SESNZ
SPORT & EXERCISE SCIENCE
NEW ZEALAND

The Journal of Sport and Exercise Science, Vol. 6, Issue 3, 153-161 (2022)

www.sesnz.org.nz

JSES

ISSN: 2703-240X

Natural development of sprint speed in girls and boys: a narrative review

Kaushik Talukdar[1, 2, 3], Craig Harrison[2], Mike R. McGuigan[2, 4]

[1]*Athlete Institute, Auckland, New Zealand*
[2]*Sports Performance Research Institute of New Zealand, Auckland, New Zealand*
[3]*Faculty of Health and Environmental Sciences, Auckland University of Technology, New Zealand*
[4]*School of Medical and Health Sciences Edith Cowan University, Australia*

ARTICLE INFO

Received: 16.02.2022
Accepted: 16.06.2022
Online: 22.08.2022

Keywords:
Sprinting
Youth
Growth

ABSTRACT

Sprinting is a fundamental motor skill in many sports. The ability to move rapidly over short distances can significantly impact the outcome of a game. The natural development of sprinting speed is similar in females and males during the first decade of life. However, due to changes in hormonal levels during puberty the development of kinetic and kinematic variables associated with sprinting may be affected in young females compared to their male counterparts. Previously researchers have investigated sprinting kinetics and kinematics in young males. However, there is a paucity of research on young females. Therefore, the purpose of this review is to highlight the biological differences between genders with regard to sprinting and the changes in kinetics and kinematics across maturation in young females.

1. Introduction

Boys and girls tend to show similar sprinting speed during the first decade of life (Borms, 1986; Malina et al., 2004), with a period of accelerated change between 5 and 9 years of age (Borms, 1986; Viru et al., 1999). Speed increases in this age group with the development of the central nervous system and subsequent improvements in coordination (Borms, 1986; Viru et al., 1999). However, from the age of 12 years, increases in sprinting speed slow considerably in girls compared to boys (Whitall, 2003). This disparity is largely due to maturational changes in body size and composition (Beunen & Malina, 1988; Butterfield et al., 2004), driven largely by hormonal changes. Because sprinting is heavily influenced by the stretch-shortening cycle (SSC) (Radnor et al., 2018), the physiological determinants of the SSC, including muscle size, fibre composition, and connective tissue/tendon stiffness (Bell et al., 1980; Lazaridis et al., 2010; Lexell et al., 1992; McLellan et al., 2011; Tillin et al., 2013), are also important to consider. Therefore, this review will highlight the differences in body composition, muscle size, fibre composition, connective tissue stiffness, growth and maturation in boys and girls regarding sprinting performance. The review will then investigate two models proposed by previous researchers to optimise sprinting performance in boys and girls and, the changes in sprinting kinetics and kinematics across maturation in the youth population.

2. Body size and composition

Insulin-like growth factor 1 (IGF-1), an important growth hormone in children, peaks during early adolescence. This anabolic hormonal surge occurs at approximately 12-13 years in girls and 15-16 years in boys (Underwood & Van Wyk, 1985). The anabolic factors can influence the development of muscle tissue hence affecting muscle strength, speed, and power around puberty in girls (Viru et al., 1999). However, this period coincides with sexual maturation in girls, which results in an increase in adipose tissue compared to their male counterparts (Malina et al., 2004; Viru et al., 1999). This can particularly impact movements during which body mass is supported, for example, running and jumping activities (Viru et al., 1999). In contrast, the androgenic effects of testosterone during puberty increases lean muscle mass in boys, which can positively impact weight to power ratio (Malina et al., 2004). Therefore, the differences in the interaction between hormonal changes and sexual maturation may provide an advantage to boys over girls when it comes to sprinting.

The changes in body size occur as a natural response to growth during early adolescence phase in boys and girls. Peak weight

*Corresponding Author: Kaushik Talukdar, Athlete Institute, New Zealand, Kaushik.talukdar21@gmail.com

velocity (PWV; the greatest rate of change in body mass) reaches 8.3kg/year in girls at about 12.5 years of age (Barnes, 1975). In boys, peak gains in weight are similar but experienced at a relatively later age (i.e., 14 years) (Barnes, 1975). Similarly, the maximum rate of linear growth, defined as PHV (Brown, Patel, & Darmawan, 2017), tends to occur at 12 years of age in females, approximately 6-12 months before the onset of puberty. During PHV, changes in height average 8 centimetres (cm) per year, with a range of 6-10.5 cm (Hoffman, 1997; Kreipe, 1994; Needleman, 2004). Boys reach PHV at approximately 14 years of age, with average gains in height ranging from 7-12 cm (Hoffman, 1997; Kreipe, 1994; Needleman, 2004).

Rapid increases in PHV and PWV can affect physical competencies, including sprinting (Malina et al., 2004). For example, previous research has shown a positive relationship between standing height and sprint speed in prepubertal boys, and leg length and sprint speed in post-pubertal boys (Meyers et al., 2017a). The positive association between height, leg length and sprint speed can be explained by the relationship between the distance the centre of mass travels after the foot hits the ground (i.e., contact length) and an increase in step length that occurs naturally as a result of growth (Lloyd et al., 2016b; Meyers et al., 2017a). In girls, Talukdar et al. (2021) reported that with every cm increase in leg length, maximal sprint decreased by 0.05 m/s in mid and post-PHV athletes.

Children also experience significant changes in body composition during puberty (Patel, Pratt, & Greydanus, 1998; Roemmich, & Rogol, 1995). For instance, both fat mass (FM) and fat-free mass (FFM) increase between 9 and 15 years of age in girls and boys (Malina et al., 2004). However, due to the development of secondary sex characteristics (e.g., wider hips, breast development), a consequence of increased growth hormone secretion, deposits of fat mass are significantly higher in girls with an average of 7.1kg compared to 3.1kg in boys (Malina et al., 2004). Moreover, proportionately more body fat is concentrated in the lower body of girls (Papai et al., 2012). The increase in body mass may inhibit force production in girls particularly during sprinting, as based on Newton's second law of motion, the greater the body mass the greater the acceleration required to displace the body. Rumpf et al. (2015) reported relative horizontal force and power to be the best predictors of maximal sprinting speed across maturation in young males (R^2 = 97-99%).

Body fat mass has also been shown to have a negative influence on sprint speed in youth athletes (Meyers et al., 2017a). For example, Meyers et al. (2017a) reported that body mass was negatively related to 30 sprint speed in both pre- and post-PHV boys (r = -0.35 & -0.47; $p < 0.05$). More specifically, in pre-PHV boys, body mass had a negative influence on step frequency (r = -0.48). In post-PHV boys, body mass negatively influenced step length ($p < 0.05$, r = -0.54) (Meyers et al., 2017a). Therefore, it is important to assess changes in height, weight, and body composition, particularly during the time of puberty as it can affect sprinting performance in the youth population.

Higher fat deposition in girls, a result of increasing oestrogen levels (Malina et al., 2004), may also affect sprinting kinetics and kinematics (Beunen & Malina,1988; Butterfield, Lehnhard, Lee, & Coladarci, 2004; Malina et al., 2004). Nagahara et al. (2019) investigated change in sprinting performance in Japanese girls between the ages of 7.0 and 15.3 years. The findings showed that girls >12.7 years became slower every year (-0.09 m/s) compared to girls <12.7 years (0.24m/s). Furthermore, the older girls had a plateau in step length and a reduction in ground reaction forces (GRFs) compared to the younger girls (Nagahara et al., 2019). Due to an increase in fat mass as girls mature, relative force production and step length can be considerably reduced, negatively impacting sprinting performance. Apart from body size and composition, there are other physiological differences between the genders that can impact sprinting performance such as SSC, muscle size, fibre composition, and muscle tendon stiffness.

3. The stretch-shortening cycle

SSC is characterised by an eccentric 'stretching' action before subsequent rapid concentric action. Sprinting, jumping and throwing utilises the SSC (Lloyd et al., 2015). It has been reported that this action (eccentric stretch before concentric) is more useful in improving the performance of the final concentric phase compared to an isolated concentric action (Flanagan & Comyns, 2008; Nicol et al., 2006). For example, jump height was reported to increase by 1-5% when preceded by countermovement (pre-stretch action) in young males (Lloyd et al., 2009). Furthermore, SSC can be categorised into fast and slow action based on ground contact time. Ground contact time shorter than 250ms is generally classified as fast SSC and ground contact time above 250ms is considered slow SSC (Flanagan & Comyns, 2008; Turner & Jeffrey, 2010). Sprinting can be considered a fast SSC activity since the ground contact time is lower than 250ms. In mid and post-PHV female athletes, the ground contact time was reported to be 170m/s (0.17s) (Talukdar et al., 2021). The function of the SSC is determined by several physiological variables, including muscle size, fibre composition, and connective tissue/tendon stiffness which may vary between genders (Radnor et al., 2018).

4. Muscle size

It is believed that increases in muscle size can contribute to the improved capacity to produce force which leads to greater performance outcomes during SSC activities (Radnor et al., 2018). Muscle size increases with growth and biological maturation with the ability to produce higher force during both concentric and eccentric actions (Kubo et al., 2001; O'Brien et al., 2010a; O'Brien et al., 2010b). More specifically, in isolated concentric and eccentric muscle actions, muscle size has been associated with quadriceps and hamstrings concentric strength and hamstring eccentric strength (Morse et al., 2008). Greater concentric strength during SSC actions can contribute towards greater impulse and rate of force development hence providing superior performance during sprinting and jumping tasks (McLellan et al., 2011; Tillin et al., 2013). In addition, as muscles increase in size during growth, the higher forces during the eccentric phase of sprinting and jumping may result in increased storage of elastic energy (Komi, 2000). Therefore, increases in lean muscle mass and size in boys can be an advantage for SSC-based activities such as sprinting compared to their female counterparts.

5. Fibre type composition

In addition to muscle size, fibre type composition can also play an important role in sprinting (Bell et al., 1980). Type 2 muscle fibres help to improve the ability to rapidly produce force resulting in greater benefit from the SSC compared to type 1 fibres (Radnor et al., 2018). It is reported that type 1 fibres decrease from approximately 65% at age 5 years to 50% at age 20 years (Lexell et al., 1992). However, limited longitudinal data have reported that gender differences in fibre type can be evident as the adolescent transitions towards adulthood. More specifically, type 1 fibre percentage tends to increase in women (51 ± 9% to 55 ± 12%) and decrease in men (55 ± 12% to 48 ± 13%) between the ages of 16 and 27 years (Bell et al., 1980; Lexell et al., 1992). Therefore, the ability to produce force rapidly in females can be limited hence affecting sprinting performance compared to their male counterparts, post PHV.

6. Muscle and tendon stiffness

Apart from muscle size and fibre type composition, tendon stiffness has also been documented to have a positive influence on sprinting performance in children (Lambertz et al., 2003). Increased tendon stiffness leads to shorter braking forces, reduced ground contact times and greater electromyographic activity that can be useful during sprinting (Lazaridis et al., 2010). Previous studies have reported that males have a higher level of stiffness compared to females in the patella and Achilles' tendon (Hicks et al., 2013; Onambele et al., 2007). In youth, Laffaye et al. (2016) found leg stiffness increased from 24.7 ± 10.6 kN · m−1 at 11-12 years to 44.1 ± 14 kN · m−1 in boys, with a small increase until 16 years (+17%) and a large increase between 17 and 20 years (+32.7%). In girls, leg stiffness increased from 26.6 ± 9 kN · m−1 at 11-12 years to 39.4 ± 10.9 kN · m−1 at 19-20 years, with a decrease in leg stiffness at 17-18 years, probably due to an increase in the percentage of fat at this age (25%). However, there are limited studies that have investigated the difference in tendon stiffness in boys and girls across maturation (Laffaye et al., 2016; O'Brien et al., 2010b). Therefore, understanding how growth, maturity and physiological mechanism associated with SSC affects sprinting kinetics and kinematics is crucial when investigating young females.

7. Assessment of growth and maturation

It has been established that rapid changes in PHV and PWV can impact sprinting performance in youth (Malina et al., 2004). Therefore, it is important to assess biological growth and not rely only on chronological age alone. The differences in timing and magnitude of growth within similar age groups of girls and boys can have a significant impact on sprinting performance (Lloyd et al., 2016; Malina et al., 2004). For example, two 12-year-old girls may have different sprinting abilities due to their height and body mass.

There are several ways to assess the growth and biological maturity of a child. The most popular clinical method utilises a plain X-ray of the left hand, wrist or knee and classifies children according to their skeletal age (Carling, Le Gall, Reilly, & Williams, 2009; Johnson, Doherty, & Freemont, 2009; Malina et al., 2004). Unfortunately, this method requires expensive equipment and an experienced investigator, thus is impractical for young athletes (Harrison, 2013). The Tanner Staging method, which classifies sexual maturity based on pubic hair development, has also been used widely in the literature (Conte et al., 2017; Faigenbaum et al., 1993; Tanner & Whitehouse, 1976). However, classification requires athletes to self-assess, which can affect the reliability of the measures (Rasmussen et al., 2015). For example, a previous study in Danish children (n = 898) reported that self-assessment and parental assessment were inaccurate in a substantial number of participants when compared with a clinical examination by trained physicians (Rasmussen et al., 2015). More specifically, half the girls tended to underestimate their exact breast development stage, and one quarter also underestimated their pubic hair. Therefore, suggesting that self-assessment of pubertal maturation can be inaccurate and unreliable.

A cheaper, non-invasive way of assessing maturation is by calculating the estimated years an individual is away from PHV. This method provides a maturity offset value using simple objective anthropometric measures, including leg length, sitting height, weight by height ratio and age (Malina et al., 2004; Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). Years from PHV can be used to characterise changes in body size, body composition and performance relative to changes in height (Malina et al., 2004). Maturity status is determined as pre-PHV (>1 year prior to PHV), circa-PHV (± 1 year from PHV), and post-PHV (> 1 year post PHV) and comparisons of any changes in performance can be made (Harrison, 2013). The Khamis-Roche method is another non-invasive and practical way of assessing maturity and includes three predictor variables: current stature (height), current weight and mid parent stature (mother's height + father's height/2) (Khamis & Roche, 1994).

Past research has incorporated the Mirwald and Khamis-Roche methods effectively to measure growth and maturation (Cumming et al., 2018; Rumpf et al., 2012). For example, Rumpf et al. (2012) used the Mirwald method to investigate sprinting kinetics and kinematics across maturation. Similarly, Cumming et al. (2018) used the Khamis-Roche method to predict adult height in a cohort of young soccer players when investigating the efficacy of bio-banding. It is important to assess growth and maturity in research with youth populations to guide safe and effective applications of training.

8. Developmental Models

Youth athlete training interventions that consider growth and maturation are essential. To support practitioners in this process, the long-term athletic development model (LTAD) was proposed (Balyi & Hamilton, 2004; Bompa, 1995). The LTAD model attempts to maintain balance between training load and competition throughout childhood and adolescence (Ford et al., 2011). It also proposes specific windows of development, termed "sensitive periods of development" for various components of fitness. When considering speed, the LTAD model suggests two training sensitive periods during childhood (Balyi & Hamilton, 2004), aligned to chronological age. The first period, occurring at 7-9 years in both genders, is aligned to a neurological spurt (Table 1) (Balyi & Hamilton, 2004). According to the LTAD

Table 1: Long term Athletic Development (LTAD): Sensitive periods for speed development (adapted from LTAD model, Balyi & Hamilton, 2005)

Speed Developmental Age														
Chronological Age	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Speed 1														
Speed 2 (Girls)														
Speed 2 (Boys)														

model, a period of accelerated brain development around age 7-9 years improves a child's ability to acquire the motor skill (Balyi & Hamilton, 2004; Higgs et al., 2008) via improvements in coordination (Cratty, 1986). The second sensitive period, occurring at 11-13 and 13-15 years of age in girls and boys, respectively, reflects a maturational window of opportunity for training (Table 1) driven by hormone-dependent hypertrophy of muscle fibres (Phillippaerts et al., 2006; Venturelli, Bishop, & Pettene, 2008; Viru et al., 1999).

However, since the LTAD model's inception, it has been critiqued for a lack of scientific rigour as the sensitive periods of development are based on chronological age as opposed to biological growth and maturity (Ford et al., 2011). For example, several factors influence speed throughout childhood, including quantitative changes in muscle cross-sectional area and length, morphological alterations to the muscle and tendon, development of SSC through neuromuscular pathways, and biomechanical factors associated with sprinting (kinetics and kinematics) (Ford et al., 2011; Radnor et al., 2018). Hence, it is important to consider these factors when investigating the potential of speed development in youth across maturation rather than rely completely on the windows of opportunity based on chronological age. It is also important to note that the majority of research investigating speed development in youth populations has been conducted in boys (Meyers et al., 2015; Meyers et al., 2016; Meyers et al., 2017a; Rumpf et al., 2015). As identified above, considering the emergence of distinct differences in physiology between the sexes with maturation, and their subsequent effects on speed, more research investigating the second LTAD window of training in girls is warranted (Papai et al., 2012).

More recently, using existing empirical research, the Youth Physical Development (YPD) model was proposed (Lloyd & Oliver, 2012). The goal of the YPD model was to establish an overall long-term strategy for physical development across childhood and adolescents. In contrast to the LTAD model, the YPD model proposes that all fitness components are trainable throughout development but that the magnitude of change differs based on maturation (Lloyd et al., 2015). More specifically, the YPD model suggests that speed can be trained at any age with a greater emphasis between 5-15 years for females and 5-16 years for males (Table 2) (Lloyd & Oliver, 2012). Furthermore, the model emphasises individualisation of training prescription due to the differences in timing, tempo, and magnitude of maturation between children (Lloyd et al., 2015). For example, it is believed that the training adaptation during pre PHV phase is predominantly neural compared to a combination of neural and hormonal during mid and post-PHV phases in both males and females (Lloyd & Oliver, 2012). In young males, it was found that plyometric training (PT) was useful in improving sprinting speed during pre-PHV, but a combination of strength training (ST) and PT was more effective during post PHV further supporting the YPD model (Lloyd et al., 2016a) However, more research is warranted if the adaption is similar across maturation in young females.

Despite their differences, both the LTAD and YPD models suggest that biological maturity should be considered when planning individual components of fitness in youth (Ford et al., 2011; Lloyd & Oliver, 2012). Furthermore, child physiology and how it changes with growth, and between the sexes, is important to understand when prescribing speed training in youth (Balyi & Hamilton, 2004; Oliver et al., 2013).

9. Determinants of speed: sprint-running performance

Several factors influence sprint performance in youth, including the motions of the body (i.e., kinematics) (Hunter, Marshall, & McNair, 2005; Meyers et al., 2016; Salo et al., 2011), the forces that produce, arrest or modify the motions of the body (i.e., kinetics) (Meylan et al., 2014; Read et al., 2016; Rumpf et al., 2015) and the measurements and proportions of the body (i.e., anthropometry) (Lloyd et al., 2016b; Meyers et al., 2016;

Table 2: Youth Physical Development (YPD): Sensitive periods for speed development (adapted from YPD model, Lloyd & Oliver 2012)

Speed Developmental Age														
Chronological Age	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Girls														
Boys														

Meyers et al., 2017b). Since the anthropometrical factors (PHV, PWV, body composition) have already been discussed in the previous sections, this section will specifically review the kinetics and kinematic associated with sprinting speed in young boys and girls across maturation.

9.1. Kinematics

Sprint speed is a product of step length and step frequency (Meyers et al., 2017b). However, the relationship between step length and frequency is not always linear (Meyers et al., 2017b). For instance, research has demonstrated a negative interaction between step length and step frequency in adult sprinters i.e., a longer step length tends to result in a lower step rate (Debaere, Jonkers, & Delecluse, 2013; Coh, Milanovic, & Kammiller, 2001; Hunter et al., 2004). The interaction between step length and step frequency is more difficult to define in youth populations due to changes in natural development (Meyers et al., 2017b). For instance, step length increases throughout childhood and adolescence as a result of changes in leg length associated with growth (Meyers et al., 2016; Schepens, Willems, & Cavagna, 1998). Read et al. (2016) reported a consistent increase in step length among boys who remained pre-PHV and boys moving from pre to post PHV (7.8 and 8%, respectively) compared to step frequency.

Previous research investigating step frequency and flight time indicated that both remain unchanged throughout childhood and in boys of advancing maturity (Meyers et al., 2015; Rumpf et al., 2015; Schepens et al., 1998). Pre-PHV boys tend to be more reliant on step frequency when sprinting (Meyers et al., 2017a), but may lack the motor coordination and strength to orientate, stabilize and apply force through their lower limbs during sprinting (Meyers et al., 2015). Therefore, there may not be any meaningful changes in step frequency and flight time in male youth across maturational levels whereas increases in step length can be observed for boys who have experienced the period of PHV.

Despite a few studies having investigated the effects of change in kinematics on sprint performance in boys, there are currently limited studies in girls. In a recent study, Talukdar and Colleagues (2022) found step length to be significantly greater in post PHV girls compared to mid-PHV girls ($p < 0.05$). It was also reported that there was no difference in contact time, flight time, step frequency between mid- and post PHV girls (Talukdar et al., 2022). In contrast, Nagahara et al. (2019) found that in young (<12.7 years) Japanese girls, step length increased by 0.08m/y but plateaued (0.01 m/y) for the older girls >12.7 years. Similarly, researchers have reported no increase in step length with minimal increase in step frequency among Slovakian girls (mean age 13.5 years) (Vanderka & Kampmiller, 2012). However, both aforementioned studies did not consider maturation and biological growth. Based on chronological age, it is difficult to conclude if growth-related factors (e.g., fat mass, PHV) during puberty played a role. Therefore, more research investigating sprinting kinematics in girls across maturation is warranted.

9.2. Kinetics

The kinetics (horizontal and vertical forces) of sprint performance have been widely investigated in adults (Brughelli, Cronin, & Chaouchi, 2011; Kuitunen, Komi, & Kyrolalinen, 2002; Nilsson & Thorsrensson, 1989; Nummela, Keranen, & Mikkelsson, 2007). Previous studies report that peak and average force increase proportionately to running speed up to 60% of maximum velocity, then remain relatively constant up to maximum velocity (Brughelli et al., 2011; Kyrolainen et al., 2001; Nilsson & Thorstensson, 1989). More specifically, during the acceleration phase, horizontal forces have been shown to significantly increase with increasing speed (Brughelli et al., 2011; Kuitunen et al., 2002; Nummela et al., 2007) and during both braking (i.e., eccentric) and propulsion (i.e., concentric) phases (Kuitunen et al., 2002; Nilsson & Thorstensson, 1989). Peak vertical forces are stable and do not differ between 70 and 100% of maximal velocity (Kuitunen et al., 2002). These studies suggest that horizontal force plays an important role in sprinting, particularly during the initial phases of acceleration to overcome inertia.

While much research has investigated how kinetics effect sprint speed in adults, there is a paucity of research investigating over-ground sprinting in youth (Meyers et al., 2015; Meyers et al., 2016; Meyers et al., 2017b; Rumpf et al., 2015). Studies utilizing non-motorized treadmills suggest that maximal force and power may be important predictors of sprint performance in boys across maturation (Meylan et al., 2014b; Rumpf et al., 2015). More specifically, vertical power has been shown to have a large impact on sprint performance in pre- and mid-PHV boys (Meylan et al., 2014b). Cross-sectional and longitudinal data collected in boys has also shown that vertical stiffness, relative maximal force, and relative leg stiffness contribute to sprint performance (Lloyd et al., 2016b; Meyers et al., 2019; Read et al., 2016).

Sprint kinetics may differ between sexes during childhood and adolescence due to changes in maturity status and growth (Rumpf et al., 2015). For instance, during puberty, higher levels of circulating androgens and growth hormones in boys (Forbes et al., 2009; Ramos Frontera, Llopart, & Feliciano, 1998; Round, Jones, Honour, & Nevill, 1999) increases force production (Rumpf et al., 2015). However, an increase in muscle mass and force-generating capacity can be limited in girls during this time due to the reduced anabolic effect of oestrogen. This difference has been shown to influence strength and power in general by decreasing connective tissue stiffness that can negatively affect sprinting kinetics in girls (Chidi-Ogbolu, & Baar, 2019; Malina et al., 2004).

There are limited studies investigating kinetics in young females (Coyler et al., 2020; Nagahara et al., 2019; Talukdar et al., 2022). Talukdar and colleagues (2022) reported greater horizontal force, maximal power and maximal velocity in post-PHV compared to mid-PHV girls ($p < 0.05$). Moreover, it was also reported that both kinetic and kinematic variables such as ground contact time, maximal power, step frequency, and step length have been shown to predict maximal sprinting speed in girls across maturation with contact time being the best predictor out of all (Talukdar et al., 2022). Nagahara et al. (2019) examined age-related differences in sprinting kinetics in (7.0-15.3 years old Japanese girls) and found an increase in the propulsive impulse of 0.024 Ns/y in the younger Japanese girls compared to -0.010 Ns/y in the older girls. However, the authors did not assess maturity status, choosing to divide the girls into two groups based on chronological age (younger <12.7 years and older >12.7 years). Even though the older girls in this study were significantly quicker than the younger girls for 25 m and 50 m sprints ($p < 0.05$), the propulsive forces during acceleration were significantly greater in younger girls compared to the older girls. This is probably due to greater growth rates in height (6.3 cm/y) in the younger girls and increases in fat mass with maturation in the older girls who might have impaired relative force production during the acceleration phase (Nagahara et al., 2019).

In addition, another recent study investigated GRFs related to sprinting speed in pre-PHV untrained boys and girls (Coyler et al., 2020). It was reported that higher velocities were attributed to greater antero-posterior GRFs across shorter ground contacts in pre-PHV boys (4.5-3.5 years before PHV) compared to (5.5-4.5 years before PHV), effect size (ES: ± 90% CI = 1.63 ± 0.69) (Colyer et al., 2020). In comparison, the increase in maximal velocities in pre-PHV girls (2.5-1.5 years before PHV) compared to (1.5-0.5 years from PHV) were not attributed to the increase in GRFs but rather due to longer ground contact time (ES: ± 90% CI = 1.00 ± 0.78). This study suggested that boys undergo a period of accelerated development in sprinting performance around 4.5-5 years before their PHV whereas rapid development in girls was observed 1.5-2 years before PHV. Furthermore, force-generating capacity in boys can help them better utilise SSC and more effectively reverse braking forces compared to their female counterparts (Colyer et al., 2020).

10. Conclusion

There is no difference in sprinting performance between boys and girls during the first decade of life, but things change during puberty. Due to the influence of oestrogen, girls tend to increase body fat mass and reduce connective tissue stiffness compared to boys, negatively impacting sprinting speed. Only a few studies investigating the effect of kinetics and kinematics on sprinting speed in youth populations have included girls. It is reported that sprinting kinetics and kinematics change across maturation and can significantly influence the maximal sprinting speed in girls. More specifically, kinetics and kinematic variables such as ground contact time, maximal power, step frequency, and step length have been shown to predict maximal sprinting speed in girls across maturation. Therefore, incorporating progressive strength and plyometric training along with frequent exposure to sprinting can improve sprinting kinetics and kinematics and increase maximal sprinting speed due to improved force-generating capacity and greater lower extremity tendon stiffness in girls approaching puberty. More research in this area is warranted, particularly studies that assess maturation. Studies that examine more specific kinematic and kinetic variables across maturation are also required.

Conflict of Interest

The authors declare no conflict of interests.

Acknowledgement

This is to acknowledge that there was no financial interest or benefit that has arisen from the direct applications of our research.

References

Balyi, I., & Hamilton, A. (2004). Long-term athlete development: Trainability in childhood and adolescence. *Olympic Coach*, *16*(1), 4-9.

Barnes, H. V. (1975). Physical growth and development during puberty. *Medical Clinics of North America*, *59*, 1305–1317.

Bell, R. D., MaCdougall, J. D., Billeter, R., & Howald, H. (1980). Muscle fiber types and morphometric analysis of skeletal muscle in six-year-old children. *Medicine and Science in Sports and Exercise*, *12*(1), 28–31.

Beunen, G., & Malina, R. M. (1988). Growth and physical performance relative to the timing of the adolescent spurt. *Exercise and Sport Sciences Reviews*, *16*(1), 503–540. https://doi.org/10.1249/00003677-198800160-00018

Bompa, T. O. (1995). *From childhood to champion athlete*. West Sedona, AZ: Veritas Publishing.

Borms, J. (1986). The child and exercise: an overview. *Journal of Sports Sciences*, *4*(1), 3—20. https://doi.org/10.1080/02640418608732093

Brown, K. A., Patel, D. R., & Darmawan, D. (2017). Participation in sports in relation to adolescent growth and development. *Translational Pediatrics*, *6*(3), 150–159. https://doi.org/10.21037/tp.2017.04.03

Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *Journal of Strength and Conditioning Research*, *25*(4), 933–939. https://doi.org/10.1519/JSC.0b013e3181c64308

Butterfield, S. A., Lehnhard, R., Lee, J., & Coladarci, T. (2004). Growth rates in running speed and vertical jumping by boys and girls ages 11-13. *Perceptual and Motor Skills*, *99*(1), 225–234. https://doi.org/10.2466/pms.99.1.225-234

Carling, C., Le Gall, F., Reilly, T., & Williams, A. M. (2009). Do anthropometric and fitness characteristics vary according to birth date distribution in elite youth academy soccer players? *Scandinavian Journal of Medicine and Science in Sports*, *19*(1), 3–9. https://doi.org/10.1111/j.1600-0838.2008.00867.x

Chidi-Ogbolu, N., & Baar, K. (2019). Effect of oestrogen on musculoskeletal performance and injury risk. *Frontiers in Physiology 9*, 1834. https://doi.org/10.3389/fphys.2018.01834

Čoh, M., Milanović, D., & Kampmiller, T. (2001). Morphologic and kinematic characteristics of elite sprinters. *Collegium Antropologicum*, *25*(2), 605–610.

Colyer, S. L., Nagahara, R., Takai, Y., & Salo, A. I. T. (2020). The effect of biological maturity status on ground reaction force production during sprinting. *Scandinavian Journal of Medicine and Science in Sports*, *30*(8), 1387-1397.

Conte, D., Favero, T., Niederhausen, M., Carpranica, L., & Tessitore, A. (2017). Effect of number of players and maturity on ball-drills training load in youth basketball. *Sports, 5*(3), 1-11. https://doi.org/10.3390/sports5010003

Cratty, B.J. (1986). *Perpetual motor development in infants and children* (3rd Ed). Englewood Cliffs, NJ: Prentice-Hall.

Cumming, S. P., Brown, D. J., Mitchell, S., Bunce, J., Hunt, D., Hedges, C., Crane, G., Gross, A., Scott, S., Franklin, E., Breakspear, D., Dennison, L., White, P., Cain, A., Eisenmann, J. C., & Malina, R. M. (2018). Premier League academy soccer players' experiences of competing in a tournament bio-banded for biological maturation. *Journal of Sports Sciences*, *36*(7), 757–765.

Debaere, S., Jonkers, I., & Delecluse, C. (2013). The contribution of step characteristics to sprint running performance in high-level male and female athletes. *Journal of Strength and Conditioning Research*, *27*(1), 1164–1224. https://doi.org/10.1519/JSC.0b013e31825183ef

Faigenbaum, A. D., Zaichkowsky, L. D., Wescott, W. L., Micheli, L.J., & Fehlandt, A. F. (1993). The effect of a twice-a-week strength training program on children. *Pediatric Exercise Science, 5*, 339-346.

Flanagan, E. P., & Comyns, T. (2008). The use of contact time and the reactive index to optimize fast stretch shortening cycle training. *Strength and Conditioning Journal, 30*(5), 32-38. doi: 10.1519/SSC.0b013e318187e25b

Ford, P., De Ste Croix, M., Lloyd, R., Meyers, R., Moosavi, M., Oliver, J., Till, K., & Williams, C. (2011). The long-term athlete development model: Physiological evidence and application. *Journal of Sports Sciences*, *29*(4), 389–402. https://doi.org/10.1080/02640414.2010.536849

Harrison, C. B. (2013). *Optimisation of aerobic fitness development in young athletes* (Doctoral dissertation, Auckland University of Technology). Retrieved from https://aut.researchgateway.ac.nz/bitstream/handle/10292/7877/HarrisonC.pdf?sequence=3&isAllowed=y.

Hicks, K. M., Onambele-Pearson, G. L., Winwood, K., & Morse, C. I. (2013). Gender differences in fascicular lengthening during eccentric contractions: The role of the patella tendon stiffness. *Acta Physiologica*, *209*(3), 235–244. https://doi.org/10.1111/apha.12159

Higgs, C., Balyi, I., Way, R., Cardinal, C., Norris, S., & Bluechardt, M. (2008). Developing physical literacy: A guide for parents of children ages 0 to 12. *Vancouver, BC: Canadian Sports Centres*. https://doi.org/10.3868/s110-003-014-0039-x

Hoffman, A.D. (1997). Adolescent growth and development. In A.D. Hoffman & D. E. Greydanus (Eds.), *Adolescent Medicine* (pp.11-22). Stanford, CT: Appleton & Lange.https://doi.org/10.1111/apha.12159

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, *21*(1), 31–43. https://doi.org/10.1123/jab.21.1.31

Johnson, A., Doherty, P. J., & Freemont, A. (2009). Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: Prospective study. *British Medical Journal*, *338*(b490), 1-4. https://doi.org/10.1136/bmj.b490

Khamis, H. J., & Roche, A. F. (1994). Predicting adult stature without using skeletal age: The Khamis-Roche method. *Pediatrics*, *95*(3), 504–507.

Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. *Journal of Biomechanics*, *33*(10), 1197–1206. https://doi.org/10.1016/S0021-9290(00)00064-6

Kreipe, R. E. (1994). Normal somatic adolescent growth and development. In McAnarney E. R., Kreipe, R. E, Orr, D. P (Eds), *Textbook of adolescent medicine,* (pp. 44-67). Philadelphia: WB Saunders.

Kubo, K., Kanehisa, H., Kawakami, Y., & Fukanaga, T. (2001). Growth changes in the elastic properties of human tendon structures. *International Journal of Sports Medicine, 22*(2), 138-43. https://doi.org/10.1055/s-2001-11337

Kuitunen, S., Komi, P. V., & Kyröläinen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise*, *34*(1), 166–173. https://doi.org/10.1097/00005768-200201000-00025

Kyrolainen, H., Belli, A., & Komi, P. V. (2001). Biomechanical factors affecting running economy. *Medicine and Science in Sports and Exercise, 33*(8), 1330-7. https://doi.org/10.1097/00005768-200108000-00014

Laffaye, G., Choukou, M. A., Benguigui, N., & Padulo, J. (2016). Age- and gender-related development of stretch-shortening cycle during a sub-maximal hopping task. *Biology of Sport*, *33*(1), 29–35. https://doi.org/10.5604/20831862.1180169

Lambertz, D., Mora, I., Grosset, J. F., & Pérot, C. (2003). Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *Journal of Applied Physiology*, *95*(1), 64–72. https://doi.org/10.1152/japplphysiol.00885.2002

Lazaridis, S., Bassa, E., Patikas, D., Giakas, G., Gollhofer, A., & Kotzamanidis, C. (2010). Neuromuscular differences between prepubescents boys and adult men during drop jump. *European Journal of Applied Physiology*, *110*(1), 67–74. https://doi.org/10.1007/s00421-010-1452-4

Lazaridis, S., Bassa, E., Patikas, D., Giakas, G., Gollhofer, A., & Kotzamanidis, C. (2010). Neuromuscular differences between prepubescents boys and adult men during drop jump. *European Journal of Applied Physiology*, *110*(1), 67–74. https://doi.org/10.1007/s00421-010-1452-4

Lexell, J., Sjöström, M., Nordlund, A. -S, & Taylor, C. C. (1992). Growth and development of human muscle: A quantitative morphological study of whole vastus lateralis from childhood to adult age. *Muscle & Nerve*, *15*(3), 404–409. https://doi.org/10.1002/mus.880150323

Lloyd, R. S., & Oliver, J. L. (2012). The youth physical development model: A new approach to long-term athletic development. *Strength and Conditioning Journal*, *34*(3), 61–72. https://doi.org/10.1519/SSC.0b013e31825760ea

Lloyd, R. S., Meyers, R. W., Hughes, M. G., Cronin, J. B., & Oliver, J. L. (2016b). The relationship between vertical and horizontal stiffness and maximal running speed in 11–15 year old boys. *Journal of Strength and Conditioning Research*, *30*, S99.

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Howard, R., De Ste Croix, M. B. A., Williams, C. A., Best, T. M., Alvar, B. A., Micheli, L. J., Thomas, D. P., Hatfield, D. L., Cronin, J. B., & Myer, G. D. (2015). Long-term athletic development- Part 1: A pathway for all youth. *Journal of Strength and Conditioning Research*, *29*(5), 1439–1450. https://doi.org/10.1519/JSC.0000000000000756

Lloyd, R. S., Oliver, J. L., Hughes, M. G., & Williams, C. A. (2009). Reliability and validity of field-based measures of leg stiffness and reactive index in youths. *Journal of Sports Science, 27*(14), 1565-73. https://doi.org/10.1080/02640410903311572

Lloyd, R. S., Radnor, J. M., Croix, M. B. D. S., Cronin, J. B., & Oliver, J. L. (2016a). Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre-and post-peak height velocity. *Journal of Strength & Conditioning Research*, *30*(5), 1239-1247.

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). *Growth, maturation, and physical activity*. Human kinetics.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). The role of rate of force development on vertical jump performance. *Journal of Strength and Conditioning Research*, *25*(2), 379–385. https://doi.org/10.1519/JSC.0b013e3181be305c

Meyers, R. W., Moeskops, S., Oliver, J. L., Hughes, M. G., Cronin, J. B., & Lloyd, R. S. (2019). Lower-Limb Stiffness and Maximal Sprint Speed in 11-16-Year-Old Boys. *Journal of Strength and Conditioning Research*, *33*(7), 1987–1995. https://doi.org/10.1519/JSC.0000000000002383

Meyers, R. W., Oliver, J. L., Hughes, M. G., Cronin, J. B., & Lloyd, R. S. (2015). Maximal sprint speed in boys of increasing maturity. *Pediatric Exercise Science*, *27*(1), 85–94. https://doi.org/10.1123/pes.2013-0096

Meyers, R. W., Oliver, J. L., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2017a). Influence of age, maturity and body size on the spatiotemporal determinants of maximal sprint speed in boys. *Journal of Strength and Conditioning Research, 31*(4), 1009-1016.

Meyers, R. W., Oliver, J. L., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2017b). New insights into the development of maximal sprint speed in male youth. *Strength and Conditioning Journal*, *39*(2), 2–10.

Meyers, R., Oliver, J., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2016). The influence of maturation on sprint performance in boys over a 21-month period. *Medicine of Science in Sport and Exercise*, *48*(12), 2555–2562.

Meylan, C. M. P., Cronin, J., Oliver, J. L., Hopkins, W. G., & Pinder, S. (2014b). Contribution of vertical strength and power to sprint performance in young male athletes. *International Journal of Sports Medicine*, *35*(9), 749-754.

Mirwald, R. L., Baxter-Jones, A. D. G., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine and Science in Sports and Exercise*, *34*(4), 689–694.

Morse, C. I., Tolfrey, K., Thom, J. M., Vassilopoulos, V., Maganaris, C. N., & Narici, M. V. (2008). Gastrocnemius muscle specific force in boys and men. *Journal of Applied Physiology*, *104*(2), 469–474.

Nagahara, R., Haramura, M., Takai, Y., Oliver, J. L., Wichitaksorn, N., Sommerfield, L. M., & Cronin, J. B. (2019). Age-related differences in kinematics and kinetics of sprinting in young female. *Scandinavian Journal of Medicine and Science in Sports*, *29*, 800–807. https://doi.org/10.1111/sms.13397

Needleman, R. D. (2000). Growth and development, In R.E. Behrman, R.M. Kliegman & H.B. Jenson (Eds.), *Nelson Textbook of Pediatrics* (16th Ed). Philadelphia: W B Saunders.

Nicol, C., Avela, J., & Komi, P. (2006). The stretch shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Medicine, 36,* 977-99.

Nilsson, J., & Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica Scandinavica*, *136*(2), 217–227.

Nummela, A., Keränen, T., & Mikkelsson, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine*, *28*(08), 655–661.

O'Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2010a). In vivo measurements of muscle specific tension in adults and children. *Experimental Physiology*, *95*(1), 202–210.

O'Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. A., & Maganaris, C. N. (2010b). Muscle–tendon structure and dimensions in adults and children. *Journal of Anatomy*, *216*(5), 631–642.

Oliver, J. L., Lloyd, R. S., & Rumpf, M. C. (2013). Developing speed throughout childhood and adolescence: The role of growth, maturation and training. *Strength and Conditioning Journal*, *35*(3), 42–48.

Onambélé, G. N. L., Burgess, K., & Pearson, S. J. (2007). Gender-specific in vivo measurement of the structural and mechanical properties of the human patellar tendon. *Journal of Orthopaedic Research*, *25*(12), 1635–1642.

Pápai, J., Tróznai, Z., Szabó, T., & Szabó, A. (2012). Fat pattern of athlete and non-athlete girls during puberty. *Anthropological Review*, *75*(1), 41–50.

Patel, D. R., Pratt, H. D., & Greydanus, D. E. (1998). Adolescent growth, development, and psychosocial aspects of sports participation: an overview. *Adolescent Medicine*, *9*(3), 425–440.

Philippaerts, R. M., Vaeyens, R., Janssens, M., Van Renterghem, B., Matthys, D., Craen, R., Bourgois, J., Vrijens, J., Beunen, G., & Malina, R. M. (2006). The relationship between peak height velocity and physical performance in youth soccer players. *Journal of Sports Sciences*, *24*(3), 221–230.

Radnor, J. M., Oliver, J. L., Waugh, C. M., Myer, G. D., Moore, I. S., & Lloyd, R. S. (2018). The influence of growth and maturation on stretch-shortening cycle function in youth. *Sports Medicine*, *48*(1), 57–71.

Ramos, E., Frontera, W. R., Llopart, A., & Feliciano, D. (1998). Muscle strength and hormonal levels in adolescents: gender related differences. *International Journal of Sports Medicine*, *19*(08), 526–531.

Rasmussen, A. R., Wohlfahrt-Veje, C., De Renzy-Martin, K. T., Hagen, C. P., Tinggaard, J., Mouritsen, A., Mieritz, M. G., & Main, K. M. (2015). Validity of self-assessment of pubertal maturation. *Pediatrics*, *135*(1), 86–93.

Read, P., Meyers, R.W., Lloyd, R.S., Hughes, M.G., Cronin, J.B., & Oliver, J.L. (2016, July). *The impact of peak height velocity on changes in sprint kinetics and kinematics in boys*. In: National Strength and Conditioning Association (NSCA) 39th National Conference, New Orleans, LA.

Roemmich, J. N., & Rogol, A. D. (1995). Physiology of growth and development: its relationship to performance in the young athlete. *Clinics in Sports Medicine*, *14*(3), 483-502.

Round, J. M., Jones, D. A., Honour, J. W., & Nevill, A. M. (1999). Hormonal factors in the development of differences in strength between boys and girls during adolescence: A longitudinal study. *Annals of Human Biology*, *26*(1), 46–62. https://doi.org/10.1080/030144699282976

Rumpf, M. C., Cronin, J. B., Oliver, J., & Hughes, M. (2015). Kinematics and kinetics of maximum running speed in youth across maturity. *Pediatric Exercise Science*, *27*(2), 277–284. https://doi.org/10.1123/pes.2014-0064

Rumpf, M. C., Cronin, J. B., Pinder, S. D., Oliver, J., & Hughes, M. (2012). Effect of different training methods on running sprint times in male youth. *Pediatric Exercise Science*, *24*(2), 170–186. https://doi.org/10.1123/pes.24.2.170

Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite sprinting: are athletes individually step-frequency or step-length reliant? *Medicine & Science in Sports & Exercise*, *43*(6), 1055–1062.

Schepens, B., Willems, P. A., & Cavagna, G. A. (1998). The mechanics of running in children. *Journal of Physiology*, *509*, 927–940. https://doi.org/10.1111/j.1469-7793.1998.927bm.x

Talukdar, K., Harrison, C., McGuigan, M., & Borotkanics., R. (2021). Kinetics and kinematics of sprinting in mid-and-post peak height velocity female athletes. *International Journal of Strength and Conditioning*, *1*(1). https://doi.org/10.47206/ijsc.v1i1.65

Tanner, J. M., & Whitehouse, R. H. (1976). Clinical longitudinal standards for height, weight, height velocity, weight velocity, and stages of puberty. *Archives of Disease in Childhood*, *51*(3), 170–179.

Tillin, N. A., Pain, M. T. G., & Folland, J. (2013). Explosive force production during isometric squats correlates with athletic performance in rugby union players. *Journal of Sports Sciences*, *31*(1), 66–76.

Turner, A., & Jeffreys, I. (2010). The stretch-shortening cycle: Proposed mechanisms and methods for enhancement. *Strength and Conditioning Journal, 32*(4), 87-99. https://doi.org/10.1519/SSC.0b013e3181e928f9

Underwood, L.E., & Van Wyk, J.J. (1985). Normal and aberrant growth. In *Williams Textbook of Endocrinology*, 7th edit, Eds: Wilson, J.D. and Foster, D.W. Philadelphia: W.B. Saunders.

Vanderka, M., & Kampmiller, T. (2012). Age-related changes of running stride kinematics in 7 to 18 year old youth. *Exercise and Quality of Life*, *4*(1), 11-24.

Venturelli, M., Bishop, D., & Pettene, L. (2008). Sprint training in preadolescent soccer players. *International Journal of Sports Physiology and Performance*, *3*(4), 558–562.

Viru, A., Loko, J., Harro, M., Volver, A., Laaneots, L., & Viru, M. (1999). Critical periods in the development of performance capacity during childhood and adolescence. *European Journal of Physical Education*, *4*(1), 75–119.

Whithall, J. (2003). Development of locomotor co-ordination and control in children. In G.J.P. Savelsberg, K., Davids, & J. Van der Kamp (Eds.), *In Development of movement coordination in children: Applications in the field of ergonomics, health sciences and sport* (pp. 251-270). London: Routledge.