Title:
The influence of maturation on sprint performance in boys over a 21-month period

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Abstract

Purpose: This study examined how the characteristics of maximal overground sprint performance are affected by the period of peak height velocity (PHV) in boys.

Methods: One hundred and eighty-nine school-aged boys completed two assessments of maximal sprint performance, separated by a 21-month period. Kinematic characteristics of sprint performance were collected during a 30 m sprint using a floor-level optical measurement system, with modelled force and stiffness characteristics also calculated. Participants were grouped according to maturation using a non-invasive predictive equation. Individuals whose maturity offset was < -0.5 yrs in both assessments were classed as ‘pre-PHV’ (n=67) while those whose maturity offset developed from < -0.5 to > 0.5 yrs in test two were classed as ‘pre-to-post-PHV’ (n=39). Participants with a maturity offset between > -0.5 and < 0.5 yrs at test 2 were removed from analysis (n = 67) to ensure that the entire pre-to-post-PHV group had experienced the PHV spurt.

Results: The pre-to-post-PHV group experienced significantly greater increases in speed (10.4 vs. 5.6%) and relative vertical stiffness (12.1 vs. 5.6%) compared to the pre-PHV group. Step frequency declined (-2.4%) and contact time increased (2.3%) in the pre-PHV group, whilst step frequency increased (2.7%) and contact time decreased (-3.6%) in the pre-to-post-PHV group. Changes in relative measures of vertical stiffness, maximal force and leg stiffness accounted for 79% and 83% of the changes in speed between assessments for pre- and pre-to-post-PHV groups, respectively.

Conclusion: As boys experience PHV there are greater increases in maximal sprint speed compared with those who remain pre-PHV. Furthermore, measures of relative stiffness and relative maximal force appear to exert an important influence on the development of maximal sprint speed in boys, regardless of maturity.

Key words: Maturity; Growth; Peak Height Velocity; Stiffness; Kinetic; Kinematic
Introduction

Sprint speed develops in a non-linear fashion throughout childhood and adolescence (16), with the suggestion that a pre-adolescent and adolescent “spurt” in performance occurs between the ages of 5-9 years and 12-14 years, respectively (38). The second adolescent “spurt” in sprint performance has been reported to occur in time with boys achieving peak height velocity (PHV) (21,29); however it has also been suggested that peak improvements in speed may occur within 8-18 months prior to PHV (2,41). More recently, significant improvements in 30m sprint performance have been observed longitudinally as boys transition from under 13s to under 15s age categories (~mid to ~ two years post-PHV) (37), whilst it has also been reported that boys who are under 13s (~mid-PHV) improved sprint performance up to twice as much as those who were under 15s (~post-PHV) when monitored over a subsequent two-year period (10). Additionally, it has been suggested that changes in sprint speed with advancing age may be removed when age-at-PHV is accounted for in statistical analysis (18,34), and that maturity may account for up to 83% of the explained variance in sprint performance in boys (34).

Maturation appears to influence sprint performance in boys; however previous studies have either been cross-sectional in nature (18,21,34), longitudinal studies with low sample sizes (10,29), or have failed to include youth that are pre-PHV (10,37); therefore potentially not capturing the true impact of the period approaching PHV. In boys, the period of PHV is characterized by rapid increases in stature and mass (16,38). Furthermore, it is acknowledged that rapid limb length increases are also observed pre-PHV (16), which may offer an explanation for observed increases in speed prior to PHV (2,41). The period of PHV is also characterized by high levels of testosterone and growth hormone (30,38) and concomitant increases in muscle mass (4). These characteristics have been associated with observed increases in strength (19,30) and power (1,15) around the period of PHV that may
facilitate positive changes in sprint performance and associated kinetic and kinematic variables.

A very small number of cross-sectional studies have investigated the influence of maturation upon changes in kinetic (34,36), kinematic (21,34,36) and stiffness (31) variables associated with sprint performance. From a kinematic perspective, changes in step length throughout childhood have been suggested to be proportional to changes in leg length, whilst no differences in step frequency exist between different age groups (36). More recent data on a non-motorized treadmill have suggested greater differences in step length compared to step frequency between boys who are pre-PHV and those post-PHV (~42% vs ~6%, respectively) (34). Furthermore, data from overground sprinting has suggested that step frequency may actually decline, whilst ground contact time increases in the pre-PHV period, before driving increases in speed once these variables stabilize around the period of PHV (21). Interestingly, despite large increases in step length in the pre-PHV period, it has been suggested that step length may explain a lower proportion of the total variance in sprint speed (~42% vs ~54% respectively) in boys who are pre-PHV compared to post-PHV (20). From a kinetic perspective, horizontal force and power have been reported to be key predictors of sprint velocity in boys who were pre- and post-PHV (34), with the ability to produce and attenuate horizontal power highlighted as a key determinant (31). Increases in relative vertical stiffness during sprinting have also been reported in youth of increasing maturation (31), and may influence the ability to maintain short periods of ground contact during maximal sprint performance.

Collectively these studies highlight the role that maturation may have upon characteristics of sprint performance in youth; however the cross-sectional nature of the studies may not truly capture the impact of growth and maturation. Recently, no acute improvements in sprint speed or its associated characteristics were observed in pre-pubertal
boys following a 6-week sled-towing training protocol, despite significant improvements in sprint speed and many associated characteristics in a combined mid- and post-PHV group (33). Such data serve to highlight the role that maturation may have upon acute training responses, yet little is known about longitudinal changes in these characteristics as a result of growth and maturation. Furthermore, the use of a non-motorized treadmill in a large proportion of the youth sprint studies published to this point (31,33,34) may limit the application of these results. The peak sprint velocities reported in studies of youth on non-motorized treadmills (31,33,34) are ~45-60% slower and step lengths ~27-38% shorter than those reported during overground studies (20–22). It is clear from these observations that the non-motorized treadmill may not be representative of maximal sprint performance in youth (32), and therefore the true values for kinematic and kinetic variables may only be elicited during overground running.

Owing to the differential methodological approaches in the current literature, there is a lack of knowledge about the longitudinal development of key determinants of sprint performance in boys, and the influence that maturation and the period of PHV may exert upon these. Thus, the aim of this research was to examine how the characteristics of maximal overground sprint performance are affected by the period of peak height velocity (PHV) in boys.

Methods and Materials

Participants

Based upon the use of the described methodology in similar populations (20–22), power analysis indicated the need to recruit 60 participants (30 per group) in order to detect significant differences in the main outcome measures with 80% power at a 5% significance level. One hundred and eighty-nine school-aged boys agreed to participate in the study.
Following an assessment of maturity, participants were classified as pre-PHV or post-PHV (maturity offset = <-0.5 years and >0.5 years, respectively) at each of the two periods of testing (T1 and T2). Those participants classified as pre-PHV at both T1 and T2 were termed the “pre-PHV” group (n = 39), whilst those who were pre-PHV at T1 but post-PHV at T2 were termed the “pre-to-post-PHV” group (n = 67). This approach facilitated the assessment of the impact of the period of PHV upon components of speed. The removal of participants with a maturity offset between -0.5 and 0.5 years (n = 67) ensured that the entire pre-to-post-PHV group would have experienced the PHV spurt, whilst allowing for the valid application of the maturity offset regression equation and the associated measurement error (23).

Descriptive characteristics of the participants are provided in Table 1. Participants reported no injuries upon enrolling into the study and all regularly participated in twice-weekly physical education classes that were 60 minutes in duration. Data pertaining to habitual, sporting or training activities of the participants outside of school curriculum time were not collected during the study. The project received ethical approval by the University’s Research Ethics committee and both participant assent and parental consent were obtained prior to testing.

Table 1 about here

Procedures

Participants were required to attend two periods of testing (T1 and T2) separated by approximately 21 months. Each testing period took place over a two-week timeframe and required participants to attend two scheduled testing sessions during physical education classes, separated by a minimum of 24 hrs. All testing sessions took place in the same indoor facility. During the scheduled testing sessions, participants were assessed for maturity status
and completed a maximal sprint test. All participants were instructed to refrain from physical activity 24 hrs before testing and to refrain from eating 1 hr prior to testing. Participants were provided with the opportunity to familiarize themselves with the test equipment and the protocol used prior to the first testing session.

Assessment of maturity. Standing height, sitting height and leg length were recorded to the nearest 0.01 m, whilst mass was recorded to the nearest 0.1 kg. These variables combined with chronological age were used to provide an estimate of maturity (23). This method provides an estimate of the age from peak height velocity (PHV) and was chosen owing to its non-invasive nature and acceptable level of measurement accuracy (± .592 years).

Sprint test. The sprint test was administered using procedures previously reported for assessing the kinematic characteristics of sprint performance in adolescent boys (20–22), whereby participants performed a maximal sprint over a 30 m track. The assessment of sprint characteristics was made via an optical measurement system (Optojump, Microgate, Italy) positioned at floor level in the 15-30 m data collection zone of the sprint 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. A finish line was established at 35 m to encourage participants to continue maximal sprinting throughout the 15-30 m data collection zone of the sprint where measurements were recorded. This distance was selected based on evidence that the majority of trained youth soccer players achieved maximal speed inside 35 m (5), and the reliability (intraclass correlation coefficient = 0.86; coefficient of variation = 4.2%) previously reported for obtaining maximal sprint performance using this methodology (22). Participants were given two trials for the sprint test and were instructed to start from a split stance position with one foot on a line positioned 0.5 m behind the starting line.
Participants were given the instructions “Ready” and “Go”, and verbal encouragement was given throughout the test to encourage maximal effort. All tests were undertaken individually and a minimum of four minutes rest was given between trials to ensure sufficient recovery. No feedback on sprint test results was given during testing.

**Sprint test variables.** Kinematic variables that were collected for each step within the 15-30 m data collection zone included speed, step length, step frequency, contact time and flight time (20–22). Acceptable levels of reliability have been reported from the assessment of spatiotemporal sprint characteristics in boys (intraclass correlation coefficient = 0.66 – 0.86; coefficient of variation = 3.8 – 5.0%) using this methodology (22). Data for all steps completed within the 15–30 m data collection zone were instantaneously recorded for each participant over their two sprint trials in both T1 and T2. All data corresponding to the fastest two consecutive steps from either trial during T1 and T2 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 prior to the data collection zone, and also those who were still accelerating at the end of the data collection zone, thereby resulting in data from only those participants achieving maximal speed between 15-30 m. One hundred and eighty-nine participants were originally tested, with 16 removed as a result of these criteria, and a further 67 removed with maturity offset between -0.5 and 0.5 years, resulting in 106 participants being taken forward for statistical analysis. Subsequently, center of mass displacement ($\Delta y_c$), leg spring compression ($\Delta L$), vertical stiffness ($k_{vert}$), leg stiffness ($k_{leg}$) and maximal force ($F_{max}$) were calculated at both T1 and T2 from the anthropometric and kinematic characteristics using previously validated modelling techniques (25,26). This approach was taken owing to its non-invasive nature as well as the low level of mean error bias ($k_{vert}$ =
2.30%; $k_{leg} = 2.54\%$) and significant regressions ($k_{vert} = P < 0.01, r^2 = 0.98; k_{leg} = P < 0.01, r^2 = 0.89$) reported with force-plate measures during overground running (25). Finally to account for differences in anthropometric measures between the pre- and pre-to-post-PHV groups, relative $k_{vert}$ and $k_{leg}$ measures were established by normalising data to leg length and body mass (17).

Statistical analyses

Means and standard deviations were calculated for all variables at both T1 and T2 time points, and also analysed in pre- and pre-to-post-PHV groups. For each group, mean difference from T1 – T2 was established for anthropometric and maturity variables, whilst percentage change was established for kinematic, force and stiffness data. Ninety-five percent confidence intervals were calculated for all mean and percentage difference calculations. In order to establish the effect of the period of PHV, a 2*2 mixed model analysis of variance (ANOVA) was used to assess within- and between-group main effects as well as group × time interactions. The assumption of normality of all data was assessed via the Kolmogorov-Smirnov test, and Mauchly’s test was used to assess non-violation of the assumption of sphericity. Where sphericity was violated, a Greenhouse-Geiser adjustment was implemented. During post-hoc analysis a Bonferroni correction was utilised to establish the location of significant differences between time points and within groups.

The strength of relationships between changes in sprint variables across time points T1 – T2 for both the pre- and pre-to-post-PHV groups was assessed via Pearson’s correlation coefficient, whilst stepwise multiple regressions were utilised in order to establish the determinants of the change in sprint speed for both groups. The assumption of independent errors during multiple regression analyses was tested via a Durbin-Watson test, with multicollinearity tested using variance inflation factor (VIF) and tolerance (8).
diagnostics. All correlation and multiple regression analyses were conducted in SPSS Statistics v. 20 for Mac. Statistical significance was accepted as $P < 0.05$, whereas the magnitude of relationships in correlation analyses were 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 ($r < 0.1$) (11).

Results

The data in *table 1* provides an account of the descriptive characteristics of the participants in the pre- and pre-to-post-PHV groups. Significant increases ($P < 0.05$) and interactions (group*time) were found for all descriptive variables except age. The pre-to-post-PHV had a significantly greater growth rate ($7.26 \pm 1.88$ cm/year vs. $6.24 \pm 1.89$ cm/year) compared to the pre-PHV group ($P < 0.05$).

Data in *table 2* highlights the results obtained during T1 and T2 and percentage differences between T1-T2 for each group. The ANOVA revealed no significant interactions (group*time) for step length, flight time, relative $F_{\text{max}}$ and relative $k_{\text{leg}}$. A main effect for time and group ($P < 0.05$) was found for step length, with the pre-to-post-PHV group having significantly ($P < 0.05$) longer steps than the pre-PHV, but both groups significantly increasing their step length between T1 and T2 ($P < 0.05$). Main effects for group were also found for relative $F_{\text{max}}$ and relative $k_{\text{leg}}$ ($P < 0.05$), with both variables significantly higher in the pre-PHV group. No significant main effects or interactions were evident for flight time ($P > 0.05$).

****Table 2 about here****
The results in figure 1 highlight the significant interactions (group*time) for speed, step frequency, contact time and relative \(k_{\text{vert}}\) \((P < 0.05)\). Between T1-T2 the pre-to-post-PHV group experienced significantly greater increases in speed \((10.4\%, \text{ CI}_{95}\% = 8.7 - 12.2\% \text{ vs. } 5.6\%, \text{ CI}_{95}\% = 4.2 - 7.1\%)\) and relative \(k_{\text{vert}}\) \((12.1\%, \text{ CI}_{95}\% = 7.2 - 17.0\% \text{ vs. } 5.6\%, \text{ CI}_{95}\% = 1.8 - 9.3\%)\) compared to the pre-PHV group, respectively. Furthermore, significant decreases in step frequency \((-2.4\%, \text{ CI}_{95}\% = -4.0 - -0.9\%)\) and significant increases in contact time \((2.3\%, \text{ CI}_{95}\% = 0.1 - 4.5\%)\) were noted in the pre-PHV group, whilst conversely, significant increases in step frequency \((2.7\%, \text{ CI}_{95}\% = 0.7 - 4.8\%)\) and decreases in contact time \((-3.6\%, \text{ CI}_{95}\% = -6.4 - -0.7\%)\) were observed in the pre-to-post-PHV group.

Correlation analyses (table 3) revealed that changes in speed between T1-T2 were significantly related to changes in step length, contact time, relative \(F_{\text{max}}\), and relative \(k_{\text{vert}}\) in both the pre- and pre-to-post-PHV groups. Furthermore, in the pre-to-post-PHV group, changes in speed had a significant positive relationship with changes in step frequency. Changes in speed in either group were not significantly related to changes in any anthropometric variables \((r = -0.11 - 0.30)\). Changes in step frequency had significant moderate-large negative relationships with changes in contact time \((r = -0.33 \text{ and } -0.63)\) and significant large-very large positive relationships with changes in relative \(k_{\text{vert}}\) \((r = 0.69 \text{ and } 0.75)\) in the pre- and pre-to-post-PHV groups, respectively. Furthermore, changes in contact time were negatively and significantly related to changes in relative \(F_{\text{max}}\) \((r = -0.65 \text{ and } -0.58)\), relative \(k_{\text{vert}}\) \((r = -0.79 \text{ and } -0.76)\) and relative \(k_{\text{leg}}\), \((r = -0.69 \text{ and } -0.65)\) in the pre- and pre-to-post-PHV groups, respectively. Changes in step length were not significantly related to changes in anthropometric measures \((r = -0.20 - 0.12)\) but had a significant positive
relationship on changes in relative $F_{\text{max}}$ ($r = 0.52$ and $0.40$) in the pre- and pre-to-post-PHV groups, respectively.

**Table 3 about here**

Multiple stepwise regression analysis (*table 4*) revealed that the majority of change in sprint speed within the pre- and pre-to-post-PHV groups could be explained by the combined change in relative $k_{\text{leg}}$, relative $F_{\text{max}}$ and relative $k_{\text{vert}}$ (79% and 83% of total explained variance, respectively). No changes in anthropometric variables contributed significantly to the regression models for any groups.

**Table 4 about here**

**Discussion**

The aim of this study was to examine the influence of the period of PHV upon the characteristics of sprint performance in boys during overground sprinting. Greater increases in sprint speed were observed in the pre-to-post-PHV group compared to the pre-PHV group. Furthermore, change in speed was best predicted by changes in relative $k_{\text{leg}}$, relative $F_{\text{max}}$ and relative $k_{\text{vert}}$, despite only relative $k_{\text{vert}}$ increasing with age. Combined, these results suggest that as boys experience PHV there are greater increases in maximal sprint speed compared to boys who remain pre-PHV. Furthermore measures of relative stiffness and relative maximal force appear to exert an important influence on the development of maximal sprint speed in boys, regardless of maturity.

These findings are comparable with previous research highlighting the positive effect of maturation upon sprint speed (21,29,34), however, would seem to contest previous claims of the greatest enhancements in sprint performance being seen prior to PHV (2,41). It
is interesting to note that previous cross-sectional studies have suggested there may be no
significant changes in sprint speed in pre-PHV boys (21); however the results of the current
study support the notion that whilst improvements in speed may be observed during the pre-
PHV period, the magnitude of change is reduced compared to those who have experienced
the period of PHV (34).

When examining the results of the kinematic characteristics of sprint performance,
it was noted that step frequency significantly decreased whilst contact time significant
increased in the pre-PHV group, yet the pre-to-post-PHV group experienced the exact
opposite pattern, with significant increases in step frequency and decreases in contact time
over the same period. Such an observation has been reported before in cross-sectional
research, with increases in contact time observed between age groups ranging 6 – 14 years
old (6). Concomitant decreases in step frequency were also observed between age groups
ranging from 6 – 10 years old, before subsequent increases being observed until 14 years old
(6). It has also been suggested that decreased step frequency and increased contact time in the
pre-PHV period may offset increases in step length that would otherwise positively
contribute to speed development (21). These observed changes have previously been
explained as a temporary disruption in motor co-ordination, often termed “adolescent
awkwardness” (21,29). While the decrements in step frequency and contact time do not
appear to have prevented the development of speed in the pre-PHV group, they may have
contributed to the lower increases in speed in the pre-PHV group compared to the pre-to-
post-PHV group. Furthermore, in keeping with previous youth (21,34) studies, no changes in
flight time were observed between groups and over the time period; highlighting the
importance of ground contact upon sprint performance, rather than the flight phase. It was
also noted that changes in contact time had large or very large negative relationships with
changes in relative $k_{vert}$ and relative $k_{leg}$ in both groups. Changes in these stiffness variables
significantly contributed to the regression models for change in sprint performance over time in both pre- and pre-to-post-PHV groups. The influence of changes in relative $k_{leg}$ may be best explained through the concept of contact length (distance travel by the center of mass during ground contact) (39). Increases in leg length have been associated with increases in contact length, with changes in leg length (via growth or leg compression) having a marked impact upon maximal speed (39); however as contact length was not measured during this study, the precise mechanisms that link the concepts of $k_{leg}$ and contact length require further investigation.

Logically the influence of increases in relative $k_{vert}$ upon sprint performance may be attributed to either a reduction in vertical displacement or increases in maximal force production. Enhanced stretch-shortening cycle function observed in boys around the period of PHV (15,31) may be attributed to reduced compliance (increased stiffness) of the musculotendious tissue (12,13), increased fascicle length (12), increase in neural firing rates (28) and the enhanced stretch reflex (9) that has been observed throughout childhood and adolescence. Such factors may contribute to enhanced fast stretch shortening cycle function (31) that would facilitate reduced displacement of the centre of mass and optimisation of ground contact time for maximal sprint performance. Furthermore, increases in muscle cross-sectional area (27) and pennation angle (3) seen throughout childhood would positively impact upon the maximal force generating capability of boys, that in turn, may also contribute to enhanced stiffness. Our data also highlight very large negative relationships between relative vertical stiffness and contact time along with a very large positive relationship with step frequency in both pre- and pre-to-post-PHV groups, respectively.

Collectively, these findings suggest that the development of relative vertical stiffness may be deemed an important aspect of youth maximal sprint performance. It could therefore be suggested that training modalities such as plyometrics, that have been shown to be effective for
speed development in youth populations (14,35), would provide favourable neuromuscular adaptation to enhance stiffness, via a reduction in the displacement of the centre of mass, and consequently provide a positive influence upon contact time and step frequency. Furthermore, it could be suggested that resistance training, an approach that is also proven to be safe and effective for youth athletes (7), may be appropriate to facilitate the enhancement of force production capabilities that would also positively contribute to enhanced stiffness.

Significant relationships were observed between the changes in speed and changes in step length for both pre- and pre-to-post PHV groups, highlighting the importance of step length in sprint performance for all stages of maturation. Increases in step length were observed for both groups over the period of study with the pre-to-post-PHV group having significantly longer steps at each time point; however no interaction was observed, suggesting that the period of PHV may not play a large role in developmental changes in this variable. Interestingly, the pre-PHV group experienced greater increases in leg length compared to the pre-to-post-PHV group over the study period, whilst greater increases in sitting height as well as overall standing height and growth rate were observed for the pre-to-post-PHV group. Such observations confirm the differential nature of the growth pattern between the lower limbs and the trunk on the approach to, and during, the period of PHV (16). Despite the observed anthropometric differences, no significant relationships were evident between changes in anthropometric characteristics and changes in step length in both groups. Previous cross-sectional studies have suggested that changes in step length may be proportional to changes in leg length (36), whilst more recently moderate relationships have been reported between measures of leg length and step length in boys who were pre- and post-PHV (20); however data from the current study do not support this proposition.

Increases in step length between time periods were significantly related to increases in relative $F_{\max}$ in both groups, highlighting the importance of force application
relative to body mass for increases in step length (40) and subsequent sprint performance. A main group effect was also evident for relative $F_{\text{max}}$, with the pre-PHV group experiencing significantly greater relative force than the pre-to-post-PHV group. This observation is in contrast to previous research that suggests post-PHV boys generate more relative vertical force compared to mid- and pre-PHV groups (34). This may in part be explained by negative associations between mass and sprint speed that have been reported in large cohorts of boys (20). As boys experience the period of PHV, they will also gain mass resulting from increases in stature, as well as increases in muscle mass (16); however as body composition was not assessed in this study, it is plausible that increases in mass may also result from increases in levels of fat mass (20) that would diminish changes in relative force production. In addition, regression analyses highlighted that changes in relative $F_{\text{max}}$ were positively associated with changes in sprint speed. These findings could therefore suggest that whilst relative $F_{\text{max}}$ may not develop naturally, or may in-fact decline, throughout the period of PHV, it is an important contributor to improved sprint performance in youth and therefore an important training focus. It could therefore be suggested that strength training should be an integral part of speed development programs for youth to facilitate enhanced neuromuscular function whilst improving body composition (7) to achieve superior relative force production capabilities. It is also important to note that the present study investigated vertical force and that previous studies utilizing non-motorised treadmills (31,33,34) have reported that horizontal force production is predictive of maximal sprint performance in male youth, therefore gains in speed and step length seen with advancing maturation may be due to increases in horizontal force. However, it is known that non-motorised treadmills reduce maximal speed and increase the horizontal force production compared to overground conditions (24) and therefore the role of horizontal force production during maximal sprint performance in boys requires further investigation in overground conditions.
Limitations

It is important that the results of this study are viewed in the context of the limitations in the study design. Firstly, the sample was derived from a school-population, and therefore the sample included a wide range of abilities and levels of training experience. Furthermore, whilst physical activity within physical education classes was controlled for all participants, the habitual, sporting and other training activities of each participant were not recorded, and therefore it is not possible to rule out the influence of additional unknown training stimuli upon the results presented.

It is also important to acknowledge that the measurement of $F_{\text{max}}, k_{\text{leg}}$ and $k_{\text{vert}}$ are extrapolated from contact time and flight time rather than directly measured via kinematic and kinetic analyses. The methods for extrapolating these data are validated in experienced adult populations (25,26), but not for the specific youth population in this study.

Conclusions

The results of this study serve to highlight the positive impact that the period of PHV has upon the development of maximal sprinting in boys. As part of natural growth and development, the period of PHV results in enhanced sprint performance, and it is suggested that the development of relative vertical stiffness and relative maximal force are important predictors of enhanced sprint performance in boys who are pre-PHV and those who experience the period of PHV. It is suggested that practitioners seeking to enhance sprint performance in boys who are pre-PHV, or who are experiencing the period of PHV, should expose them to integrated training modalities, inclusive of strength training and plyometrics, to enhance force production relative to body weight and stiffness-related variables. Furthermore, it seems that the pre-PHV period is characterised by decrements in contact time
and step frequency that may result from challenges associated with differential growth patterns, and therefore this would seem a key window in which to focus upon technical drills to offset these growth related decrements in performance.

Acknowledgements

No sources of funding were obtained for the present study. The authors thank the participants for their significant contribution to this longitudinal study. Thanks also go to Ian Gardner and the Physical Education staff at St Cenydd Comprehensive School, Caerphilly, Wales for their assistance with the project. The authors also thank Dr Michael Stembridge and Daniel Newcombe for their assistance with data acquisition.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

Conflict of Interest

No conflicts of interest exist in the present study. Citations of commercial organizations and trade names in the present study do not constitute an official endorsement or approval of the products or services of these organizations.

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Figure captions

Figure 1. Data for speed, relative $k_{vert}$, step frequency and contact from pre- and pre-to-post-PHV groups across the two time points. Key: ◆ = pre-PHV group; ■ = pre-to-post-PHV group; * = Significant difference between testing occasions within same group ($P < 0.05$); ^ = Significant difference between groups within the same test interval ($P < 0.05$); X = Significant interaction (group*time), ($P < 0.05$); $k_{vert}$ = vertical stiffness.