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Title:

Asymmetry during maximal sprint performance in 11-16 year old boys

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Abstract

Purpose: The aim of this study was to examine the influence of age and maturation upon magnitude of asymmetry in the force, stiffness and the spatiotemporal determinants of maximal sprint speed in a large cohort of boys.

Methods: Three-hundred and forty-four boys between the age of 11–16 years completed an anthropometric assessment and a 35 m sprint test, during which sprint performance was recorded via a ground-level optical measurement system. Maximal sprint velocity, as well as asymmetry in spatiotemporal variables, modeled force and stiffness data were established for each participant. For analysis, participants were grouped into chronological age, maturation and percentile groups.

Results: The range of mean asymmetry across age groups and variables was 2.3–12.6%. The magnitude of asymmetry in all the sprint variables was not significantly different across age and maturation groups ($p > .05$), except relative leg stiffness ($p < .05$). No strong relationships between asymmetry in sprint variables and maximal sprint velocity were evident ($r_s < .39$).

Conclusion: These results provide a novel benchmark for the expected magnitude of asymmetry in a large cohort of uninjured boys during maximal sprint performance. Asymmetry in sprint performance is largely unaffected by age or maturation and no strong relationships exist between the magnitude of asymmetry and maximal sprint velocity.

Key words

Speed; Growth; Maturation; Stiffness; Force

Introduction

The concept of asymmetry during human locomotive activities has been studied in the literature as a potential injury risk factor (7,51,55), a basis for appropriate programming of injury prevention interventions (18), and a mechanism to enhance coaching knowledge about performance (54). Previous studies in adult populations have investigated asymmetry using isokinetic dynamometry (10,21), force plates (1), multidirectional acyclical jumping tasks (18,26), cyclical rebound jumping tasks (14) and submaximal running (3,7,55). Some studies have investigated relationships between maximal sprint performance and asymmetry in jump performance (50), asymmetry in lean mass (4) and asymmetry in muscle architecture (29), yet the data pertaining to the actual asymmetry during maximal sprint performance is very sparse (12,27). Specifically, only one study has examined maximal sprint asymmetry in a youth population (49), but this involved sprinting on a non-motorized treadmill as opposed to overground conditions.

An understanding of the expected magnitude of asymmetry in non-injured athletes would be useful to assist in the prescription of training and facilitates a better understanding of any diagnostic information collected; however the magnitudes of asymmetry may vary depending upon the mode of locomotion and the variables of interest. It has also been suggested that asymmetry values exceeding 10 – 15% may predispose athletes to increased injury risk (17); however there is a large variability in the magnitude of asymmetry reported in non-injured populations. Asymmetry in vertical forces and spatiotemporal characteristics during sprinting in injury-free adults has been reported to range 0.18-4.33% during overground running (13), whilst an average of 17% asymmetry has been reported for force, power and work in non-injured male youth whilst sprinting on a non-motorized treadmill (49). However, it is important to note that the maximal sprint velocities reported from studies on non-motorized treadmills may be ~80% of those achieved during overground sprinting (24). Specifically, non-motorized treadmills studies in male youth (46) report velocities that are approximately 50% slower than data recently reported during overground studies in similar populations (33). Such a decrement in performance is likely to result from the influence of treadmill inertia, and has been suggested to result in altered sprint kinetics and kinematics in youth (48). Furthermore, a variety of calculations for asymmetry have been utilized in the literature, including ratios of asymmetry between left and right limbs (49), and asymmetry angles (13). Whilst the asymmetry angle has been suggested to not suffer from artificial inflation (59), the use of left and right comparisons in both calculations may be questioned for group comparisons when considering the independent behaviors an athletes “propulsive” and “stick” leg during running performance (11). It is therefore clear that asymmetry values vary considerably dependent on the population studied, the mode of assessment during sprint task, the variables of interest and the method of calculation. Until a broader understanding of the expected magnitude of asymmetry in non-injured youth populations is established for sprint performance during overground running, the application of an arbitrary threshold for injury risk in youth remains questionable.

Developing an understanding of asymmetry in youth populations is of particular interest due to the role of growth and maturation in changes in athletic performance (28,56) and injury risk (5,44). Sprint speed is known to develop in a non-linear fashion throughout childhood and adolescence (28,56), with fluctuations in performance (33,43) and injury risk (5,44) reported to occur around the time of peak height velocity (PHV); however little is known about the changes in asymmetry in relation to growth and maturation. It has been suggested that the rapid growth experienced around the period of PHV may result in temporary disruption in sprint performance termed “adolescence awkwardness” (43). Furthermore, during periods of growth it has been suggested that loading from daily movement tasks may produce bilateral asymmetry in skeletal dimensions (23). It could therefore be suggested that growth and maturation may have impact upon asymmetry in sprint performance resultant from asymmetry bone growth and disrupted motor coordination. The few studies examining asymmetry in youth populations have reported that the magnitude of asymmetry during skilled soccer performance is similar between the ages of 6 and 10 (53) and that asymmetry during non-motorized sprint performance is constant across maturation groups that span the period of PHV (49). These data may suggest that growth and maturation has a limited impact on the level of asymmetry in sprint performance despite clear changes in performance capacity and growth over the same period; however no large cohort studies have investigated this concept in youth during overground sprinting.

The determinants of sprint performance have been well researched within adult populations (9,20,39,57); however data to support the relationships between the magnitude of asymmetry and sprint performance are somewhat limited, and no studies have investigated this concept in youth populations. In youth populations, it has been suggested that power, horizontal force, step length and contact time are significant predictors of sprint performance (46), with some evidence to support a maturational effect in the ability to absorb and produce power (47). Furthermore, maturation may not only predict sprint performance in youth (46), but also may influence the reliance of boys upon step frequency or step length to elicit maximal sprint performance (35). It has also been suggested that both vertical and leg stiffness (16,47,52) may contribute to sprint performance in boys. Whilst all of the aforementioned sprint characteristics may be deemed important for sprint performance in youth, the evidence to describe the expected magnitude of asymmetry of these variables in non-injured youth is somewhat limited.

From a sprint performance perspective, some strong relationships (r = .70) between asymmetry in ground reaction force during single-leg jumping and 10 m sprint time have been shown in adults (50), however no studies have attempted to examine this relationship in youth, nor during maximal velocity sprinting. A clearer understanding of the relationships between asymmetry and performance may help to assess the importance of addressing asymmetry for the enhancement of sprint performance.

Finally, the substantial changes in strength, power (32) and rate of change in anthropometric variables (28) that boys experience around the time of PHV, may cause temporary disruption in motor control (43) that in turn may lead to fluctuations in asymmetry of sprint performance. Knowledge of the changes in the magnitude of these asymmetries with age and maturation could be important for all professionals within a multidisciplinary team working with youth athletes from both diagnostic and prognostic perspectives. Therefore, given the limited research into the nature of asymmetry during maximal sprint performance in youth, the aim of this study was to examine the influence of age and maturation upon the magnitude of asymmetry in the force, stiffness and the spatiotemporal determinants of maximal sprint speed in a large cohort of boys.

Methods and Materials

Participants

Three-hundred and forty-four school-aged boys (mean ± *s*: age 13.2 ± 1.4 yrs, height 1.56 ± 0.12 m, mass 55.2 ± 15.5 kg) agreed to participate in the study. Age from PHV was -0.93 ± 1.34 years, as predicted from anthropometric measures (36). Participants reported no injuries prior to, or during the testing period, and were engaged in twice weekly, 60-minute physical education classes. No data related to habitual or supplementary physical activity outside of this curriculum time were collected. The project received ethical approval by the University's Research Ethics committee, and both participant assent and parental consent were obtained prior to testing.

Procedures

All data collection sessions were scheduled during physical education classes with testing taking place over a two-week period and within the same indoor facility. Participants were required to complete maximal sprint testing and an anthropometric assessment during a single testing session. Participants were instructed to wear their standard physical education clothing and footwear, asked to refrain from physical activity 24 hours before testing and to refrain from eating one hour prior to testing. Participants were provided with the opportunity to familiarise themselves with the test equipment and protocols prior to the first testing session.

Anthropometric assessment. Following previously published guidelines on the assessment of stature (8), standing height and sitting height were measured to the nearest cm, while body mass was measured to the nearest 0.1 kg. These data were used in order to establish the maturity status of each participant using previously reported regression equations to calculate a maturity offset (years from PHV) (36).

This approach was taken owing to the non-invasive and practical nature of the assessment and its acceptable levels of error (± 0.59 years) (36).

Sprint test. The sprint test required participants to perform two trials of a maximal 35 m sprint while data pertaining to the spatiotemporal characteristics of the sprint performance were collected via a floor-level optical measurement system (Optojump, Microgate, Italy) within the 15-30 m section of the test track. In each sprint trial participants were instructed to start 0.5 m behind the start line in a split stance, before being given the commands “Ready” and “Go”. Verbal encouragement was provided throughout each trial, with a minimum of four minutes rest provided between trials to ensure sufficient recovery. This approach has been effectively utilised in large cohorts of boys (33), and has been reported to have acceptable levels of reliability (ICC: .79-.86; CV: 3.8-5.0%) (34).

Data reflecting the maximal velocity and the spatiotemporal characteristics (step length, step frequency, ground contact time and flight time) of each participants’ sprint performance were calculated instantaneously for each step taken within the 15-30 m data collection zone via a Windows XP laptop running specialist software (Optojump, Microgate, Italy). All data were collected at a sampling rate of 1000Hz and subsequently exported to spreadsheet software (Excel for Mac 2011, Microsoft, USA) for further data processing and analysis. Subsequently, vertical stiffness (k_{vert}), leg stiffness (k_{leg}), maximal force (F_{max}), displacement of centre of mass (Δy_c) and leg spring displacement (ΔL^{-1}) during ground contact were calculated from the anthropometric and spatiotemporal characteristics (38). These variables were defined as:

- Vertical stiffness (k_{vert}): The ratio (kN·m^{-1}) of the modeled peak ground reaction force (F_{max}) over the modeled maximal vertical displacement of the centre of mass (Δy_c).

$$k_{vert} = (F_{max} \cdot \Delta y_c^{-1})/m \qquad [1]$$

where:

$$F_{max} = m \cdot g \cdot \pi/2 \cdot ((CT/ FT)+1)$$

$$\Delta y_c = (Fmax/m) \cdot (CT^2/ \pi^2) + g \cdot (CT^2/ 8)$$

m being participants body mass (kg), *g* being gravitational force, *CT* being the ground contact time and *FT* being the flight time, and:

- Leg stiffness *(k_{leg}):* The ratio (kN·m^{-1}) of the modeled peak ground reaction force (F_{max}) over the modeled leg spring displacement (ΔL^{-1}) during ground contact

$$k_{leg} = F_{max} \cdot \Delta L^{-1} \qquad [2]$$

where:

$$\Delta L^{-1} = L - \sqrt{}L^2 - ((Speed \cdot CT)/2)^2 + \Delta y_c$$

L being leg length (m) and *Speed* being mean forward running velocity (m.s^{-1})

Finally, relative vertical and leg stiffness measure were calculated by normalising data to leg length and body mass (31). This modelling 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 ($k_{vert} = p < .01$, $R^2 = .98$; $k_{leg} = p < .01$, $R^2 = .89$) reported with force-plate measures during overground running (37).

From the two trials conducted, the trial where the highest maximal velocity was reached over two consecutive steps was taken forward for analysis (33). Subsequently, the values corresponding to the spatiotemporal, force and stiffness characteristics for each leg were averaged across all data points in the 15-30 m data collection zone, and a percentage asymmetry was calculated. Percentage asymmetries were expressed as the magnitude of the difference between the minimum and maximum values across the averaged spatiotemporal, force and stiffness data collected for each leg, and subsequently expressed as a percentage as defined below:

$$\% \text{ Asymmetry} = (\text{Maximum value} - \text{minimum value} / \text{maximum value} * 100) \qquad [3]$$

This approach has been taken to account for the role of a “propulsive” and “stick” leg, whereby greater positive work may be completed by the “propulsive” leg, whilst greater stiffness may be evident in the “stick” leg (11). This is especially important to ensure that inter-participant variations in limb dominance were not masked during group-based asymmetry comparisons (2).

Statistical Analyses

Means and standard deviations were calculated for all variables described. These data were analysed in both chronological and maturational groups. In line with previous research (33), chronological groups were defined by age on the date of the test (U12 – U16), whilst maturational groups were partitioned according to their maturity offset, whereby: Group 1 (G1) = more than 2.5 years before PHV; Group 2 (G2) = -2.49 to -1.5 years from PHV; Group 3 (G3) = -1.49 to -0.5 years from PHV;

Group 4 (G4) = -0.49 to 0.5 years from PHV; Group 5 (G5) = 0.51 to 1.5 years from PHV. In order to establish the magnitude of asymmetry across the sample, asymmetry values that represented the 10th, 25th, 50th, 75th and 90th percentiles across the whole sample were also calculated through rank ordering. Participants were also divided into 1st-10th, 11th-25th, 26th-50th, 51st-75th, 76th-90th and 91st-100th percentile groups for each spatiotemporal, force and stiffness variable. This approach was adopted in order to examine differences in maximal sprint velocity across percentile groups, allowing the influence of the magnitude of asymmetry in each variable upon the maximal sprint velocity to be examined.

The assumption of normality of all data was assessed via the Kolmogorov-Smirnov test, and parametric or non-parametric analyses were deployed where appropriate. Comparisons between the magnitude of asymmetry across chronological and maturational groups were made via a series of Kruskal-Wallis tests, with post-hoc analysis of pairwise comparisons achieved through multiple Mann-Whitney U tests with Dunn-Sidak corrections applied. Percentile groups for asymmetry of each spatiotemporal, force and stiffness variable were examined using a one-way ANOVA to determine if groups differed for maximal sprint velocity. 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 were identified by either using Tukey’s HSD or Games- Howell post hoc analysis, where equal variances were and were not assumed, respectively. Spearman’s rho correlations were used in order to identify relationships between the magnitude of asymmetry and maximal sprint velocity within the whole sample, as well as chronological and maturation sub-groups. Statistical significance was accepted at $p < .05$, while correlation coefficients greater than 0.7 were classified as “strong”, 0.45-

0.7 were “moderate”, 0.2-0.45 “weak”, and less than 0.2 representing “no relationship” (40). All statistical analyses were conducted on IBM SPSS Statistics for Mac v22.

Results

The descriptive characteristics of the participants in each chronological and maturation group are shown in Tables 1 and 2, respectively. The results in Tables 3 and 4 show the mean magnitude of asymmetry within each chronological and maturation group, respectively. No significant differences were found in the magnitude of asymmetry for speed, step length, step frequency, ground contact time, flight time, F_{max}, relative k_{vert} across all chronological groups. The magnitude of asymmetry in relative k_{leg} was significantly higher in the U13 group compared to the U12 and U14 groups (χ^2 (4) = 12.36, $p < .05$ and χ^2 (4) = 19.09, $p < .05$, respectively), but no significant differences existed between all other groups. The maturation group analysis revealed no significant differences in the magnitude of asymmetry between all five maturation groups for all variables assessed. Finally, no significant differences were observed between the maximal sprint velocity achieved by participants within the asymmetry percentile groups for all spatiotemporal, force and stiffness variables, with the exception of those in the 0-10th percentile group for flight time, who were significantly faster than those in the 26th-50th and 51st-75th percentile groups ($F_{(5, 338)}$ = 1.482, $p < .05$).

****Tables 1, 2, 3 and 4 about here****

The correlation analyses of the whole sample revealed that no significant relationships were evident between the magnitude of asymmetry in any sprint test variable and maximal sprint velocity. When relationships were examined in individual chronological age groups, no significant relationships were found between sprint velocity and magnitude of asymmetry. Maturation group analysis of the relationships between sprint velocity and the magnitude of asymmetry in the spatiotemporal, force and stiffness variables also revealed no significant relationships between the majority of variables, with the exception of weak correlations observed for: maximal sprint velocity and step frequency asymmetry (r_s (37) = .39, $p < .05$) in G1; maximal sprint velocity and flight time asymmetry (r_s (80) = -.27, $p < .05$) as well as relative k_{vert} asymmetry (r_s (80) = -.24, $p < .05$) in G3; and maximal sprint velocity and step length asymmetry in G4 and G5 (r_s (60) = -.28, $p < .05$ and r_s (63) = -.28, $p < .05$, respectively).

The percentiles for the magnitudes of asymmetry for each variable across the whole sample are provided in table 5.

****Table 5 about here****

Discussion

The aim of this study was to establish the influence of age and maturation upon the magnitude of asymmetry that exists during maximal sprint performance in boys. It would appear that the magnitude of asymmetry in most spatiotemporal, force and stiffness measures were similar across groups of boys with contrasting chronological and maturational ages. No strong relationships between the magnitude of asymmetry and maximal sprint velocity were evident and no differences in sprint velocity were found across asymmetry percentile groups for the majority of variables assessed in this study.

Comparison of the range of mean asymmetry across chronological and maturational age groups and all variables (2.3-12.6%) is problematic due to the differing approaches to data acquisition and calculations of asymmetry employed in the current youth literature. Maximal force data from the present study (2.3-3.7%) was lower than that reported for horizontal and vertical force in studies from a similar population (14.7 – 15.4%), although calculations of asymmetry in this study did not account for inter-participant differences in limb dominance, and a non-motorized treadmill was used for data acquisition (49). This method results in reduced peak running velocities compared to the overground conditions that were utilised in the present study (33,48). Furthermore, no spatiotemporal or kinematic variables were reported in their study and although further data pertaining to asymmetry in kinetic, kinematic and spatiotemporal sprint variables are available (3,13), all other existing studies have utilized adult populations. The majority of variables reported fell within or below the 10-15% threshold that may be considered normal and acceptable (18,19,30,41), with the exception of flight time and relative k_{vert} at the 90th percentile and relative k_{leg} at the 75th and 90th percentiles; however any direct comparison of data is again made difficult due to differing methodological approaches that have been utilised and populations studied.

Quantification of the magnitude of asymmetry has been suggested to be of value for the monitoring of recovery following ACL reconstruction in youth populations (22), and also may be predictive of reoccurrence of ACL injury (42). It has further been suggested that asymmetry exceeding 10-15% (18,19,30,41) may be a threshold that represents heightened injury risk; however, it is clear from previous research (3,13,49) and the data presented in this study that the magnitude of asymmetry varies considerably depending upon a number of methodological factors.

The data presented within this study serves as a novel benchmark for the magnitude of asymmetry in male youth, while the presentation of percentile data facilitates an improved understanding of the normal magnitudes of asymmetry in youth populations. Given the high proportion of pelvic and lower limb injuries that youth athletes sustain during sprinting (45), the ability to measure asymmetry in a functionally relevant sprint task is appealing, with technological advances making such measures more accessible. It may be that sprint asymmetry provides a more direct predictor of injury risk than less functionally specific tasks of asymmetry, such as jumping, but further research is needed to confirm this proposition.

The results across the chronological age groups suggested that the magnitude of asymmetry is relatively similar across different age groups, with the exception of relative k_{leg} that showed a temporary increase in the magnitude of asymmetry in the U13 group. The reason for relative k_{leg} showing fluctuations in asymmetry, despite no significant change in other variables, remains unclear; however other studies in youth populations have reported decrements in leg stiffness between the ages of 10-12 years during bilateral hopping tasks (25) and in the year before PHV during sprinting (43), with the phenomenon of 'adolescent awkwardness' provided as a rationale for these performance decrements. Such an explanation would seem a plausible rationale for changes in asymmetry based upon observed decrements in motor control and performance that may be derived from differential timings of the growth spurt in the legs and trunk (28,43); however as this decrement in asymmetry was not observed in maturation groups, the precise mechanisms remain unclear.

The results also indicated that the magnitude of asymmetry was similar between maturational groups, indicating that maturation may not influence the magnitude of asymmetry in the variables assessed in this study. It has been suggested that maturation influences sprint speed as well as the associated spatiotemporal (33), kinematic and kinetic (46) determinants in youth. It has been proposed that this influence may result from greater movement variability and physiological differences associated with maturation (28,56). The results from this study may also suggest that the magnitude of asymmetry in sprint performance may be largely pre-determined by the age of 11 years old, and remain stable thereafter. Such a theory may align with the evidence that gait variability in youth may be equal to adult values by 11-14 years of age (15); however these data include both male and female participants and further research into asymmetry during maximal sprinting in younger male participants (< 11 years old) is warranted to substantiate these propositions.

The relationships between asymmetry and performance have often been debated, with the suggestion that some level of asymmetry may be considered a normal consequence of sports performance (58) and movement variability may actually be encouraged for improved sprint performance (6). Conversely, some evidence suggests that greater asymmetry during jumping results in slower sprint times (50). The results of this present study suggested that there were no strong relationships between the maximal sprint velocity achieved and the magnitude of asymmetry in almost all the variables assessed. This would suggest that the magnitude of asymmetry might not be an important aspect of higher levels of sprint performance.

Given that the relationships between variables that reached significance were inconsistent across all maturation groups, these data might imply that the nature of the relationship between asymmetry and performance may be differential depending on the stage of maturation, however the strength of the relationships reported are weak, and further longitudinal training studies would be required to assess the relevance of these observations.

The results presented should be viewed in light of the limitations of the study. Firstly, although a large cohort of boys was recruited, the cross-sectional nature of the analysis may result in different interpretations of the impact of growth and maturation upon performance compared to longitudinal studies (56). Secondly, although the spatiotemporal data in this study were measured directly via the optical measurement system, force and stiffness data were modeled rather than directly measured. In this instance, force plate instrumentation was not viable for testing a large cohort in a school setting and all modeling equations have been previous validated as an acceptable practical alternative (37).

In summary, the results of this study provide a novel benchmark for the expected magnitude of asymmetry in a large cohort of uninjured boys during maximal sprint performance. Such data are important for all members of multi-disciplinary teams working with youth populations as they provide guidance on the expected levels of asymmetry during overground maximal sprint performance over a range of important spatiotemporal, force and stiffness variables. Furthermore, asymmetry in the majority of variables associated with sprint performance appear to be largely unaffected by age or maturation. Therefore, practitioners monitoring asymmetry during sprinting with youth populations should not expect large deviations in the magnitude of asymmetry with advancing age and maturation. The impact of acute or chronic changes in the magnitude of asymmetry during sprinting is currently unknown; however based upon the data presented in this study, changes in asymmetry would not be expected as part of natural growth and development in boys aged 11-16 years old. On this basis future research should aim to evaluate the longitudinal trends in the magnitude of asymmetry during sprint performance in youth, and seek to establish thresholds for specific variables and data collection techniques where the magnitude of asymmetry poses a heightened risk of injury occurring. Finally, no strong relationships exist between the magnitude of asymmetry and maximal sprint velocity in youth and therefore asymmetry may be considered a normal part of maximal sprinting that appears to not exert influence upon maximal sprint velocity in boys.

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Table 1. Participant characteristics according to chronological age group (Mean ± SD).

	U12	**U13**	**U14**	**U15**	**U16**
n	85	77	70	70	42
Age (years)	11.5 ± 0.3*	12.5 ± 0.3*	13.5 ± 0.3*	14.5 ± 0.3*	15.5 ± 0.3*
Height (m)	1.46 ± 0.07*	1.52 ± 0.08*	1.58 ± 0.08*	1.65 ± 0.08*	1.71 ± 0.10*
Mass (kg)	41.2 ± 9.2*	47.3 ± 11.5^	53.1 ± 14.0^	61.4 ± 14.7$^{\#}$	65.1 ± 16.8$^{\#}$
Maturity offset (years)	-2.3 ± 0.5*	-1.7 ± 0.6*	-0.8 ± 0.7*	0.2 ± 0.7*	1.1 ± 0.9*

Key: * = Significantly different to all other groups, *p* < .05; ^ = Significantly different to U12, U15 and U16 year groups, *p* < .05, $^{\#}$ = Significantly different to U12, U13 and U14 year groups, *p* < .05.

Table 2. Participant characteristics according to maturation group (Mean ± SD).

	G1	**G2**	**G3**	**G4**	**G5**
n	37	104	80	60	63
Age (years)	11.5 ± 0.4*	12.1 ± 0.7*	13.2 ± 0.8*	14.3 ± 0.7*	15.0 ± 0.8*
Height (m)	1.39 ± 0.05*	1.48 ± 0.05*	1.58 ± 0.05*	1.65 ± 0.05*	1.73 ± 0.07*
Mass (kg)	33.8 ± 4.5*	42.8 ± 7.6*	53.6 ± 9.7*	60.0 ± 10.1*	70.8 ± 15.6*
Maturity offset (years)	-2.8 ± 0.3*	-2.0 ± 0.3*	-1.0 ± 0.3*	0.0 ± 0.3*	1.1 ± 0.8*

Key: * = Significantly different to all other groups, *p* < .05.

Table 3. The magnitude of asymmetry (%) between legs for participants in different chronological age groups.

	U12	**U13**	**U14**	**U15**	**U16**
Speed	3.6 ± 2.7	4.2 ± 3.5	3.1 ± 2.3	3.1 ± 2.9	2.8 ± 1.8
Step length	2.7 ± 2.0	3.8 ± 4.1	2.5 ± 2.2	3.5 ± 3.0	2.4 ± 2.6
Step frequency	3.5 ± 2.8	4.2 ± 3.0	3.4 ± 2.4	3.1 ± 2.5	3.5 ± 2.6
Contact time	3.7 ± 2.9	2.9 ± 2.4	3.0 ± 2.3	3.1 ± 2.2	3.0 ± 2.4
Flight time	6.1 ± 4.1	7.7 ± 5.3	5.8 ± 3.7	6.4 ± 5.2	6.9 ± 6.1
Relative F_{max}	3.1 ± 2.0	3.3 ± 2.6	2.3 ± 1.9	3.4 ± 2.6	3.4 ± 3.1
Relative k_{vert}	6.6 ± 5.1	6.1 ± 4.6	5.8 ± 4.2	5.2 ± 3.9	5.6 ± 3.9
Relative k_{leg}	9.0 ± 7.8*	12.6 ± 8.3^	8.0 ± 6.9*	9.9 ± 7.3	10.6 ± 7.9

Key: F_{max} = modeled peak ground reaction force, k_{vert} = vertical stiffness, k_{leg} = leg stiffness, * = significantly different to U13 group (*p* < .05), ^ = Significantly different to U13 and U14 group (*p* < .05).

Table 4. The magnitude of asymmetry (%) between legs for participants in different maturation groups.

	G1	G2	G3	G4	G5
Speed	3.6 ± 3.2	3.8 ± 2.7	3.7 ± 3.4	2.9 ± 2.2	3.1 ± 2.3
Step length	3.1 ± 3.4	3.1 ± 2.9	3.0 ± 3.0	2.6 ± 2.4	3.3 ± 3.1
Step frequency	3.7 ± 2.8	4.1 ± 2.9	3.2 ± 2.6	3.2 ± 2.6	3.4 ± 2.5
Contact time	4.0 ± 3.3	3.4 ± 2.6	2.9 ± 2.1	2.8 ± 2.2	3.1 ± 2.3
Flight time	5.7 ± 3.8	7.1 ± 4.8	6.1 ± 4.6	5.7 ± 4.5	7.4 ± 5.8
Relative F_{max}	3.2 ± 2.0	3.2 ± 2.4	2.6 ± 2.1	2.7 ± 2.3	3.7 ± 2.9
Relative k_{vert}	6.9 ± 5.7	6.7 ± 4.6	5.4 ± 4.1	5.1 ± 4.1	5.3 ± 3.7
Relative k_{leg}	9.8 ± 7.3	10.1 ± 7.9	10.2 ± 8.5	8.5 ± 6.0	10.9 ± 8.4

Key: F_{max} = modeled peak ground reaction force, k_{vert} = vertical stiffness, k_{leg} = leg stiffness.
Note: No significant differences (*p* > .05) shown between all groups for each variable listed.

Table 5. Percentiles for the magnitude of asymmetry (%) in spatiotemporal, force, displacement and stiffness variables for the whole sample.

	10th	25th	50th	75th	90th
Speed	0.5	1.3	3.0	4.7	7.1
Step length	0.4	1.0	2.3	4.2	6.8
Step frequency	0.5	1.2	3.1	5.2	7.2
Contact time	0.4	1.2	2.7	4.6	6.6
Flight time	1.1	2.7	5.6	9.3	13.5
Relative F_{max}	0.5	1.1	2.6	4.5	6.5
Relative k_{vert}	1.1	2.3	4.9	8.6	12.0
Relative k_{leg}	1.8	4.5	7.9	13.9	20.3

Key: F_{max} = modeled peak ground reaction force, k_{vert} = vertical stiffness, k_{leg} = leg stiffness.