6-13) involve playing a variety of sports to provide fun and excitement though sport. After this stage, youth may choose to enter the specializing years (age 13-15)-a stage where sport involvement is limited to one or two roles and the role of deliberate practice is increased-or the recreational years (age 13+), in which they remain active for life through recreational sport. The investment years (age 15+) focus on achieving an elite level of performance in one activity. In this stage, the most important elements are strategic, competitive and skill development characteristics of sport.

Since its conception, subsequent athletic development models focused on physical fitness have aligned themselves with the DMSP's stages of participation [8, 9], as has a more recent version of the YPD [13]. Furthermore, several position statements and studies support DMSP's sampling approach to help prevent burnout and overuse injuries in youth [1, 14-17]. Sampling different sports can develop a variety of fundamental movement skills (FMS), enhancing a young person's overall athleticism [1]. The DMSP describes participation and performance pathways based on chronological age. This means the proposed stages and their respective age ranges do not account for individual differences in timing and tempo of maturation, training age, and movement competency - all of which are important in the developing athlete [1, 5]. Training age refers to the number of years an athlete has been performing organized training and can vary based on context [4]. For example, an athlete who has been formally training for a sport for a number of years, but is new to resistance training, would have a training age of zero for resistance training. Nonetheless, the DMSP emphasizes the importance of sampling before specializing - a consistent theme throughout subsequent models describing the physical development of youth.

Following an examination of coaching knowledge and practice, McKeown and Ball [18] concluded that the most popular model of LTAD used by practitioners was the model proposed by Balyi and Hamilton [3] shown towards the middle of figure 1. This model provides a framework whereby specific fitness components align to either chronological age or maturation. The authors recommended using peak height velocity (PHV), as opposed to chronological age, as a reference point for periods of enhanced trainability, or "windows of adaptation" [3]. Due to differing rates of maturation, PHV typically occurs around age 11.5 years and 13.5 years in North American females and males, respectively [19]. However, biological age only serves as the basis for the critical windows for strength and endurance (shown by boxes with dashed lines in Figure 1) with windows for speed, skill and suppleness based on chronological age (shown by boxes with solid line). According to this model, practitioners should emphasize aerobic development at the onset of PHV, while strength should be a focus approximately 12-18 months after PHV. Windows of opportunity are based on periods when fitness is naturally developing during growth and maturation, and the theory supposes that those periods represent a time when youth will be most responsive to training [20]. Balyi and colleagues [3, 21] further suggested that a failure to fully exploit a window of opportunity with adequate training would forever lower future adult potential. However, the existence of windows of opportunity has been questioned due to a lack of supporting empirical data [22]. Another feature of the Balyi and Hamilton [3] LTAD model is the use of stages to organize physical training progression. The FUNdamentals stage (age 6-9 males, 6-8 females) occurs during early childhood and refers to a period where children should learn fundamental movement skills in a fun environment. The emphasis during the Learning to Train stage (age 9-12 males, 8-11 females) is to learn fundamental sport-skills during a “window of adaptation” for motor coordination. Youth learning to move competently in fundamental and sport-specific skills serve as the basis for the FUNdamentals and Learning to Train stages. The Training to Train stage (age 12-16 males, 11-15 females) is a key time to develop physical fitness. The difference in age reflects the fact that girls mature earlier than boys and suggests maturation will interact with physical training. The Training to Compete (age 16-18 males, 15-17 females) and Training to Win (age 18+ males, 17+ females) stages are aimed at optimizing and maximizing fitness and sport performance. Lastly, the Retirement/Retention stage focuses on retaining ex-athletes in sport via coaching, officiating, administration or other avenues. The LTAD model undoubtedly offers a systematic approach to training and several of these stages have been subsequently featured in resistance training [5], plyometric [6] and weightlifting models [7].

Recent literature has questioned the suitability of the term "athlete" when delineating constructs surrounding the athletic development of youth [1]. Some argue that the term "athlete" in the long-term athlete development model renders the structure as a means to solely developing athletes [13]; however, in light of the global numbers of obese/overweight and physically illiterate children, LTAD should really be an initiative for all youth. Although originally presented as a participation model, the Balyi and Hamilton [3] model promotes high volumes of conditioning and training around adolescence, particularly through the 10,000 hour rule; however, the suitability of this approach has been questioned in the literature [22, 23]. The need to accumulate 10,000 hours of training (or deliberate practice) appears to be a misconception and may even be detrimental to long-term development [24]. The 10,000 hour rule for elite sporting attainment has been attributed to the work of Ericsson, Krampe [25]; but, in an editorial, Ericsson suggested that his work had been misrepresented and that the 10,000 hour rule was somewhat of a misnomer [26]. Ericsson [26] then claims that it is possible to reach an international level in much less time, consistent with findings from Baker and Young [27] that show elite level attainment in sport can occur with 4,000 to 6,000 hours of training which indicates that deliberate practice is more important than the quantity. Attempting to accumulate 10,000 hours of training may also increase the risk of overuse or acute injury or illness, especially during periods of rapid growth that are often synonymous with a loss of coordination [16, 24, 28, 29].

Since the inception of the Balyi and Hamilton [3] model, several subsequent development models [4, 5] and position statements regarding youth development [1] have discussed the importance of maturation on training adaptation. The YPD model (Lloyd and Oliver [4], bottom of Figure 1) was introduced to provide an evidence-based approach to training youth, describing how training and maturation may interact in the development of physical fitness. Additionally, the

YPD model acknowledged the impact of training history, baseline fitness levels and sex differences on the decision making process of training prescription. In contrast to the LTAD model, the YPD includes nine physical qualities: fundamental movement skill (FMS), sport-specific skill (SSS), mobility, agility, speed, power, strength, hypertrophy, and endurance and metabolic conditioning (MC). An important construct of the YPD model is that research indicates that all physical qualities are trainable throughout childhood and adolescence, albeit that the magnitude and underlying adaptive mechanisms may differ according to maturation [4]. For example, a coach may place an emphasis on coordination and plyometrics in prepubertal children and hypertrophy and a combination of strength training and plyometrics in postpubertal youth [30].

The YPD advocates that providing youth with opportunities to learn and challenge their coordinative abilities through the manipulation of task, individual and environmental constraints during a period of heightened central nervous system adaptability, should lead to improved motor skill development. In this regard, both the YPD and LTAD models are similar in that they prioritize the development of fundamental movement skills and movement competency from a young age. A subsequent Composite Youth Development model has been proposed [13], drawing from earlier talent [2] and physical [4] development models. The incorporation of DMSP stages offers a psychosocial emphasis throughout childhood and adolescence. This provides a holistic focus ensuring the child or adolescent maintains a healthy, physically active lifestyle [13].

## Resistance training models for athletic development

Research demonstrates that participating in elite youth sport alone, without the addition of supplementary physical training, fails to optimize athletic development [31-33]. Resistance training refers to the specialized method of conditioning whereby an individual is working against resistive loads to enhance health, fitness and performance and includes the use of body weight, machines, free weights, bands and medicine balls [34, 35]. The most common forms of resistance training include bodyweight plyometric training, traditional strength training using external weight, or a combination of both of these. The use of resistance training as early as possible in a young athlete's development appears crucial [31-33]. Several position statements on LTAD [1], resistance training for youth [34-38] and injury prevention [14, 17] advocate the use of resistance training as an appropriate training method to improve sport performance and decrease risk of injury in youth. Furthermore, practitioners working with youth should understand the influence of growth and maturation on physiological adaptations and consider these factors when designing resistance training programs.

A meta-analysis by Behringer, vom Heede [39] showed an interaction of maturity on strength gains following resistance training interventions; more mature children made greater gains in strength but immature children still made meaningful improvements. A later review by the same group [40] also showed that strength training transferred greater gains to running, jumping and throwing in immature children compared to mature children. Work by Behm, Young [41], as well as several experimental studies [31-33], show that resistance training is most specific to strength gains compared to other components of fitness. However, coaches often successfully utilize resistance training to improve power, speed, agility and even aerobic fitness performance of youth [41, 42].

The development of several resistance training models [5-7] align with the stages and concepts from earlier general LTAD models [2-4]. A combination of a resistance training [5], plyometric [6] and weightlifting [7] model is shown below in figure 2. The figure demonstrates the overlap between several popular models to provide a more comprehensive description of when and how to implement various types of resistance training with youth.

[Insert Figure 2.]

Figure 2. A summary of resistance training (top, redrawn and adapted from Granacher et al. [5]), plyometric (middle, [6]) and weightlifting (bottom, [7]) models. The dashed boxes at the bottom are aligned to different stages of the Balyi and Hamilton [3] model.

A conceptual model of resistance training, shown towards the top of Figure 2, was proposed within a systematic review on the effects of resistance training on muscular fitness (strength, power, endurance) [5]. The Granacher et al. [5] framework aligned four stages (FUNdamentals, Learn to Train, Train to Train, Train to Compete) of the Balyi and Hamilton [3] model to chronological age, biological age, maturity, type of training and training adaptations. Early general models of athletic development recognized the importance of individualizing training to movement competency [3, 4], but they provided no guidelines on training prescription. Granacher et al. [5] have extended that concept by detailing how practitioners should use resistance training skill competency to determine the types of activities youth should engage in and how this should progress over time. Those activities are based on the popular forms of resistance training including plyometric and traditional strength training using bodyweight and external loading.

Plyometric training is a type of resistance training that refers to activities that initiate an eccentric stretch of the muscle-tendon unit, resulting in a greater concentric contraction [6]. A model for plyometric training [6] is shown in the middle section of figure 2 and aligns to the stages of the Balyi and Hamilton [3] LTAD model. However, recent literature recommends using technical competency and maturational status to progress training, rather than chronological ages typically associated with the LTAD stages [4, 5]. Several reviews suggest that as an athlete enters puberty, the intensity of resistance training and plyometrics should increase according to technical competency [5, 6]. Plyometric intensity is typically based on eccentric loading [6], so exercises should progress from minimal eccentric loading (jumps in place and standing jumps) to high eccentric loading (drop jumps) as technical competence increases. Irrespective of age and maturity status, technically incompetent athletes will likely benefit from learning how to hinge and properly load for a jump or only perform the concentric portion of a jump, before moving on to countermovement jumps and then depth jumps.

Weightlifting training, a more specialized form of resistance training, has received far less attention than traditional strength and plyometric training in youth populations. Though there is one meta-analysis demonstrating the positive effect of weightlifting training on vertical jump performance [43], a lack of studies precludes any similar analyses with youth. Weightlifting interventions in youth athletes incorporate the snatch, clean and jerk and the various derivatives of each, in addition to common resistance training movements such as squats, presses and pulls [44-46]. Though research on the effects of weightlifting on athleticism is scarce, existing evidence supports the safety [46, 47] and potential benefits on motor skill performance in youth [44, 45]. Due to the limited amount of research on youth weightlifting, a small body of empirical evidence informs the existing models [7, 48, 49].

A peer-reviewed model for developing weightlifting in youth has been proposed and is shown towards the bottom of figure 2 [7]. The model utilizes four stages that loosely align to the LTAD model of Balyi and Hamilton [3]: Fundamental Weightlifting Skills (FUNdamentals), Learning Weightlifting (Learning to Train), Training Weightlifting (Training to Train), and Performance Weightlifting (Training to Compete and Training to Win). Each stage is progressively more structured training and emphasis shifts from physical literacy - which involves the development of FMS and fundamental sporting skills [50] - to technical competence, to performance. It should be noted that although FMS is related to physical literacy, it is not a causal relationship. This means that just because a child is proficient at objectively measured FMS assessments does not mean he or she is physical literate, and vice versa. Within the model, using a top down approach to teaching weightlifting progressions is consistent with previous literature [44, 46]. This refers to learning movements starting from the mid-thigh, or power position, before progressing to the knee and finally the floor. Although the author provides suggested age ranges for stages, all athletes should enter the model at the earliest stage and progress according to technical competency as training age increases. However, if an athlete enters the model later in their development, he or she may progress through the stages faster as technical competency improves. The same premise remains for young athletes that demonstrate technical competency; they may progress through the stages at a faster rate. The United States and Canadian national governing bodies have also adapted the Balyi and Hamilton [3] model, despite its criticisms, to create weightlifting specific models [48, 49].

## Fitness-specific models for athletic development

The evolution of athletic development models has resulted in the production of more detailed models of specific fitness components related to power [9], speed [10], agility [11] and aerobic fitness [8]. These models have informed the resistance training model of Granacher et al. [5] and align to the stages of the DMSP [8, 9] or maturation [10, 11]. Figure 3 shows how the integration of models specific to different components of fitness can provide an integrated plan.

[Insert Figure 3.]

Figure 3. Summary of resistance training and power, speed, agility and aerobic models. The closed boxes are stages aligned to the DMSP while the dashed boxes are stages defined by

maturation status. FMS = fundamental movement skills; RFD = rate of force development; COD = change of direction; SSG = small sided game; HIIT = high intensity interval training.

## Strength

Strength is a primary outcome of resistance training but there is not a standalone model dedicated to it as a fitness component. Therefore, it is shown in relation to the Granacher et al. [5] model. As discussed earlier, a secondary outcome of improving strength through resistance training is that its benefits transfers to all other fitness components [4]. Figure 3 also highlights that technical competency is task specific and coaches should program training methods accordingly. For example, a young athlete may be technically competent in power training methods but poor in agility training methods.

## Power

Muscular power is an important component for athletic development due to its relationship with activities such as running [41], jumping [44] and sport-specific tasks such as track and field throws [51, 52]. An evidence-based model of power development was developed by Meylan et al. [9] based on a systematic review of 12 studies. The power development model overlaps with aspects from the resistance training models as strength training, plyometrics and weightlifting are common forms of power training.

The model of power development uses stages from the DMSP to organize four variables of power training: integration, session duration, session frequency, and block duration. The power development model also begins to address some of the lack of detail on programming from previous resistance training models. The sampling years are broken into two phases (age 5-8, age 9-12) due to the many mental and physical changes during this age period. The primary goals for this phase of training are to develop FMS, agility, balance and coordination with high velocity components. This reflects the common philosophy of other general and specific models to prioritize the development of fundamental movement skills before progressing to more complex and demanding tasks. Proper jumping and landing technique should be taught to maximize explosive training and reduce the risk of injury associated with deficiencies in load absorption [53]. During the specialization years (age 13-15), an increase in volume, intensity, movement complexity and the addition of weightlifting movements to improve powerful triple extension of the lower body should accompany training, provided technical competency is sufficient. During the investment years (16+), training should continue to develop maximal strength, as well as more sport-specific movements and higher intensity plyometric training.

## Speed

The differences in speed between players in relatively high and low levels of competition demonstrate the importance of speed for athletic development [54, 55]. There is also a strong relationship between sprinting and other measures of performance such as jumping and strength [56, 57]. Due to the importance of speed on athletic performance, there are several meta-analyses [41, 58] and reviews [59] on youth speed development. A series of guidelines provided in a narrative review by Oliver, Lloyd [10] highlighted the importance of FMS and resistance training to maximize speed development. As with power training, speed training incorporates a large emphasis on different forms of resistance training.

In the review of Oliver, Lloyd [10], stages of speed development were defined by maturational status and training age, rather than chronological age, which aligns to the YPD model, and included early childhood (age 0-7), prepubertal (age 7-12), circumpubertal (age 11-15 males, age 12-15 females) and late adolescence (age 16+ males, age 15+ females). In line with the YPD model, the authors suggest that training during early childhood should focus on FMS and strength training through active play and games that encourage good running technique. The circumpubertal stage should focus on sprint technique and maximal sprints for speed development and while adding hypertrophy to the resistance training programme to maximize any structural adaptations associated with increased force production and thus, greater stride length [60]. Lastly, the late adolescence stage features maximal sprints and complex training methods, which have been shown to improve repeated sprint ability and change of direction (COD) in youth [61, 62]. Throughout childhood and adolescence, the pathway suggests that, given the known transfer of non-specific sprint training to speed, complimentary resistance training supports speed development [41, 59]. The guidelines provided by Oliver, Lloyd [10] organize training stages by maturation with training age as a key component, as technical competency should always drive progression. This model further highlights the importance of FMS development prior to more complex non-specific training methods (e.g. plyometric and strength training). Furthermore, developing FMS through free play and small-sided games may enhance the coupling of FMS to more complex sport skills, and should be included throughout development due to links with athletic motor skills and long-term effects of physical activity [70, 71].

## Agility

The development of agility is important for most field and court team sports due to the need to react and change direction in reaction to external stimuli. Agility refers to a rapid whole-body movement with change of velocity or direction in response to a stimulus. Since true agility must require a response to an external stimulus [63], COD speed is the variable typically assessed instead throughout the literature. Several systematic reviews have examined the effect of resistance training on agility [64, 65] and change of direction [42] in youth. Many other experimental studies have investigated the relationship of COD with other measures of athletic performance [54, 66, 67] as well as the trainability of COD using both specific and non-specific training methods

[33, 68]. Although not proposed as a standalone model, a narrative review by Lloyd, Read [11] proposed three main components of agility training (FMS, COD speed, and reactive agility training (RAT)) and attempted to show how training focus could change with increases in technical competency (Figure 3).

Adolescent awkwardness refers to the temporary loss in motor coordination during a period of rapid growth and is characterized by greater movement variability and decreased movement proficiency [69]. Athletes experiencing "adolescent awkwardness" during the circumpubertal years may need coaches to give special attention to body position and technique as they learn to coordinate their longer limbs. Although the training percentage breakdown are arbitrary example values, the concept of progressing from FMS to more complex training modes throughout development is central to athletic development [4, 5] and other fitness specific models [8-10]. Lloyd, Read [11] also suggest strength, plyometric and combined training are effective in improving COD speed and practitioners should implement these appropriately alongside agility training. This concept is similar to the YPD model's approach to simultaneously training all fitness components. Additionally, as with speed, games and free play can serve as effective methods for coupling FMS with more complex sport skills.

## Aerobic fitness

Aerobic fitness is an important component in team sport performance to help sustain a high work-rate throughout a match [72], to aid with recovery [73] and to help maintain quality technical and tactical decision making [74]. An evidence-based model for aerobic fitness development in youth team sport players was developed by Harrison, Gill [8] from a systematic review of 14 studies.

This model aligns to the developmental stages of the DMSP. Harrison, Gill [8] proposed that training during the sampling stage should be fun and engaging and include strength and speed components, similar to previous recommendations given in the YPD model [4]. During the sampling stage, sessions should be no longer than 60 minutes and performed up to 6 times per week through forms of deliberate practice and/or play. Training during the specialization stage should last between 8-28 minutes up to 5 times per week and should focus on mastery of sport specific skills through small-sided games (SSG) and high-intensity interval training (HIIT). Following previous recommendations [1, 34], it is suggested that training load be monitored as repetitive loading during the adolescent spurt can increase risk of overuse injuries [24]. During the investment stage, the primary focus is improving performance in competition. In addition to small-sided games, Harrison, Gill [8] recommends high-intensity interval training and/or sprint training 1-3 times per week.

A requirement of training at all stages is that some or all of the work should be completed at an average high-intensity of ≥85% HR max to promote gains in aerobic fitness [75]. The need for youth to engage in high-intensity exercise to improve their maximal oxygen uptake is in agreement with previous reviews [76, 77]. Although there is no mention of resistance training in the model, evidence suggests resistance training may improve muscular endurance performance in youth [39, 78, 79] and thus should remain a central component of any athletic development program. Because this model aligns to the DMSP, stages are defined by participation rather than biological or training age. Due to the influence of maturation on physiological adaptations, practitioners should consider maturity status when prescribing training methods for youth. For instance, as prepubertal youth are more reliant on aerobic metabolism, they may need to train at relatively higher intensities to experience training adaptations [80].

# Conclusion

The growth of youth sport and physical training as a method to improve health has led to a growing interest in LTAD. Early general models suggest sampling multiple activities from an early age to develop a variety of movement patterns, as well as considering the interaction of maturation on the training response. These models provided stages for subsequent guidelines and conceptual models regarding resistance training modalities such as plyometric training and weightlifting. Furthermore, subsequent models have used existing frameworks to provide more detail into developing specific fitness components throughout childhood and adolescence. The models and guidelines presented in this paper should help direct coaches and practitioners to proper application of LTAD programs.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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