



UNIVERSITY OF  
GLOUCESTERSHIRE

This is a peer-reviewed, post-print (final draft post-refereeing) version of the following published document, Accepted author manuscript version reprinted, by permission, from *Pediatric Exercise Science*, 2025, 37(4): pp378-pp389, <https://doi.org/10.1123/pes.2023-0150>. © Human Kinetics, Inc. and is licensed under All Rights Reserved license:

**Baker, James, Read, Paul J ORCID logoORCID:  
<https://orcid.org/0000-0002-1508-8602>, Graham-Smith, Philip,  
Monaco, Mauricio, Varamenti, Evdokia, Cardinale, Marco and  
Jones, Thomas W (2025) Physical Determinants of Sprint and  
Long Jump Performance in Male Youth Track-and-Field  
Athletes With Differing Maturity Statuses. *Pediatric Exercise  
Science*, 37 (4). pp. 378-389. doi:10.1123/pes.2023-0150**

Official URL: <http://dx.doi.org/10.1123/pes.2023-0150>

DOI: <http://dx.doi.org/10.1123/pes.2023-0150>

EPrint URI: <https://eprints.glos.ac.uk/id/eprint/14461>

#### **Disclaimer**

The University of Gloucestershire has obtained warranties from all depositors as to their title in the material deposited and as to their right to deposit such material.

The University of Gloucestershire makes no representation or warranties of commercial utility, title, or fitness for a particular purpose or any other warranty, express or implied in respect of any material deposited.

The University of Gloucestershire makes no representation that the use of the materials will not infringe any patent, copyright, trademark or other property or proprietary rights.

The University of Gloucestershire accepts no liability for any infringement of intellectual property rights in any material deposited but will remove such material from public view pending investigation in the event of an allegation of any such infringement.

PLEASE SCROLL DOWN FOR TEXT.

- 1
- 2
- 3 Blind Title:
- 4 Physical determinants of sprint and long jump performance in male youth track and field athletes with differing
- 5 maturity statuses

## 6 Abstract

7  
8 Purpose: This study examined the physical determinants of 60m sprint and long jump (LJ) performance and  
9 differences between maturity groups in physical characteristics in young male track and field athletes.  
10 Methods: Competition results, countermovement jump (CMJ), isometric leg press (ILP), 10-5 repeated jump  
11 test and 50m sprint were collected over 3 seasons for 54 male athletes (age  $13\pm 1$  years; stature  $160.0\pm 8.9$  cm;  
12 body mass,  $48.0\pm 9.8$  kg; predicted adult height  $92.2\pm 5.5\%$ ) grouped by maturity status: approaching- ( $n = 16$ ),  
13 circa- ( $n = 19$ ) and post-Peak Height Velocity (PHV) ( $n = 19$ ). Results: There were significant between-group  
14 differences in 60m, LJ, and all physical testing variables ( $P < 0.001$ ,  $g = 0.88-5.44$ ) when comparing the  
15 approaching- and circa-PHV groups with the post-PHV group. Significant differences were identified between  
16 the approaching- and circa-PHV groups in 40m ( $P = 0.033$ ,  $g = 0.89$ ), 50m ( $P = 0.024$ ,  $g = 1.64$ ) and 60m ( $P < 0.001$ ,  
17  $g = 0.89$ ) sprint times. Valid multivariate models were established for 60m and LJ, using the whole sample,  
18 with several CMJ, ILP and 50m sprint variables important for projecting performance. Conclusion: Large  
19 differences in performance across maturity groups highlight the importance of understanding athletes' maturity  
20 status to accurately interpret performance. Several physical performance variables were important for  
21 projecting competition 60m and LJ performance.

22

23

24 Funding Statement: There were no sources of funding for this study.

25

26

27

28

29

30 Keywords:

31 Athletics, growth, maturation, speed, power

## 32 INTRODUCTION

33 Track and field events consist of running, jumping, and throwing, with performance outcomes largely affected  
34 by genetic factors and physical characteristics (6). Success in track and field is dependent on high levels of  
35 strength, speed, endurance, and power(3,18,44,53), with the exact contribution of these qualities varying  
36 depending on the event. These physical qualities are affected by training, age, growth, and  
37 maturity(32,36,46,50); therefore, at the youth level, results are likely to be influenced by growth. Within a  
38 single chronological age group, large variations exist in the status, timing, and rate of maturation, especially  
39 between 12-15 years of age(33). Earlier maturing athletes have advantages in terms of size, strength, power,  
40 and speed compared to their on-time or later developing peers(13). However, there is limited research  
41 examining the impact of growth and maturation on performance in youth track and field.

42  
43 Existing research on track and field at the youth level has focused on the relative age effect(4,9), injuries(35)  
44 and progression from junior to senior rankings(5,26). The impact of maturity on performance has not been  
45 adequately examined in track and field. Improving our understanding of how maturity affects performance  
46 will enable practitioners to evaluate young athletes more accurately, resulting in more informed decision-  
47 making around selection, deselection, and progression within talent pathways. Previous research has indicated  
48 that, in national track and field rankings, only a small percentage of highly ranked youth progress to the senior  
49 level(5,6,26). This may be a result of early maturing athletes dominating the sport at younger ages before  
50 declining, as maturity differences are less apparent, and the later developing athletes catch up.

51  
52 The physical determinants of elite performance have been examined previously in short sprint and long jump  
53 senior athletes(18,21,40,44,53). High-level performers in these events generate greater levels of force and  
54 power relative to body weight in short periods (3,18,44,53), given the short ground contact times in sprinting  
55 (34,54) and during long jump take-off(18,19). Research has shown world class elite sprinters to have  
56 significantly higher jump height, propulsive and braking forces in the CMJ, compared to sub-elite counter parts

57 (3). Peak isometric force, rate of force development, CMJ height and drop jump height have been shown to be  
58 strongly associated with sprint, bound, and jump test performance in elite horizontal jumpers. Tests including  
59 a stretch-shortening cycle component were noted as demonstrated stronger relationships than purely concentric  
60 tests (18). However, the underlying physical determinants of sprint and jump performance in youth track and  
61 field athletes at differing maturity statuses, using a similar battery of tests, remains unexplored.

62  
63 A growing body of research has shown improvements in strength, power(14,38,49,50,52), sprinting  
64 speed(15,36,41,52), and stretch-shortening cycle function (2,27,45) with advancing age, growth, and  
65 maturation. These findings can be attributed to changes in muscle size, fiber-type, architecture, activation,  
66 mechanical tendon properties, and neuromuscular function (45,46). In youth athletes, research measuring  
67 sprint performance, strength, and power indices has identified a performance improvement with advancing  
68 maturity status(15,39,41). Meylan et al. (39)showed that a 10% increase in strength and power results in a 1.6  
69 to 2.4% improvement in sprint performance within a maturity group. Edwards et al. (15) reported differences  
70 in maximum speed and mechanical sprint variables between the post-PHV, pre-, and mid-PHV groups.  
71 However, there were no differences between the two least mature groups over short distances (5m and 10m).  
72 Meaningful reductions in sprint split times emerged only beyond 15m in the post-PHV group. The running  
73 technique (increased stride length and reduced stride frequency) and anthropometric changes from pre- to post-  
74 PHV are contributing factors to improved maximal speed with maturation(36,37). Improvements in stretch-  
75 shortening cycle function owing to increases in strength and muscle pre-activation (27,46) may also contribute  
76 to improvements over longer distances at maximum speed, where the ability to produce high forces in short  
77 ground contact times is important.

78  
79 Cumulatively, these findings suggest that advanced maturity leads to improved performance in sprint and jump  
80 events. Given that all previous studies utilized untrained school children (36, 37) or team sport athletes (15,  
81 41, 46, 52), there is a need to investigate the effects on performance within a cohort of high-level youth

82 track and field athletes. In addition, the physical performance determinants are not well established in these  
83 cohorts. Sprint performance was also only assessed over shorter distances than event distances (<40m). Given  
84 that changes in performance outcomes may be more apparent as sprint distance increases(15), it would appear  
85 to indicate that maturity divergences over specific track and field distances and the key physical determinants  
86 of these performances should be examined.

87  
88 Therefore, the aims of this study were to 1) examine between-group differences as defined by maturity status  
89 in the 60m sprint, long jump, and a physical testing battery; 2) identify key physical determinants of sprint and  
90 long jump performance; 3) determine whether different test variables are more useful for projecting  
91 performance at different stages of maturity; 4) provide maturity status benchmarks for the 60m and LJ, based  
92 on a group of highly trained, young male athletes of differing maturity status specifically selected for a national  
93 track and field development program. 60m and LJ were selected because the format of these events was  
94 consistent across the age groups within the study. Other events, such as the hurdles and throwing events, utilize  
95 different hurdle heights and spacing, and implement weights, respectively across the age categories limiting  
96 our ability to provide meaningful performance comparisons.

97

## 98 METHODS

### 99 **Study Design**

100 This cross-sectional study examined data collected within a national sports academy over three seasons (2019-  
101 22) during the first physical testing and competition period at the end of the 8-week general preparatory phase  
102 in November, or during the second testing and competition period in February. The weekly schedule included  
103 two athletics sessions, two strength and conditioning sessions, and one of each of the following: swimming,  
104 gymnastics, and a multi-sport session, where athletes would typically participate in invasion games (e.g.,  
105 basketball, handball). To be included in the study, a complete profile of competition results (60m sprint and  
106 long jump [LJ]) had to be collected within a 31-day period of physical testing (50m sprint, countermovement

107 jump [CMJ], 10-5 repeated jump test [10-5 RJT], Isometric Leg Press [ILP], and anthropometric and maturity  
108 assessments). Due to scheduling restrictions within the academy, physical testing was completed during two  
109 separate sessions. The maturity assessments, 10-5 RJT, CMJ were completed in the first session and ILP during  
110 the second session. Each participant was only sampled once for the present study, on the first occasion where  
111 both the competition and physical testing had both been completed in the required timeframe. A standardized  
112 warm up was completed by all athletes prior to testing.

113

#### 114 **Participants**

115 Fifty-four male youths (age  $13\pm 1$  years; stature  $160.0\pm 8.9$  cm; body mass,  $48.0\pm 9.8$  kg; percentage of predicted  
116 adult height  $92.2\pm 5.5\%$ ) of different maturity statuses (approaching-PHV  $n=16$ ; circa-PHV  $n=19$ , post-PHV  
117  $n=19$ ) were recruited from an elite development academy for Track and Field (Athletics) into the academy is  
118 permitted following the national talent ID selection process. See table 1 for detailed participant characteristics  
119 for each maturity group. All the subjects were part of the athletics national talent development programme and  
120 participated in competitions at a local, regional, and national level. Athletes are exposed to 16 hours a week of  
121 structured technical training including formalized strength and conditioning. Participants were required to have  
122 been a member of the academy for a minimum of three months and a maximum of three years. Ethical approval,  
123 parental consent, and participant assent were obtained from the Institutional Review Board prior to  
124 commencement of the study.

125

#### 126 **Procedures**

127

##### 128 Anthropometry

129 Athletes' stature, sitting height, and body mass were recorded on a calibrated measurement platform  
130 (Harpenden Stadiometer, Holtain Limited, Crosswell, UK) and weighing scale (M304601, ADE Hamburg,  
131 Germany), respectively.

132  
133 Adult Predicted Height (Bone Xpert)  
134  
135 Hand-wrist radiographs, standing height, and body mass measurements were used to determine the skeletal  
136 age, and subsequently, the calculation of predicted adult height. Skeletal age was assessed using standard  
137 radiographs (Digital Diagnost; Philips, USA) of the radius, ulna, carpals, metacarpals, and phalanges(31).  
138 Roentgenograms were evaluated by automated processing of digital images using the computerized BoneXpert  
139 ® determination method (51) according to the manufacturer’s recommendations (version 3.1.4, Visiana, Holte,  
140 Denmark), and skeletal age and predicted adult height were determined according to the TW-II protocol. The  
141 specific details of these methods have been previously published(29).  
142  
143 Maturity status  
144  
145 Maturation status was calculated using the final predicted adult height from the BoneXpert software. Stature  
146 measurements were then used to calculate each participant’s current Percentage of Predicted Adult Height  
147 (%PAH) and were classified using the following thresholds: pre-PHV (<85% PAH), approaching-PHV (≥85–  
148 <90% PAH), circa-PHV (≥90–<95%PAH), and post-PHV (≥95% PAH)(13).  
149  
150 Collection and analysis of saliva samples  
151 Salivary testosterone was collected as an additional marker of maturation status, as part of routine athlete  
152 monitoring processes within the development programme for athletics. Athletes arrived at the test venue before  
153 10 am to avoid diurnal variations in salivary testosterone levels(22). According to the manufacturer’s  
154 recommendations (Salimetrics, PA, USA), participants were instructed to refrain from eating or brushing their  
155 teeth within 60 min of sample collection. They were then asked to rinse their mouth with water, sit quietly for

156 10 min, and place the SalivaBio Oral Swab (SOS) under the tongue for 2 min to collect saliva. The swabs were  
157 then transferred into collection kits and stored at -20°C until data collection was completed.

158  
159 On the day of analysis, the samples were thawed and spun for 15 min at 1500 g. The enzyme-linked  
160 immunosorbent assay (ELISA) method was used to determine the salivary free testosterone concentrations  
161 (Salimetrics, PA, USA). Absorbance was measured using an automated plate reader (Tecan Infinite 200Pro,  
162 CH). The inter-assay coefficient of variation (CV) ranged from 5.6% to 14.1%, and the intra-assay variability  
163 was <6.0% in all measurements (10,20).

164  
165 Competition Data (60m and Long Jump)  
166 The results were collected during official indoor athletic competitions hosted by the academy, for which the  
167 lead investigator was present at all the events. Indoor competition was chosen because it provided a consistent  
168 environment without wind. The sixty-meter (60m) and long jump (LJ) events took place on an indoor athletics  
169 track that met the IAAF standards for international competition. The 60m event was electronically timed using  
170 the FinishLynx photo-finish technology timing system (Haverhill, MA, USA), the athletes started from blocks  
171 and participated in a heat and a final, if they qualified. In the LJ event, athletes had three jumps and started  
172 their approach from a distance determined with their coach, typically between 20-30m. Jump distance was  
173 measured with a metal measuring tape from the take-off board to the athletes nearest imprint in the sand. Spikes  
174 were worn by all athletes during both events. The competition results were uploaded into an internal database  
175 and retrieved later for the study. The best performance in each event was used in the analysis, regardless of  
176 where it occurred in the competition.

177  
178 10-5 Repeated Jump Test  
179 The 10-5 RJT was completed using a contact jump mat (Smartspeed, Vald Performance, Brisbane, Australia).  
180 The test was initiated with a countermovement jump, followed by 10 consecutive reactive maximal jumps,

181 keeping their hands on their hips throughout. Participants were instructed to jump ‘as high as possible and  
182 minimize the time spent on the ground’. The five jumps with the highest flight time (FT) and ground contact  
183 time (GCT)  $< 250 \text{ m}\cdot\text{s}^{-1}$  were used for the analysis. The reactive strength index (RSI) was calculated as the  
184 FT divided by the GCT (both in milliseconds). The mean RSI, FT, GCT, and jump height (JH) were calculated  
185 for the five selected jumps. Athletes completed two trials with 3 minutes rest. The trial with the highest mean  
186 RSI was used in the analysis. Further details of the methods, validity, and reliability of the 10-5 RJT protocol  
187 have been previously published(2).

188

### 189 Countermovement Jump

190 Participants performed three maximal countermovement jumps on a dual-force platform system (ForceDecks  
191 FD4000, Vald Performance, Brisbane, Australia) sampling at 1000 Hz, with their hands placed on their hips(7).  
192 They were instructed to stand perfectly still prior to being given the command to ‘jump as high as possible’,  
193 resetting their foot position between trials. All 3 jumps were performed within 60 seconds. The variables used  
194 in the analysis were CMJ jump height (CMJ JH), relative power (RP), mean peak eccentric power, mean peak  
195 concentric power, and mean total force.

196 The onset of movement was defined as the point when the total vertical force deviated -20 N from the body  
197 weight determined during the quiet standing phase, and the take-off was set to the point when the total vertical  
198 force dropped below 10 N. Jump height was calculated from the total vertical force (summation of left and  
199 right forces), and its first derivative was used to determine vertical velocity. The eccentric phase was defined  
200 as the point from the movement onset to the instant at which the vertical velocity was zero (the maximum  
201 downward displacement of the center of mass). The concentric phase was then characterized as the point from  
202 zero center of mass velocity to take off. Power was calculated as the product of the total vertical force and  
203 vertical velocity.

204

## 205 50m sprint

206 Three maximal 50m sprints were performed whilst being tracked using a laser speed gun sampling at 100 Hz  
207 (Laveg LDM 300C, Jenoptik, Jena), positioned approximately 3m behind the zero line. The subjects performed  
208 the sprints individually, starting each run in an upright position 0.5m behind the zero line. Subjects were  
209 instructed to “run as fast as possible through the 50m marker before slowing down”.

210  
211 Data were exported into a bespoke Excel analysis spreadsheet to determine 10m split times and instantaneous  
212 velocity and smoothed using 5- and 51-point moving averages, respectively(18). The variables extracted for  
213 analysis included: (0-50m), (0-40m), (0-30m), (0-20m), (0-10m), (0-5m), as well as the maximum  
214 instantaneous velocity and the distance at maximum velocity.

## 215 216 Isometric Leg Press

217 A 45-degree leg press (Plated Loaded Linear Leg Press, Hammer Strength, Des Plaines, IL, USA) was adapted  
218 with a mounted 60 × 40 cm single force plate (Kistler, model 9281E, Winterthur, Switzerland) to assess  
219 isometric leg extension peak and relative force. The knee angle was set to 110 ° using a manual goniometer.  
220 Athletes worked through a progressive warm up at a self-determined 50, 70 and 90% of maximum effort for 5  
221 s, with at least 1 min rest between each. The athletes were instructed to start with a small push to remove any  
222 slack from the machine, and then to ‘push as hard as possible’ for 5 s. Athletes were verbally encouraged to  
223 maintain their effort for the duration of each trial. Two trials were completed, with 3 minutes rest between  
224 each. Data were collected using Kistler BioWare software and processed to calculate the resultant force of  
225 each trial. The trial with the highest peak force was used for analysis.

## 226 227 STATISTICAL ANALYSIS

### 228 Maturational Differences

229 Descriptive statistics (mean [SD]) for anthropometric data, competition results, and physical tests were  
230 calculated for each maturity group. Normality was tested using the Shapiro-Wilk test. The following variables  
231 were not normally distributed ( $P < 0.05$ ): age, PPAH, 30m time, 40m time, ILP peak force and relative force,  
232 CMJ RP, mean peak concentric power, mean total force, and salivary testosterone. All other variables were  
233 normally distributed. Athletes were grouped according to their current PPAH: pre-PHV ( $< 85\%$ ), approaching-  
234 PHV ( $\geq 85\text{-}<90\%$ ), circa-PHV ( $\geq 90\text{-}<95\%$ ) and post-PHV ( $\geq 95\%$ )(13). Kruskal-Wallis one-way analysis of  
235 variance was performed to examine any between group differences for all variables, with the alpha level set at  
236  $P < 0.05$ . Dwass-Steel-Critchlow-Fligner pairwise comparisons were performed to identify differences between  
237 the groups. Hedges'  $g$  effect sizes (ES) were also calculated to interpret the magnitude of between group  
238 differences using the following classification: standardized mean difference of 0.2 (small), 0.5 (moderate), 0.8  
239 (large) and 1.1 (very large)(23). Benchmarks were calculated for the 60m and LJ using the mean and standard  
240 deviation for each maturity group and the following Z-score thresholds: excellent ( $> 1.5$ ), good (0.5 to 1.5),  
241 average (-0.5 to 0.5), below average (-0.5 to -1.5) and poor ( $< -1.5$ ).

242

#### 243 Multivariate data analysis

244 Analyses were conducted using SIMCA 16.0 (MKS AB, Umeå, Sweden). Multivariate data analysis (MVDA)  
245 methods were used to examine whether competition 60 m sprint and long jump performance could be projected  
246 using a combination of laboratory and field-tested strength and power indices. Principal component analysis  
247 (PCA) was used to analyze the relationships between the strength and power indices, and to assess any hidden  
248 structures and patterns via the reduction of data dimensions. Orthogonal projections to latent structures (OPLS)  
249 were employed to identify linear relationships between two groups of variables: (1) sprint and long jump  
250 performance and (2) speed, strength, and power indices. The specific details of these methods have been  
251 published previously(16,25).

252 Sprint and long jump performances ( $Y$  variables) were projected from speed, strength, and power metrics ( $X$   
253 variables), and  $R^2VY$  is the cumulative percentage of the variation of the response explained by the model

254 after the last component. The  $R^2$  is a measure of how well the model fits the data.  $R^2VYAdj$  is the cumulative  
255 percentage of the variation in the response, adjusted for degrees of freedom, explained by the model after the  
256 last component.  $Q^2VY$  is the cumulative percentage of the variation in the response predicted by the model  
257 after the last component, according to cross-validation.  $Q^2$  indicates how well the model projects new data,  
258 and permutations (one less cycle than the number of X variables) of the models were deemed valid if the  
259 intercept was  $< 0$ , or if all permuted  $Q^2$  values were below the original model value.  $R^2$  and  $Q^2$  should be  $> 0.8$   
260 and  $> 0.5$ , for well-modelled data (extracted from the SIMCA-P + Handbook).

261  
262 To evaluate the importance of specific strength and power metrics for projecting sprint and long jump  
263 performance, variable influence on projection (VIP) analyses were conducted. In the OPLS model, VIP  
264 summarizes the importance of the X variables for both the X and Y models. VIP is normalized and the average  
265 squared VIP value is 1; thus, a  $VIP > 1$  indicates that the variable is important for projection, and a value  $< 0.5$   
266 indicates that the variable is not important for the projection(16). Block-wise multiple linear regression (MLR)  
267 analyses were run for equivalent models to confirm that the inferences generated by OPLS were reflective of  
268 the underlying data. The Root Mean Square Error (RMSE) was calculated for all OPLS and MLR models to  
269 determine which models had the best predictive ability.

270  
271 Models were constructed for 60 m sprint and long jump performance for all athletes combined and then by  
272 maturation status: approaching, circa, and post-PHV. Specific variables such as speed, strength, and power  
273 metrics (*X* variables) were included in the models for the 60m Sprint. 20m sprint time was included as a  
274 measure of acceleration because it has a strong relationship with maximum speed(1). The ILP peak and relative  
275 force were selected based on the high forces required to overcome inertia in the block start of a sprint, and  
276 previous research has indicated that relative force-producing capabilities differentiate faster and slower  
277 athletes(44,53). The ability to rapidly produce large forces relative to body mass is required to accelerate

278 quickly. Beattie et al. (6) found a difference in CMJ jump height and relative power between elite (0.57m  
279  $\pm 0.03$ ;  $75.0 \text{ W}\cdot\text{kg}^{-1} \pm 2.6$ ) and sub-elite male sprinters ( $0.44\text{m} \pm 0.01$ ;  $68.2 \text{ W}\cdot\text{kg}^{-1} \pm 3.2$ ). Therefore, we included  
280 several metrics from the CMJ test: jump height, relative power, mean peak eccentric and concentric powers,  
281 and mean total force. Throughout a race, flight times increase and contact times decrease as the maximal  
282 velocity is achieved. Contact times at the top speed in elite sprinters are typically 80-100ms (34,54) making  
283 the ability to produce high forces in minimal times a key ability for sprinters. Hence, we included the RSI,  
284 jump height, flight time, and contact time from the 10-5 RJT.

285 For the long jump, 30m time was selected as the young athletes in this cohort typically use this distance for  
286 their approach to the take-off board. Senior athletes used up to 40m, so this distance was also included. The  
287 ILP peak and relative force were used because of the requirement to produce extremely high forces at take-  
288 off(18). Power variables (CMJ jump height, relative power, mean total force, and mean eccentric and  
289 concentric peak power) were selected, given the need to produce force quickly in a stretch-shortening cycle  
290 action in the take-off at the board and during the approach run. RSI, CT, and FT from 10-5 RJT were included  
291 as the ability to respond to a high impact and reverse an eccentric action to a concentric action in a minimal  
292 time frame necessary at take-off.

293

## 294 RESULTS

### 295 Maturation Differences

296 Table 1 shows the age, maturity, anthropometry, competition performance, and physical testing results of all  
297 athletes in the study according to their maturity status:

298

299 <TABLE 1 HERE>

300

301 Significant between groups differences ( $P<0.001$ ) with a large ES were present for age ( $g=1.25$  to  $3.07$ ).  
302 Pairwise comparisons indicated differences between the approaching- and post-PHV and circa- and post-PHV  
303 groups ( $P<0.001$ ). Stature increased significantly between the maturity groups with large ES ( $g=1.02$  to  $2.66$ ).  
304 There were also large differences in body mass between approaching- and circa-PHV ( $P=0.020$ ,  $g=1.26$ ),  
305 approaching- and post-PHV ( $P<0.001$ ,  $g=2.77$ ), and circa- to post-PHV ( $P<0.001$ ,  $g=0.83$ ). PPAH was  
306 significantly different corresponding to large ES between all 3 maturity groups ( $g=2.91$  to  $5.83$ ). Saliva  
307 testosterone levels were significantly different between the approaching- and post-PHV ( $P<0.001$ ,  $g=1.31$ ) and  
308 circa- and post-PHV groups ( $P=0.001$ ,  $g=1.09$ ), but not between the approaching and circa-PHV ( $P=0.083$ ,  
309  $g=0.33$ ) groups.

310  
311 The 60m sprint and long-jump competition and physical testing results for each maturation group are shown  
312 in table 1. 60m sprint time decreased significantly with advancing maturity ( $P<0.001$ ) with a large ES when  
313 comparing the approaching- to circa-PHV ( $P<0.001$ ,  $g=0.89$ ) and circa- to post- PHV ( $P<0.001$ ,  $g=1.67$ )  
314 groups. A very large ES was observed between approaching- and post-PHV groups ( $g=3.14$ ). The long jump  
315 distance also increased across maturity groups. However, significant differences were only present between  
316 the circa- and post-PHV ( $P=0.023$ ,  $g=0.94$ ) and approaching- and post-PHV ( $P=0.002$ ,  $g=1.52$ ) group  
317 comparisons, with large and very large ES, respectively.

318  
319  
320 In the CMJ, no significant differences were found between the approaching and circa-PHV groups for any of  
321 the variables. Comparisons between the approaching- and post-PHV groups revealed significant differences  
322 and very large ES for all variables: JH ( $P<0.001$ ,  $g=1.96$ ), relative power ( $P<0.001$ ,  $g=1.44$ ), mean peak  
323 eccentric power ( $P=0.005$ ,  $g=1.34$ ), mean peak concentric power ( $P<0.001$ ,  $g=1.95$ ), and mean total force  
324 ( $P=0.004$ ,  $g=1.22$ ). Similarly, the differences between circa- and post-PHV were all statistically significant  
325 with large to very large ES: JH ( $P<0.001$ ,  $g=1.54$ ), relative power ( $P<0.001$ ,  $g=1.25$ ), mean peak eccentric

326 power ( $P=0.012$ ,  $g=1.05$ ), mean peak concentric power ( $P=0.001$ ,  $g=1.61$ ), and mean total force ( $P=0.006$ ,  
327  $g=1.03$ ).

328  
329 In the 10-5 RJT, significant differences in RSI, FT, and JH were observed. RSI increased significantly between  
330 the approaching and post-PHV groups ( $P=0.015$ ), displaying a large ES ( $g=0.88$ ). There were no significant  
331 differences between those who were approaching- to circa-PHV ( $P=0.265$ ,  $g=0.49$ ) or circa- and post-PHV  
332 ( $P=0.176$ ,  $g=0.46$ ). FT increased significantly with a large ES between approaching- and post-PHV ( $P=0.027$ ,  
333  $g=0.87$ ) and circa- to post-PHV ( $P=0.011$ ,  $g=0.95$ ), but not between the approaching- and circa-PHV groups  
334 ( $P=0.942$ ,  $g=0.02$ ). There were no significant differences in the mean CT across the groups.

335  
336 Isometric leg press results revealed significant increases in peak force with maturity status, but no significant  
337 difference was observed in relative force. There were no statistically significant differences in the peak force  
338 between the two least mature groups ( $P=0.822$ ,  $g=0.15$ ). Peak force increased when comparing the  
339 approaching and post-PHV groups ( $P=0.003$ ,  $g=1.15$ ), as well as those who were circa- and post-PHV  
340 ( $P=0.001$ ,  $g=1.18$ ), corresponding to a very large ES.

341  
342 Significant differences were observed for all measured variables in the 50m sprint between maturity groups  
343 (see table 1). Pairwise comparisons revealed no significant differences for the 5m, 10m, 20m, and 30m time  
344 between the approaching-PHV and circa-PHV groups ( $P>0.05$ ,  $g=0.66-0.83$ ). However, significant reductions  
345 with large to very large ES were observed for the 40m ( $P=0.033$ ,  $g=0.89$ ) and 50m ( $P=0.024$ ,  $g=1.64$ ) split  
346 times. The maximum velocity also increased ( $P=0.001$ ,  $g=1.04$ ) between the two groups. Significant  
347 differences were present in all the split times and maximum velocities when comparing the approaching- and  
348 post-PHV groups with very large ES that increased with each subsequent split time ( $g=1.79-5.44$ ). Circa and  
349 post-PHV group differences were also significant with large to very large ES ( $g=0.98$  to  $2.78$ ), again increasing

350 with sprint distance. For the distance at maximum velocity, a significant between-group difference existed  
351 between the approaching and post-PHV groups only ( $P=0.021$ ,  $g=0.81$ ).

352  
353 Multivariate data analysis

354 The details of the OPLS models for long jump and sprint performance (Y variables) are presented in table 2.  
355 In all cases, the MLR models exhibited a greater RMSE than that of the OPLS models. When analyzing the  
356 whole sample, valid projective models were identified for the 60m and LJ with several speed, strength and  
357 power indices from the 50m, ILP and CMJ important for projecting performance. No variables from the 10-5  
358 RJT were able to project performance in either event. The specific variables and their relative importance to  
359 performance are shown in figure 1, plots a) and d) for the whole sample. When analyzing within the maturity  
360 groups, valid models could not be established for all three maturity groups in either event. The valid models  
361 were in the approaching- and circa-PHV models for the LJ, and in the circa- and post-PHV for the 60m. Fewer  
362 variables, only from the CMJ and 50m sprint, were able to project performance in the maturity group models.  
363 The specific variables and their relative importance for projecting performance in are shown in figure 1, in  
364 plots b) and c) for the 60m and plots e) and f) for the LJ.

365  
366 <TABLE 2 HERE>

367  
368 < FIGURE 1 HERE>

369 Figure 1. Multivariate models for the 60m and long jump

370  
371 <TABLE 3 & 4 HERE>

372  
373 Tables 3 and 4 provide the maturity group benchmarks for the 60m sprint and long-jump events using Z-scores.



## 375 DISCUSSION

376 The current study aimed to examine the between-group differences between athletes of different  
377 maturity status in 60m and long jump performance and a physical testing battery including speed,  
378 strength and power indices commonly used in athlete monitoring and talent identification processes.  
379 An additional aim was to establish whether variables from the physical tests were able to project  
380 performance in the 60m and LJ within this sample of elite male youth track and field athletes of different  
381 maturity statuses. Significant differences with moderate to very large effect sizes ( $P < 0.001$ ,  $g = 0.88$ -  
382  $5.44$ ) were found in performance in the competition events and physical tests between the maturity  
383 groups. Valid multivariate models were established for the 60m and LJ in the whole sample and some  
384 of the maturity groups with several speed, strength and power indices important for projecting  
385 performance.

386

387 The first aim of our study was to examine between-group differences in competitive events and physical  
388 tests across maturity groups. Significant reductions in sprint time with large to very large ES ( $g = 0.89$ -  
389  $3.14$ ) in the 60m sprint time were present in all three maturity groups. This is consistent with previous  
390 research that has examined speed in youth over shorter distances (15,36,48,52), highlighting the  
391 potential advantage for early maturing athletes within their chronological age group category. This  
392 reinforces the importance of understanding the maturity status of athletes to understand the true context  
393 of performance in the youth track and field.

394

395 In the long jump, performance increased with advancing maturity; however, there were no significant  
396 differences between approaching-PHV and circa-PHV athletes. The smaller ES compared to the 60m  
397 sprint may be due to the greater skill component in the long jump. Athletes must convert their horizontal  
398 velocity into a vertical velocity at take-off on the board. Relatively younger and less mature athletes  
399 (approaching- and circa-PHV) are still developing these skills. We have observed they do not generate  
400 as much speed during the approach and are not strong enough to maximize the conversion of horizontal  
401 speed to vertical force production for take-off. This has connotations for coaches when considering the

402 training age during maturation. In this case, the athlete might have the speed capacity to be a good  
403 jumper in the future but may not have the technical ability and strength to use the speed, or vice versa.

404

405 This study is the first to examine anthropometry, maturity, event performance speed, strength, and  
406 power metrics concurrently in a youth track and field cohort involved in a development training  
407 program. Significant differences were observed between the maturity groups in all the physical tests.  
408 The largest differences and ES were typically from approaching- to post-PHV and circa-PHV to post-  
409 PHV, whereas the effect sizes were moderate between approaching- and circa-PHV. The 50m sprint  
410 test, with split times at 5- and 10m intervals assesses how the athletes perform in acceleration and  
411 maximal velocity phases when sprinting compared to the sole outcome measure in the 60m sprint. In  
412 the acceleration phase (represented by the 5-30m times), there were no significant differences between  
413 the approaching- and circa-PHV groups. This is consistent with other research in youth populations,  
414 where differences between the least mature groups over similar distances were not clear(15,36). In the  
415 present study, significant differences with large to very large effect sizes appeared in the 40m, 50m split  
416 times and maximum velocity. This emphasizes the need to examine a more comprehensive speed profile  
417 and utilize specific distances when testing to fully understand how speed develops in young athletes.

418

419 The lack of differences in the acceleration phase (0-30m) between the approaching- and circa-PHVs  
420 may be explained by several factors. First, body mass significantly increased in relation to changes in  
421 stature and potentially peak weight velocity (PWV). Therefore, inertia would have been greater at the  
422 start for the more mature group. Second, there were no significant increases in any strength or power  
423 variables that would have helped them overcome their higher mass, which is possibly related to  
424 testosterone levels remaining similar between the groups. Without changes in hormone levels, muscle  
425 mass, and muscle characteristics, increases in force production are unlikely. Third, rapid changes in  
426 stature and leg length may also result in some degree of disruption in technique and motor coordination  
427 in the form of adolescent awkwardness(43). Significant differences emerged between the approaching-  
428 and circa-PHV groups in the split times at 40m and 50m, and the maximum velocity may be explained

429 by the increase in leg length, and thus stride length, between the two groups (37). Speed being the  
430 product of stride length and stride frequency, the greater stride length of circa-PHV athletes likely  
431 enabled them to achieve higher speeds once they had overcome inertia and any coordination or technical  
432 challenges at the start. In contrast, the post-PHV athletes were significantly faster at all split times and  
433 maximum velocities compared to the other groups, consistent with previous research(15,36,48). This is  
434 likely a result of the increase in strength and power observed in the physical tests combined with further  
435 increases in stride length (related to further increases in leg length). Meaningful differences in RSI were  
436 found only between approaching- and post-PHV athletes, which is consistent with previous research,  
437 where significant increases in RSI were indicated between the least and most mature athletes only (2).  
438 The large increases in strength and power in the post-PHV group are likely a reflection of the increased  
439 levels of testosterone compared with the two least mature groups. While all athletes completed two  
440 strength & conditioning sessions per week in the academy, higher testosterone availability in the post-  
441 PHV group may have led to greater improvements in strength and power(12).

442

443 The second aim of this study was to analyze whether speed, strength and power indices from the  
444 physical testing battery were able to project competition performance in the 60m and long jump events.  
445 Valid multivariate models were established using OPLS and PCA methods for 60m and LJ, with several  
446 variables considered important for projection, when all athletes were grouped together. In both the 60m  
447 and long jump, speed, power, and strength variables from the 50m, CMJ, and ILP, respectively, were  
448 important for projecting performance in the whole sample. The data indicates that sprinting speed, the  
449 ability to produce high isometric peak force, CMJ jump heights and power relative to body weight are  
450 important for projection of long jump and 60m sprint performance in youth athletes. These findings are  
451 consistent with research in senior athletes, where similar qualities were correlated with performance in  
452 high-level sprinters and horizontal jumpers(3,18,44,53,54). In the present study, the CMJ was the most  
453 important variable for projecting performance in the long jump, whereas approach speed was identified  
454 as the most important factor in senior athletes in previous research(18). The magnitude of the correlation  
455 between vertical jumping and sprinting variables has been well defined in various populations; (8,11)

456 however, recent observations suggest that this relationship decreases as the level of performance of the  
457 athlete increases (24). These findings may also reflect that sprinting ability is still developing in younger  
458 athletes, and comparatively, a CMJ is a relatively simpler task to express their abilities.

459

460 The third aim was to determine whether different test variables are more useful for projecting  
461 performance at different stages of maturity. When the models were constructed separately for the three  
462 maturity groups. The multivariate models couldn't be established for all groups. Valid models were  
463 only established in the approaching- and circa-PHV groups in the LJ, and circa- and post-PHV groups  
464 in the 60m. Within the models for these groups, only variables from the CMJ and 50m sprint were able  
465 to project performance in both events (see figure 1). Smaller sample sizes may have affected within  
466 group comparisons, due to greater variability. In addition, less mature athletes (i.e. approaching-PHV)  
467 have previously been shown to have greater variability in jumping task performance (17,28), and similar  
468 jump metrics were unable to differentiate between elite youth footballers and a non-elite control group  
469 at a similar stage of maturity (pre-PHV)(41). Within the post-PHV group, there was a wide range of  
470 chronological ages (13.3–15.8 years), reflecting the variance in the timing of maturation. Relatively  
471 younger post-PHV athletes may have accumulated less training and therefore may not have performed  
472 as well in the competition events or physical tests, creating greater variability. Finally, changing PPAH,  
473 a continuous variable, into a categorical variable by grouping according to the percentage thresholds,  
474 although simple and convenient, can cause a significant loss of statistical power and residual  
475 confounding(47).

476

477 No metrics from the 10-5 RJT were able to project performance in either of the competitive events.  
478 These findings might reflect the fact that stretch-shortening cycle (SSC) abilities are still developing  
479 during maturation. Athletes experiencing rapid increases in stature and body mass might display a  
480 higher level of disruption to their performance levels in this test (2,43). The emergence of CMJ eccentric  
481 power as an important variable for projection in the post-PHV group, which is related to SSC function,  
482 may indicate that these variables will begin to differentiate performance levels once maturity-related

483 adaptations to muscles and tendons occurred, contributing to the development of SSC function(45).  
484 Whilst the 10-5 RJT did not project performance in our study, we propose that it would still be a useful  
485 test to track SSC development longitudinally, given that reactive strength has shown to be reliable, and  
486 valid with young athletes(2), and correlated with performance in senior track and field athletes(18).

487

488 The fourth aim was to provide maturity group benchmarks for the 60m and LJ to enhance coaches'  
489 ability to interpret performance (see tables 3 and 4). Based on the significant differences identified in  
490 performance between the maturity groups in both events (and physical testing measures) this approach  
491 would appear to be valuable for the athlete and key stakeholders. It can be used to provide the coach,  
492 athlete and parents with an alternative perspective on current performance levels in age group track and  
493 field competitions, where large inter-individual differences in maturity exist but are not currently  
494 accounted for. Future research should aim to establish similar benchmarks for more track and field  
495 events.

496

497 When interpreting the findings of this study, some limitations should be acknowledged. First, the  
498 sample size was relatively small, particularly when grouped by maturity status. Second, limitations in  
499 the PPAH grouping should be considered when interpreting the results or applying the approach used  
500 in the current study. A reduction in statistical power was associated with changing a continuous variable  
501 (PPAH) to a categorical variable (47) when grouping was applied according to percentage thresholds  
502 (13). Future research should explore alternative methods to evaluate competition and test performance  
503 against age and maturity to avoid compromising the statistical power. In addition, there is conflicting  
504 evidence regarding the efficacy of the PPAH method in correctly assigning athletes to maturity  
505 groups(30,42). Despite these potential limitations, using PPAH offers a practical, time-efficient solution  
506 to determine the maturity status repeatedly, overcoming medical restrictions on the number of X-rays  
507 and the time-consuming nature of the measurement and analysis procedures.

508

509 In conclusion, the significant differences and large effect sizes found between maturity groups in both  
510 competition and physical tests have highlighted the potential inequality of the youth track and field  
511 when differences in maturity status are present. Therefore, determining the maturation status appears to  
512 be very important for coaches, athletes, and parents when interpreting current performance in youth  
513 track and field athletes. Valid models for the projection of 60m sprint and long jump performances were  
514 established across several metrics from the CMJ, ILP and 50m sprint test, validating the selection of  
515 these tests. The validity of the models in the whole sample suggests that coaches and sports scientists  
516 can confidently utilize the CMJ, ILP and 50m Sprint to assess strength, power, and speed qualities in  
517 male youth track and field athletes (aged 12-16) to project performance.

518

#### 519 PRACTICAL APPLICATIONS

520 Using tables 3 and 4, coaches can evaluate performance in the 60 m and long jump events by considering  
521 an athlete's individual maturity status in addition to any age group evaluations. The reader can create  
522 similar benchmarks for the physical tests using the means and standard deviations from table 1 and the  
523 Z-score grading bands highlighted above. Using these benchmarks may assist in talent identification  
524 processes in young athletes, where maturity differences exist. This potentially allows less mature  
525 athletes' talent to be recognized when their potential is hidden when compared to age-based standards.

526

527 The CMJ and 50 m sprint tests may be the most useful and practical for practitioners looking to  
528 differentiate 60 m and long jump performance levels in young track and field athletes. The authors  
529 recommend monitoring growth and maturation when working with male adolescent athletes in the sport.  
530 Establishing maturity status will enable practitioners to make more informed decisions about athletes'  
531 training and more accurately evaluate current performance using the maturity-based benchmarks  
532 provided. Bio-banding is a process that has been utilized in team sports, such as soccer, where athletes  
533 are grouped according to maturity status rather than chronological age to create a more balanced  
534 competition(13). It is not currently applied in youth track and field, but it could provide an alternative

535 competition format to ensure that all athletes are appropriately challenged against athletes of a similar  
536 maturity status.

537

#### 538 ACKNOWLEDGEMENTS

539

540 The authors express their gratitude to CB and SS for their contribution to the data collection process.

541 In addition, KM and JA for their help in processing data ready for analysis. The authors have no

542 conflicts of interest to disclose and there are no sources of funding for this research.

543

#### 544 REFERENCES

545 1. Baker D, Nance S. The relation between running speed and measures of strength and power in  
546 professional rugby league players. *J Strength Cond Res.* 1999;13(3):230–235.

547 2. Baker J, Shillabeer B, Brandner C, Graham-Smith P, Mills P, Read P. Reliability, validity, and  
548 performance characteristics of elite adolescent athletes at different stages of maturity in the 10 to 5  
549 repeated jump test. *Pediatr Exerc Sci.* 2021;34(1):20–27.

550 3. Beattie K, Tawiah-Dodoo J, Graham-Smith P. Countermovement jump characteristics of  
551 world-class elite and sub-elite male sprinters. *Sports Performance and Science Reports.* 2020;7(1):1-4.

552 4. Bezuglov E, Shoshorina M, Emanov A, et al. The relative age effect in the best track and field  
553 athletes aged 10 to 15 years old. 2022;1–10.

554 5. Boccia G, Cardinale M, Brustio PR. Elite junior throwers unlikely to remain at the top level in  
555 the senior category. *Int J Sports Physiol Perform.* 2021 Sep 1;16(9):1281–1287.

556 6. Boccia G, Cardinale M, Brustio PR. World-class sprinters' careers: early success does not  
557 guarantee success at adult age. *Int J Sports Physiol Perform.* 2021 Mar 1;16(3):367–374.

558 7. Bosco C, Komi P V, Ito A. Prestretch potentiation of human skeletal muscle during ballistic  
559 movement. *Acta Physiol Scand.* 1981 Feb;111(2):135–140.

- 560 8. Bosco C, Tsarpela O, Foti C, et al. Mechanical behaviour of leg extensor muscles in male and  
561 female sprinters. *Biol Sport* [Internet]. 2002;19(3):189–202.
- 562 9. Brustio PR, Kearney PE, Lupo C, et al. Relative age influences performance of world-class  
563 track and field athletes even in the adulthood. 2019;10(1395):1-10.
- 564 10. Butler GE, Walker RF, Walker R V, Teague P, Riad-Fahmy D, Ratcliffe SG. Salivary  
565 testosterone levels and the progress of puberty in the normal boy. *Clin Endocrinol (Oxf)*. 1989  
566 May;30(5):587–596.
- 567 11. Colyer SL, Stokes KA, Bilzon JJ, Cardinale M, Salo AIT. Physical predictors of elite  
568 skeleton start performance. *Int J Sports Physiol Perform*. 2017 Jan;12(1):81–89.
- 569 12. Crewther BT, Pastuszak A, Sadowska D, Górski M, Cook CJ. The digit ratio (2D:4D) and  
570 testosterone co-predict vertical jump performance in athletic boys: Evidence of organizational and  
571 activational effects of testosterone on physical fitness. *Physiol Behav*. 2022 Jul 1;251:113816.
- 572 13. Cumming SP, Lloyd RS, Oliver JL, Eisenmann JC, Malina RM. Bio-banding in sport:  
573 applications to competition, talent identification, and strength and conditioning of youth athletes.  
574 *Strength Cond J*. 2017;39(2):34–47.
- 575 14. Dobbs IJ, Oliver JL, Wong MA, Moore IS, Lloyd RS. Movement competency and measures  
576 of isometric and dynamic strength and power in boys of different maturity status. *Scand J Med Sci  
577 Sports*. 2020 Nov;30(11):2143–2153.
- 578 15. Edwards T, Weakley J, Banyard HG, et al. Influence of age and maturation status on sprint  
579 acceleration characteristics in junior Australian football. *J Sports Sci*. 2021 Feb;1–9.
- 580 16. Eriksson L, Byrne T, Johansson E, Trygg J, Vikström C. Multi- and megavariable data analysis:  
581 basic principles and applications. Malmö: Umetrics; 2013.
- 582 17. Gerodimos V, Zafeiridis A, Perkos S, Dipla K, Manou V, Kellis S. The contribution of stretch-  
583 shortening cycle and arm-swing to vertical jumping performance in children, adolescents, and adult  
584 basketball players. *Pediatr Exerc Sci*. 2008;20(4):379–389.
- 585 18. Graham-Smith P, Brice P. Speed, strength & power characteristics of horizontal jumpers. In:  
586 *International Society of Biomechanics in Sport*. University of Michigan, Marquette; 2010.

- 587 19. Graham-Smith P, Lees A. A three-dimensional kinematic analysis of the long jump take-off. J  
588 Sports Sci. 2005;23(9):891–903.
- 589 20. Granger DA, Schwartz EB, Booth A, Arentz M. Salivary testosterone determination in studies  
590 of child health and development. *Horm Behav.* 1999 Feb;35(1):18–27.
- 591 21. Hay JG, Miller JA, Canterna RW. The techniques of elite male long jumpers. *J Biomech.*  
592 1986;19(10):855–866.
- 593 22. Hayes LD, Bickerstaff GF, Baker JS. Interactions of cortisol, testosterone, and resistance  
594 training: Influence of circadian rhythms. Vol. 27, *Chronobiology International.* 2010. p. 675–705.
- 595 23. Hedges L V, Olkin I. *Statistical Methods for Meta-analysis.* New York: Academic Press; 1985.
- 596 24. Jiménez-Reyes P, Samozino P, García-Ramos A, Cuadrado-Peñañiel V, Brughelli M, Morin  
597 JB. Relationship between vertical and horizontal force-velocity-power profiles in various sports and  
598 levels of practice. *PeerJ.* 2018;2018(11):1–18.
- 599 25. Jolliffe I. *Principal Component Analysis.* Berlin, Heidelberg: Springer Berlin Heidelberg;  
600 2010.
- 601 26. Kearney PE, Hayes PR. Excelling at youth level in competitive track and field athletics is not  
602 a prerequisite for later success. *J Sports Sci.* 2018;36(21):2502–2509.
- 603 27. Lloyd RS, Oliver JL, Hughes MG, Williams CA. Age-related differences in the neural  
604 regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal  
605 hopping. *Journal of Electromyography and Kinesiology.* 2012;22(1):37–43.
- 606 28. Lloyd RS, Oliver JL, Myer GD, De Ste Croix MB, Wass J, Read PJ. Comparison of drop  
607 jump and tuck jump knee joint kinematics in elite male youth soccer players: Implications for injury  
608 risk screening. *J Sport Rehabil.* 2019;29(6):760–765.
- 609 29. Lolli L, Johnson A, Monaco M, Cardinale M, Di Salvo V, Gregson W. Tanner-Whitehouse  
610 and modified Bayley-Pinneau adult height predictions in elite youth soccer players from the middle  
611 east. *Med Sci Sports Exerc.* 2021 Dec 1;53(12):2683–2690.
- 612 30. Lolli L, Johnson A, Monaco M, Di Salvo V, Atkinson G, Gregson W. The percentage of  
613 mature height as a morphometric index of somatic growth: a formal scrutiny of conventional simple  
614 ratio scaling assumptions. *Pediatr Exerc Sci.* 2022;35(2):107–115.

- 615 31. Malina RM. Skeletal age and age verification in youth sport. *Sports Med.* 2011 Nov  
616 1;41(11):925–947.
- 617 32. Malina RM, Bouchard C, Bar-Or O. Growth, maturation and physical activity. Champaign,  
618 IL: Human Kinetics; 2004.
- 619 33. Malina RM, Rogol AD, Cumming SP, Coelho E Silva MJ, Figueiredo AJ. Biological  
620 maturation of youth athletes: assessment and implications. *Br J Sports Med.* 2015;49(13):852–859.
- 621 34. Mann R V. The mechanics of sprinting and hurdling. 2nd ed. Scotts Valley: CreateSpace  
622 Independent Publishing Platform; 2013.
- 623 35. Martínez-Silvan D, Wik EH, Alonso JM, et al. Injury characteristics in male youth athletics: A  
624 five-season prospective study in a full-time sports academy. *Br J Sports Med.* 2021;55(17):954–960.
- 625 36. Meyers RW, Oliver JL, Hughes MG, Cronin JB, Lloyd RS. Maximal sprint speed in boys of  
626 increasing maturity. *Pediatr Exerc Sci.* 2015;27(1):85–94.
- 627 37. Meyers RW, Oliver JL, Hughes MG, Lloyd RS, Cronin JB. Influence of age, maturity, and  
628 body size on the spatiotemporal determinants of maximal sprint speed in boys. *J Strength Cond Res.*  
629 2017 Apr;31(4):1009–1016.
- 630 38. Meylan CM, Cronin J, Hopkins WG, et al. Adjustment of measures of strength and power in  
631 youth male athletes differing in body mass and maturation. *Pediatr Exerc Sci.* 2014 Feb;26(1):41–48.
- 632 39. Meylan CMP, Cronin J, Oliver JL, Hopkins WG, Pinder S. Contribution of vertical strength  
633 and power to sprint performance in young male athletes. *Int J Sports Med.* 2014 Sep 30;35(9):749-  
634 754.
- 635 40. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical  
636 determinants of 100-m sprint running performance. *Eur J Appl Physiol.* 2012;112(11):3921–3930.
- 637 41. Murtagh CF, Brownlee TE, O’Boyle A, Morgans R, Drust B, Erskine RM. Importance of  
638 speed and power in elite youth soccer depends on maturation status. *J Strength Cond Res.*  
639 2018;32(2):297–303.
- 640 42. Parr J, Winwood K, Hodson-Tole E, et al. Predicting the timing of the peak of the pubertal  
641 growth spurt in elite male youth soccer players: evaluation of methods. *Ann Hum Biol.* 2020 May  
642 18;47(4):400–408.

- 643 43. Philippaerts RM, Vaeyens R, Janssens M, et al. The relationship between peak height velocity  
644 and physical performance in youth soccer players. *J Sports Sci.* 2006;24(3):221–230.
- 645 44. Rabita G, Dorel S, Slawinski J, et al. Sprint mechanics in world-class athletes: A new insight  
646 into the limits of human locomotion. *Scand J Med Sci Sports.* 2015;25(5):583–594.
- 647 45. Radnor J, Oliver J, Waugh C, Myer G, Moore I, Lloyd R. The influence of growth and  
648 maturation on stretch-shortening cycle function in youth. *Sports Medicine.* 2018 Jan;48(1):57–71.
- 649 46. Radnor JM, Oliver JL, Waugh CM, Myer GD, Lloyd RS. Muscle architecture and maturation  
650 influence sprint and jump ability in young boys: a multi-study approach. *J Strength Cond Res.*  
651 2022;36(10):2741–2751.
- 652 47. Royston P, Altman DG, Sauerbrei W. Dichotomizing continuous predictors in multiple  
653 regression: a bad idea. *Stat Med.* 2006 Jan 15;25(1):127–141.
- 654 48. Rumpf MC, Cronin JB, Oliver JL, Hughes M. Assessing youth sprint ability-methodological  
655 issues, reliability and performance data. *Pediatr Exerc Sci.* 2011;23(4):442–467.
- 656 49. De Ste Croix MBA, Armstrong N, Chia MYH, Welsman JR, Parsons G, Sharpe P. Changes in  
657 short-term power output in 10- to 12-year-olds. *J Sports Sci.* 2001 Feb;19(2):141–148.
- 658 50. De Ste Croix MBA, Armstrong N, Welsman J. Concentric isokinetic leg strength in pre-teen,  
659 teenage and adult males and females. *Biol Sport.* 1999;16(2):75–86.
- 660 51. Thodberg HH, Lomholt JF, Jenni O, Caflisch J, Ranke M, Kreiborg S. Adult Height  
661 Prediction Models. In: Preedy VR, editor. *The Handbook of Growth Monitoring in Health and*  
662 *Disease.* London: Springer; 2012. p. 27–57.
- 663 52. Till K, Jones B. Monitoring anthropometry and fitness using maturity groups within youth  
664 rugby league. *J Strength Cond Res.* 2015 Mar;29(3):730–736.
- 665 53. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved  
666 with greater ground forces not more rapid leg movements. *J Appl Physiol.* 2000;89(5):1991–1999.
- 667 54. Wild J, Bezodis N, Blagrove R, Bezodis I. A Biomechanical Comparison of Accelerative and  
668 Maximum Velocity Sprinting: Specific Strength Training Considerations. *Professional Strength &*  
669 *Conditioning.* 2011;(21):23–36.
- 670