INTRODUCTION

Sprint running is a fundamental motor skill required to be successful not only in sprint events within track and field, but also in many team sports. Longitudinal analyses have shown sprint ability to develop rapidly across preadolescence in both boys\(^1\)-\(^3\) and girls,\(^3\) driven by increases in muscle mass and the development of the nervous system.\(^3\) A second period of rapid development in sprint ability occurs in boys around
12-15 years of age at the time (or shortly after) the adolescent growth spurt is typically exhibited. However, this second phase of accelerated development may not necessarily occur in girls. Although both sexes will exhibit increases in muscle mass across this phase, girls will naturally accrue greater fat mass during puberty, compromising their force-generating capacity relative to body mass and therefore sprint capacity.

The aforementioned growth-related gradient of the development of sprint ability, which has been attributed to increases in propulsive forces and step length, implicates maturity status as an important factor to consider when assessing junior athletes’ progression. Indeed, early-maturing Belgian soccer players have been shown to have higher sprint performance levels compared with on-time or late-maturing players of the same chronological age. The adolescent growth spurt begins on average around the ages of 10 (girls) and 12 (boys) years in European children, but this is generally 1-2 years earlier in Japanese children, with peak height velocity (PHV) occurring approximately two years after this onset of growth. However, maturation timing and tempo is highly individual with some individuals maturing in advance or delay of their same-age peers. Accordingly, given the aforementioned links between growth and sprint performance, studies have called for maturity status to be assessed, monitored, and accounted for within talent identification and athletic development pathways. Indeed, bio-banding strategies (where athletes are matched based on physical attributes rather than chronological age) are already being implemented in sports such as tennis and soccer. Better understanding of the maturity-associated developments in sprint ability could allow practitioners working with youth athletes to more-holistically evaluate an athlete’s ability and progress and to implement similar strategies to reduce maturity-related biases.

The most objective estimation methods for biological maturation (X-ray imaging to obtain skeletal age) are expensive, invasive, and not practical in applied settings. For this reason, non-invasive measures of somatic maturation have been developed and are more commonly used to assess an individual’s biological maturity status in practical settings. An example of such non-invasive estimation methods is that of Mirwald, whereby maturity offset (age from peak height velocity [PHV]) is estimated using anthropometric measurements (height, sitting height, and weight) and validated regression equations. Age at PHV enables researchers or practitioners to consider each individual’s maturation status and timing, which allows more accurate assessment and monitoring of athletic development.

The ground reaction forces applied during sprinting dictate acceleration of the centre of mass (ignoring air resistance) and are therefore fundamental to understanding how a given sprint performance is achieved. While previous studies have investigated the ground reaction forces produced during sprinting by both boys and girls across different chronological ages, to our knowledge, no study has considered the influence of maturity status. This study aimed to elucidate the kinetic factors which explain the changes in sprinting performances that occur across biological maturation in Japanese boys and girls.

2 | METHODS

2.1 | Participants

One hundred and fifty-three Japanese schoolchildren (80 boys and 73 girls) without previous sprint training were recruited to participate in this study [mean (SD), range: age = 9.4 (1.6) years, 6.6-12.1 years; height = 1.32 (0.10) m, 1.11-1.59 m; mass = 29.8 (7.7) kg, 19.2-56.8 kg]. An institutional research ethics committee approved this study, and all participants and their parents provided written informed consent prior to the commencement of the study.

2.2 | Procedure

Anthropometric data (standing height, sitting height, and mass) were collected using a stadiometer and domestic scale prior to the completion of a teacher-led warm-up including stretching and two 30-m practice sprints. For the height measurements, participants were asked to sit or stand upright and look straight ahead, with their trunk touching the back bar of the stadiometer. Participants then each performed one or two 50-m maximal effort sprints on an indoor running track. Each child wore their own sports shoes and started from a standing position 0.5 m behind the start line. A long force platform system consisting of 52 force platforms (1000 Hz; TF-90100, TF-3055; Tec Gihan, Uji, Japan) was used to collect the three-dimensional ground reaction forces produced through a 51-m section from 1 m behind the start line to the 50-m mark (see Nagahara and Morin for schematic of the force platform system). Participants were verbally encouraged to maintain maximal effort throughout the entire sprint. Unfortunately, some trials were unusable due to children stepping outside the force platforms or other problems occurring in data collection. However, all participants recorded at least one valid run. In the cases where two acceptable trials were recorded, data from only the faster trial were analysed.

2.3 | Data processing

Anthropometric data (height, sitting height, and mass) were combined with age to allow a non-invasive estimate the maturity offset to be obtained according to previously validated
sex-specific equations, and this offset was then added to the participant’s current age to provide an estimated age of PHV. The children were then categorised into maturation groups according to their estimated maturity offset: 5.5 to 4.5 years before PHV (group 1), 4.5 to 3.5 years before PHV (group 2), 3.5 to 2.5 years before PHV (group 3), 2.5 to 1.5 years before PHV (group 4), 1.5 to 0.5 years before PHV (group 5), and 0.5 years before PHV to 0.5 years after PHV (group 6).

Force data were firstly filtered using a fourth-order low-pass Butterworth filter with a 70-Hz cutoff frequency derived through residual analysis. Resultant force was computed using the antero-posterior and vertical forces. A 20-N threshold of force in the vertical direction was used to detect touchdown and take-off. As the lowest number of steps taken by any individual was 26, comparisons were made across these steps only. Average step velocity was calculated as the product of step length and step frequency, which were extracted from the spatiotemporal force platform data, as described by Colyer, Nagahara, and Salo. It was not possible to use the force data to calculate velocity directly due to some children clearly moving at the start of the trial. Mean ground reaction forces produced across each contact period were computed.

2.4 | Statistical analysis

One-way ANOVA was used to investigate the effect of maturation group on maximum and average velocities. To assess the groups between which differences could be observed, post hoc group comparisons were conducted using standardised differences (the mean difference divided by the pooled standard deviation), with a smallest worthwhile effect of ±0.2. Effect sizes were also used to assess step-by-step differences in ground reaction force variables and contact time between consecutive maturation groups when differences in maximum or average velocities were detected. The magnitudes of the effect sizes were interpreted on the following scale: <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2, moderate; 1.2 to 2.0, large; and >2.0, very large. Effects were deemed clear if the effect was larger than the smallest worthwhile effect (in either direction) and the 90% confidence intervals (CI) did not overlap the opposite smallest worthwhile threshold.

When differences in mean force production across a contact were detected, statistical parametric mapping (SPM) was used to assess which parts of the ground reaction force waveforms were different using open-source SPM 1D software. Force data were firstly normalised to 101 nodes (101% stance) before SPM two-sample t-tests were applied to each of the 101 nodes resulting in a SPM t curve. Using random field theory, which describes probabilistic behavior of random curves and accounts for the smoothness of the data, a critical threshold ($\alpha = 0.05$) was set (above which only 5% of random curves with the same smoothness would exceed). If the SPM t curve exceeded the critical threshold, the force at those specific nodes was deemed to be significantly different between groups. Finally, the probability that the observed supra-threshold regions of the SPM t curve with the same geometry could have resulted from repeated samplings of equally smooth random curves was computed.

3 | RESULTS

Across maturation groups, mean values for height, mass, average velocity, and maximum velocity all progressively increased in both boys and girls, as shown in Table 1. Only one girl was categorised into maturation group 1 and only one boy fell within maturation group 5. Thus, data from these participants were excluded from subsequent analyses. Maximum and average velocity increased significantly ($P < .001$) between maturation groups 1 (5.23 and 4.72 m/s, respectively) and 2 (5.88 and 5.33 m/s, respectively) in the boys (effect sizes ± 90% CI = 1.63 ± 0.69 and 1.69 ± 0.52, respectively). Conversely, the only statistically significant change in maximum velocity between consecutive maturation groups in girls was observed between groups 4 and 5 (5.45 vs 5.94 m/s), with a moderate-large post hoc effect size ($P = .04$; effect size ± 90% CI = 1.00 ± 0.78) observed. No statistically significant changes were observed in average velocity across consecutive maturation groups in the girls; however, a moderate-large effect size (effect size ± 90% CI = 0.96 ± 0.82) was observed between maturation groups 5 (5.45 m/s) and 6 (5.60 m/s). Additionally, the maximum velocity of the boys exceeded that of the girls at the same maturity status (maturation groups 2 to 4, effect sizes ± 90% CI ranged from 1.43 ± 0.29 to 2.00 ± 0.35). The step-averaged velocity profiles for each maturation group are provided in Figure 1.

The rates of change in height and mass across consecutive maturation groups indicated that the greatest change in height was between maturation groups 1 and 2 for the boys (0.09 m/years), and between maturation groups 4 and 5 and maturation groups 5 and 6 for the girls (0.10 m/years), the latter coinciding with the estimated PHV for girls. Similarly, for the girls, the greatest change in mass across maturation groups was between maturation groups 5 and 6 (10.1 kg/years). The mass changes in boys were, however, less pronounced compared with the girls across the maturation groups studied here (maximum rate between groups 2 to 3, 5.2 kg/years).

A bell-shaped pattern within the estimated ages at PHV was observed for both girls and boys (Figure 2), with the estimated age at PHV typically being later in boys (12.9 ± 0.7 years) than girls (11.8 ± 0.5 years).

The mean ground reaction forces produced by the two consecutive maturation groups where the differences in maximum and
average velocities were observed are presented in Figure 3 (maturation groups 1 and 2 for boys) and Figure 4 (maturation groups 4 and 5 for girls). Improvements between maturation groups 1 and 2 were accompanied by higher mean antero-posterior forces during early acceleration (mean effect size across first six steps = 0.90 ± 0.53). Additionally, higher resultant force production accompanied by reduced contact times were observed as participants approached maximum velocity (mean effect size across steps 12 to 18 = 0.58 ± 0.54 and −0.48 ± 0.54, respectively).

The specific phases of stance where force production differences were observed between the boys in maturation groups 1 and 2 primarily occurred during late braking phase and early-mid propulsion. As there are too many variables and steps to show all of the comparisons, Figure 5 presents typical examples of the differences. On this occasion, antero-posterior forces produced across steps 4 and 20 are shown, with higher antero-posterior forces observed in maturation group 2 compared to group 1 (14%-77% stance; Figure 5). Interestingly, during the maximum velocity phase (step 20), higher antero-posterior forces during the early braking phase (6%-8% stance) and mid-propulsion (61%-78% stance) were also found in maturation group 2 compared with maturation group 1 (Figure 5).

Conversely, the development of maximum velocity between maturation groups 4 and 5 for the girls (where the greatest differences in sprint performance across maturation groups were observed) appeared to be less attributable to improvements in mean force production (mean effect size ± 90% CI for resultant force production across all 26 steps = −0.002 ± 0.64 in comparison with 0.48 ± 0.54 for the boys). However, there was evidence for increased ground contact time, particularly across the acceleration phase (Figure 4).

There was some evidence for similar developments in the force waveforms in the girls compared to those observed in the boys, with higher antero-posterior forces during the braking phase observed during acceleration (Figure 6). However, these differences were not statistically significant (steps 4 and 7 shown in Figure 6).
This study has identified specific aspects and phases of force production that appear to be affected by maturity status in the period leading to PHV. For the boys studied here (from 5.5 to 1.5 years before PHV), there was evidence for one period of accelerated development in sprint ability (between those 5.5 and 4.5 years before PHV [group 1] and those between 4.5 and 3.5 years before PHV [group 2]). Conversely, for the girls (whose maturity status ranged from 4.5 years before PHV to 0.5 years after PHV), a difference in ground reaction force production and therefore sprint performance was observed between those 2.5 and 1.5 years before PHV (group 4) and those between 1.5 to 0.5 years before PHV (group 5). Across these respective periods of development, maximum velocity increased by 12.4% for the boys and 9.0% for the girls. These progressions in sprint capacity were closely aligned with periods of accelerated growth. Additionally, these were associated with improvements in antero-posterior force production allowing more effective reversal of the braking phase to more rapidly generate higher propulsive impulse.

Collectively, previous research has revealed two general periods of rapid development (from ages 5–8 years and age 11/12 onwards, the latter occurring around PHV) using both cross-sectional and longitudinal study designs. Given the limited age ranges of participants in this study and due to the fact that girls on average mature earlier than boys, only one of these periods of rapid development was captured for each sex in this study. Nevertheless, the mean ages of the groups where differences were observed in this study (see Table 1) seem to align with this aforementioned previous research.

The period of development in sprint ability for girls in this study was, however, slightly earlier (around 10–11 years, equating to 2.5 to 1.5 years before PHV) than previously found. Yague and De La Fuente previously suggested that the changes in sprint ability coincide with changes in height and mass for both sexes. Indeed, the girls in this study exhibited the greatest increases in height between maturation groups 4 and 5 and groups 5 and 6 (0.10 and 0.09 m/years, respectively; Table 1). Perhaps importantly, however, is the observed concomitant large increase in mass between groups 5 and 6 (10.1 kg/years...
Accrual of fat mass around PHV is a well-known consequence of maturation in girls, which may compromise relative force generating capacity. This potentially underpins the lack of increase in sprint capacity at PHV in the girls studied here.

A clear pattern in the stance-averaged ground reaction forces was observed for the differences between the boys in maturation groups 1 and 2 (Figure 3). Increased (resultant) force production was also clear particularly across initial acceleration and following maximum velocity attainment. More specifically, antero-posterior force production during early acceleration and vertical force production during the maximum velocity phase were enhanced (effect sizes = 0.90 and 0.54, respectively), and this seemed to be associated with shorter contact durations (effect size = −0.48). Each of these adaptations are known to be advantageous for sprint performance, where the ability to produce high forces across the short contact phases is associated with higher maximum velocity during treadmill sprinting and high antero-posterior force production dictates accelerative capacity. The likely drivers of the observed adaptations across maturation groups include increased muscle cross-sectional area, particularly of the knee extensors and hip flexors, increased pennation angle, and neural factors. These maturation-related differences have important implications for the evaluation of sprint performance and talent identification in youth.
Thus, individual differences in maturation and growth should be taken into account (potentially using concepts such as bio-banding) in order to holistically evaluate youth sprinters’ abilities and more effectively prescribe training.

When the entire ground reaction force waveforms were examined, notable changes in antero-posterior force production were observed. Across early acceleration (e.g., fourth step shown in Figure 5), boys in maturation group 2 seemed to be able to reverse high eccentric braking forces more effectively than those in maturation group 1 and to generate higher antero-posterior forces in the early-to-mid propulsive phase (differences observed from 14%-77% of stance). Additionally, at maximum velocity (step 20 shown in Figure 5), there was evidence for increased initial braking forces in the early braking phase, but reduced braking forces in the late braking phase from maturation groups 1 to 2. This was accompanied by enhanced force production during mid-propulsion. Collectively, these results perhaps implicate enhanced stretch shortening ability as a potential mechanism for these maturation-specific enhancements. In fact, previous studies have observed improved utilisation of the stretch-shortening cycle across maturation during hopping and jumping tasks. Moreover, increases from pre- to post-PHV in leg stiffness, maximal force, and leg stiffness during sprinting have been shown to account for 83% of the changes in maximum 30-m sprinting performance, which could be related to enhanced
capacity to rapidly reverse braking forces. The mechanisms behind such adaptations could include the previously observed age-related increases in musculotendon unit stiffness\(^3\) and enhanced stretch reflex\(^2\) in children. The finding of increased propulsive impulse, which may be augmented by the aforementioned enhanced stretch-shortening ability, mirrors that of previous studies\(^5\) where this was associated with age-related sprint performance enhancements due to increased step length.

Across the period of apparent accelerated development in girls between maturation groups 4 (2.5 to 1.5 years before PHV) and 5 (1.5 to 0.5 years before PHV), the changes in mean force production did not appear to follow the same pattern as that of the boys and the effect sizes were largely trivial or small (Figure 4). This could be explained by the observed increase in ground contact time across the entire acceleration phase, which collectively would result in higher horizontal impulses being produced, if force production did not decrease (which overall it did not seem to; Figure 4).

Previous findings have also indicated superior running velocities in boys compared with girls at the same chronological age.\(^2\) The current findings confirm that this is also the case when adjusted for maturity status (Table 1). When children reach Tanner (a sexual maturity scale) stage 2 (approximately age 9-11 in Japanese children; Matsuo\(^3\)), circulating levels of testosterone are higher in boys than girls, which provides a likely explanation for differences in athletic ability across sexes certainly across maturation groups 3 and 4 in this study. Circulating testosterone is widely known to play an important role in regulation of pubertal growth and lean mass accrual in boys,\(^3\) but may also influence motor function via short-term mechanisms.\(^2\) Nonetheless, this does not explain the sex differences in sprint performance across
maturation groups 2 (when girls and boys were around 7.5 and 8.5 years old, respectively, and have similar circulating testosterone levels). It has been suggested that Japanese boys tend to have higher exposure to athletic activities and exercise during childhood than Japanese girls and therefore could be considered more likely to acquire higher levels of skill during these years. More research is required to fully elucidate the reasons behind these sex differences.

It is important to acknowledge the limitations of this study, which primarily involve the estimation of maturity offset from anthropometric measures. This provided a non-invasive, practical means to estimate maturity status and is a validated method which has been shown to be applicable in average maturing children. However, the accuracy of this estimation is lower for early or late maturing individuals and individuals who are further away from their age at PHV (ie, younger and older youth). Additionally, these equations are based on data from a sample of Canadian children and subsequent cross-validated using data from Flemish children. Thus, the generalisability to Japanese children is unknown. For these reasons, the children in this study were categorised into year-long maturation groups to somewhat alleviate the effect of these known inaccuracies on the maturity offset calculation. We strongly recommend practitioners consider this uncertainty when calculating individuals’ maturity offsets. Nonetheless, the estimated age of PHV along with the height and weight growth changes with age seem to align well with longitudinal data from Japanese populations, which suggest that Japanese children mature 1-2 years earlier (~11-12 years in boys and ~10-11 years in girls) than their European counterparts. Additionally, the bell-shaped curve of predicted ages at PHV (Figure 2) provides some confidence that the estimation methods did not introduce considerable biases or skews in the data.

The cross-sectional nature of this study also somewhat limits the conclusions that can be drawn as individual variation in sprint ability (excluding that due to maturation differences) could influence the results. Nonetheless, this is a unique dataset from a large number of untrained schoolchildren who will have been exposed to a similar level of physical education and sports participation, and so we believe these results to primarily reflect the natural

**FIGURE 6** Mean ± SD antero-posterior force waveforms produced by girls in maturation groups 4 (red) and 5 (black) during the second (top left panel) and seventh step (top right panel) and SPM two-sample t-test outputs for the differences between groups (groups 4 vs 5; bottom panels).
development in sprint ability across stages of maturation. Longitudinal studies of ground reaction force production during sprinting, whereby the same individuals are tracked across childhood and adolescence, would greatly add to this field.

**PERSPECTIVE**

Sprint ability and the ground reaction force production that underpins sprint-running performance are affected by maturity status. This study suggests that boys undergo a period of accelerated development in sprint performance around 4.5-5 years before their maximum rate of growth (PHV). Conversely, a development of sprint ability in the girls studied here (who were of similar chronological age but more advanced maturity status) occurred around 1.5-2 years before PHV. In both cases, this appears to be mediated by rapid increases in height and (likely lean) mass. However, improvements in the ability to more effectively reverse the braking forces and better-utilise a stretch-shortening cycle to generate higher propulsive forces in early-mid propulsion were also apparent, particularly in young boys. These findings further highlight the importance of assessing, monitoring, and considering individual differences in growth and maturation in youth athletes.\(^\text{14,15}\) It should be noted that the most beneficial training methods for youth athletes at these various maturation stages remains to be elucidated. However, this study provides further support for bio-banding approaches aimed to not only improve the assessment, selection, and talent identification of youth athletes but also to improve youth sport participation experiences as a whole.

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**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

**ORCID**

Steffi L. Colyer \(\text{https://orcid.org/0000-0002-4973-6591}\)

Ryu Nagahara \(\text{https://orcid.org/0000-0001-9101-9759}\)

Aki I.T. Salo \(\text{https://orcid.org/0000-0002-8055-2854}\)

**REFERENCES**

1. Meyers RW, Oliver JL, Hughes MG, Cronin JB, Lloyd RS. Maximal sprint speed in boys of increasing maturity. *Pediatr Exerc Sci*. 2015;27:85-94.

2. Philippaerts RM, Vaeyens R, Janssens M, et al. The relationship between peak height velocity and physical performance in youth soccer players. *J Sports Sci*. 2006;24:221-230.

3. Viru A, Loko J, Harro M, Volver A, Laaneots L, Viru M. Critical periods in the development of performance capacity during childhood and adolescence. *Eur J Phys Educ*. 1999;4:75-119.

4. Meyers RW, Oliver JL, Hughes MG, Lloyd RS, Cronin JB. The influence of maturation on sprint performance in boys over a 21-month period. *Med Sci Sports Exerc*. 2016;48:2555-2562.

5. Nagahara R, Takai Y, Haramura M, et al. Age-related differences in spatiotemporal variables and ground reaction forces during sprinting in boys. *Pediatr Exerc Sci*. 2018;30:335-344.

6. Towlson C, Cobley S, Parkin G, Lovell R. When does the influence of maturation on anthropometric and physical fitness characteristics increase and subside? *Scand J Med Sci Sports*. 2018;28:1946-1955.

7. Nagahara R, Haramura M, Takai Y, et al. Age-related differences in kinematics and kinetics of sprinting in young female. *Scand J Med Sci Sports*. 2019;29:800-807.

8. Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev*. 1988;16:503-540.

9. Rommers N, Mostaert M, Goossens L, et al. Age and maturity related differences in motor coordination among male elite youth soccer players. *J Sports Sci*. 2019;37:196-203.

10. Taranger J, Hägg U. The timing and duration of adolescent growth. *Acta Odontol Scand*. 1980;38:57-67.

11. Nakano T, Sei M, Ewis AA, Munakata H, Onishi C, Nakahori Y. Weight and height growth velocities of Japanese boys and girls between age 7 and 14 years: a critical window for early adolescent overweight risk. *J Med Invest*. 2010;57:124-132.

12. Romann M, Cobley S. Relative age effects in athletic sprinting and corrective adjustments as a solution for their removal. *PLoS ONE*. 2015;10:e0122988.

13. Jones MA, Hitchen PJ, Stratton G. The importance of considering biological maturity when assessing physical fitness measures in girls and boys aged 10 to 16 years. *Ann Hum Biol*. 2000;27:57-65.

14. Cumming SP, Lloyd RS, Oliver JL, Eisenmann JC, Malina RM. Bio-banding in sport: applications to competition, talent identification, and strength and conditioning of youth athletes. *Strength Cond J*. 2017;39:34-47.

15. Malina RM, Cumming SP, Rogol AD, et al. Bio-banding in youth sports: background, concept, and application. *Sports Med*. 2019;49:1671-1685.

16. Mirwald RL. An assessment of maturity from anthropometric measurements. *Med Sci Sports*. 2002;34:689.

17. Nagahara R, Morin J-B. Sensor insole for measuring temporal variables and vertical force during sprinting. *Proc Inst Mech Eng P J Sport Eng Technol* 2018;232:369-374.

18. Colyer SL, Nagahara R, Salo AIT. Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms. *Scand J Med Sci Sports*. 2018;28:1784-1792.

19. Hopkins WG, Marshall SW, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41:3-12.

20. Pataky TC. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin*. 2012;15:295-301.

21. Papaiaakovou G, Giannakos A, Michailidis C, et al. The effect of chronological age and gender on the development of sprint
performance during childhood and puberty. *J Strength Cond Res*. 2009;23:2568-2573.

22. Yague PH, De La Fuente JM. Changes in height and motor performance relative to peak height velocity: A mixed-longitudinal study of Spanish boys and girls. *Am J Hum Biol*. 1998;10:647-660.

23. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol*. 2000;89:1991-1999.

24. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol*. 2012;112:3921-3930.

25. O’Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. Muscle-tendon structure and dimensions in adults and children. *J Anat*. 2010;216:631-642.

26. Tottori N, Suga T, Miyake Y, et al. Hip flexor and knee extensor musclearity are associated with sprint performance in sprint-trained preadolescent boys. *Pediatr Exerc Sci* 2018;30:115.

27. Binzoni T, Bianchi S, Hanquinet S, et al. Human gastrocnemius medialis Pennation Angle as a Function of Age: From Newborn to the Elderly. *J Physiol Anthropol Appl Human Sci*. 2001;20:293-298.

28. Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, Lloyd RS. The influence of growth and maturation on stretch-shortening cycle function in youth. *Sports Med*. 2018;48:57-71.

29. Lloyd RS, Oliver JL, Hughes MG, Williams CA. Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol*. 2012;22:37-43.

30. Lloyd RS, Oliver JL, Hughes MG, Williams CA. The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in Pre and Postpubescent boys. *J Strength Cond Res*. 2011;25:1889-1897.

31. Lambertz D, Mora I, Grosset JF, Péro C. Evaluation of musculo-tendinous stiffness in prepubertal children and adults, taking into account muscle activity. *J Appl Physiol*. 2003;95:64-72.

32. Grosset JF, Mora I, Lambertz D, Perot C. Changes in stretch reflexes and muscle stiffness with age in prepubescent children. *J Appl Physiol*. 1985;2007(102):2352-2360.

33. Matsuo N. Skeletal and sexual maturation in Japanese children. *Clin Pediatr Endocrinol*. 1993;2:1-4.

34. Delemarre-van de Waal HA, van Coeverden SC, Rotteveel J. Hormonal determinants of pubertal growth. *J Pediatr Endocrinol Metab*. 2001;14(Suppl 6):1521-1526.

35. Crewther BT, Cook C, Cardinale M, Weatherby RP, Lowe T. Two emerging concepts for elite athletes: The short-term effects of testosterone and cortisol on the neuromuscular system and the dose-response training role of these endogenous hormones. *Sports Med*. 2011;41:103-123.

36. Chen X, Sekine M, Hamanishi S, et al. Lifestyles and health-related quality of life in Japanese school children: a cross-sectional study. *Prev Med*. 2005;40:668-678.

37. Mills K, Baker D, Pacey V, Wollin M, Drew MK. What is the most accurate and reliable methodological approach for predicting peak height velocity in adolescents? A systematic review. *J Sci Med Sport*. 2017;20:572-577.

38. Malina RM, Koziel SM. Validation of maturity offset in a longitudinal sample of Polish boys. *J Sports Sci*. 2014;32:424-437.

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