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

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Abstract

Purpose: 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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31 1. Introduction

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

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

56 Whether similar periods of non-linear development in sprint speed are evident in girls is
57 unknown, with little data currently available considering the influence of growth and/or
58 maturation, and their interaction, on sprint performance in girls. In one of the few studies to
59 examine sprint development **cross-sectionally** in untrained girls, a plateau in peak velocity
60 (V_{peak}) was observed from 12-13 years onwards compared to 15 years in their male peers
61 (Papaiakovou et al. 2009). **In a similar cross-sectional design**, Nagahara et al. (2019) reported

62 a plateau in V_{peak} at 12.7 years in girls which was attributed to no further increases in step
63 length. However, with no maturity assessment in these studies, whether this plateau is
64 attributable to age per se or rather to concomitant growth and maturation related changes,
65 technique, or kinematic alterations, cannot be elucidated. With no evidence available regarding
66 the development of speed in response to training in girls, further inferences regarding the
67 influence and interaction of sex and training are precluded.

68 In addition to kinematic factors (i.e., stride length/rate), sprint performance is determined by
69 kinetic parameters such as horizontal and vertical force (Morin, Jeannin, Chevallier, & Belli,
70 2006; Morinc, Edouard & Samozino, 2011; Rumpf, Cronin, Oliver & Hughes, 2013; Samozino
71 et al. 2016). However, the evidence exploring the kinetic determinants of sprint performance
72 in paediatric populations has predominately been derived from **cross-sectional studies and non-**
73 **motorised treadmills, limiting its generalisability** (Rumpf et al. 2012 & 2015a). Moreover, the
74 majority of these studies have focused solely on the development of maximal velocity (Meyers
75 et al. 2015; Meyers et al. 2017; **Nagahara et al. 2017**; Rumpf et al. 2015a), thereby considering
76 only a small component of sprint performance, or have utilised mean velocity data over a given
77 distance (i.e. 5 meters; Mendez-Villanueva et al. 2010; Papaiakovou et al. 2009). These
78 methodological limitations may be addressed by recent advances in radar technology and
79 macroscopic biomechanical modelling techniques which enable velocity, power and force to
80 be calculated near instantaneously across an entire sprint (Samozino et al. 2016;
81 Simperingham, Cronin & Ross, 2016). Force-velocity-Power (F-v-P) profiling has been
82 validated against force plate data, demonstrating high reliability in elite adult sprinters
83 (Samozino et al. 2016). Additionally, the combination of radar technology and F-v-P profiling
84 has been deemed highly reliable in both trained and untrained paediatric participants (Runacres,
85 Bezodis, Mackintosh & McNarry, 2019). Consequently, such methods could provide important
86 insights to the kinetic parameters underpinning differences in sprint performance according to
87 sex, maturity, and training status.

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

95 2. Methods

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

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

120 2.1 Experimental Procedures

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

127 Prior to the sprint protocol, all participants completed a standardised five-minute warm-up
128 which consisted of **two minutes low-intensity jogging, two minutes sprint specific drills (i.e.,**
129 **high knees, heelflicks, skipping etc.)** concluding with one maximal 30 m sprint acting as a
130 familiarisation trial. Subsequently, participants completed two maximal sprints over a distance
131 of 35 m to avoid premature deceleration. **The two sprint bouts were separated by at least two**
132 **minutes of active recovery.** Both sprints were conducted from a two-point standing start to
133 minimise vertical displacement during the early phases of the sprint (Mero, Komi & Gregor,
134 1992), with participants instructed to start sprinting using auditory cues (i.e.
135 “3....2....1...GO”). All sprint trials were conducted outside on a surface the participants were
136 comfortable performing on, with a mean temperature and wind speed of $13.5 \pm 1.9^{\circ}\text{C}$ and 2.3
137 $\pm 1.0 \text{ m}\cdot\text{s}^{-1}$, respectively. **All data was collected over a 6-month period from October-March**
138 **and took place either at the start of a training session for the trained participants or the start of**
139 **a PE lesson for the control participants. These measures were collected in isolation and not part**
140 **of a wider testing battery.** Where possible, participants ran with the prevailing wind behind
141 them to control the effects this can have on performance (Linthorne, 1994). Velocity was
142 measured throughout both sprint trials using a radar gun (STALKER ATS II, Plano, Texas,
143 USA), mounted on a tripod positioned 10 m behind the start line, in accordance with
144 manufacturer instructions. The radar gun recorded velocity at a frequency $> 46 \text{ Hz}$, allowing
145 near instantaneous power and force to be modelled throughout the duration of the sprint. **This**
146 **protocol has demonstrated good intra-day reliability (Intra-class correlations: 0.75-0.88;**
147 **Coefficient of Variation: 1.9-9.4%) in both trained and untrained paediatric populations**
148 **(Runacres et al. 2019).**

149 2.2 Biomechanical Modelling

150 The full details of the macroscopic biomechanical model are presented in Samozino et al
151 (2016). However, briefly, prior to data processing, the first 0.3 seconds of the trial were deleted,
152 in line with previous recommendations (Samozino, 2018), following which the raw velocity-
153 time ($v_h(t)$) data were modelled using a mono-exponential curve. Following integration of the
154 $v_h(t)$ curve, the horizontal displacement ($x_h(t)$) was obtained, with further derivation providing
155 the horizontal acceleration ($a_h(t)$) of the participant’s centre of mass (Samozino, 2018).
156 According to the fundamental laws of dynamics, the horizontal antero-posterior force ($F_h(t)$)
157 was calculated considering aerodynamic drag (Morin et al. 2011; Samozino et al. 2016).
158 Subsequently, power output was determined as the product of force and velocity. All power
159 and force variables were interpolated to 0.1 seconds intervals, with peak power (P_{peak} ; W) and

160 peak force (F_{peak} ; N) defined as the highest values recorded during the 30 m sprint. Moreover,
161 to allow for the comparison between training, sex, and maturity groups, P_{peak} and F_{peak} were
162 ratio and allometrically scaled by body mass, using methods reported elsewhere (Nevill, Bate
163 & Holder, 2006). Time to peak power ($t_{P_{\text{peak}}}$; s) was determined as the time from sprint start
164 to P_{peak} , with mean power (P_{mean} ; W) and force (F_{mean} ; N) defined as the average power and
165 force throughout the sprint. Thirty-meter sprint time (30mT) was defined as the time elapsed
166 from the start of the sprint until $x_h(t)$ first exceeded 30 m. Peak velocity (V_{peak} ; $\text{m}\cdot\text{s}^{-1}$) was
167 derived from the mono-exponential $v_h(t)$ curve, with the modelled velocities over the same
168 time period as P_{mean} used to determine mean velocity (V_{mean} ; $\text{m}\cdot\text{s}^{-1}$). Finally, fatigue rate (FR;
169 $\text{W}\cdot\text{s}^{-1}$) was determined as the average rate of power decline per second from P_{peak} until 30mT,
170 with mechanical efficiency index (D_{RF}) represented by the slope of the linear decline of force
171 production with increasing velocity. All variables were calculated for both sprints, but only the
172 fastest sprint (as determined by 30mT) was carried forward for analysis.

173 2.3 Statistical Analyses

174 All values are presented as mean \pm SD unless otherwise stated, with all statistical analyses
175 conducted in SPSS (version 26.0, IBM, Armonk, NY, USA) and significance accepted as $p <$
176 0.05. Multivariate ANOVAs were used to identify significant differences in performance
177 variables between **training, sex, and maturity** groups and any interaction effects, with
178 Bonferroni corrections to post-hoc tests where appropriate. Cohens d was also calculated, with
179 effect sizes considered trivial (≤ 0.20), moderate (0.21 – 0.60), large (0.61 – 0.80) or very large
180 (≥ 0.81).

181 Hierarchical multiple linear regression was used to ascertain the determinants of 30 m sprint
182 time according to maturity group. Predictor variables were entered **using a backward**
183 **elimination method where all possible predictor variables were entered into the model and then**
184 **subsequently removed to check their overall effect on the model.** Collinearity between potential
185 predictors was investigated **before entry into the model** using the variance inflation factor to
186 determine trivial ($\text{VIF} = 1$), moderate ($1 < \text{VIF} \leq 5$) and high ($\text{VIF} > 5$) collinearity (Daoud,
187 2017). If high co-linearity was found between variables, the variable explaining the greatest
188 proportion of variance was retained (Daoud, 2017). The adequacy of the regression model was
189 determined using the normality of residual values.

190 3. Results

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

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

199 *3.1 Influence of training status*

200 As shown in Table 2 and Table 3, trained youth had a higher P_{peak} than their untrained
201 counterparts ($F_{(1,244)} = 38.8$, $p < 0.01$, $d = 1.05$), which persisted even after ratio ($F_{(1,244)} = 24.6$,
202 $p < 0.01$, $d = 0.78$) or allometric scaling ($F_{(1,244)} = 21.6$, $p < 0.01$, $d = 0.71$). Trained youth also
203 had a higher F_{peak} ($F_{(1,244)} = 7.4$, $p < 0.01$, $d = 0.52$), although this difference was ameliorated
204 following ratio and allometric scaling ($p > 0.68$). Trained participants had a higher V_{peak} ($F_{(1,244)}$
205 $= 131.0$, $p < 0.01$, $d = 1.78$), V_{mean} ($F_{(1,244)} = 134.3$, $p < 0.01$, $d = 1.80$) and a faster 30mT ($F_{(1,244)}$
206 $= 121.0$, $p < 0.01$, $d = 1.71$) when compared to their untrained counterparts. Finally, trained
207 children and adolescents had a slower $t_{P_{\text{peak}}}$ and a higher P_{mean} , relative P_{mean} and FR ($p <$
208 0.05), but there was no significant difference between athletes and controls for D_{RF} ($F_{(1,244)} =$
209 0.95 , $p > 0.33$).

210 *3.2 Influence of Sex*

211 Boys produced a significantly higher F_{peak} and P_{peak} than girls (Table 2 and 3, respectively),
212 which remained significantly higher after allometrically scaling for body mass (Scaled P_{peak} :
213 $F_{(1,244)} = 14.8$, $p < 0.01$, $d = 0.57$; Scaled F_{peak} : $F_{(1,244)} = 32.3$, $p < 0.01$, $d = 0.27$). Boys also
214 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
215 < 0.01 , $d = 0.51$), V_{peak} ($F_{(1,244)} = 14.0$, $p < 0.01$, $d = 0.53$), V_{mean} ($F_{(1,249)} = 19.3$, $p < 0.01$, $d =$
216 0.59), a faster 30mT ($F_{(1,244)} = 13.7$, $p < 0.01$, $d = 0.52$) and FR ($F_{(1,249)} = 22.1$, $p < 0.01$, $d =$
217 0.55) than girls. However, there were no significant sex differences for $t_{P_{\text{peak}}}$ ($F_{(1,244)} = 0.69$,
218 $p > 0.14$) or D_{RF} ($F_{(1,244)} = 1.51$, $p > 0.35$).

219 *3.3 Influence of Maturity*

220 As shown in Tables 2 and 3, post-PHV adolescents produced a higher P_{peak} and F_{peak} than both
221 the pre- and circa-PHV groups (all $p < 0.01$), with significantly higher values similarly

222 observed for circa-PHV adolescents in comparison to the pre-PHV group ($p < 0.05$). However,
223 after ratio and allometric scaling for body mass, no significant differences persisted between
224 any maturity groups ($p > 0.05$). Post-PHV adolescents also had a significantly higher V_{peak} ,
225 30mT, and D_{RF} than all other maturity groups ($p < 0.05$), with no significant differences evident
226 between pre-PHV and circa-PHV children. There was no significant effect of maturation on
227 any other sprint variable ($p > 0.05$). The magnitude of difference in V_{peak} , P_{peak} , relative P_{peak} ,
228 scaled P_{peak} , 30mT, and D_{RF} was significantly smaller between pre-and-circa-PHV children
229 (0.4 – 5.1%) compared to circa-and-post-PHV adolescents (8.9 – 20.5%).

230 3.4 Interaction between sex, maturity, and training status

231 There was a significant interaction effect between sex and maturity on $t_{\text{P}_{\text{peak}}}$ ($F_{(2,244)} = 4.3$, p
232 < 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} ($F_{(2,244)} =$
233 5.0 , $p < 0.01$). Specifically, there was significantly less difference in $t_{\text{P}_{\text{peak}}}$ between post-PHV
234 boys and girls (5%) compared to pre-PHV (14.8%) and circa-PHV (17.0%) boys and girls.
235 Conversely, there was a greater sex difference in relative P_{mean} and V_{peak} in circa-PHV
236 adolescents (46.9% and 19.8%, respectively) compared to pre-PHV (5.4% and 3.2%) or post-
237 PHV youth (11.6% and 5.6%). A greater sex difference was also evident in F_{peak} for pre-PHV
238 children (53.5%) compared to circa-PHV (10.6%) or post-PHV adolescents (21.6%).

239 A significant sex, maturity and training interaction effect was also apparent on P_{peak} ($F_{(2,244)} =$
240 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
241 F_{peak} ($F_{(2,244)} = 3.3$, $p < 0.05$). Specifically, less difference was observed in P_{peak} and F_{peak}
242 between trained and untrained circa-PHV boys and girls (P_{peak} : 26.7%; F_{peak} : 28.3%) compared
243 to those found in pre-PHV (P_{peak} : 42.3%; F_{peak} : 36.1%) or post-PHV youth (P_{peak} : 38.0%; F_{peak} :
244 33.7%). Furthermore, the biggest differences in relative F_{peak} and scaled F_{peak} were observed
245 between trained and untrained post-PHV boys and girls (both 24.5%) compared to pre-PHV
246 children (relative F_{peak} : 7.8%; scaled F_{peak} : 9.1%) and circa-PHV adolescents (relative F_{peak} :
247 13.3%; scaled F_{peak} : 13.9%).

248 3.5 Determinants of Sprint Performance

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

253 in pre-PHV children which increased to 75% and 80% in circa-PHV and post-PHV adolescents,
254 respectively.

255 **INSERT TABLE 2 HERE**

256 **INSERT TABLE 3 HERE**

257 **INSERT TABLE 4 HERE**

258

259 4. Discussion

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

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

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

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

305 The results of the current study are in accord with Meyers et al. (2015) and Rumpf et al. (2015a)
306 who attributed the lack of performance improvements in sprint times in circa-PHV boys to
307 ‘adolescent awkwardness’ (Buenen et al. 1998). Adolescent awkwardness is a phenomenon
308 attributed to a period around PHV where adolescents experience a decline or plateau in
309 performance, thought to be reflective of a temporary disruption in motor control (Buenen et al.
310 1998). Whilst adolescent awkwardness does not affect all adolescents (Lloyd et al. 2015), the
311 present study suggests girls may be more susceptible to adolescent awkwardness than boys as
312 circa-PHV girls, irrespective of training status, had a lower V_{peak} and a slower 30mT compared
313 to their pre- or post-PHV counterparts. Whilst the mechanistic basis for adolescent
314 awkwardness is not well understood, Freitas et al. (2015) suggested that sex differences in
315 neuromuscular maturation may impact upon gross motor control and possibly affect girls to a

316 greater extent than boys. Contrastingly, Vandorpe et al. (2011) suggest girls have superior
317 motor control to boys which could indicate that sex-differences in motor control may be
318 domain and/or skill specific. Moreover, Radnor et al. (2022) in their 18-month longitudinal
319 study indicate that muscle architecture is a significant predictor of sprint performance in boys
320 and, given the sexual dimorphism in muscle type and architecture during growth and
321 maturation, likely contributes to sex differences in adolescent awkwardness. It is, however,
322 pertinent to note that currently no objective maximal criteria for anaerobic performances are
323 available and it could therefore be postulated that sub-maximal efforts may have been accepted
324 in the pubertal girls, although this seems unlikely given the motivation provided during each
325 sprint, the longer sprint distance to minimise deceleration, and the consistency of performance
326 decline observed in all participants. Nevertheless, future research is warranted to establish
327 maximal sprint criteria and to further elucidate the potential underlying mechanisms for these
328 apparent sex differences.

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

344 Whilst there are strengths associated with the current study, including the sample size and the
345 quantification of sprint kinetics in a field-based setting that enhances the ecological validity,
346 there are limitations which must be acknowledged. First, no spatiotemporal variables (i.e. stride
347 length) were assessed which could have provided greater insight into the kinetic and
348 spatiotemporal interaction on sprint development in youth. Furthermore, whilst all trained

349 participants were part of a LTAD program, they were all involved in a similar training regime,
350 precluding inferences regarding the effectiveness of different training methodologies on the
351 kinetic sprint profile. In the absence of objective criteria of maximal effort, it is possible that
352 some participants produced submaximal efforts, potentially producing spurious associations.
353 However, motivational techniques were used throughout all tests, which, coupled with an
354 extended finish line (35 m), minimised this risk. Additionally, the measurement error
355 associated with the maturity offset equations of Mirwald et al. (2002) means that some
356 participants may have been incorrectly identified as pre-, circa-, or post-PHV. However, given
357 the large sample size within this study this error is minimised. Finally, the ecological validity
358 of a field-based sprint has been questioned, especially in team sports (Mendez-Villaneuva et
359 al. 2010; Rommers et al. 2018), thus repeated sprint ability may provide greater insights into
360 fatiguability over multiple sprints.

361 5. Conclusions

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

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482 **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·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}

483 BMI = Body Mass Index; _# indicate a significant difference between the same maturity and sex between training groups. * Significant difference between sex between the
484 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
485 of the same sport and sex

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492 **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·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·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·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·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·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·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·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} (%·s·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

493 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
 494 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 ($p < 0.05$)
 495 ^a significantly different to pubertal adolescents within the same training group ($p < 0.05$); ^b significant difference compared to the trained equivalents ($p < 0.05$)

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498 **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·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·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·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·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·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·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·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} (%·s·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}

499 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
500 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 <
501 0.05); ^a significantly different to pubertal adolescents within the same training group (p < 0.05), ^b significant difference compared to the trained equivalents (p < 0.05).

502 **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 **

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

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