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The effect of sex, maturity, and training status on maximal sprint performance kinetics

Runacres, A. [1,2], Mackintosh, K.A. [1], McNarry, M.A. [1 *]

[1] Applied Sports, Technology, Exercise and Medicine (A-STEM) Research Centre, Swansea University, United Kingdom

[2] Institute of Sport, Manchester Metropolitan University, Manchester, United Kingdom

*** Corresponding author:**

Professor Melitta McNarry, Email: m.mcnarry@swansea.ac.uk

ORCID ID's:

Runacres, A.: 0000-0002-8251-2805

Mackintosh, K.A.: 0000-0003-0355-6357

McNarry, M.A.: 0000-0003-0813-7477

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Abstract

Purpsose: The development of sprint running during youth has received renewed interest, but fundamental questions remain regarding the development of speed in youth, especially the influences of sex, training, maturity status. *Methods*: 147 team-sport trained (69 girls; 14.3 ± 2.1 years) and 113 untrained (64 girls; 13.8 ± 2.7 years) children and adolescents completed two 30 m sprints separated by two minutes active rest. Velocity was measured using a radar gun at >46 Hz, with power and force variables subsequently derived from a force-velocity-power profile. *Results*: Boys produced a significantly higher absolute peak power (P_{peak}; 741 ± 272 vs. 645 ± 229 W; $p < 0.01$) and force (F_{peak}; 431 ± 124 vs. 398 ± 125 N; $p < 0.01$) than girls, irrespective of maturity and training status. However, there was a greater sex difference in relative mean power and peak velocity in pubertal adolescents (46.9% and 19.8%, respectively) compared to pre-pubertal (5.4% and 3.2%) or post-pubertal youth (11.6% and 5.6%). *Conclusion*: Sprint development in youth is sexually dimorphic which needs considering when devising long-term training plans. Further research is needed to explore the independent, and combined effects of, sex, training, and maturity status on sprint performance kinetics in youth.

Keywords: Children, Adolescents, Performance, Power, Force

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1. Introduction

Over-ground sprint running has become a popular method of performance assessment over the past decade (Meyers et al. 2015; Meyers et al. 2017; Rumpf, Cronin, Oliver & Hughes 2015a; Rumpf et al. 2015b), partly due to the importance of speed in many athletic and sporting activities (Lloyd & Oliver, 2012; Meylan, Cronin, Oliver & Hughes, 2010). Indeed, over-ground sprinting is commonly used within long-term athlete development (LTAD) programs and talent identification test batteries (Meylan et al. 2010; Unnithan et al. 2012). However, despite this increasingly widespread use, fundamental questions remain to be resolved in terms of the development of speed in youth, especially with regards to the influences of sex and maturity, and their interaction with each other and training status.

The development of speed throughout adolescence is a non-linear process with cross-sectional evidence in untrained boys from non-motorised treadmills suggesting that sprint kinetics (i.e., force and power) only significantly increase from pre- to pubertal maturity statuses, displaying a plateau thereafter (Meyers et al. 2015; Meyers et al. 2017; Rumpf et al. 2015). Moreover, early maturing boys demonstrated faster 30 m sprint times than their age-matched average and late maturing counterparts (Rommers et al. 2018). This period of accelerated development is thought to be mediated by changes in anthropometric variables, increases in muscle cross sectional area and neuromuscular adaptations, including improved synchronisation of motor units and recruitment of type II muscle fibres (Dotan et al. 2012; Van Praagh, 2000; van Praagh & Doré, 2002). Similarly, cross-sectional training studies have reported an increased trainability in sprint performance surrounding PHV compared to six-months pre-and-post (Philippaerts et al. 2006; Rommers et al. 2018; Rumpf et al. 2012). More specifically, in a mixed-longitudinal study involving youth footballers, 30 m sprint time was reported to improve by 0.4 s in the six-months surrounding PHV compared to only 0.2 s six-months pre-and-post PHV (Philippaerts et al. 2006).

Whether similar periods of non-linear development in sprint speed are evident in girls is unknown, with little data currently available considering the influence of growth and/or maturation, and their interaction, on sprint performance in girls. In one of the few studies to examine sprint development cross-sectionally in untrained girls, a plateau in peak velocity (V_{peak}) was observed from 12-13 years onwards compared to 15 years in their male peers (Papaiakovou et al. 2009). In a similar cross-sectional design, Nagahara et al. (2019) reported a plateau in V_{peak} at 12.7 years in girls which was attributed to no further increases in step length. However, with no maturity assessment in these studies, whether this plateau is attributable to age per se or rather to concomitant growth and maturation related changes, technique, or kinematic alterations, cannot be elucidated. With no evidence available regarding the development of speed in response to training in girls, further inferences regarding the influence and interaction of sex and training are precluded.

In addition to kinematic factors (i.e., stride length/rate), sprint performance is determined by kinetic parameters such as horizontal and vertical force (Morin, Jeannin, Chevallier, & Belli, 2006; Morinc, Edouard & Samozino, 2011; Rumpf, Cronin, Oliver & Hughes, 2013; Samozino et al. 2016). However, the evidence exploring the kinetic determinants of sprint performance in paediatric populations has predominately been derived from cross-sectional studies and non-motorised treadmills, limiting its generalisability (Rumpf et al. 2012 & 2015a). Moreover, the majority of these studies have focused solely on the development of maximal velocity (Meyers et al. 2015; Meyers et al. 2017; Nagahara et al. 2017; Rumpf et al. 2015a), thereby considering only a small component of sprint performance, or have utilised mean velocity data over a given distance (i.e. 5 meters; Mendez-Villanueva et al. 2010; Papaiakovou et al. 2009). These methodological limitations may be addressed by recent advances in radar technology and macroscopic biomechanical modelling techniques which enable velocity, power and force to be calculated near instantaneously across an entire sprint (Samozino et al. 2016; Simperingham, Cronin & Ross, 2016). Force-velocity-Power (F-v-P) profiling has been validated against force plate data, demonstrating high reliability in elite adult sprinters (Samozino et al. 2016). Additionally, the combination of radar technology and F-v-P profiling has been deemed highly reliable in both trained and untrained paediatric participants (Runacres, Bezodis, Mackintosh & McNarry, 2019). Consequently, such methods could provide important insights to the kinetic parameters underpinning differences in sprint performance according to sex, maturity, and training status.

Therefore, the primary aim of this study was to determine whether the kinetics of sprint performance differ with respect to sex, maturity, and training status. The secondary aims were to determine whether the kinetic determinants of sprint performance differ according to maturity status, and whether non-linear development patterns are evident. It was hypothesised that participants who were male, part of a training group, and more mature would have superior sprint performance compared to females, the control group, and their less mature counterparts, respectively.

2. Methods

Prior to any testing ethical approval was granted by the Swansea University Ethics Committee (approval number: SWA_2019_18). Trained children and adolescents were recruited through the national governing body for Hockey and Football and were competing at a national/international level. Team sport athletes were selected to form the trained group within this study as sprint performance is an integral part of successful performance with youth team sport athletes completing up to 50 near maximal sprints throughout the duration of a match (Buchheit, Mendez-Villanueva, Simpson, & Bourdon, 2010; McLellan & Lovell, 2013). The trained children and adolescents had been training in their sport for 3.0 ± 1.5 years and were currently completing 8 ± 2 hours per week of sport-specific supervised training. Untrained participants were recruited from local schools and were thought not to be involved in any formal exercise training outside of curricular physical education by their teachers.

Statistical power tests indicated that to achieve a power of at least > 0.90, and an alpha of 0.95, a sample size of 208 participants was needed with an even split between trained and untrained groups with a similar spread of sex and maturity status (Rosner, 2011). To account for participant drop-out initially 300 participants were recruited; 40 participants (20 trained) were removed from the study as they did not complete all elements of the study. The final sample consisted of 260 (133 girls) participants, which comprised 147 (14.3 ± 2.1 years; 69 girls) and 113 (13.8 ± 2.7 years; 64 girls) trained and control youth, respectively. Online parent/guardian consent and a medical pre-screening questionnaire were completed using a custom-built online form (Survey Monkey, Dublin, Ireland). Participants were excluded if their parent/guardian reported they had any known cardiovascular, kidney, metabolic, or any other condition that would have prevented them from completing the study protocol. Written informed assent was obtained from each participant prior to data collection. Ethics approval was granted by the institutional ethics committee, with all procedures conforming to the Declaration of Helsinki.

2.1 Experimental Procedures

Standing and sitting stature were measured to the nearest 0.1 cm using a portable stadiometer (Seca 213, Seca, Chino, CA, USA), with body mass measured to the nearest 0.1 kg using electronic scales (Seca 803, Seca, Chino, CA, USA). Subsequently, individual maturity offset was estimated using the predictive peak height velocity (PHV) equations devised by Mirwald et al. (2002), with participants classed as pre-PHV if more than one year prior to PHV, circa-PHV if within a year of PHV, and post-PHV if more one-year post-PHV.

Prior to the sprint protocol, all participants completed a standardised five-minute warm-up which consisted of two minutes low-intensity jogging, two minutes sprint specific drills (i.e., high knees, heelflicks, skipping etc.) concluding with one maximal 30 m sprint acting as a familiarisation trial. Subsequently, participants completed two maximal sprints over a distance of 35 m to avoid premature deceleration. The two sprint bouts were separated by at least two minutes of active recovery. Both sprints were conducted from a two-point standing start to minimise vertical displacement during the early phases of the sprint (Mero, Komi & Gregor, 1992), with participants instructed to start sprinting using auditory cues (i.e. "3….2….1…GO"). All sprint trials were conducted outside on a surface the participants were comfortable performing on, with a mean temperature and wind speed of 13.5 ± 1.9ºC and 2.3 ± 1.0 $m \cdot s^{-1}$, respectively. All data was collected over a 6-month period from October-March and took place either at the start of a training session for the trained participants or the start of a PE lesson for the control participants. These measures were collected in isolation and not part of a wider testing battery. Where possible, participants ran with the prevailing wind behind them to control the effects this can have on performance (Linthorne, 1994). Velocity was measured throughout both sprint trials using a radar gun (STALKER ATS II, Plano, Texas, USA), mounted on a tripod positioned 10 m behind the start line, in accordance with manufacturer instructions. The radar gun recorded velocity at a frequency > 46 Hz, allowing near instantaneous power and force to be modelled throughout the duration of the sprint. This protocol has demonstrated good intra-day reliability (Intra-class correlations: 0.75-0.88; Coefficient of Variation: 1.9-9.4%) in both trained and untrained paediatric populations (Runacres et al. 2019).

2.2 Biomechanical Modelling

The full details of the macroscopic biomechanical model are presented in Samozino et al (2016). However, briefly, prior to data processing, the first 0.3 seconds of the trial were deleted, in line with previous recommendations (Samozino, 2018), following which the raw velocity-time ($v_h(t)$) data were modelled using a mono-exponential curve. Following integration of the $v_h(t)$ curve, the horizontal displacement ($x_h(t)$) was obtained, with further derivation providing the horizontal acceleration ($a_h(t)$) of the participant's centre of mass (Samozino, 2018). According to the fundamental laws of dynamics, the horizontal antero-posterior force ($F_h(t)$) was calculated considering aerodynamic drag (Morin et al. 2011; Samozino et al. 2016). Subsequently, power output was determined as the product of force and velocity. All power and force variables were interpolated to 0.1 seconds intervals, with peak power (P_{peak}; W) and peak force (F_{peak}; N) defined as the highest values recorded during the 30 m sprint. Moreover, to allow for the comparison between training, sex, and maturity groups, P_{peak} and F_{peak} were ratio and allometrically scaled by body mass, using methods reported elsewhere (Nevill, Bate & Holder, 2006). Time to peak power (t_P_{peak}; s) was determined as the time from sprint start to P_{peak}, with mean power (P_{mean}; W) and force (F_{mean}; N) defined as the average power and force throughout the sprint. Thirty-meter sprint time (30mT) was defined as the time elapsed from the start of the sprint until $x_h(t)$ first exceeded 30 m. Peak velocity (V_{peak}; $m \cdot s^{-1}$) was derived from the mono-exponential $v_h(t)$ curve, with the modelled velocities over the same time period as P_{mean} used to determine mean velocity (V_{mean}; $m \cdot s^{-1}$). Finally, fatigue rate (FR; $W \cdot s^{-1}$) was determined as the average rate of power decline per second from P_{peak} until 30mT, with mechanical efficiency index (D_{RF}) represented by the slope of the linear decline of force production with increasing velocity. All variables were calculated for both sprints, but only the fastest sprint (as determined by 30mT) was carried forward for analysis.

2.3 Statistical Analyses

All values are presented as mean ± SD unless otherwise stated, with all statistical analyses conducted in SPSS (version 26.0, IBM, Armonk, NY, USA) and significance accepted as $p < 0.05$. Multivariate ANOVAs were used to identify significant differences in performance variables between training, sex, and maturity groups and any interaction effects, with Bonferroni corrections to post-hoc tests where appropriate. Cohens *d* was also calculated, with effect sizes considered trivial (≤ 0.20), moderate ($0.21 - 0.60$), large ($0.61 - 0.80$) or very large (≥ 0.81).

Hierarchical multiple linear regression was used to ascertain the determinants of 30 m sprint time according to maturity group. Predictor variables were entered using a backward elimination method where all possible predictor variables were entered into the model and then subsequently removed to check their overall effect on the model. Collinearity between potential predictors was investigated before entry into the model using the variance inflation factor to determine trivial (VIF = 1), moderate ($1 < \text{VIF} \leq 5$) and high (VIF > 5) collinearity (Daoud, 2017). If high co-linearity was found between variables, the variable explaining the greatest proportion of variance was retained (Daoud, 2017). The adequacy of the regression model was determined using the normality of residual values.

3. Results

Except for BMI ($p > 0.26$), all anthropometric variables were significantly higher maturity stage ($p < 0.01$), irrespective of sex or training status (Table 1). Trained children were taller and had a lower BMI than their untrained counterparts ($p < 0.05$). Pre-PHV athletes were lighter than their untrained counterparts ($p < 0.05$), whereas circa- and post-PHV athletes were heavier ($p < 0.05$). Boys were significantly taller than girls at all stages of maturity, irrespective of training status ($p < 0.05$), and pre-PHV and post- PHV untrained girls were significantly lighter than their male counterparts ($p < 0.05$).

****INSERT TABLE 1 HERE****

3.1 Influence of training status

As shown in Table 2 and Table 3, trained youth had a higher P_{peak} than their untrained counterparts ($F_{(1,244)} = 38.8$, $p < 0.01$, $d = 1.05$), which persisted even after ratio ($F_{(1,244)} = 24.6$, $p < 0.01$, $d = 0.78$) or allometric scaling ($F_{(1,244)} = 21.6$, $p < 0.01$, $d = 0.71$). Trained youth also had a higher F_{peak} ($F_{(1,244)} = 7.4$, $p < 0.01$, $d = 0.52$), although this difference was ameliorated following ratio and allometric scaling ($p > 0.68$). Trained participants had a higher V_{peak} ($F_{(1,244)} = 131.0$, $p < 0.01$, $d = 1.78$), V_{mean} ($F_{(1,244)} = 134.3$, $p < 0.01$, $d = 1.80$) and a faster 30mT ($F_{(1,244)} = 121.0$, $p < 0.01$, $d = 1.71$) when compared to their untrained counterparts. Finally, trained children and adolescents had a slower t_P_{peak} and a higher P_{mean}, relative P_{mean} and FR ($p < 0.05$), but there was no significant difference between athletes and controls for D_{RF} ($F_{(1,244)} = 0.95$, $p > 0.33$).

3.2 Influence of Sex

Boys produced a significantly higher F_{peak} and P_{peak} than girls (Table 2 and 3, respectively), which remained significantly higher after allometrically scaling for body mass (Scaled P_{peak}: $F_{(1, 244)} = 14.8$, $p < 0.01$, $d = 0.57$; Scaled F_{peak}: $F_{(1,244)} = 32.3$, $p < 0.01$, $d = 0.27$). Boys also demonstrated a higher P_{mean} ($F_{(1,244)} = 33.5$, $p < 0.01$, $d = 0.64$), relative P_{mean} ($F_{(1,244)} = 11.0$, $p < 0.01$, $d = 0.51$), V_{peak} ($F_{(1,244)} = 14.0$, $p < 0.01$, $d = 0.53$), V_{mean} ($F_{(1,249)} = 19.3$, $p < 0.01$, $d = 0.59$), a faster 30mT ($F_{(1,244)} = 13.7$, $p < 0.01$, $d = 0.52$) and FR ($F_{(1,249)} = 22.1$, $p < 0.01$, $d = 0.55$) than girls. However, there were no significant sex differences for t_P_{peak} ($F_{(1,244)} = 0.69$, $p > 0.14$) or D_{RF} ($F_{(1,244)} = 1.51$, $p > 0.35$).

3.3 Influence of Maturity

As shown in Tables 2 and 3, post- PHV adolescents produced a higher P_{peak} and F_{peak} than both the pre- and circa-PHV groups (all $p < 0.01$), with significantly higher values similarly observed for circa-PHV adolescents in comparison to the pre- PHV group ($p < 0.05$). However, after ratio and allometric scaling for body mass, no significant differences persisted between any maturity groups ($p > 0.05$). Post-PHV adolescents also had a significantly higher V_{peak}, 30mT, and D_{RF} than all other maturity groups ($p < 0.05$), with no significant differences evident between pre-PHV and circa-PHV children. There was no significant effect of maturation on any other sprint variable ($p > 0.05$). The magnitude of difference in V_{peak}, P_{peak}, relative P_{peak}, scaled P_{peak}, 30mT, and D_{RF} was significantly smaller between pre-and-circa-PHV children (0.4 – 5.1%) compared to circa-and-post-PHV adolescents (8.9 – 20.5%).

3.4 Interaction between sex, maturity, and training status

There was a significant interaction effect between sex and maturity on t_P_{peak} ($F_{(2,244)} = 4.3$, $p < 0.05$), relative P_{mean} ($F_{(2,244)} = 3.9$, $p < 0.05$), V_{peak} ($F_{(2,244)} = 5.6$, $p < 0.01$) and F_{peak} ($F_{(2,244)} = 5.0$, $p < 0.01$). Specifically, there was significantly less difference in t_P_{peak} between post-PHV boys and girls (5%) compared to pre-PHV (14.8%) and circa-PHV (17.0%) boys and girls. Conversely, there was a greater sex difference in relative P_{mean} and V_{peak} in circa-PHV adolescents (46.9% and 19.8%, respectively) compared to pre-PHV (5.4% and 3.2%) or post-PHV youth (11.6% and 5.6%). A greater sex difference was also evident in F_{peak} for pre-PHV children (53.5%) compared to circa-PHV (10.6%) or post-PHV adolescents (21.6%).

A significant sex, maturity and training interaction effect was also apparent on P_{peak} ($F_{(2,244)} = 3.8$, $p < 0.05$), F_{peak} ($F_{(2,244)} = 5.9$, $p < 0.01$), relative F_{peak} ($F_{(2,244)} = 3.1$, $p < 0.05$) and scaled F_{peak} ($F_{(2,244)} = 3.3$, $p < 0.05$). Specifically, less difference was observed in P_{peak} and F_{peak} between trained and untrained circa-PHV boys and girls (P_{peak}: 26.7%; F_{peak}: 28.3%) compared to those found in pre-PHV (P_{peak}: 42.3%; F_{peak}: 36.1%) or post-PHV youth (P_{peak}: 38.0%; F_{peak}: 33.7%). Furthermore, the biggest differences in relative F_{peak} and scaled F_{peak} were observed between trained and untrained post-PHV boys and girls (both 24.5%) compared to pre-PHV children (relative F_{peak}: 7.8%; scaled F_{peak}: 9.1%) and circa-PHV adolescents (relative F_{peak}: 13.3%; scaled F_{peak}: 13.9%).

3.5 Determinants of Sprint Performance

Model 1 in which only training status and sex were entered explained 33%, 53% and 37% of the variance in 30mT in pre-PHV, circa-PHV, and post-PHV children and adolescents, respectively (Table 4). Subsequently, scaled P_{peak} and D_{RF} were found to be significant predictors of performance across all maturity groups, explaining 65% of the variance in 30mT in pre-PHV children which increased to 75% and 80% in circa-PHV and post-PHV adolescents, respectively.

****INSERT TABLE 2 HERE****

****INSERT TABLE 3 HERE****

****INSERT TABLE 4 HERE****

4. Discussion

This is the first study to investigate the influence of sex, training, and maturity status on the kinetic sprint profile in a large sample of children and adolescents. Overall, the findings that boys produced a higher P_{peak} and F_{peak} than girls even after allometric scaling and irrespective of maturity suggest potential sex-related are evident even pre-PHV. Moreover, V_{peak}, P_{peak}, relative P_{peak}, scaled P_{peak}, 30mT, and D_{RF} were all affected by maturation with a greater magnitude of change observed between circa-and-post pubertal adolescents when compared to pre-and-circa-PHV participants. Moreover, given that training and sex account for ~20% more variance in 30mT in circa-PHV adolescents than pre- and post-PHV participants, these findings provide evidence that the development of sprint performance is partly sexually dimorphic which should be considered in the design of training programmes in youth.

A significant interaction between sex, maturity and training status was identified for V_{peak}, with a greater difference between trained and untrained circa-PHV participants (19.8%) compared to their pre- and post-PHV counterparts (< 11.0%). This supports the growing body of evidence regarding the non-linear development of sprint performance throughout growth and maturation (Meyers et al. 2015; Meyers et al. 2017; Moran, Sandercock, Rumpf & Parry, 2016; Papaiakovou et al. 2009; Rumpf et al. 2015a), but also indicates the potential potency of training on sprint performance around the time of PHV. Despite the non-linear increases in V_{peak}, 30mT was only significantly faster in post-PHV adolescents compared to pre- and circa-PHV participants, with no significant differences between pre- and circa-PHV participants. These findings are in direct contrast to the Papiakovou et al. (2009) who reported near linear increases in maximum velocity with age. Such discrepancies are likely due to Papiakovou et al. (2009) not accounting for maturity status, with the timing and tempo of maturity varying between individuals, even of the same age, sex and ethnicity (Rogol, 2002; Rogol, Roemmich

& Clark, 2002). Therefore, potential maturational differences between participants within age categories described in Papiakovou et al. (2009) may have produced spurious associations.

The lack of differences in 30mT between pre-PHV children and circa-PHV adolescents in the present study could be explained, at least in part, by the lack of significant difference in the technical ability to apply force, indicated by D_{RF}. Indeed, D_{RF} was only significantly lower in post-PHV adolescents, compared to both pre- and circa-PHV participants. A more positive D_{RF} indicates a greater ability to maintain a greater horizontal force production at higher sprinting velocities (Morin et al. 2011; Rossi et al. 2017), with D_{RF} shown to be more important for sprint performance than total force production in a sample of recreationally active adults (Morin et al. 2011). These results appear discordant with the only other study reporting changes in D_{RF} in a paediatric population which reported a significant difference in D_{RF} between children and adolescents (Rossi et al. 2017). However, with no assessment of maturity it is unclear whether the same patterns in this study were apparent in Rossi et al. (2017) highlighting the importance of accounting for maturity in studies of this type. In accord with the present study, these observations were independent of relative $F_{peak,}$ and allometrically scaled F_{peak}, which remained constant between children and adolescents. Building on the findings of Rossi et al. (2017), the current study shows that maturity-, as well as age-, related differences in D_{RF} may also be evident and explain a significant proportion of variance in sprint performance. Maturity-related differences in D_{RF} may be attributable to differences in segmental growth rates in relation to the trunk (Rumpf et al. 2015a). However, given the cross-sectional nature of this study, no conclusions regarding the impact of differing growth rates can be drawn, thus necessitating future research using a longitudinal design.

The results of the current study are in accord with Meyers et al. (2015) and Rumpf et al. (2015a) who attributed the lack of performance improvements in sprint times in circa-PHV boys to 'adolescent awkwardness' (Buenen et al. 1998). Adolescent awkwardness is a phenomenon attributed to a period around PHV where adolescents experience a decline or plateau in performance, thought to be reflective of a temporary disruption in motor control (Buenen et al. 1998). Whilst adolescent awkwardness does not affect all adolescents (Lloyd et al. 2015), the present study suggests girls may be more susceptible to adolescent awkwardness than boys as circa-PHV girls, irrespective of training status, had a lower V_{peak} and a slower 30mT compared to their pre- or post-PHV counterparts. Whilst the mechanistic basis for adolescent awkwardness is not well understood, Freitas et al. (2015) suggested that sex differences in neuromuscular maturation may impact upon gross motor control and possibly affect girls to a greater extent than boys. Contrastingly, Vandorpe et al. (2011) suggest girls have superior motor control to boys which could indicate that sex-differences in motor control may be domain and/or skill specific. Moreover, Radnor et al. (2022) in their 18-month longitudinal study indicate that muscle architecture is a significant predictor of sprint performance in boys and, given the sexual dimorphism in muscle type and architecture during growth and maturation, likely contributes to sex differences in adolescent awkwardness. It is, however, pertinent to note that currently no objective maximal criteria for anaerobic performances are available and it could therefore be postulated that sub-maximal efforts may have been accepted in the pubertal girls, although this seems unlikely given the motivation provided during each sprint, the longer sprint distance to minimise deceleration, and the consistency of performance decline observed in all participants. Nevertheless, future research is warranted to establish maximal sprint criteria and to further elucidate the potential underlying mechanisms for these apparent sex differences.

This study tentatively indicates that sprint development during adolescence may be sexually dimorphic, particularly around PHV, which may be explained, at least in part, by key differences in the hormonal milieu manifest from the onset of puberty. Specifically, close to PHV, boys experience a greater increase in androgenic hormones, including testosterone and growth hormone, than girls, which is associated with increased fat free mass (Farr, Laddu & Going, 2014; Fellmann & Coudert, 1994), muscle cross sectional area (Armstrong, 2007; van Praagh, 2000; van Praagh & Doré, 2002), and proportion of type II muscle fibres in boys (van Praagh & Doré, 2002). These hormonal changes led to the 'trigger' hypothesis being proposed (Katch, 1983) whereby adaptations and performance improvements in response to a training stimulus would be enhanced following the onset of puberty. Whilst the 'trigger' hypothesis is largely refuted in relation to cardiorespiratory fitness (Armstrong, 2007; Armstrong & McNarry, 2016; Rowland, 1997), the present study indicates that sprint performance responses to a sports specific training plan may also be blunted during PHV in boys and girls respectively. However, specific sprint training interventions in circa-PHV adolescents is need to confirm this postulation.

Whilst there are strengths associated with the current study, including the sample size and the quantification of sprint kinetics in a field-based setting that enhances the ecological validity, there are limitations which must be acknowledged. First, no spatiotemporal variables (i.e. stride length) were assessed which could have provided greater insight into the kinetic and spatiotemporal interaction on sprint development in youth. Furthermore, whilst all trained participants were part of a LTAD program, they were all involved in a similar training regime, precluding inferences regarding the effectiveness of different training methodologies on the kinetic sprint profile. In the absence of objective criteria of maximal effort, it is possible that some participants produced submaximal efforts, potentially producing spurious associations. However, motivational techniques were used throughout all tests, which, coupled with an extended finish line (35 m), minimised this risk. Additionally, the measurement error associated with the maturity offset equations of Mirwald et al. (2002) means that some participants may have been incorrectly identified as pre-, circa-, or post-PHV. However, given the large sample size within this study this error is minimised. Finally, the ecological validity of a field-based sprint has been questioned, especially in team sports (Mendez-Villaneuva et al. 2010; Rommers et al. 2018), thus repeated sprint ability may provide greater insights into fatiguability over multiple sprints.

5. Conclusions

In conclusion, this was the first study to examine kinetic changes in sprint development in trained and untrained boys and girls, accounting for maturity status. Sprint performance increases may be attributed to increases in power, and an improved technical ability to apply force, irrespective of sex. Moreover, this study provides evidence that sprint development is sexually dimorphic, but future research is warranted to establish the underlying mechanisms in more detail.

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Table 1 – Anthropometric and maturity characteristics of the trained and untrained participants

	Trained Participants (n = 147)						Control Participants (n = 113)					
	Pre-PHV (n = 34)		Circa-PHV (n = 47)		Post-PHV (n = 66)		Pre-PHV (n = 36)		Circa-PHV (n = 48)		Post-PHV (n = 29)	
	Boys (n = 17)	Girls (n = 17)	Boys (n = 32)	Girls (n = 15)	Boys (n = 29)	Girls (n = 37)	Boys (n = 22)	Girls (n = 14)	Boys (n = 14)	Girls (n = 34)	Boys (n = 13)	Girls (n = 16)
Age (years)	12.1 ± 0.8	11.2 ± 1.7	14.2 ± 0.8 [a]	13.1 ± 0.8 [a]	16.7 ± 1.4 [ab]	15.8 ± 1.5 [ab]	11.5 ± 0.9	11.4 ± 0.3	14.3 ± 0.8 [a]	13.6 ± 0.3 [a]	16.7 ± 1.0 [ab]	15.3 ± 0.7 [ab]
Stature (m)	1.58 ± 0.07	1.50 ± 0.10* [a]	1.68 ± 0.07	1.58 ± 0.08* [a]	1.74 ± 0.06	1.64 ± 0.07* [a]	1.49 ± 0.08 [#]	1.41 ± 0.06 [#*]	1.57 ± 0.09 [# a]	1.52 ± 0.07 [# *ab]	1.64 ± 0.11 [# *ab]	1.60 ± 0.06 [# *ab]
Body Mass (kg)	47.7 ± 7.1	42.5 ± 8.8	55.5 ± 6.8 [a]	51.5 ± 9.3 [a]	63.9 ± 5.2 [a]	58.5 ± 8.9 [a]	52.0 ± 15.3 [#]	36.9 ± 13.5 [# *]	49.3 ± 12.0 [#]	50.9 ± 13.5 [#]	61.3 ± 11.7 [# ab]	50.9 ± 7.0 [#] *
BMI ($kg \cdot m^{-2}$)	19.0 ± 1.5	18.7 ± 2.1	19.7 ± 1.8	20.5 ± 2.4	21.1 ± 2.0	21.7 ± 2.4	23.0 ± 5.3 [#]	18.3 ± 4.6 [#]	20.0 ± 3.7 [#]	22.0 ± 5.9 [#]	22.9 ± 5.3 [#]	20.8 ± 2.4 [#]
Maturity Offset (years)	-1.66 ± 0.45	-1.97 ± 0.85	-0.05 ± 0.54 [a]	+0.30 ± 0.36 [a]	+2.44 ± 0.79 [ab]	+2.17 ± 0.89 [ab]	-2.11 ± 0.75	-2.31 ± 0.77	-0.38 ± 0.54 [a]	-0.16 ± 0.50 [a]	+1.93 ± 0.92 [ab]	+1.45 ± 0.71 [ab]

BMI = Body Mass Index; [#] indicate a significant difference between the same maturity and sex between training groups. * Significant difference between sex between the same maturity and sport group. [a] Significant difference compared to pre-pubertal children of the same sport and sex. [b] Significant difference compared to pubertal adolescents of the same sport and sex

Table 2 – 30m sprint performance variables in boys

	Trained participants			Control Participants		
	Pre-PHV	Circa-PHV	Post-PHV	Pre-PHV	Circa-PHV	Post-PHV
t_P_{peak} (s)	0.54 ± 0.11	0.55 ± 0.12	0.61 ± 0.13[a]	0.43 ± 0.13[b]	0.55 ± 0.16[b]	0.50 ± 0.19[ab]
P_{peak} (W)	685.8 ± 119.2	864.7 ± 200.0*	957.4 ± 251.6*[a]	620.4 ± 142.3[b]	596.0 ± 202.8*[b]	822.5 ± 222.6*[ab]
Relative P_{peak} ($W \cdot kg^{-1}$)	14.3 ± 2.7	15.6 ± 2.9	14.9 ± 3.6	12.6 ± 3.6[b]	12.4 ± 4.5[b]	13.8 ± 4.4[b]
Scaled P_{peak} ($W \cdot kg^{-b}$)	9.3 ± 1.8	9.8 ± 1.8	9.2 ± 2.2	8.1 ± 2.5[b]	8.0 ± 3.0[b]	8.6 ± 2.8[b]
P_{mean} (W)	219.0 ± 47.7	277.2 ± 61.8*	337.6 ± 106.1*[a]	157.4 ± 53.8[b]	188.2 ± 64.7*[b]	229.5 ± 65.5*[ab]
Relative P_{mean} (W)	4.6 ± 0.9	5.0 ± 0.8	5.2 ± 1.5 *	3.1 ± 0.8[b]	3.9 ± 1.2[b]	3.8 ± 1.2*[b]
V_{peak} ($m \cdot s^{-1}$)	6.60 ± 0.56	6.84 ± 0.42	7.06 ± 0.81*[a]	5.40 ± 0.75[b]	6.06 ± 0.94[b]	6.02 ± 0.88*[ab]
V_{mean} ($m \cdot s^{-1}$)	5.62 ± 0.36	5.80 ± 0.30	5.87 ± 0.53*[a]	4.81 ± 0.55[b]	5.16 ± 0.64[b]	5.20 ± 0.65*[ab]
30mT (s)	5.35 ± 0.35	5.19 ± 0.27	5.15 ± 0.47*[a]	6.31 ± 0.74[b]	5.92 ± 0.97[b]	5.86 ± 0.80*[ab]
F_{peak} (N)	390.6 ± 69.8	467.9 ± 96.2*	502.4 ± 102.4*[a]	420.6 ± 95.4[b]	366.1 ± 113.4*[b]	502.7 ± 139.3*[ab]
Relative F_{peak} ($N \cdot kg^{-1}$)	8.1 ± 1.2	8.4 ± 1.4	7.8 ± 1.4	8.4 ± 2.0	7.5 ± 2.2	8.3 ± 2.2
Scaled F_{peak} ($N \cdot kg^{-b}$)	8.7 ± 1.2	9.0 ± 1.5	8.3 ± 1.5	8.9 ± 2.1	7.9 ± 2.3	8.8 ± 2.3
FR ($W \cdot s^{-1}$)	137.3 ± 34.7	189.0 ± 86.4*	180.6 ± 73.6*	120.0 ± 41.2[b]	95.4 ± 52.3*[b]	159.0 ± 65.6*[b]
D_{RF} ($\% \cdot s \cdot m^{-1}$)	-7.83 ± 1.39	-7.77 ± 1.25	-7.08 ± 1.33*[a]	-8.50 ± 1.59[b]	-7.43 ± 1.08*[b]	-8.10 ± 1.85[b]

All variables reported as mean ± SD. t_P_{peak} = Time to peak power, P_{peak} = Peak Power, P_{mean} = Mean Power, V_{peak} = Peak Velocity, V_{mean} = Mean Velocity, 30mT = 30 m Sprint Time, F_{peak} = Peak Force, FR = Fatigue Rate, D_{RF} = Mechanical Efficiency Index. * significantly different to pre-pubertal children within the same training group ($p < 0.05$) [α] significantly different to pubertal adolescents within the same training group ($p < 0.05$); [b] significant difference compared to the trained equivalents ($p < 0.05$)

Table 3 –30 m sprint performance variables in girls

	Trained Participants			Control Participants		
	Pre-Pubertal	Pubertal	Post-Pubertal	Pre-Pubertal	Pubertal	Post-Pubertal
t_P_{peak} (s)	0.62 ± 0.11	0.52 ± 0.05	0.59 ± 0.14^{a}	0.48 ± 0.13^{b}	0.44 ± 0.11^{b}	0.61 ± 0.26^{b}
P_{peak} (W)	547.5 ± 179.9	664.7 ± 132.5*	798.6 ± 167.7*^{a}	358.3 ± 73.8^{b}	561.6 ± 233.1*^{b}	517.1 ± 222.5*^{ab}
Relative P_{peak} ($W \cdot kg^{-1}$)	13.2 ± 4.8	13.0 ± 2.1	13.8 ± 2.4	10.5 ± 2.3^{b}	11.1 ± 3.4^{b}	10.1 ± 3.9^{b}
Scaled P_{peak} ($W \cdot kg^{-b}$)	8.6 ± 3.2	8.3 ± 1.4	8.6 ± 1.5	6.9 ± 1.9^{b}	7.1 ± 2.2^{b}	6.4 ± 2.5^{b}
P_{mean} (W)	189.0 ± 56.5	214.3 ± 45.0*	274.9 ± 61.2*^{a}	110.8 ± 26.2^{b}	140.3 ± 36.2*^{ab}	172.5 ± 39.3*^{ab}
Relative P_{mean} (W)	4.6 ± 1.5	4.2 ± 0.87	4.7 ± 0.85*	3.2 ± 0.55^{b}	2.8 ± 0.5^{b}	3.4 ± 0.7*^{b}
V_{peak} ($m \cdot s^{-1}$)	6.58 ± 0.62	6.31 ± 0.63	6.68 ± 0.56*^{a}	5.51 ± 0.45^{b}	5.16 ± 0.44^{b}	5.70 ± 0.54*^{ab}
V_{mean} ($m \cdot s^{-1}$)	5.49 ± 0.50	5.43 ± 0.43	5.62 ± 0.33*^{a}	4.79 ± 0.34^{b}	4.61 ± 0.35^{b}	4.84 ± 0.45*^{b}
30mT (s)	5.50 ± 0.49	5.55 ± 0.44	5.35 ± 0.31*^{a}	6.29 ± 0.45^{b}	6.54 ± 0.52^{b}	6.25 ± 0.62^{b}
F_{peak} (N)	310.8 ± 85.2	393.9 ± 68.7*	447.2 ± 92.1*^{a}	240.9 ± 41.6^{b}	395.5 ± 154.4*^{b}	434.6 ± 130.3*^{ab}
Relative F_{peak} ($N \cdot kg^{-1}$)	7.4 ± 2.0	7.7 ± 0.6	7.7 ± 1.2	7.1 ± 1.3	7.8 ± 2.0	6.5 ± 2.3
Scaled F_{peak} ($N \cdot kg^{-b}$)	7.8 ± 2.1	8.2 ± 0.7	8.2 ± 1.3	7.3 ± 1.7	8.2 ± 2.1	6.9 ± 2.4
FR ($W \cdot s^{-1}$)	102.4 ± 48.7	143.2 ± 40.5*	171.9 ± 47.8*	56.1 ± 19.4^{b}	98.0 ± 48.0*^{b}	79.3 ± 48.0*^{b}
D_{RF} ($\% \cdot s \cdot m^{-1}$)	-7.45 ± 1.37	-8.07 ± 0.65	-7.20 ± 1.35*^{a}	-8.04 ± 1.38^{b}	-7.99 ± 1.57^{b}	-6.49 ± 1.57*^{ab}

All variables reported as mean ± SD. t_P_{peak} = Time to peak power, P_{peak} = Peak Power, P_{mean} = Mean Power, V_{peak} = Peak Velocity, V_{mean} = Mean Velocity, 30mT = 30 m Sprint Time, F_{peak} = Peak Force, FR = Fatigue Rate, D_{RF} = Mechanical Efficiency Index; * significantly different to pre-pubertal children within the same training group ($p < 0.05$); $^{\alpha}$ significantly different to pubertal adolescents within the same training group ($p < 0.05$), ^{b} significant difference compared to the trained equivalents ($p < 0.05$).

Table 4 – Predictor variables for 30 m time for each maturity group

Group	Predictor Variables	β	Standard Error	R^2
Pre-PHV	Training Status	0.55	0.13	0.33 **
	Sex	-0.11	0.10	0.33 **
	Scaled P_{peak}	-0.19	0.03	0.60 **
	D_{RF}	-0.12	0.04	0.65 **
Circa-PHV	Training Status	0.60	0.09	0.53 **
	Sex	0.19	0.10	0.53 **
	Scaled P_{peak}	-0.20	0.02	0.70 **
	D_{RF}	-0.14	0.04	0.75 **
Post-PHV	Training Status	0.47	0.07	0.37 **
	Sex	0.06	0.05	0.37 **
	Scaled P_{peak}	-0.23	0.02	0.73 **
	D_{RF}	-0.13	0.02	0.80 **

Training Status (1 = Trained, 2 = Control), Sex (Boys = 1, Girls = 2), Scaled P_{peak} = Allometrically scaled peak power, PHV = Peak height velocity, D_{RF} = Mechanical Efficiency Index. ** $p < 0.01$