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Title:

Lower limb stiffness and maximal sprint speed in 11-16-year-old boys

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Stiffness and sprint speed in boys

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No funding has been received for this work.

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Lower-limb stiffness and maximal sprint speed in 11-16-year-old boys

ABSTRACT

The purpose of the study was to examine the relationship between vertical stiffness, leg stiffness and maximal sprint speed in a large cohort of 11-16-year-old boys. Three-hundred and thirty-six boys undertook a 30 m sprint test using a floor-level optical measurement system, positioned in the final 15 m section. Measures of speed, step length, step frequency, contact time and flight time were directly measured whilst force, displacement, vertical stiffness and leg stiffness, were modeled from contact and flight times, from the two fastest consecutive steps for each participant over two trials. All force, displacement and stiffness variables were significantly correlated with maximal sprint speed ($p \leq 0.05$). Relative vertical stiffness had a very large ($r > 0.7$) relationship with sprint speed, while vertical center of mass displacement, absolute vertical stiffness, relative peak force, and maximal leg spring displacement had large ($r > 0.5$) relationships. Relative vertical stiffness and relative peak force did not significantly change with advancing age ($p > 0.05$), but together with maximal leg spring displacement accounted for 96% of the variance in maximal speed. It appears that relative vertical stiffness and relative peak force are important determinants of sprint speed in boys aged 11-16 years, but are qualities that may need to be trained due to no apparent increases from natural development. Practitioners may wish to utilize training modalities such as plyometrics and resistance training to enable adaptation to these qualities due to their importance as predictors of speed in youth.

KEY WORDS

Youth; Sprinting; Maturity; Vertical Stiffness; Leg Stiffness; Force

INTRODUCTION

The natural development of speed throughout childhood and adolescence is thought to follow a non-linear process (8), with fluctuating improvements in sprint performance occurring in preadolescent and adolescent periods (24). The physiological factors that influence the development of speed in childhood have been explored from both an age- and maturity-related perspective (8,11). Prior to the onset of puberty, boys show accelerated improvements in sprint performance, which are primarily attributed to neurological adaptations, such as improved motor recruitment and coordination patterns (8). Peak gains in sprint speed performance are reported to coincide with circa- and post-peak height velocity (PHV), and circa- Peak Weight Velocity (PWV) around the time of the adolescent growth spurt (11,17). Owing to the increases in limb-length, muscle mass, and hormonal levels during this stage of development, which are associated with improved muscular strength and power output (24), a maturational influence of speed development appears likely (5). Unfortunately, while data on the developmental trends in maximal running speed in boys exist, there is a paucity of research that has examined the determinants of maximal running speed in youth.

Stiffness is thought to be a determinant of sprint speed in youth (3,6,20) and adults (1,2). The spring-mass model is often used to calculate vertical and leg stiffness measures, with the lower limb acting as the “spring” and the center of mass serving as the “mass” (4). Vertical stiffness is used to describe the vertical motion of the center of mass during ground contact at the middle of the stance phase, and is defined as the ratio of the maximal force to the vertical displacement of the center of mass as it reaches its lowest point (15). However, during running the leg contacts the ground at an angle when the center of mass is not directly over the foot (9). In order to quantify this measure of stiffness when horizontal motion is involved, leg stiffness has been calculated using the force-time curve sine method based on flight times, contact times, leg length, body mass and running velocity (15). Having greater vertical stiffness is thought to enhance running performance by aiding the lower body's ability to resist large displacements of the center of mass during the landing (eccentric) phase, while also increasing the rate of force development during the push-off (concentric) phase (2). Previous research has investigated the relationship between vertical stiffness and sprint running performance in a small sample (n = 11) of 16 year old males, and found that vertical stiffness measured during hopping was significantly correlated (r = 0.68) with maximal velocity but not with acceleration (3). Furthermore, significant positive relationships (r = 0.56) have been reported between vertical stiffness and running speed in a small mixed gender sample (n= 10) of 5 – 10 year old children (6), however the participants were only instructed to run "fast" or "slow" during the assessment and therefore maximal velocity may not have been achieved. Though there is supporting evidence that leg stiffness is a key determinant of maximal sprint velocity in adult populations (1,2) but not in youth (6), the small sample sizes and methodological limitations of studies in the current body of literature may mask the true contribution of leg stiffness to maximal running speed in youth.

While it is known that sprint speed is influenced by age and maturation (11), literature that specifically focuses on the natural development of stiffness characteristics throughout childhood and adolescence remains scarce. Rumpf and colleagues (20) showed that both vertical and leg stiffness contributed to maximal sprint velocity in a sample of male athletes of contrasting maturity status. However, the reported maximal running velocities, which were collected on a non-motorized treadmill, were approximately 50 percent slower than data reported recently in a similar large cohort of boys during overground sprinting (11). Thus, it remains to be determined how vertical and leg stiffness contribute to overground sprint performance in male youth. Therefore, the aim of the study was to examine the relationship between force, vertical stiffness and leg stiffness with maximal sprint speed in a large cohort of 11-16-year-old boys.

METHODS

Experimental approach to the problem

A large sample of school-aged boys were grouped according to age and subsequently tested for maximal running speed using an optical measurement system (Optojump, Micrograte, Italy). Sprint performance variables directly measured during sprint trials included running speed, step length, step frequency, contact time and flight time. Additional variables were modeled from the spatiotemporal data including maximal ground reaction force (F_{max}), center of mass displacement (Δy_c), leg spring compression (ΔL), vertical stiffness (K_{vert}) and leg stiffness (K_{leg}).

Subjects

Three hundred and seventy-five boys aged 11–16 years agreed to participate in the study. Descriptive details (means and standard deviations) for all anthropometric variables per chronological age group are provided in *Table 1*. Maturation was determined using a sex-specific maturity offset prediction equation (13) derived from anthropometric variables, including body mass, standing height, and sitting height. Subsequently, leg length was derived from the difference between standing and sitting heights. Participants reported no injuries at the time of testing and were all regularly participating in bi-weekly physical education classes, however, none of the participants were engaged in formal strength and conditioning programs. Physical education classes followed national curriculum guidelines and were 60 minutes in duration. Participants were instructed to wear school-issued physical education clothing, refrain from physical activity 24 hours prior to testing, and avoid food consumption one hour prior to testing. All testing sessions occurred during scheduled physical education classes and within the same indoor facility, with the equipment orientated in the same positions. All participants were provided the opportunity to familiarize themselves with the test protocols prior to commencing data collection. The institutional ethical committee, in accordance with the declaration of Helsinki, granted ethical approval, and subsequently parental/guardian consent as well as child assent were obtained before testing. The study conforms to the Code of Ethics of the World Medical Association (approved by the Ethics Advisory Board of Swansea University).

Table 1 near here

Procedures

Sprint test

The sprint test followed the same procedures as those previously utilized in male youth (10–12), requiring participants to sprint maximally along a 30 m track. Participants began the sprint in a split stance on a line 0.5 m behind the start line and were instructed to sprint with maximal effort down the testing track. A finish line was placed at 35 m in order to encourage participants to sprint maximally throughout the 15-30 m section of the track where the data were collected. Initiation of the test protocol was consistent throughout; “ready” informed participants to adopt the split stance ready position, while “go” was the verbal stimulus to start sprinting. All participants completed two trials of the protocol and verbal encouragement was provided throughout each trial. A minimum of four minutes passive rest was given between trials to ensure sufficient recovery.

Sprint test variables

The assessment of vertical and leg stiffness measures were calculated from spatiotemporal sprint characteristics via an optical measurement system (Optojump, Mircrogate, Italy), positioned at floor level in the 15-30 m section of the track. Data for the sprint characteristics were instantaneously collected at a sampling rate of 1000 Hz using a Windows XP laptop via specialist software (Optojump, Microgate, Italy), and subsequently exported to Microsoft Excel for data processing. Data obtained from the optical measurement system were used to automatically calculate the following variables:

- *Speed:* Calculated by dividing the distance (in meters) between alternate foot contacts (step length) and the time taken (in seconds) between these contacts (flight time + contact time), with units expressed as distance per unit of time ($m.s^{-1}$).
- *Step length:* The distance (in meters) between the foot tip of alternate foot contacts (i.e., the distance between left and right foot contacts).
- *Step frequency:* The rate (in Hertz) of lower limb movements as defined by the number of steps taken per second.
- *Contact time:* The amount of time (in seconds) the participant spends during the stance phase of the sprint, where the foot is in contact with the floor.
- *Flight time:* The amount of time (in seconds) between alternate foot contacts, where the participant is not in contact with the floor.

Using the methods previously identified by Morin and colleagues (15,16), force, displacement as well as vertical and leg stiffness components were calculated from contact and flight times from the two fastest consecutive strides for each participant over two trials. The variables were processed with equations 1-5 and defined as the following:

- *Peak ground reaction force* (*F_{max}*)*:* The maximal ground reaction force during the contact phase (kN) where *m* is the subjects body mass (in kg), *g* is gravity, t_C is contact time (in s) and flight time is t_f (in s).

$$F_{max} = m \, . \, g \, . \frac{\pi}{2} \, . \, (\frac{t_f}{t_c} + 1) \qquad (1)$$

- *Peak vertical center of mass displacement* (Δy_c): The vertical displacement of the center of mass to its lowest point during contact.

$$\Delta y_c = -\frac{F_{max}}{m} \cdot \frac{{t_c}^2}{\pi^2} + g \cdot \frac{{t_c}^2}{8} \qquad (2)$$

- *Maximal leg spring displacement* (ΔL): The difference between leg length when standing and leg length when the center of mass is at its lowest point, where *L* is leg length.

$$\Delta L = L - \sqrt{L^2 - \left(\frac{v_c . t_c}{2}\right)^2} + \Delta y_c \qquad (3)$$

- *Absolute vertical stiffness* (*K_{vert}*)*:* The ratio (kN·m^{-1}) of the modeled peak ground reaction force (F_{max}) over the modeled vertical displacement of the center of mass (Δy_c).

$$K_{vert} = F_{max} \cdot \Delta y_c^{\ -1} \qquad (4)$$

- *Absolute leg stiffness* (*K_{leg}*)*:* The ratio (kN·m^{-1}) of the modeled peak ground reaction force (F_{max}) over the modeled leg length variation (ΔL) during ground contact

$$K_{leg} = F_{max} \cdot \Delta L^{-1} \qquad (5)$$

This modelling approach was taken owing to its non-invasive nature as well as the low level of mean error bias in all variables (F_{max} = 3.24%; Δy_c = 2.34%; ΔL = 0.67%; K_{vert} = 2.30%; K_{leg} = 2.54%) and significant regressions between modelled stiffness characteristics ($K_{vert} = p < .01$, $r^2 = .98$; $K_{leg} = p < .01$, $r^2 = .89$) and force-plate measures during overground running (15). Relative vertical and leg stiffness measures were quantified by normalizing data to both leg length and body mass (kg) (9).

Sprint test data processing

Data for all steps completed within the 15-30 m data collection zone were instantaneously recorded for participants over their two sprint trials. Subsequently all data corresponding to the fastest two consecutive steps from either trial were extracted and averaged for analysis. If a participant was deemed to have obtained their fastest steps from the last or first foot contact recorded in the 15–30 m data collection zone, then their data were excluded from the analysis. This exclusion was enforced to remove those participants who had already achieved maximal speed before the data collection zone and also those who were still accelerating at the end of the data collection zone (n = 22), thereby resulting in data from only those participants achieving maximal speed between 15–30 m being included for subsequent analysis (n = 375). The approach to data processing adopted in this study has been previously shown to be reliable for the assessment of the spatiotemporal characteristics (intraclass correlations: 0.66 – 0.86; coefficient of variation: 3.8 – 5.0%) in boys (12). Due to the novel modeling approaches in this study, the reliability of all force, displacement and stiffness variables, as well as the estimations of contact and flight length, was assessed with a cohort of 49 boys (age: 14.1 ± 0.7 years, range: 12.9 – 15.7 years) over three trials during a two week period alongside the main study. Data revealed moderate-very large levels of reliability related to all modeled variables for intraclass correlation (F_{max} = 0.96; relative F_{max}

= 0.66; Δy_c = 0.77; ΔL = 0.99; K_{vert} = 0.92; K_{leg} = 0.94; relative K_{vert} = 0.85; relative K_{leg} = 0.93) and coefficient of variation values (F_{max} = 4.99%; relative F_{max} = 4.99%; Δy_c = 7.61%; ΔL = 2.29%; K_{vert} = 7.53%; K_{leg} = 6.33%; relative K_{vert} = 7.53%; relative K_{leg} = 6.33%).

Statistical analyses

Descriptive statistics (means ± standard deviations) were calculated for all force, displacement, stiffness and spatiotemporal characteristics for each chronological age group. The assumption of normality was assessed via the Kolmogorov-Smirnov test. A one-way analysis of variance (ANOVA) was conducted to determine differences between the age groups. Homogeneity of variance was assessed via Levene’s statistic and where violated, Welch’s adjustment was used to correct the F-ratio. The location of significant differences between groups was identified by either using Bonferroni or Games-Howell post-hoc analysis, where equal variances were and were not assumed, respectively. Pearson correlation coefficients were used to determine the strength of relationships between all sprint test variables and maximal running speed, with the strength of relationships classified as either; almost perfect (r = >0.9), very large (r = 0.7- 0.9), large (r = 0.5 – 0.7), moderate (r = 0.3-0.5), small (r = 0.1-0.3) or trivial (r = <0.1) (7). Stepwise multiple regression analyses were employed to establish the contribution of stiffness-related determinants of speed across the entire sample, and separately for those participants deemed to be Pre- (< -0.5 years) and Post-PHV (> 0.5 years) according to the maturity offset. This approach facilitated the examination of the role of maturation whilst accounting for the measurement error of the prediction equation for maturity offset (13). The assumption of independent errors during the multiple regression analyses was tested via a series of Durbin-Watson tests, whilst multi-collinearity was tested using variance inflation factor (VIF) and tolerance diagnostics. All statistical analyses were conducted in SPSS Statistics v. 20 for Mac, with statistical significance set at an alpha level of $p < 0.05$.

RESULTS

The results in *Table 2* indicate no significant differences ($p > 0.05$) in maximal speed between the under 12 years (U12) and under 13 years (U13) age groups. However, the under 14 years (U14) and under 15 years (U15) groups were significantly faster ($p < 0.05$) than the U12 boys, while under 16 years (U16) were significantly faster ($p < 0.05$) than the boys in all of the younger age groups. Similarly, step length was significantly longer ($p < 0.05$) in U14 and U15 compared to the U12 and U13 group, while U16s had significantly longer steps ($p < 0.05$) than all other groups. Step frequency and flight time did not differ significantly across all groups ($p > 0.05$), whilst the only significant differences for contact time were between the U12 and U15 groups ($p < 0.05$).

Table 2 about here

The results in *Table 3* shows there were no significant differences ($p > 0.05$) in relative F_{max} for boys across any of the age groups. While no significant differences ($p > 0.05$) in absolute K_{leg} were observed, absolute K_{vert} significantly increased with age ($p < 0.05$). No significant between-group differences in relative K_{vert} or vertical displacement (Δy_c) characteristics were observed across the age groups. However, there were significant decreases in relative K_{leg} between the U12s and the U15s, while the U16s had significantly lower relative K_{leg} than the U12-U14 age groups. Furthermore, both the U14 and U15 groups had significantly greater ($p < 0.05$) leg spring displacement (ΔL) than the U12s and U13s. In addition, the U16s displayed significantly greater ($p < 0.05$) ΔL than all other age groups.

Table 3 near here

All force, displacement and stiffness related variables had significant relationships ($p < 0.05$) with speed, however, the magnitudes of these relationships varied (*Table 4*). Speed had a very large positive relationship with relative K_{vert} ($r^2 = 0.53$; $p < 0.05$). Absolute K_{vert}, Δy_c, relative F_{max}, and ΔL were all moderately related to speed ($r^2 = 0.16$ – 0.24; $p < 0.05$), while all of the other variables had small relationships ($r^2 = 0.03$; $p < 0.05$). Furthermore, a moderate relationship was found between leg length and ΔL ($r = 0.45$; $p < 0.05$), whilst contact time was found to have a very large negative relationship with both ΔL and relative F_{max} ($r = -0.78$; $p < 0.05$ and $r = -0.77$; $p < 0.05$, respectively). An almost perfect negative relationship existed between Δy_c and step frequency ($r = -0.96$; $p < 0.05$), whilst relative F_{max} had a very large relationship with step length ($r = 0.79$; $p < 0.05$, respectively).

Table 4 near here

Multiple stepwise regression analysis across the whole sample showed that variation in maximal running speed was best explained by relative K_{vert}, ΔL and relative F_{max}, which accounted for 96% of the total variance. The addition of absolute F_{max}, absolute K_{leg} and absolute K_{vert} marginally improved the predictive ability of the regression equation to 97%. When examined separately for Pre- and Post-PHV sub-groups, relative K_{vert}, ΔL and relative F_{max} remained the strongest predictors of speed, accounting for 96% and 98% of the total explained variance, respectively.

Table 5 near here

DISCUSSION

The aim of this study was to examine the natural development of stiffness properties during maximal sprint speed in a large sample of young boys of contrasting age. It was observed that relative vertical stiffness, relative peak force and maximal leg spring displacement explained 96% of the variance of sprint speed. Despite significant increases in sprint speed with age, relative force and relative vertical stiffness did not significantly change; while maximal leg spring displacement did increase with age.

In the current study, maximal sprint speeds were similar in the youngest two age groups and increased significantly in the U14-U16's. Based on descriptive data, this would suggest that speed was stable in the pre-PHV age groups, but increased around and beyond the period of PHV (11,17). The results also indicated that step frequency was constant across groups, whilst step length increased across age groups. This may indicate that changes in speed were proportional to changes in step length (22); however, it has been suggested that when boys are divided into maturation groups that step frequency decreases and contact time increases across pre-pubertal groups of advancing maturity, and only once these decrements in performance stabilize around the period of PHV are significant increases in sprint speed observed (11). A similar pattern was observed in this study, although the age-group rather than maturation-group analysis appears to have influenced the results of the between-group significances observed. While it may therefore be concluded that sprint speed is influenced by age and maturation (11,17,21), literature that specifically focuses on the natural development of stiffness characteristics throughout childhood and adolescence is limited.

The results from the between-group analysis in the current study revealed that increases in speed coincided with increases in absolute vertical stiffness across all age groups. Similar results have previously been found across boys of a similar age during a pre-, mid- and post-PHV analysis (20). Significant increases in absolute peak force were observed from U13 with advancing age. Increases in absolute vertical force across boys of a similar age and maturation status have been previously reported and were largely attributed to increases in body mass, however increases in relative vertical force were only observed for those post-PHV (21). In the current study, both relative vertical stiffness and relative peak force measures remain unchanged across all age groups. Collectively, these results may suggest that absolute increases in peak forces can be expected as a result of natural increases in muscle cross-sectional area during growth (23). Furthermore, with no observed differences in relative force production in the current study, a negative influence of increased body mass during sprint performance cannot be ruled out (10). On this basis, neurological sources of increased force production such as motor unit activation, coordination, recruitment and firing (18) may be considered important for sprint performance in boys. Furthermore, it is also likely that the significant increases in body mass associated with the older age groups would require a greater level of overall stiffness to maintain the magnitude of center of mass displacement during ground contact (9).

Analysis revealed that absolute leg stiffness remained constant in boys with advancing age, yet relative leg stiffness decreased significantly in the U15s and U16s. Increases in mass have been shown to be associated with increases in relative leg stiffness in children aged 5-10 years (6), and therefore it might be expected that the increases in mass seen across age groups may continue to exert this influence. This proposition was not supported in the current study, however the comparative values (6) may not have been derived from maximal sprinting, resulting in a relative stiffness values that were ~67% lower than the current study. The results of the present study ascertain that the concomitant significant increases in absolute maximal force and leg spring displacement resulted in absolute leg stiffness remaining unchanged with age. Furthermore, the decrements in relative leg stiffness experienced by the more mature boys, likely reflect changes in body size that occur around and after the pubertal growth spurt. Specifically, significant increases in leg length may have resulted in reduced leg stiffness due to greater compression of the leg as a ratio of leg length. Conversely, previous research has found leg stiffness increased significantly with maturation during sprinting on a non-motorized treadmill (20). However, it should be noted that making comparisons between these studies is problematic, given the different methodologies adopted to measure speed and stiffness properties. Data from a study of boys of similar age and maturity during non-motorized treadmill sprinting (20) reported maximal velocities between 46-58% slower, and relative leg stiffness values 62-80% lower than those of the current study. These differences may be in part be explained by the influence of treadmill inertia, meaning those younger participants with a lower body mass would be placed at a disadvantage in overcoming the initial treadmill resistance, consequently altering their sprint kinematics and kinetics (19). These observations further reinforce the importance of assessing spatiotemporal and stiffness characteristics during overground running in order to elicit true maximal values for each variable of interest.

The results of the study revealed that both absolute and relative leg stiffness had a small relationship with speed and were not predictors of maximal sprinting velocity, which differs from previous literature (20). Conversely, relative vertical stiffness had a very large relationship with maximal sprint speed ($r = 0.73$) and was the most important predictor of speed in the regression analyses, explaining over 50% of the variance. It is thought that those who possess greater stiffness have a more rapid release of elastic energy during fast SSC activities such as sprinting, where angular joint displacement is minimal (1). Furthermore, the results of this study highlighted that vertical displacement had an almost perfect negative relationship with step frequency (r = -0.96), emphasizing the importance of limited displacement of the center of mass upon step frequency in male youth. Researchers have reported increases in vertical stiffness with increasing running velocity in adult populations (1,2,15), as well as in children (6) and adolescent populations (3). Chelly and Denis (3) previously identified muscular power as a key determinant of both acceleration and maximal speed, but found that only vertical stiffness was correlated with maximal sprinting velocity in 16-year-old boys. The findings of the current study are the first to demonstrate that relative vertical stiffness has a major role in determining sprint speed. Interestingly, although the present study revealed that relative vertical stiffness is a quality that does not significantly change between ages 11 and 16 years as a result of natural development, this is contrary to the known increases in muscle-tendon stiffness with advancing age (25). If age-related increases in muscle-tendon stiffness do contribute to increases in speed, this must be due to an increase in step length, as there are only minimal changes in step frequency with advancing age; however further research is needed to confirm this.

Studies in adults (1,14,26,27), and more recently in youth (3,21), have shown that force production has a major role in determining sprint speed. In the current study, relative measures of peak force were related (r = 0.42) to sprint speed and were a better predictor of maximal sprint velocity than absolute peak force. While absolute peak force appears to be influenced by age, measures of relative peak force are not. Furthermore, relative force production had a very large positive relationship with step length (r = 0.79), and a very large negative relationship (r = -0.77) with contact time, highlighting the importance of force production over a short period of ground contact to achieve greater distance between foot contacts during sprinting (27). Therefore, our results support the existing evidence regarding the importance of relative force for the propulsive component of developing maximal sprint velocity in youth, whilst also highlighting that relative forces do not improve as part of natural growth and development. Consequently, it is suggested that male youth should also engage with training modalities to enhance relative force production.

Interestingly, maximal leg compression had a moderate relationship to, and was an important predictor of maximal sprint speed. This finding may reflect the importance of contact length during the ground contact phase of sprinting (26), whereby boys with greater leg compression may also have travelled a further distance when in contact with the ground. Interestingly, only 20% common variance was observed between leg length and leg compression. This result may highlight the independent effects that leg length and leg compression have upon contact length and the possible role of technical factors such as lower limb angles at touchdown. It has been suggested that leg stiffness decreases with a less vertical orientation of the leg at touchdown (greater limb angle from the vertical) (9), however at this stage these inferences remain speculative as these other mediating factors were not assessed in this study. Novel findings from the current study demonstrate that maximal leg compression and relative force production have an important role in developing maximal sprint speed in young boys. However, it should be noted very large negative relationships were observed between ground contact time and relative leg compression ($r = -0.78$). That is, those who exhibited greater leg compression are likely to have also utilized shorter period of ground contact. This may highlight that increases in compression does not impose a negative impact upon contact times and concomitant step frequency. Conversely, the relationships between contact time and leg compression with relative force production (r

= -0.77 and 0.47, respectively) suggest that those producing more relative force were doing so in shorter periods of ground contact but with less leg compression. This may highlight differential strategies employed by male youth to manage the period of ground contact; however, further research is required to explore these concepts.

Collectively, these findings would seem to provide contradictory recommendations; firstly the need to compress the legs more to potentially allow for greater contact length; whilst secondly the need to produce greater relative force over shorter periods of ground contact to increase step length; and thirdly, the need to minimize center of mass displacement and increase vertical stiffness for enhanced step frequency. The results of the study also indicate that leg compression increases with age, whilst relative vertical stiffness and center of mass displacement do not. Furthermore, given the increases in absolute force production and vertical stiffness observed in this study, the negative influence of increases in stature and particularly mass cannot be ignored (10). It may therefore be postulated that whilst additional leg compression may offer some beneficial effects to sprint performance in youth, the enhancement of relative force production and relative vertical stiffness may be qualities that deserve more attention during training. This approach should ensure enhanced SSC function and step frequency, whilst synergistically enhancing step length to maximize sprint performance in male youth.

The propositions made in this study should be viewed in the context of the limitations associated with the study. It should be acknowledged that the validity of the modeling equations for force, displacement and stiffness have been previously reported (15), these variables are not directly measured. Given the limitations of non-motorized treadmills (19), and the substantial financial outlay required for a series of in-ground force plates, the method presented here offers practitioners a practical alternative to assess force, displacement and stiffness during sprinting.

PRACTICAL APPLICATIONS

The results of this study indicate that relative vertical stiffness, relative peak force, and maximal leg spring displacement are the most important determinants of maximal sprint speed in boys, explaining 96% of performance. While maximal leg spring displacement increases naturally with growth and maturation during childhood, this is not the case for relative vertical stiffness and relative peak force. Cumulatively, this suggests that to facilitate increases in sprint speed, boys will benefit from varied resistance training interventions that are targeted to enhance relative force production, rate-of-force development, and relative stiffness properties.

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Table 1. Mean (± SD) values of each groups' descriptive characteristics.

Group	*N*	Age (yrs)	Standing height (m)	Sitting height (m)	Leg length (cm)	Body mass (kg)	Maturity offset (yrs from PHV)
U12	155	11.9 ± 0.5	1.49 ± 0.09	0.75 ± 0.04	0.74 ± 0.06	45.1 ± 13.1	-2.1 ± 0.2
U13	63	12.6 ± 0.3^{a}	1.51 ± 0.08	0.76 ± 0.04	0.76 ± 0.05	46.2 ± 11.5	-1.7 ± 0.2 ^{a}
U14	65	13.5 ± 0.3^{ab}	1.59 ± 0.08^{ab}	0.80 ± 0.05 ^{ab}	0.79 ± 0.05 ^{ab}	53.3 ± 13.4 ^{ab}	-0.8 ± 0.2 ^{ab}
U15	57	14.5 ± 0.3^{abc}	1.65 ± 0.09^{abc}	0.83 ± 0.05 ^{abc}	0.82 ± 0.05 ^{abc}	61.3 ± 14.6 ^{abc}	0.2 ± 0.2 ^{abc}
U16	35	15.6 ± 0.3^{abcd}	1.73 ± 0.08^{abcd}	0.87 ± 0.04 ^{abcd}	0.86 ± 0.04 ^{abcd}	69.1 ± 16.39 ^{abc}	1.3 ± 0.2 ^{abcd}

Key: U12 = under 12 years; U13 = under 13 years; U14 = under 14 years; U15 = under 15 years; U16 = under 16 years; PHV = peak height velocity; ^{a} = sig. greater than U12; ^{b} = sig. greater than U13; ^{c} = sig. greater than U14; ^{d} = sig. greater than U15

Table 2. Spatiotemporal characteristics during maximal sprinting across age groups.

Age group (yrs)	Speed (m/s)	Step length (m)	Step frequency (Hz)	Contact time (s)	Flight time (s)
U12	6.26 ± 0.58	1.54 ± 0.13	4.06 ± 0.31	0.137 ± 0.019	0.110 ± 0.015
U13	6.40 ± 0.56	1.59 ± 0.14	4.04 ± 0.33	0.138 ± 0.019	0.110 ± 0.016
U14	6.66 ± 0.78[a]	1.69 ± 0.17[b]	3.95 ± 0.33	0.143 ± 0.022	0.113 ± 0.016
U15	6.79 ± 0.89[b]	1.72 ± 0.17[b]	3.95 ± 0.38	0.147 ± 0.024[a]	0.108 ± 0.020
U16	7.42 ± 0.81[c]	1.86 ± 0.18[c]	4.00 ± 0.36	0.145 ± 0.019	0.107 ± 0.017

Key: U12 = under 12 years; U13 = under 13 years; U14 = under 14 years; U15 = under 15 years; U16 = under 16 years; [a] = sig. greater than U12; [b] = sig. greater than U12 and U13; [c] = sig. greater than all other age groups.

Table 3. Force, displacement and stiffness characteristics during maximal sprinting across age groups.

Age group (yrs)	F_{max} (N)	Relative F_{max} (N·kg^{-1})	Δy_c (m)	ΔL (m)	Absolute K_{vert} (kN·m^{-1})	Absolute K_{leg} (kN·m^{-1})	Relative K_{vert} (kN·m^{-1})	Relative K_{leg} (kN·m^{-1})
U12	1250 ± 304	28.1 ± 2.7	0.03 ± 0.00	0.11 ± 0.02	42.2 ± 8.6	12.2 ± 3.8	71.8 ± 13.2	20.9 ± 5.5
U13	1270 ± 263	27.8 ± 2.7	0.03 ± 0.01	0.11 ± 0.02	42.6 ± 8.0	11.7 ± 3.1	72.5 ± 13.9	19.8 ± 4.6
U14	1471 ± 312^{b}	28.0 ± 2.9	0.03 ± 0.01	0.12 ± 0.02^{b}	47.2 ± 11.6^{a}	12.3 ± 3.2	72.0 ± 15.4	19.1 ± 5.0
U15	1638 ± 350^{c}	27.0 ± 2.9	0.03 ± 0.01	0.13 ± 0.03^{b}	53.0 ± 13.8^{c}	13.1 ± 4.6	72.7 ± 14.9	18.1 ± 5.5^{e}
U16	1851 ± 385^{d}	27.0 ± 2.5	0.03 ± 0.01	0.16 ± 0.03^{d}	61.0 ± 16.0^{d}	12.6 ± 4.4	76.8 ± 14.0	15.9 ± 3.8$_{f}$

Key: U12 = under 12 years; U13 = under 13 years; U14 = under 14 years; U15 = under 15 years; U16 = under 16 years; F_{max} = modeled peak ground reaction force; Δy_c = modelled maximal vertical displacement of the centre of mass; ΔL = modelled leg length variation during ground contact; K_{vert} = vertical stiffness; K_{leg} = leg stiffness; ^{a} = sig. greater than U12; ^{b} = sig. greater than U12 and U13; ^{c} = sig. greater than U12, U13 and U14; ^{d} = sig. greater than all other age groups; ^{e} = sig less than U12; ^{f} = sig less than U12, U13 and U14

Table 4. Pearson's Correlations (r) between speed, force and stiffness characteristics.

Variable	Fmax	Relative F_{max}	Δy_c	ΔL	Absolute K_{vert}	Absolute K_{leg}	Relative K_{vert}	Relative K_{leg}
Speed	0.16*	0.42**	0.47**	0.41**	0.49**	-0.18**	0.73**	-0.10**

Key: F_{max} = modelled peak ground reaction force; Δy_c = modelled maximal vertical displacement of the centre of mass; ΔL = modelled leg length variation during ground contact; K_{vert} = vertical stiffness; K_{leg} = leg stiffness; * = Significant relationship between variables, $p < 0.05$; ** = Significant relationship between variables, $p < 0.01$.

Table 5. Predictor variables for maximal sprint speed in the whole sample.

Predictor variables	Regression equation	Adjusted r^2 value
Constant	-1.236	
Relative k_{vert}	0.410	0.536
ΔL	14.380	0.866
Relative F_{max}	0.106	0.962
F_{max}	0.001	0.967
Absolute k_{leg}	-0.054	0.972
Absolute k_{vert}	-0.008	0.973

Key: ΔL = modeled leg length variation during ground contact; K_{vert} = vertical stiffness; F_{max} = Maximal force; K_{leg} = leg stiffness