ABSTRACT
SPEED IS A FUNDAMENTAL COMPONENT OF MANY SPORTS, AND THE ABILITY TO SPRINT IS OFTEN A DISTINGUISHING CHARACTERISTIC OF SUCCESSFUL PERFORMANCE. THIS ARTICLE REVIEWS EVIDENCE EXAMINING SPEED DEVELOPMENT DURING CHILDHOOD AND ADOLESCENCE, WITH A SPECIFIC FOCUS ON THE IMPACT OF MOVEMENT SKILL AND PHYSIOLOGICAL AND BIOMECHANICAL FACTORS. GUIDELINES ARE PROVIDED TO ASSIST STRENGTH AND CONDITIONING COACHES WITH LONG-TERM PLANNING OF TRAINING TO MAXIMIZE SPEED DEVELOPMENT THROUGHOUT CHILDHOOD AND ADOLESCENCE.

INTRODUCTION
Speed has been shown to be a distinguishing characteristic of successful sports performance in both children (16,35) and adults (34). Developing speed is a primary goal of many conditioning programs. Although speed represents a generic term referring to the ability to move rapidly, within overground sports, speed has been further broken down to include first step quickness (11), acceleration, maximal speed, and game speed (18). These components of speed are all likely to develop throughout childhood, as children grow and mature; however, the mechanisms that underpin these developments and the trainability of speed throughout childhood and adolescence are less clear. Unfortunately, there is a lack of research that examines the development and trainability of the different phases of sprinting in childhood and adolescence. This review will consider the development of speed in the generic sense.

SPRINTING AS A FUNDAMENTAL MOVEMENT SKILL
Fundamental movement skills (FMSs) require children to master object control and locomotion skills; the latter including the ability to hop, jump, run, and sprint (42). Childhood is likely to reflect a particularly important period of time for children to develop movement skills associated with sprinting. Up until 7 years, the central nervous system is rapidly developing and children achieve their adult gait by this time (47). Although sprint ability is often measured as a performance outcome (i.e., sprint time) more in-depth analysis is needed to establish if children are sprinting in a proficient and skillful manner.

van Beurden et al. (43) state that children should display a mature sprinting technique by the third grade, but contemporary evidence suggests that this is not the case. van Beurden et al. (43) reported that approximately 60% of third and fourth grade Australian boys and girls rated poor when sprinting was assessed as a movement skill. Stratton et al. (42) observed that in 9–10 year olds in the United Kingdom, only approximately 25% of boys and 20% of girls were proficient in sprinting, whereas Cowley et al. (10) reported that only 5% of 5- to 8-year-old New Zealand children could demonstrate mature form across a selection of locomotor skills. A failure to master FMSs, including sprinting, may produce a proficiency barrier preventing children from developing more complex skills (14) and prevent participation in physical activities that require those skills (43).

KEY WORDS: sprinting; accelerated adaptation; trainability; stride frequency; stride length
Given the importance of sprinting in most sports, development of locomotor movement skills in childhood should be a priority. It has been suggested that this could be achieved with tailored physical education programs and modification of social and physical environments (43). Coordination patterns may also need to be reinforced throughout adolescence when body dimensions are rapidly changing. In the longitudinal data presented by Philippaerts et al. (33), sprint performance was shown to decline around the start of the growth spurt, approximately 12 months before peak height velocity (PHV). This impaired sprint performance was attributed to the rapid growth of the limbs, resulting in “adolescent awkwardness” and causing a temporary disruption to motor coordination. However, children in the study of Philippaerts et al. (33) seemed to subsequently correct for any period of awkwardness, as sprint performance then improved around the time of PHV.

**PHYSIOLOGICAL FACTORS IN SPEED DEVELOPMENT DURING CHILDHOOD**

Speed is suggested to develop in a non-linear process throughout childhood and adolescence (29), with preadolescent and adolescent spurs in performance identified (45). These natural spurts in performance have been termed periods of accelerated adaptation; with the preadolescent spurt primarily attributed to neural development and the adolescent spurt primarily to endocrine-mediated development (25,45). Some authors have suggested that periods of naturally occurring accelerated adaptation represent windows of opportunity where training responsiveness will be increased (41) or even that a failure to maximize speed development during such periods will limit future potential (2,3). Such opinions have come under criticism due to a lack of empirical evidence to support these claims (1,13). Gender differences in speed development become apparent at the onset of puberty, with girls making limited gains in speed throughout adolescence, whereas boys can make large gains (5,32).

Adaptations in the central nervous system will underpin the majority of the gains in speed observed during prepubescence, as children refine their motor recruitment and coordination patterns (29). Central nervous system adaptation can continue throughout adolescence (6), which may explain why the Long-Term Athlete Development model advocates a window of opportunity for developing speed based on chronological age around the early to mid phase of the second decade of life (2,3). A large maturational influence on speed development seems likely given that adolescence will be associated with increases in limb lengths, increased muscle mass, changes to intrinsic muscle-tendon properties, and development of anaerobic metabolism (13). Peak gains in sprint speed have also been shown to occur around the time of PHV (33), providing more support for a maturational influence. Other studies have shown weak to moderate associations between maturation and speed development during childhood (16,48). Such studies may be limited in the sensitivity of their measures to quantify maturation.

**BIOMECHANICAL FACTORS IN SPEED DEVELOPMENT DURING CHILDHOOD**

In its simplest form, speed can be considered as the product of stride length (SL) and stride frequency (SF). In a study of adults whose maximal sprint speeds spanned a large range (6.2–11.1 m/s), Weyand et al. (46) found that SF did not influence maximal speed, with increased speed attributed to a longer SL instead. Similarly, Schepens et al. (30) reported a 3-fold increase in maximal speed from infancy to adulthood, with SF slightly decreasing after early childhood before reaching a plateau and increased speed attributed to proportional increases in SL. Similarly, Oliver et al. (31) across a number of studies and with children ranging from pre- to postpubertal have shown that increases in speed throughout childhood are predominantly related to increases in SL and less influenced by changes in SF.

Although SF and SL describe speed, they should be viewed as outcome measures rather than mechanisms of speed production, and that training SF and SL per se may be misguided (15). Instead, there is a need to consider the factors that contribute to producing a high SF and long SL, how these develop through childhood, and the extent to which any underlying mechanisms are trainable. Unfortunately, there is a scarce amount of research available to answer all of these questions in a pediatric population. Ultimately, the ground contact period is considered the key phase of sprinting, as this is the only time when a sprinter can generate force against the ground to affect their velocity (46). Consequently, ground reaction forces and derivatives of this (rate of force development, impulse, power, and leg stiffness) are thought to be primary determinants of speed (7,15,46). Given that SF and SL change independently at maximal speed throughout childhood (40), different mechanisms are likely to underpin their development. For instance, a high SF will require a high rate of force development (39), which is associated with a high leg stiffness and a reliance on muscle preactivation and stretch reflexes (12) and are known to develop throughout childhood (26); whereas, a long SL will be influenced by peak ground reaction forces (46) and the ability to maximally recruit motor units.

Greater attention may be given to the effects of SL on maximal speed, given that the body of evidence suggests SL plays a more important role than SF (40,46). In the study of Weyand et al. (46), greater SLs and shorter ground contact times were correlated to faster sprint times, leading the authors to conclude that faster sprinters apply greater vertical ground reaction forces during reduced periods of ground contact. Published data to confirm this suggestion in adults and children is currently lacking. Results from Oliver et al. (31) have shown that in 11- to 16-year olds, although increased SL explained...
increased speed, it was not accompanied by concomitant decreases in ground contact time. Consequently, ground contact times, or more mechanistically, the speed of muscular contraction, do not improve with natural development around the adolescent years. The improvements in observed SL are likely to be attributed to an increase in the relative forces applied rather than the time over which this force is applied. Improvements in force application may be mediated by both quantitative changes in the amount of lean muscle mass and qualitative changes in muscle-tendon architecture that is associated with maturation (such as increased intrinsic stiffness or increased pennation of muscle fibers) and improved neural recruitment strategies (13). Salo et al. (39) have suggested that adult sprinters who are more powerful generate more force and are more reliant on SL to achieve maximal speed, whereas athletes who are less able to generate force and power are more reliant on the ability of the central nervous system to produce a high SF to elicit maximal velocity. Translating this theory to youth would suggest that younger less powerful children may be more reliant on a high SF to achieve maximal speed and older more mature and powerful children more reliant on SL.

In one of the few studies to examine the determinants of speed production in adolescents, Chelly and Denis (7) reported that muscle power was a key determinant of both acceleration and maximal speed, with leg stiffness also contributing to the development of maximal speed. Oliver et al. (31) suggest that power and horizontal force explain nearly all of the variance in maximal running speed in children ranging from pre- to postpubescence. This is likely because of increases in power and force, enabling children to produce a longer SL and consequently faster sprint speed. It may also be speculated that increased limb length around the growth spurt is responsible for increasing SL and ultimately sprint speed. Increased limb length would influence contact length (the distance covered when the foot is in contact with the ground), but this contributes less to SL than the aerial phase.

As iterated above, the period of ground contact is the only phase in sprinting where force can be produced, and it is this force production that influences SL and speed (15,46). Younger children compensate for their shorter legs by increasing their maximal SF more than that of older children and adults, but once children reach 12 years of age, they attain 95% of their adult leg length, and consequent increases in speed are accompanied by relatively small changes in limb length (40). It has also been shown that morphological characteristics and not leg length differentiate between sprinters of differing ability (23), suggesting muscular factors will have more of an influence than anatomical factors in speed production.

To summarize, growth leads to increased leg length, and this can improve step length (when in contact with the ground). However, the majority of the SL is achieved during the aerial phase, the duration of which remains largely unchanged throughout childhood and adolescence (40). Concomitant increases in muscle mass and morphological adaptations in muscle structure that accompany changes in leg length will aid force production, facilitating an ability to propel the body further forward during the aerial phase. Although a reduced ground contact time would enable a higher SF this is not something that occurs as part of the natural development process, if anything, ground contact times may increase and SF decrease slightly with maturation.

### TRAINABILITY OF SPEED DURING CHILDHOOD

The theory of “windows of opportunity” suggests a period of time during childhood when responsiveness to training will be maximized, and, potentially, that a failure to fully use such a period will limit future achievement (2,3). There is a lack of empirical evidence to support this theory (1,13), and no studies have specifically been designed to test such a hypothesis. However, many discrete studies have all shown a variety of training methods to elicit speed gains in children and adolescents. These studies show that FMSs (42), coordination (43), stabilization, and proprioceptive training (21) can elicit speed gains in prepubescent children. Plyometric training has been reported to succeed at improving speed for athletes who are prepubescent (22), circumpubescent (30), and fully mature (36). Strength training has also been demonstrated to transfer to speed gains in prepubescent (17), circumpubescent (8), and postpubescent (9) athletes.

While individual experimental studies provide some insight into the trainability of speed in childhood and adolescence, recent review articles help to build a more comprehensive evidence base. In a review of plyometric training in children aged 5–14 years, Johnson et al. (19) concluded that this type of training had a large effect on measures of jumping and running. Although Behringer et al. (4) only reported a low effect size when reviewing the transfer of strength training to speed gains, the authors did conclude that resistance training is an effective way for enhancing speed performance in children and adolescents. Behringer et al. (4) also reported that speed gains from strength training were more pronounced in younger less-mature participants, contradicting the theory that strength training may be limited until the maturational trigger of puberty is reached (20). Contrary to this, Rumpf et al. (38) suggested from their review that strength training has greater speed benefits in postpubertal youths. As per the recent Youth Physical Development model (25), these findings support the role for continued strength training throughout childhood and adolescence. Rumpf et al. (38) specifically reviewed the scientific literature to elucidate information on the trainability of speed throughout childhood. The authors performed a meta-analysis, grouping results by maturation (pre-, circum-, and post-PHV), and mode of training (sprint, strength, plyometric, and combined training). With all children combined, Rumpf et al. (38) reported
average gains in sprint performance of 3.5% after sprint training, 2.7% after both plyometric and combined training, and 1.1% after strength training alone. Given the low random variation associated with sprint performance in childhood (37), these results provide encouraging findings that children are able to make meaningful training induced gains in sprint performance.

Rumpf et al. (38) also concluded that there was an interaction between maturation and mode of training; children pre-PHV benefited most from plyometric and sprint training, children circum-PHV benefited most from plyometric and strength training (although there were limited data for this category), and children post-PHV benefited most from combined training and strength training programs. From these results, there seems to be an interaction between growth, maturation, and training; children pre-PHV benefited most from training that is associated with neural adaptations, whereas children post-PHV benefited most from training that may be associated with both neural and morphological adaptations. Unfortunately, limited information is available on any biomechanical changes underpinning training induced gains in speed during childhood. It may be that prepubescent children benefit most from neural training strategies because these allow them to increase contraction rates and SF, whereas adolescent athletes also benefit from circulating androgens, allowing them to make gains in force generating capacity and SL. Research is needed to confirm this.

**SUMMARY AND RECOMMENDATIONS**

Although SF and SL are routinely used to describe speed, these should not necessarily form the focus of training. Instead the period of ground contact represents the time when a sprinter can generate propulsive forces, and training should focus primarily on this period. A number of authors have identified the importance of a reduced ground contact period to enhance speed (15,28,46), with Lockie et al. (28) concluding that training to improve sprint performance should focus on good technique, with short ground contact times, and emphasizing stretch-shortening cycle function. Goodwin (15) also suggests that coupled with ground contact times, training should also focus on contact length because this represents a further element of the ground contact phase and a relatively small change can substantially improve performance. It is not known how contact length develops with maturation, but it seems likely that improvements will be predominantly attributed to increased leg length. Naturally, speed seems to develop in children because of anatomical growth and an increased ability to generate force and power resulting in an increased SL. Force and power generating capacity are likely to be trainable throughout childhood and adolescence. However, it seems that maximizing speed development during this time will also require training to improve factors that are known not to naturally develop (ground contact time and SF) or factors that are likely to only develop because of anatomical growth (leg length and contact length).

**Figure.** Guidelines for the long-term planning of training to maximize speed development throughout childhood and adolescence. Note: “Strength” training refers to all forms of resistance training that are appropriate, given the ability, development stage, and training age of the athlete (25).
From the evidence reviewed above, examining the interaction of growth and maturation with training, the figure provides guidelines for the long-term planning of training to maximize speed development throughout childhood and adolescence. These should be viewed as evolving guidelines as more research in this field is needed. A long-term program should incorporate sprint-specific training supplemented with FMSs, and strength and plyometric training to develop a range of interrelated physical abilities that contribute to speed. During early childhood, rapid central nervous system development leads to accelerated improvements in movement skills. During this period, children should be exposed to exercises that promote and refine efficient locomotor movement skills. During preadolescence, training adaptations will continue to be predominantly neural in basis, and the introduction of physical conditioning should aim to improve factors that will assist in the rapid production of force against the ground, such as plyometrics. This should aim to facilitate longer SLs and shorter ground contact times, using a selection of exercises that mimic the different movement patterns and joint displacements associated with different phases of sprinting.

Around puberty, there should be a greater focus on strength and conditioning; incorporating strength exercises that promote horizontal force production and progressing toward a program that enhances muscle hypertrophy around the time of peak weight velocity, to increase the potential to produce force. Plyometric drills can continue to be used to help express force at speed and begin to incorporate more complex drills requiring greater eccentric loading and impulse. By the postpubescence phase, the accumulation of training history should require less focus on fundamental technical training and greater attention to developing expression of maximal speed. The volume of training is likely to increase; training should focus on developing maximal strength (to facilitate force production) together with explosive exercises, such as plyometrics and maximal sprints (to facilitate force expression). Complex training is an example of a training mode that could be introduced to stimulate further adaptation and provide an efficient use of training time. More detailed guidelines on plyometric and weightlifting training progression and adaptations throughout childhood and adolescence are available elsewhere (24,27).

The coach should use these guidelines to help produce a long-term plan for developing speed, and to inform the types of exercises that are most appropriately aligned to different stages of growth and maturation. The focus of this approach is to maximize long-term gains in speed. It should be emphasized that similar to adults, programming for youths should always take an individualized approach (25) and the coach will need to consider the needs of each athlete to maximize the likelihood of continued progress through a long-term program.

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