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The Long-Term Athlete Development model: Physiological evidence and application

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Abstract

Within the UK, the "Long Term Athlete Development" (LTAD) model has been proposed by a variety of national governing bodies to offer a first step to considering the approach to talent development. The model, which is primarily a physiological perspective, presents an advancement of understanding of developing athletic potential alongside biological growth. It focuses on training to optimize performance longitudinally, and considers sensitive developmental periods known as "windows of opportunity". However, it appears that there are a number of problems with this theoretical model that are not necessarily transparent to coaches. Principally, the model is only one-dimensional, there is a lack of empirical evidence upon which the model is based, and interpretations of the model are restricted because the data on which it is based rely on questionable assumptions and erroneous methodologies. Fundamentally, this is a generic model rather than an individualized plan for athletes. It is crucial that the LTAD model is seen as a "work in progress" and the challenge, particularly for paediatric exercise scientists, is to question, test, and revise the model. It is unlikely that this can be accomplished using classical experimental research methodology but this should not deter practitioners from acquiring valid and reliable evidence.

Keywords: *Long-Term Athlete Development Model, growth and maturation, youth athletes*

Introduction

Talent development is holistic in nature due to the complex interaction of interdisciplinary issues that directly impact on athletic opportunity and progression. Such concepts have been critically acknowledged and documented in a recent comprehensive report (Bailey et al., 2010). Bailey and colleagues (2010) discuss such interactions methodically and recommend future considerations to sport and physical activity stakeholders who wish to enhance participation and performance levels. Such discussion has also been documented in recent review articles (Burgess & Naughton, 2010; Phillips, Davids, Renshaw, & Portus, 2010). Although we recognize such considerations are significant, this review focuses upon the popular "Long-Term Athlete Development" (LTAD) model (Balyi & Hamilton, 2004), which by design is fundamentally based upon physiological principles and which will be the sole focus here. The requirement to identify new methods by which talent can be nurtured (which in itself is contentious as to its definition) is paramount for coaches and practitioners. In particular, direct techniques to advance paediatric sporting development are of significant interest. However, within this specific population there are many extraneous factors (including degree of maturation, and anatomical, neurological, hormonal, and musculoskeletal changes in structure) that must be incorporated within the planning of any form of physical training (Malina, Bouchard, & Bar-Or, 2004; Tihanyi, 1990). These factors relate to an integrated development of genes and hormones that are coordinated according to a biological clock and other factors (i.e. nutrients and environmental factors), which are time independent but which all affect the physiological systems of the body (Malina

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et al., 2004; Tihanyi, 1990). However, prior to the last decade, the amalgamation of all these factors had not been accounted for, something which has hindered our understanding of the effects of training on paediatric athletes (Balyi & Hamilton, 2004). Currently, the most relevant and well-known model to include such paediatric developmental considerations has been held to be the LTAD model (see Figure 1).

Although the LTAD model is not novel (Bompa, 1995; Riordan, 1977), it has been constructed on the basis that it combines successfully employed training methods alongside a greater scientific basis for children and adolescents (Balyi & Hamilton, 2004; Harre, 1982). Worldwide, as the LTAD model has been advanced it has been adopted and applied by national governing bodies, and consequently practitioners, for the development of children into elite athletes (Badminton England, 2006; British Gymnastics, 2006; England and Wales Cricket Board, 2005). The model attempts to balance training load and competition throughout childhood and adolescence, as previously it has been suggested that there has been too much focus placed upon results rather than assisting optimal development processes (Balyi & Way, 1995; Bompa, 1995). Although Platonov (1988) highlights the number of hours required to maximize each development stage from initial basic training through to adult maintenance, the LTAD model principally distinguishes four stages of training development that account for enhancing general athletic capabilities and sport specialization after pubertal changes: FUNdamental phase, Training to train phase, Training to compete phase, and Training to win phase (Balyi & Hamilton, 2004). It is suggested that through objective physiological assessment tools (e.g. peak height velocity, peak weight velocity), coaches can account for individual maturation rates for each athlete so that they can apply the relevant training protocols depicted in each phase of the model. Such practice advances chronological age classification, which seems to be inherently flawed due to variation in growth and maturational rates between individuals and subsequent variance in training "readiness" as will be discussed later in this review (Balyi & Hamilton, 2004; Bompa, 1995). In addition, using appropriate training stimuli linked to natural growth and maturation processes (an additional factor from this model) utilizes the concept that there are "windows of opportunity" to accelerate and enhance physical development.

Two contemporary UK coaching texts have directly advocated the underlying concepts and application of the LTAD model for practitioners in sports performance and athletic development (Balyi & Stafford, 2005; Balyi & Williams, 2009). The texts highlight to practitioners that the model is a coaching framework that has been constructed using a variety of sources and experiences.

However, at present and to the best of the authors' knowledge, there is a distinct lack of empirical data to support such a long-term periodized model. Therefore, the LTAD model must be viewed as a work in progress and caution is urged to ensure that the model does not become too enshrined as "fact". Much of the evidence lacks any significant longitudinal or experimental data, and includes animal-based literature to rationalize its structure (Szmodis, 1991). Indeed, Balyi and Hamilton (2004) highlight that their work is based on "empirical observations", which although apparently well informed, lack scientific validity due to inherent subjectivity issues. In addition, it appears that there is no evidence that failure to exploit these "windows of opportunity" with appropriate training will result in inhibited development and that the athlete will experience a "ceiling" effect on performance. Bailey et al. (2010) correctly question whether the "windows of opportunity" actually raise the ceiling for future potential or just allow an athlete to reach their ceiling performance level at a younger age. Beunen and Malina (1996) clearly show individual variance in the rate of athletic performance development associated with growth and maturation, but there seems to be a lack of clarity on the training stimulus required to facilitate these developmental spurts. Due to the lack of an agreed method of quantifying training *per se*, and the lack of paediatric data, plus the wide range of stimuli needed for different sports, it appears an almost impossible task to elucidate the stimulus–training response question. The model has recently come under some direct criticism from practitioners for such reasons (e.g. Bailey et al., 2010), indicating a scientific examination of the LTAD model specifically would seem to be very appropriate. The aim of this review is to examine physiological fitness components located within the LTAD model with regards to trainability, to distinguish if this has been effectively encompassed within the prescriptions of the model, and to directly evaluate the concept of "windows of opportunity".

Impact of growth and maturation on athletic performance

Physical literacy

There have been numerous references to physical literacy in the literature over the years and also many philosophical and physiological debates, mainly by physical educators, over its importance throughout the human life span (Whitehead, 2001, 2004). Physical literacy has been defined as the extent of a

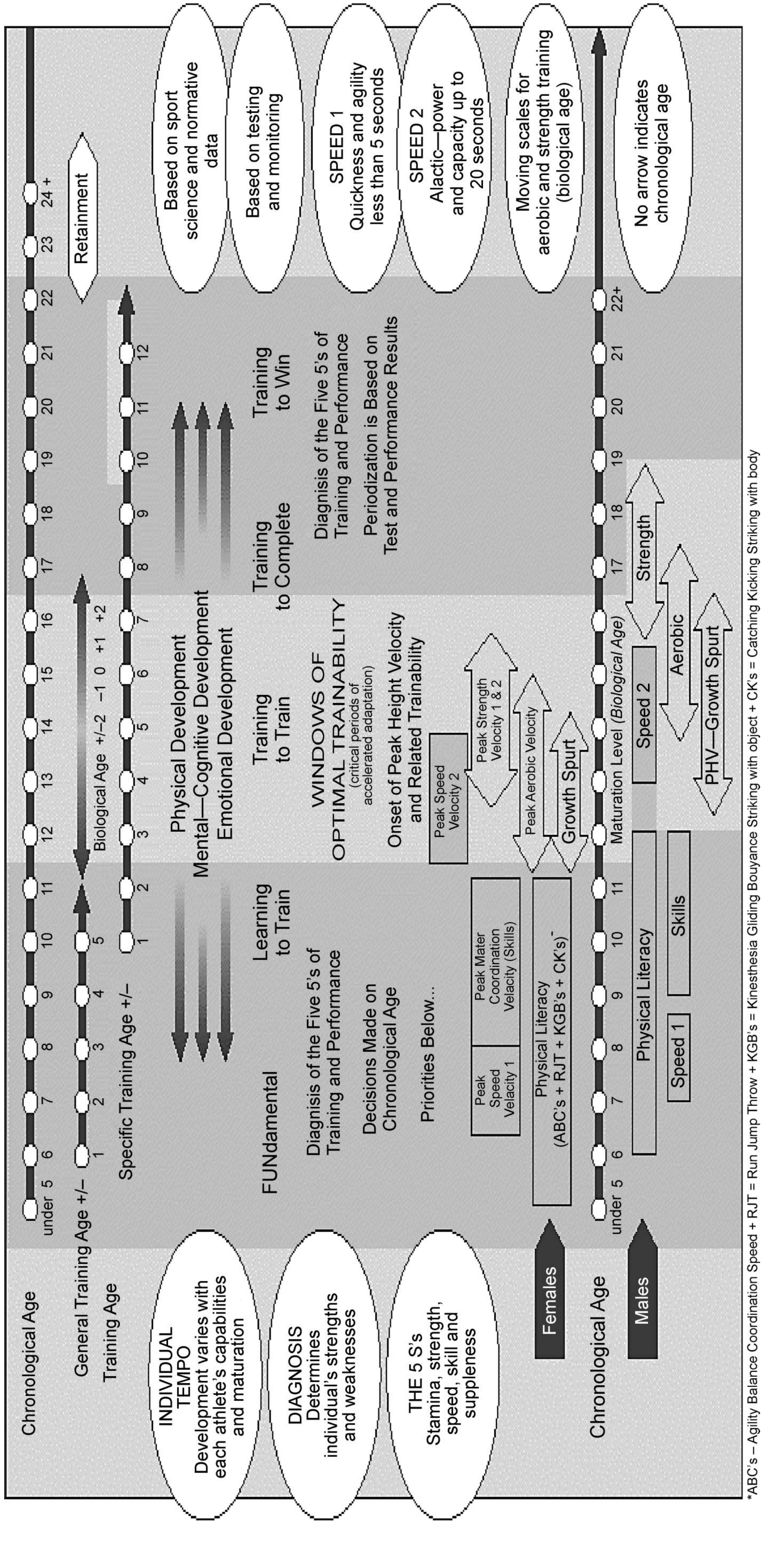

Figure 1. Adaptation to training and optimal trainability (adapted from Balyi & Way, 2002; in Balyi & Hamilton, 2004).

person's ability to capitalize on his or her embodied dimension (Whitehead, 2004) or as a combination of kinaesthetic intelligence and the ability for skilful actions (Arnold, 1979). Physiologically, physical literacy is the development and the competence in fundamental movement skills (e.g. walk, run, jump, throw) and fundamental sport skills (e.g. catch, hop, gallop) that permit a child (or adult) to move confidently in a wide range of physical activity, rhythmic, and sport situations (Higgs et al., 2008). It is has been shown that, compared with the typically developing child, children with motor learning difficulties demonstrate less physical literacy, are less active and more disruptive in regular physical education classes and during "school holidays" (Bouffard, Watkinson, Thompson, Dunne, & Romanow, 1996), and have lower overall fitness (Hands & Larkin, 2006). While the negative effects of reduced movement proficiency on health-related fitness have been well documented in children (Okely, Booth, & Chey, 2004; Okely, Booth, & Patterson, 2001a, 2001b), the literature regarding the importance of developing physical literacy and motor skill fitness for LTAD is limited.

The development of fundamental movement skills starts at birth and may continue until 11–12 years of age, depending on the complexity of the skill (Gabbard, 1992). Many scientists have proposed that each of the fundamental movements has a series of developmental stages, with each stage possessing a different degree of complexity (Flinchum, 1975; Gabbard, 1992; McClenaghan & Gallahue, 1978). Children need to acquire mature fundamental movement patterns to improve their performance (Gabbard, 1992; McClenaghan & Gallahue, 1978), and acquiring mature patterns requires greater speed, balance, control, strength, and coordination to be able to pass through different stages. The scientific literature regarding the natural process of motor development fitness may partly support the LTAD model for the development of physical literacy. From a neurological perspective, Rabinowicz (1986) noted the periods of peak brain maturation through childhood. Such development at 6–8 years and 10–12 years of age seems to coincide with the "windows of opportunity" for physical literacy tasks (fundamental and sports specific) in the LTAD model (Balyi & Hamilton, 2004; Higgs et al., 2008) and improvements in motor coordination (Cratty, 1986). However, such developments may represent accelerated periods of development, but there is no evidence that such periods offer greater "sensitivity" to training.

The literature regarding the trainability of physical literacy provides some scientific evidence to support the LTAD model, although it is not completely convincing. The variety and diversity of the indicators chosen to express the proficiency of physical literacy makes it particularly difficult to draw clear conclusions, and further work to provide clarification in this area is certainly required. The importance of providing learning opportunities in the early years of life for the development of cross-body coordination and fundamental movement skills has been reported previously (Dennis, 1960; McGraw, 1935, 1959). However, in more recent years, several studies have investigated the effect of training on physical literacy during childhood. Ingle and colleagues (Ingle, Sleap, & Tolfrey, 2006) showed that a mixture of plyometrics and resistance training could improve fundamental sport skills temporarily among early pubertal boys, although the authors only measured strength-related performance outcomes and not the actual quality of fundamental sport skills. Graf et al. (2005) showed that a long-term school-based intervention can improve aspects of physical literacy among 6- to 9-year-olds, but a 6 year follow-up study demonstrated that a year-long intervention during childhood did not have long-lasting effects on overall physical literacy (Barnett et al., 2009). In both instances, however, movement quality was not assessed. These data would seem to contradict the "windows of opportunity" concept proposed in the LTAD model, whereby training within certain physical literacy skills at certain stages may result in greater long-term development of those skills. Gallahue and Ozmun (1998) and Gallahue and Donnelly (2003) also suggest a "proficiency barrier", whereby progression onto more advanced specialized or sports-specific skills are dependent on the prior foundation of fundamental movement patterns, reinforcing the motor development literature. Evidently there is much inconsistency in the current literature surrounding the long-term effects of fundamental movement/sport skills training, both in terms of methodology and outcome, and further multidisciplinary, longitudinal research is required. Flinchum (1975) have shown the importance of providing instruction for rapid development of more complex movements such as mature throwing patterns among 5-year-olds. Furthermore, Derri and colleagues (Derri, Tsapakidou, Zachopoulou, & Kioumourtzoglou, 2001) conducted a 10 week music and movement programme with children aged 4–6 years, and reported significant improvements in the quality of more complex movement patterns. Further work by Deli and colleagues (Deli, Bakle, & Zachopoulou, 2006) suggested that "free play" (compared with instruction) seemed unable to guarantee the development of more complex skills, lending support to Gabbard (1992), who suggested that "Proficient kicking, like proficient throwing, may not be achieved through the natural course of childhood development" (p. 295).

In summary, it appears that there is reasonable anecdotal and some physiological evidence to support the idea of enhanced neural and muscular adaptations (due to the plasticity of the neuromuscular system) through exposure to regular and structured fundamental movement skills and fundamental sport skills training in childhood. However, further research is needed to quantify the existence of the "window of opportunity" concept for fundamental movement/sport skills, and if training these, especially in the earlier years, could manifest it through the later stages of the athletic development models.

Aerobic performance

The development of aerobic fitness and its impact on performance is influenced by growth-related changes to an individual's central and peripheral cardiovascular system, muscular function, cellular capacity, body composition, and metabolic capability (Rowland, 1985). The intra- and inter-degree of influence these components have upon aerobic fitness varies throughout childhood and adolescence (Naughton, Farpour-Lambert, Carlson, Bradney, & Van Praagh, 2000). Peak oxygen uptake, acknowledged as the "gold standard" criterion method of assessing an individual's aerobic fitness (Jones & Carter, 2000; Naughton et al., 2000), increases from infancy into adulthood, possibly in a linear fashion with body size (Armstrong & Welsman, 1994; Bouchard, Malina, & Pérusse, 1997; Viru et al., 1999). Although there is a large amount of supportive literature to suggest that from a young age children naturally possess a well-developed aerobic capacity (Boisseau & Delamarche, 2000), different methods of physical training have been shown to enhance the development of aerobic capacity in children and adolescence (Viru et al., 1999). For example, it has been suggested that relatively high-intensity prolonged training will produce significant gains (Tolfrey, Campbell, & Batterham, 1998; Williams, Armstrong, & Powell, 2000). In support of this, Mahon (2008) noted that low-intensity training often results in a minimal training stimulus response during paediatric interventions.

Nevertheless, several authors have suggested that there are natural accelerated and decelerated periods of development during maturation (Baquet, Van Praagh, & Berthoin, 2003; Harro, Lintsi, & Viru, 1999; Viru et al., 1999). These are highly individualized, which can be attributed in part to the fluctuating rates of anatomical, neurological, muscular, metabolic, and hormonal development (Naughton et al., 2000; Viru et al., 1999). Kobayashi et al. (1978), Payne and Morrow, (1993), and Baquet et al. (2003) suggest that there is an exponential rise in peak oxygen uptake following peak height velocity and puberty, in what Katch (1983) and Rowland (1997) describe as the "trigger hypothesis". Although there is discrepancy in the literature, Viru et al. (1999) have reviewed several longitudinal studies to show that peak development of relative aerobic capacity ($ml \cdot kg^{-1} \cdot min^{-1}$) occurs between 12 and 16 years in both boys and girls. However, Viru et al. (1999) also reported that cross-sectional research shows that the peak development period for aerobic capacity occurs at 10–16 and 7–13 years in boys and girls, respectively. Nevertheless, the credibility of the latter evidence can be questioned because it is based on non-causative observations. Furthermore, results from previous studies suggest that children and adolescents are significantly less efficient (related to aerobic metabolism) in energy expenditure during movement than adults and that children consume more energy per unit of body mass during locomotion at a given speed (Cavagna et al., 1983; De Jaeger et al., 2001; Schepens et al., 2004). Plausible explanations can be attributed to differences in body size, lack of neuromuscular maturity, and an inability to effectively deliver oxygen to the required muscles in children, which become adult-like with increasing growth and maturation (Cavagna, Franzetti, & Fuchimoto, 1983; De Jaeger, Willems, & Heglund, 2001; Schepens, Bastien, Heglund, & Willems, 2004). However, it seems that the potential for improving economy of movement and physical performance is likely influenced by training as well. However, few investigations have specifically addressed appropriate training prescription or identification of sensitive periods to enhance economy of movement subsequent to improvements through physical development (Naughton et al., 2000). It might be postulated that overall economy of movement will be continuously enhanced with physical activity and exercise through childhood and adolescence (Baquet et al., 2003).

After acknowledging this literature and when focusing on the concept of "windows of opportunity", Naughton et al. (2000) state that the growth-related improvements from aerobic training in well-trained male adolescent athletes (compared with well-trained pre-adolescent males) relate to changes in hormone secretions during maturation. Moreover, Naughton et al. (2000) suggest that training aerobic fitness when there is a lack of circulating metabolites, thus resulting in a reduced training adaptation response, supports the "windows of trainability" concept of the LTAD model. For example, Weber and colleagues (Weber, Kartodihardjo, & Klissouras, 1976) have suggested that there is a decreased sensitivity to aerobic fitness training response that occurs in the middle of the peak height velocity when compared with the years surrounding it.

Alternatively, some authors have suggested that most sensitive training adaptations to aerobic fitness actually occur before peak height velocity, including Rowland (1985) who identified a 10.1% and 8.8% improvement in peak oxygen uptake during this period in boys and girls, respectively. Thus it would appear that there are discrepancies in the literature in terms of when these actual "windows" occur. Perhaps this discrepancy can be related to the fact that much of the evidence for this fitness component is based on cross-sectional studies, which restricts inferences due to methodological restraints. The lack of longitudinal data is also coupled with the imprecise assessment of training stimulus, which is required to elicit peak development (Baquet et al., 2003). Both Naughton et al. (2000) and Baquet et al. (2003) conclude that the findings are obscured further by genetic background and training load, which are rarely reported. Therefore, attributing any adaptive response in line with physical development is flawed due to the variation in the magnitude of the stimulus. In addition, it appears that research has focused on participants during pre-pubertal years rather than adolescents, and has not accounted for initial peak oxygen uptake values (Tolfrey et al., 1998). Such a lack of the recognition of these fundamental aspects limits the direct investigation of the "windows of trainability" concept, and may indeed mean that application by practitioners is inappropriate at present.

Long-term studies that map changes in aerobic capacity during growth and measure the influence of physical activity or training concurrently are required. As discussed previously, the complexity of the research design to answer such a problem may render the project impractical, and thus progression in this area will perhaps not occur. Nevertheless, until more comprehensive consistent evidence is available, it is inappropriate to state that young participants should only train aerobic fitness during prescribed "windows of opportunity". Aerobic fitness should be actively developed throughout childhood and adolescence (Shephard, 1992).

Anaerobic performance

Speed. Both boys and girls show similar sprint speed during the first decade of life (Borms, 1986; Malina et al., 2004), with a period of accelerated adaptation suggested to occur between the ages of 5 and 9 years in both sexes (Borms, 1986; Viru et al., 1999). From the age of 12 years, the rate of progression of speed development is dramatically reduced in females compared with males (Whitall, 2003), with the arrival of the fourth puberty stage being suggested to mark the end of maximal speed development in girls not involved in sport (Szczesny & Coudert, 1993). This disparity between the sexes is attributed to maturational changes in body dimensions and composition (Beunen & Malina, 1988; Butterfield, Lehnhard, Lee, & Coladarci, 2004). A second period of accelerated adaptation has been reported to occur around the age of 12 years in girls and between 12 and 15 years in boys (Borms, 1986).

The development of speed throughout childhood will be influenced by quantitative changes in muscle cross-sectional area and length, biological and metabolic changes, morphological alterations to the muscle and tendon, neural/motor development, as well as biomechanical and coordination factors. The integration of all of these systems makes it difficult to identify precise mechanisms responsible for any speed gains achieved throughout childhood. The initial period of accelerated adaptation observed before the end of the first decade of life has been suggested to be linked to the development of the central nervous system and improved coordination (Borms, 1986; Viru et al., 1999). This assumption is supported by the rapid growth of the central nervous system during the first 7 years of life (Malina et al., 2004), and the observation that coordination patterns of locomotor skills reach adult levels by the same age (Whitall, 2003).

Increased muscle size and length during adolescence support a maturational influence on speed development, although Butterfield et al. (2004) found no association between longitudinal growth rates of height and body mass and improved running speed in children aged 11–13 years. Although 2 years may be considered brief for a longitudinal study, the above findings may also reflect a limitation of the current LTAD model, which relies on growth rates to identify maturational status. Increases in muscle substrates and enzymes associated with anaerobic energy production provide another means for improving speed immediately before and during the teenage years (Eriksson, 1980). Physical properties of the muscle and tendon architecture will also influence the ability to produce speed. These properties include the reported marked increases in the surface area of the muscle–tendon junction from childhood into adulthood, which is accompanied by a reduced number of Golgi organs in the mature state (Ovalle, 1987). As a consequence of these changes in the biomechanical properties of muscle and connective tissue, a ten-fold increase in muscle–tendon stiffness has been observed in the first two decades of life (Lin, Brown, & Walsh, 1997). Changes in muscle stiffness will also be influenced by neural factors, with firing rates (Whitall, 2003), twitch times (Lin et al., 1997), reflex muscle activity (Grosset, Mora, Lambertz, & Perot, 2007), and co-activation (Lambertz, Mora, Grosset, & Perot, 2003) all being shown to develop through childhood in a manner that would favour increased speed production.

The current LTAD model speculates that two "windows of opportunity" exist to maximize training gains in childhood. These "windows" are related to chronological age and occur at approximately 7–9 years in both boys and girls, with a second window between 11 and 13 years in girls and between 13 and 15 years in boys. The fact that the second window is staggered by 2 years between girls and boys can be interpreted as more of a maturational, as opposed to a chronological, "window of opportunity". A maturational role in the second "window of opportunity" is supported by Viru et al. (1999), who speculated that speed training gains during this period were related to hormone-dependent selective hypertrophy of fast-twitch fibres in both boys and girls. Surprisingly, research examining the trainability of speed during childhood is sparse. Venturelli and colleagues (Venturelli, Bishop, & Pettene, 2008) found that the magnitude of speed gains were similar for pre-adolescent soccer players involved in coordination training and traditional straight-line sprint training. This finding supports a role of coordination and neural control in speed development prior to maturation, although whether these factors are more trainable during pre-adolescence is not known. Philippaerts et al. (2006) reported that sprint speed in youth footballers showed the largest gains around the time of peak height velocity, suggesting a combined training and maturational affect. However, the longitudinal data presented by Philippaerts et al. (2006) showed a decline in sprint performance in the 12 months preceding peak height velocity, and any subsequent gains may simply have reflected a correction of the previously impaired performance. Improvements in speed around peak height velocity may also be related to increased lower limb length, reflecting an entity that is clearly not trainable. Rapid periods of physical growth may disrupt motor coordination in some individuals, a phenomenon known as "adolescent awkwardness" (Beunen & Malina, 1988; Philippaerts et al., 2006). However, the timing and magnitude of this phenomenon is still unknown and it is difficult to evaluate if this observation is being enshrined as "fact" when based on limited empirical evidence.

While there is limited research available on the trainability of speed throughout childhood, some research has investigated possible mechanisms responsible for training gains during childhood. Sprint training has been shown to increase concentrations of substrates and enzymes utilized during anaerobic metabolism in 11-year-olds (Eriksson, 1980) and adolescent boys (Cadefau et al., 1990; Fournier et al., 1982). However, the magnitude of the training-induced change is reported to be below that of adults and any adaptation is lost following a detraining period (Fournier et al., 1982). The magnitude of the response and rapid detraining would suggest metabolic factors are unlikely to be constrained to maximizing gains during a window of opportunity in childhood. Sprint training has also been shown to have a limited effect on catecholaminergic responses to sprint exercise in adolescent girls, which disappears with detraining (Botcazou et al., 2006). Therefore, any combined speed training and maturational effects appear to have a limited influence on the sympo-adrenal response. In a 6 month study of youth soccer players, Gravina et al. (2008) reported a significant correlation between changes in testosterone concentrations and changes in sprint performance. Although these findings support a maturational relationship for improved speed for players involved in a training programme, the correlation was only modest ($r = 0.34$, $P < 0.05$) and with $< 12\%$ shared variance between the two variables other factors need to be considered. Identifying a single mechanism responsible for improved speed during childhood is unlikely. Instead, a number of biological, neural, and biomechanical factors will influence the development of speed. These factors may develop at different rates for different individuals and may be linked to both age and maturation. The trainability of factors associated with speed development during childhood remains unclear.

Strength. The development of muscle strength is a multi-faceted, performance-related fitness component that is underpinned by muscular, neural, and mechanical factors (De Ste Croix, 2008). The complex interaction of these components makes the study of the increase in muscle strength during growth and maturation challenging. As strength is an essential component of most aspects of performance, it is surprising that very little is known about the factors associated with strength development during childhood compared with the other fitness components discussed in this review. This may be attributed to the difficulty in measuring internal forces and the inherent methodological problems associated with determining external force. As there are no physiological markers that a maximal effort has been given, the methodological and assessment choices are critical in paediatric studies of muscle strength (De Ste Croix, 2007). However, the findings of studies on the age- and sex-associated changes in strength are relatively consistent, especially for the lower limbs. Caution, however, must be taken when transferring this knowledge to other muscle joints, as the development in strength appears to be both muscle action and joint specific (De Ste Croix, 2008).

Strength increases in both boys and girls until about the age of 14 years, when it begins to plateau in girls and a spurt is evident in boys. By 18 years there are few overlaps in strength between boys and girls, although this simplistic model utilizing chronological age as a marker for development in strength does not take into account the individual timing and tempo of growth and maturation (an issue seen with all the fitness components). The exact ages at which sex differences become apparent appear to be both muscle group and muscle action specific and data have indicated that differences in upper body strength between the sexes occur earlier than differences in lower body strength (Gilliam, Villanacci, Freedson, & Sady, 1979; Round, Jones, Honour, & Nevill, 1999). What is less clear is the complex interaction of factors that contribute to strength (the production of force) during childhood and adolescence. Few well-controlled longitudinal studies have concurrently examined the influence of known variables using appropriate statistical techniques (De Ste Croix, Armstrong, Welsman, & Sharpe, 2002; Round et al., 1999; Wood, Dixon, Grant, & Armstrong, 2004). Most studies that have determined maturation have shown that it does not exert an independent effect when other factors, such as stature and body mass, are accounted for (De Ste Croix et al., 2002; Hansen, Klausen, & Muller, 1997; Maffulli, King, & Helms, 1994). Also, the assumption that muscle cross-sectional area is the most important parameter in strength development throughout childhood and adolescence does not hold when examined with other known variables (Deighan, Armstrong, & De Ste Croix, 2003; De Ste Croix et al., 2002). Consistently, stature appears to play a key role in strength development and this may be attributed to the strength spurt that has been linked to peak height velocity, and the muscle moment arm (for a detailed explanation of the muscle moment arm, see Wood et al., 2004).

Strength training is now deemed to be safe and effective for children and adolescents when appropriately designed and supervised (Christou et al., 2006; Falk & Tenenbaum, 1996). Well-established guidelines for youth resistance training (e.g. Faigenbaum et al., 2009; Stratton et al., 2004) recommend resistance training for enhancement of muscular strength in youths, with improvements in body composition (Sothern et al., 2000) and motor performance (Christou et al., 2006), and reductions in injury (Faigenbaum et al., 2009) further advantages. Research studies have demonstrated that strength is trainable during childhood and adolescence, with Faigenbaum and colleagues (2001) reporting strength gains in children as young as 5 years. However, a large variation in strength gains exists between studies, with improvements ranging from 5.3% (Faigenbaum, Westcott, Loud, & Long, 1999) to 87.0% (Faigenbaum, Zaichkowsky, Westcott, Micheli, & Fehlandt, 1993) in untrained participants. Several factors may contribute to this variation, including the baseline measure of strength, the age range of participants, training programme designs (e.g. frequency, volume, and intensity), muscle group/action assessed, and exercises/assessments used. These all make the evaluation of training responses difficult.

The LTAD model states that strength is always trainable but recommends the optimal "window of trainability" for boys is 12–18 months following peak height velocity, while for girls it is immediately after peak height velocity or at the onset of the menarche (Balyi & Hamilton, 2004). However, research examining the optimal "window of trainability" is limited and there appear to be no longitudinal strength training studies that have determined peak height velocity and that have appropriately controlled for growth and maturation. Only three studies (Lillegard, Brown, Wilson, Henderson, & Lewis, 1997; Pfeiffer & Francis, 1986; Vrijens, 1978) could be found that compared the trainability of strength across different maturational ages. Vrijens (1978) found greater arm and leg strength improvements in a post-pubertal (16.8 years) group compared with a pre-pubertal (10.5 years) group, who improved lower back and abdominal strength to a greater degree following an 8 week training programme. However, both Lillegard et al. (1997) and Pfeiffer and Francis (1986) found no differences in the percentage magnitude of strength training response between different maturational training groups. Therefore, current research supporting the LTAD model's optimal "window of trainability" for strength is speculative, with only one study concluding that the strength training response is greater after puberty. Based on current research, strength training can be undertaken by children, as long as the programme is designed and supervised by professionals. Further research examining strength training gains against biological age (age at peak height velocity; Mirwald, Bailey, Cameron, & Rasmussen, 1981) are required to determine if an optimal window of strength trainability does exist. In addition, research should also focus on the training variables (e.g. volume, frequency, load, and rest periods) for optimum strength training gains in children and adolescents.

Power. Rapid developments in muscular power have been established in pre-pubescent children between the ages of 5 and 10 years (Branta, Haubenstricker, Seefeldt, 1984). These periods of accelerated development are largely attributable to enhanced neuromuscular coordination. A secondary spurt has been associated with the onset of puberty in girls between 9 and 12 years, and in boys between the ages of 12 and 14 years (Beunen, 1997), with significant development in leg power at the ages of 14 and 15 years (Blanksby, Bloomfield, Ackland, Elliott, & Morton, 1994). The latter spurt is related to a combination of hormonal, muscular, and mechanical factors caused by the onset of puberty (as seen with the other fitness components). When aligning the velocity curve of lower limb power development in relation to peak height velocity, previous research has identified an adolescent spurt beginning 1.5 years before peak height velocity, and peaking 0.5–1.0 year after peak height velocity (Beunen & Malina, 1988). Like muscular strength, therefore, while accelerations in muscular power may occur around the time of peak height velocity, peak muscular power would appear to coincide more readily with peak weight velocity, suggesting that both increases in muscle mass and motor unit activation are strongly linked to muscular power. Butterfield et al. (2004) reported a strong correlation between vertical jump height and the growth rates of their pre-adolescent sample ($r = 0.95$, $P < 0.05$). Growth-related changes in both leg length and muscle mass were associated with increased vertical jump height, and these structural changes were deemed to override any negative effects of the concomitant increase in body mass (Butterfield et al., 2004).

As with a number of other physical components, sex-related differences appear to exist in muscular power from pre- to post-adolescence, with differences becoming more apparent at the age of 14 years onwards, as a result of the increased leg length and muscle volume in males (Temfemo, Hugues, Chardon, Mandengue, & Ahmaidi, 2009). Observations of cross-sectional data show sex-related differences in mean countermovement jump height scores of 7- to 11-year-old girls and boys (Isaacs, 1998). Butterfield et al. (2004) reported differences in their baseline measures of vertical jump height between boys and girls aged 11–13 years, and also highlighted that the growth rate of jumping for boys significantly exceeded that of girls by 1.91 cm every 4 months over a 9 month period. Research has revealed significant differences between stages of sexual maturity and vertical jump height performance in boys (11–16 years), even when the influences of body mass and stature were removed (Jones, Hitchen, & Stratton, 2000). However, differences between sexual maturity stages and vertical jump performance were not statistically significant among girls. But the greater effect of sexual maturation on muscular power output in boys during the adolescent growth spurt highlights the likely attributable increases in androgen concentrations – notably growth hormone, testosterone, and thyroid hormone – between boys and girls (Rogol, 1996; Viru et al., 1999). More recently, a neuromuscular spurt was evident in male athletes characterized by an increase in both vertical jump height and the ability to attenuate landing forces (Quatman, Ford, Myer, & Hewett, 2006). Within the female sample, a reduction in both vertical jump height and take-off force highlighted the contrasting effects of maturation on lower limb explosive strength.

In addition to muscle cross-sectional area (Jacobs, Sjodin, & Svane, 1982), neurological changes (Blimkie & Bar-Or, 1996), motor coordination (Isaacs, 1998), fibre type composition (Mero, Jaakkola, & Komi, 1991), and prior training experience (Bencke et al., 2002) have all been postulated to be determining mechanisms for lower limb explosive strength in youths. Despite these suggestions, limited data exist for the combined effects of maturation and trainability on lower limb muscular power adaptations. Chiodera et al. (2008) implemented a 33 week, three lessons per week motor abilities physical education programme for boys and girls between the ages of 6 and 10 years. Results revealed significant improvements (6–10 cm; $P < 0.01$) in long jump distance for all ages and for both sexes, suggesting that trainability, as well as growth and maturational factors, may have a positive effect on power development throughout childhood in both males and females. Other studies have reported statistical differences between playing ability and vertical and horizontal jump tests (Gissis, Kalapotharakos, Sotiropoulos, Komsis, & Manolopoulos, 2006; Vaeyens et al., 2006), and significant improvements in lower limb muscular power following a 6 week combination of plyometrics and resistance training (Faigenbaum et al., 2007). However, without longitudinal data for corresponding measures of maturity status and muscular power, the existence of any "windows of opportunity" remains unclear, as does the question of whether or not adaptations are greater for those athletes who are exposed to power-based training during, as opposed to outside of, any such "windows".

The current LTAD model provides no indication of a "window of opportunity" for power development during childhood. This may be due to the fact that as the product of force (strength) and velocity (speed), the "windows of opportunity" have already been included in the model for the component parts of power production. However, given the importance of muscular power for athletic success, it may be appropriate to consider the most appropriate period during which to train for power during childhood. Owing to the minimal number of longitudinal-based studies examining the interaction of growth, maturation, and trainability on muscular power, it is difficult to identify whether a window of opportunity exists to maximize power development.

Windows of opportunity

Undeniably, the basis of the LTAD model centres around annual training and competition design, which have been well documented previously (Bompa, 1995; Harre, 1982; Norris & Smith, 2002; Wilke & Madsen, 1986). However, the model also maps physiological adaptations associated with growth and maturation, through maximizing training "windows of opportunity" as repeatedly highlighted throughout this review. Essentially, these are critical/sensitive periods for accelerated development of motor performance based on a suitable training stimulus during appropriate maturational time periods (Guzalovsky, 1977). Nevertheless, as noted above (in several previous sections), the actual concept of the development periods related to increased adaptive properties to factors stimulating development (i.e. training and exercise), as well as the potential negative implications, require further scientific verification. It seems that the appropriate application of training in line with maturation highlighted above may have a significant influence on peak performance through cell, tissue, organ, and whole-system specialization (Balyi & Hamilton, 2004; Wenger, McFayden, & McFayden, 1996). Certainly in the applied literature it has been documented that conducting a training intervention outside of a "window of opportunity" will result in few if any training gains and may actually be detrimental to future adaptations (Zaichkowsky, Zaichkowsky, & Martinek, 1980), but there is a clear lack of supporting evidence for such an assertion.

The present authors' acknowledge the difficulties in the quantification of physical activity and training in young participants, as well as controlling this during applied investigations. This in part can explain why there is a lack of agreement in the literature. Loko and colleagues (Loko, Sikkut, & Aule, 1996) noted that there is evidence to suggest that the best effect of training and the development of performance capabilities is achieved when natural growth is at its peak. However, paradoxically there is a possible consequence that the full potential of the individual is not achieved when early specialization and intensive training occur during these "windows of opportunity". Without supportive and objective data to help confirm/reject these ideas, inferring any optimal training recommendations for successful athletic pathways for young participants is perhaps unsuitable. It is the opinion of the present authors that this needs to be made clearer to coaches and practitioners by national governing bodies.

Notwithstanding the empirical issues, the actual terms of reference for "window of opportunity" require clarification. It seems a "critical period", related to exercise training, is an opening to effectively exploit a unique situation, which is vital to adhere to, otherwise full athletic potential will not be achieved. Whereas the term "sensitive period" implies an opening when extra gains may be expected for the same efforts. Based upon this strategy, it is clear that implications to the use of such labels, together with significant consequences for important constructs such as specialization, should be considered too. Furthermore, the term "window" suggests that the periods open and close, when in fact they may open and remain so on to and throughout adulthood (Viru et al., 1999).

In short, with issues related to definition and the obvious lack of objective evidence, the authors' belief is that the proposition that if young participants do not utilize these "windows of opportunity" they will never reach maximum athletic is unjustified. Furthermore, when utilizing fundamental training principles within a long-term periodized plan, the period of a "training emphasis" should be presented. Again, coaches and practitioners should be made more aware of the importance of training to advance all fitness components throughout childhood and adolescence during non-sensitive periods as well, principally because of different individual maturation development rates and all components are trainable to some extent (Suslov, 2002). By doing so this should further help coaches avoid issues around early specialization, and optimize general athletic development of young performers.

Summary and implications

A number of studies have identified the numerous physical developmental processes that occur during childhood and adolescence and how they might influence short- and long-term athletic performance (Baquet et al., 2003; Boisseau & Delamarche, 2000; Naughton et al., 2000; Viru et al., 1999). The most prominent ideology to help to optimize long-term athletic performance preparation in line with this is the LTAD model (Balyi & Hamilton, 2004). This model has received supported in contemporary coaching texts (Balyi & Stafford, 2005; Balyi & Williams, 2009). Certainly, the model succeeds in offering practitioners a coaching framework using plausible principles. However, from the components reviewed in this paper (physical literacy, aerobic and anaerobic performance), there is little evidence to support the LTAD claims, possibly due to the number of physiological factors that influence performance. Similarly, Norris and Smith (2002) correctly state that the most essential component of an effective training programme is the concept of individualization. This appears to be a further limitation of the LTAD model (Balyi & Hamilton, 2004), even with physiological age classifications due to their own limitations (Beunen, 1990; Janz & Mahoney, 1997). Moreover, Viru et al. (1999) concisely state that the lack of evidence between athletic performance and trainability against ontogenetic development make any conclusions inaccurate, particularly for the notion of "windows of opportunity". Similarly, although such information has been applied to specific physiological development and training practices for children and adolescents, it appears that there is a lack of consensus on the impact of such hormonal and metabolic changes within review articles (Boisseau & Delamarche, 2000; Naughton et al., 2000). This is primarily due to the practical issues and restrictions surrounding paediatric research (Boisseau & Delamarche, 2000).

A key rationale for this review is how the LTAD model is currently being understood and applied by coaches and practitioners. It is the opinion of the authors that coaches should be better educated in how to interpret and use the information within the model, in light of its positive and negative issues. Subjectively, it appears that the model has been widely prescribed to date, but it seems the knowledge transfer of the generic principles that make up the model are not being disseminated to allow coaches to comprehend and adapt the model to suit the individual needs of their own athletes. Furthermore, the model would be more suitable if it were to be more holistically orientated, encompassing some of the key interdisciplinary perspectives seen elsewhere (Bailey et al., 2010).

Therefore, while it should be clearly stated that the LTAD model has advanced coaches' and practitioners' understanding of the importance of physiological principles and biological maturation alongside training young athletes, there are many unexplained/unsupported premises that undermine it. Preliminary research to help practitioners to better understand fundamental development issues of children and adolescents is urgently required. Whether a situation is reached whereby an evaluation of the application of the model is conducted remains uncertain. What is more certain is that future recommendations to help enhance physical athletic performance from infant to adult must be based on empirical evidence (Beunen & Malina, 1996). With this in mind, we recommend to key sporting stakeholders that they should look to advance the scientific underpinning of their recommendations by supporting appropriate applied scientific investigations to enhance our understanding of developing the youth athlete.

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