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1 **Accuracy of maturity prediction equations in individual elite football**
2 **players**

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30 **Accuracy of maturity prediction equations in individual elite football**
31 **players**

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33

34 **Abstract**

35 **Background:** Equations predicting age at peak height velocity (APHV) are often used to assess
36 somatic maturity and to adjust training load accordingly. However, no information is available
37 on the intra-individual accuracy of APHV-estimations over time.

38 **Aim:** Purpose of this study is to assess the accuracy of prediction equations for the estimation
39 of APHV in individual elite youth soccer players.

40 **Subjects and methods:** Anthropometric measurements were conducted at least every three
41 months in 17 adolescent elite football players (11.9 ± 0.8 years) from seasons 2008-2009 to
42 2011-2012. APHV was estimated at each measurement point by four predominant prediction
43 equations. Predicted APHV was compared to the player's observed APHV using one-sample-
44 t-tests and equivalence-tests. Longitudinal stability was assessed by comparing the linear
45 coefficient of the deviation to zero.

46 **Results:** In none of the players, predicted APHV was equivalent to the observed APHV. A
47 difference with a large effect size (Cohen's $d > 0.8$) was found in 87% of the cases. Furthermore,
48 the prediction was not stable over time in 71% of the cases.

49 **Conclusions:** None of the assessed prediction equations is accurate in estimating APHV of
50 individual players nor stable over time, which makes it challenging to construct training
51 programmes by predicted time from APHV.

52 **Keywords;**

53 Growth, maturation, soccer, puberty, adolescence

54 **Introduction**

55 Puberty is an important phase in the development of youth athletes. Neuroendocrine alterations
56 associated with puberty influence the growth in size, the timing of the adolescent growth spurt
57 (Marceau et al. 2011), as well as the improvements in strength, power, speed and aerobic and
58 anaerobic fitness (Goswami et al. 2014; Leyhr et al. 2018). However, the timing of peak gains
59 in body mass, strength and power occurs, on average, after peak height velocity (PHV) while
60 peak gains in aerobic fitness occur coincident with PHV (Beunen and Malina 1988; Philippaerts
61 et al. 2006). Moreover, the timing (when specific events associated with maturation occur) and
62 tempo (rate) of growth and maturation varies among individuals and is largely a result of
63 heritable traits (i.e. genes) (Marceau et al. 2011). Accordingly, the development of physical and
64 physiological characteristics may show a fluctuating, non-linear pattern over time (Malina et
65 al. 2005).

66 Identification, selection, transfer and development of youth athletes are related to differences
67 in individual biological maturity status among high-level youth athletes (Meylan et al. 2010;
68 Malina et al. 2015). Moreover, puberty coincides with a stage of player development where
69 there is increased emphasis on player selection and de-selection and where the physical
70 demands and intensity of training sessions and competition increase (Tierney et al. 2016). A
71 selection bias towards male football players advanced in maturation emerges from
72 approximately 11 years of age and increases with age.(Johnson et al. 2017) In contrast, late
73 maturing players have been shown disproportionately represented in youth football (Johnson et
74 al. 2017).

75 A commonly used indicator of maturational timing is predicted age at PHV, based on several
76 anthropometric dimensions (Mirwald et al. 2002; Moore et al. 2015; Franssen et al. 2018). The
77 original prediction equation (2002) estimates the maturity offset, an indicator of the time before

78 or after the age of PHV, from chronological age (CA), height, weight, sitting height and
79 estimated leg length. This prediction equation has since been modified (Moore 1, includes age
80 and sitting height) and simplified by eliminating sitting height from the equation (Moore 2,
81 includes age and height) (Moore et al. 2015). More recently, the linear prediction equation has
82 been extended to a polynomial prediction equation estimating a maturity ratio (Fransen et al.
83 2018).

84 The authors of the original equations report error margins around one year in boys (Mirwald et
85 al. 2002; Moore et al. 2015). In addition, several validation analyses in longitudinal samples
86 spanning from 8 through 18 years report major limitations of the original and modified
87 equations. Predicted ages at PHV increase, on average, with CA at prediction, have a reduced
88 range of variation, and have major limitations with early and late maturing youth defined by
89 observed ages at PHV (Malina and Koziel 2014a, 2014b; Malina et al. 2016; Koziel and Malina
90 2018). At best, the prediction equation may be useful within a narrow CA band among average
91 maturing boys. Consistent with the validation studies, an increase in the average predicted age
92 at PHV was noted in a sample of elite football players 9 and 15 years of age (Rommers et al.
93 2019).

94 The preceding observations question the utility of the maturity offset or age at PHV prediction
95 equations for individuals and have implications in the context of individualizing training
96 prescriptions, identifying a player's potential and assessment of injury risk. Hence, the accuracy
97 of predicted ages at PHV in individual youth football players during the interval of adolescence
98 merits attention. In this context, the aim of this study is to investigate the accuracy and
99 longitudinal stability of predicted ages at PHV in elite youth football player who were measured
100 at least every three months during adolescence.

101

102 **Subjects and methods**

103 *Participants*

104 Data were collected from seasons 2008-2009 through 2011-2012 in a professional youth
105 football academy in the Netherlands. Players were selected by the academy based on estimated
106 potential in terms of technical, tactical, social and physical skills. All players in the youth
107 academy were measured on a regular basis. Seventeen players (n=17; Caucasian n = 10, African
108 n = 5, Middle Eastern n = 2) were longitudinally followed over at least two years. To ensure a
109 high temporal follow-up around the adolescent growth spurt, only players with at least 15
110 measurement points over an interval that spanned at least two years around the age of PHV
111 were included in this study. After medical checks all participating players were found healthy
112 and had no known growth disorders.

113 *Procedures*

114 All measurements in this study were part of the regular programme of the club and supervised
115 by the medical staff. All parents and players signed a contract with the club approving their
116 child would take part in the academy's regular programme including professional training and
117 testing and were informed bi-annually on the progress and assessments of their child's
118 performance and growth status. The study followed the principles of the Declaration of
119 Helsinki.

120 *Anthropometric Assessment*

121 Body dimensions were measured frequently (range every 1 to 6 months) by trained movement
122 scientists prior to a training session in the controlled environment of the dressing rooms.
123 Following the protocol described in Lohman et al. (1988), height was measured (Seca 213i) to

124 the nearest 0.1 centimetre. Sitting height was measured (Seca 213i) with the player sitting on a
125 stool of standardized height. Sitting height was subtracted from standing height to estimate leg
126 (sub ischial) length. Weight was measured (Seca 803) to the nearest 0,1 kilogram.

127 *Age at peak height velocity*

128 Age at PHV was predicted using the original equation for boys (2002), the two modified
129 equations (2015) and the maturity ratio (2018) (Table 1). The first three equations predict
130 maturity offset; age at PHV is estimated as CA minus predicted offset. With the maturity ratio
131 protocol, CA was divided by the maturity ratio to estimate age at PHV.

132 *** Insert Table 1 near here ***

133 *Analyses*

134 Descriptive statistics of the first measurement of each player are presented as means with
135 corresponding standard deviations (SD). Age at PHV for individual players was than estimated
136 with Preece-Baines model I (Preece and Baines 1978). The height records of seventeen players
137 were successfully modelled and were used in the analysis.

138 The deviation between observed age at PHV and predicted ages at PHV with each of the four
139 prediction equations (predicted age at PHV – observed age at PHV) was calculated at each
140 observation for individual players. The observed and the predicted ages at PHV were then
141 compared in each player using one sample t-tests. Subsequently, tests of equivalence using
142 Cohen's d as an effect size, 90% confidence intervals, and pre-determined upper and lower
143 equivalence bounds of ± 0.25 , were calculated to evaluate if the differences were sufficiently
144 sizeable for practical consideration (Lakens et al. 2018). Effect sizes were interpreted as small

145 when Cohen's d was > 0.2 , as moderate with Cohen's d was > 0.5 and as large with Cohen's d
146 was > 0.8 (Cohen 1988).

147 Linear regression was used to investigate the stability of the deviation over the interval of the
148 observations. Due to the small monthly increase in height, monthly measurements and
149 estimated growth velocities are affected by measurement, diurnal and potentially seasonal
150 variability. Therefore, linear regression was used instead of actual data points. To visualize the
151 stability of deviation over the course of the study, regression lines for the four prediction
152 equations were plotted by years from observed PHV for each individual player. If the deviation
153 of the linear coefficient of the regression line for each prediction within individuals was equal
154 to zero, stability of predicted ages at PHV was accepted. All analyses were performed in R
155 (version 3.5.4), with alpha level of significance set at 0.05.

156 In order to visualise the individual growth patterns of the included players, we fitted cubic
157 splines from the age of the first to the last measurement in Microsoft Excel using the SRS1
158 cubic spline software (SRS1 Software, LLC, Boston, MA, USA) with data interpolated to three-
159 month intervals.

160

161 **Results**

162 *Predicted and observed APHV*

163 Anthropometric characteristics at baseline are summarized in Table 2.

164 *** Insert Table 2 near here ***

165 Observed ages at PHV based on Preece-Baines model I ranged from 12.55 to 15.18 years with
166 mean of 13.8 ± 0.7 years (Table 3). Average predicted ages at PHV based on the four prediction
167 equations of ranged from 13.2 to 15.5 years (Mirwald), from 13.3 to 15.3 years (Moore 1), from
168 12.9 to 14.8 years (Moore 2) and from 13.2 to 15.1 years (Fransen). The mean and SD of the
169 predicted ages at PHV with each of the four prediction equations for individual players are
170 summarized in Table 3.

171 *** Insert Table 3 near here ***

172 The ranges of predicted ages at PHV with each prediction equation for individual players are
173 presented in Table 3. With the Mirwald equation, none of the players showed a mean age of
174 predicted PHV that was equivalent to and not statistically different from the observed age at
175 PHV. There were no instances in which predicted ages at PHV were equivalent to the observed
176 age at PHV. In 87% of the predictions, the predicted ages at PHV were not equivalent to the
177 observed age at PHV with the effect size showing a large effect. In seven players, two
178 predictions were less than observed age at PHV, while in most players, predicted ages at PHV
179 were higher than observed age at PHV.

180 *Longitudinal stability of the predicted ages at PHV*

181 The stability of the deviation of the predicted ages at PHV from observed age at PHV over time
182 is shown for each prediction equation in four randomly selected players in Figure 1. The
183 regression lines depict the deviation of predicted ages at PHV from observed age at PHV over
184 the interval of observation by years from observed PHV at prediction; a horizontal line indicates
185 stable predictions over time. Table 4 shows the range the deviation for each prediction equation
186 and the linear coefficients of the regression lines for each individual player. None of the four
187 equations has a stable prediction over time in more than 45% of the players. The Mirwald and
188 Fransen predictions have more stable predictions than the simplified Moore equations. Overall,
189 the results indicate that a maximum of three predicted ages at PHV in a single individual show
190 relative stability over CA ranges represented in the sample. For most players predicted ages at
191 PHV with only one or two equations show stability, but stable predicted ages at PHV with a
192 specific equation over time vary within and among individuals.

193 *** Insert Figure 1 ***

194 *** Insert Table 4 ***

195

196 **Discussion**

197 Predicted ages at PHV derived with the four prediction equations in a longitudinal sample of
198 elite youth football players differed significantly from and were not equivalent to observed age
199 at PHV estimated with Preece-Baines model I for individual players. Moreover, predicted ages
200 at PHV were not stable in most players across the chronological age span represented in the
201 sample.

202 ***Comparison to other studies***

203 Validation studies of the original prediction equation (Mirwald et al. 2002) in longitudinal
204 samples of Polish (Malina and Koziel 2014a) and American (Malina et al. 2016) boys and of
205 the modified equations (Moore et al. 2015) in the Polish boys (Koziel and Malina 2018)
206 showed, on average, reduced variation in predicted compared to observed ages at PHV, later
207 predicted than observed ages at PHV in early maturing boys and earlier predicted than observed
208 ages at PHV in late maturing boys. Moreover, cross-sectional studies of elite football players
209 have indicated advanced skeletal and sexual maturity status compared to the general population
210 (Malina 2011; Malina et al. 2012). Nevertheless, allowing inter-individual differences in
211 biological maturity status and timing, intra-individual variation in predicted ages at PHV is
212 considerable and relatively few predictions approximated observed age at PHV (Koziel and
213 Malina 2018).

214 The initial study, on the Mirwald equation in Polish boys showed, on average, a stable deviation
215 between predicted and observed ages at PHV in *average* maturing boys between 13 and 15
216 years of age (Malina and Koziel 2014a). This was not consistent with observations for 15 of the
217 17 boys in our sample who had an observed age at PHV that could be classified as average. A
218 possible explanation for the difference is the frequency of measurements in the present study

219 compared to annual observations the study of Polish boys (Malina & Koziel, (2018). On the
220 other hand, it is possible that predictions in the present study were affected by measurement
221 variability in height, weight and sitting height across observations in addition to seasonal
222 fluctuations in growth in height and weight. Growth in height is also generally more rapid in
223 the spring/summer and slower in the fall/winter, while growth in weight shows the opposite
224 season pattern (Cole 1998). Seasonal variation in growth may affect predictions made across
225 the football season. It has also been suggested that growth in height occurs in mini-spurts
226 followed by intervals of no increase (LampI and Johnson 1993).

227 The prediction equation of Fransen et al. (2018) was validated in a mixed-longitudinal sample
228 of elite youth football players, and as such it was expected that the prediction equation would
229 yield more reliable results. This, however, was not the case in the present study.

230 ***Strengths and limitations***

231 The strength of this study may be the high frequency of measurements during the interval of
232 the adolescent growth spurt which permitted a closer evaluation of the growth elite football
233 players. On the other hand, the high frequency of measurements is also a limitation from the
234 perspective measurement variability (inter- and intra-observer) in direct (height, sitting height,
235 weight) and derived (estimated leg length) variables, and the relatively close intervals between
236 measurements. As noted earlier, other potential confounding factors are diurnal and seasonal
237 variation in growth. In addition, estimates of growth rate over short intervals have a larger
238 variance (Tanner et al. 1966; Roche and Himes 1980). It should also be acknowledged that the
239 Preece-Baines model I is a mathematical growth model that has an error margin. This model,
240 however indicates a clear estimate of the age at PHV, which is not the case for cubic splines for
241 example, showing several peaks in some individuals (see Figure 2).

242 Although the majority of players in our sample were of Caucasian origin, we also included
243 players of different ethnicity. The variation in ethnicity is representative for contemporary elite-
244 level youth football teams. This is of relevance as the prediction equations as well as Preece-
245 Baines model I were based on samples of European ancestry, while ethnic variation in the
246 proportion of leg length to stature is well documented (Malina et al. 2004). As such, care is
247 warranted in generalizing the observations, although they were consistent with several
248 validation studies of the maturity offset/predicted age at PHV protocol.

249 *Practical recommendations for training and future directions*

250 Puberty is a critical period of talent development (Lloyd et al. 2014; Malina et al. 2015).
251 However, it is characterized by considerable inter-individual variation in the timing of the
252 growth spurt in body size and also several indicators of fitness – strength, explosive power and
253 aerobic power in males, both athletes and non-athletes (Philippaerts et al. 2006).

254 Some evidence indicates a peak incidence of injury around the predicted time of PHV (van der
255 Sluis et al. 2015; Read et al. 2017). It is common to decrease the workload and adjust exercises
256 during the interval of PHV and to focus on individualized training plans (Lloyd and Oliver
257 2013; Lloyd et al. 2016). For optimal management of training load and in order to maximise
258 athlete development during the interval of PHV, the importance of continuous assessment of
259 growth of youth athletes during the pubertal period has been suggested (Lloyd et al. 2014).
260 Given the non-invasiveness, time and cost efficiency, and immediate outcome predicted
261 maturity offset and/or age at PHV is attractively simple and is increasingly, if not uncritically,
262 used to individualise training and competition programmes (Cumming et al. 2017). However,
263 as shown in the present study, the individual accuracy of all four prediction equations for
264 estimating a player's age at PHV is questionable, and use of the prediction equations in this
265 context is not recommended.

266 Growth in height during adolescence varies considerably among individuals. This individuality
267 of somatic growth emphasizes the need to closely monitor growth status in order to establish
268 training goals. In this context, it is recommended that youth players should be measured at
269 three-month intervals in order to establish meaningful changes and to minimize the influence
270 of daily fluctuations and measurement variability (Lloyd et al. 2014). Such measures can be
271 taken in conjunction with estimates of maturity status to provide a more comprehensive picture
272 of growth and maturity status. Monitoring growth velocity is relatively easy to establish in
273 practice and has the advantage that it considers the non-linear character of growth.
274 Nevertheless, attention to potential seasonal variation in growth should not be overlooked.
275 Future research could focus on adapting training goals and modalities relative to estimated
276 velocities of growth in height during the interval of the adolescent spurt and specific stage of
277 pubertal development (pubic hair, genital) in an effort to individualize training. The authors
278 would like to propose the hypothesis that more frequent assessments of growth will show ‘mini-
279 growth-spurts’ (Figure 2), despite the limitations of the reliability of frequent measurements,
280 and will make it possible to adjust training programs (i.e. intensity, volume and training
281 forms/activities) accordingly. If ‘mini-growth-spurts can be confirmed in future studies than we
282 would like to suggest revising the bio-banding concept by constructing the bands around the
283 rate of growth-velocity rather than maturity offset or percentage of adult stature. Moreover, to
284 support the practitioner in the future with a more accurate tool to assess growth spurts during
285 puberty for 1) the design of athlete development programmes and 2) the assessment of injury
286 risk - a combination of the current equations and growth velocity tracking can be more a valid
287 option. The challenges of this concept are: 1) it is not known how accurate individual
288 extrapolations of frequently measured growth data in the past are for the growth curve ahead,
289 and 2) no cut-off growth-velocity-rates are established by which coaches can adjust their

290 training. Although his concept might be audacious, it might help the coach to more accurately
291 guide individual pathways of athletes during their transition from adolescents to adults.

292 ***Conclusion and practical implications***

293 The results of this longitudinal study in elite youth football players suggested that none of the
294 four equations for predicting age at PHV provides an accurate prediction in individuals. The
295 stability of predictions within individuals was also poor. By inference, the utility of the
296 prediction equations has major limitations. Therefore, we do not recommend the use of the
297 prediction equations to prescribe individualized training programmes or to assess injury risk in
298 youth elite level football players. Future studies could focus on the evaluation of the reliability
299 of frequent measurements of growth (growth tracking) in order to capture possible ‘mini-
300 growth-spurts’ and to assess the associated injury risk and optimal training accordingly.

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305 **Declaration of interest statement**

306 The authors report no conflict of interest.

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398

399

400 **Table 1.** Overview of the maturity offset/maturity ratio prediction equations for boys

Mirwald	Maturity offset = $-9.236 + (0.0002708 \times \text{leg length} \times \text{sitting height}) - (0.001663 \times \text{age} \times \text{leg length}) + (0.007216 \times \text{age} \times \text{sitting height}) + (0.02292 \times (\text{weight by height ratio}) \times 100)$
Moore 1	Maturity offset = $-8.128741 + (0.0070346 \times (\text{age} \times \text{sitting height}))$
Moore 2	Maturity offset = $-7.999994 + (0.0036124 \times (\text{age} \times \text{height}))$
Fransen	Maturity ratio = $6.986547255416 + (0.115802846632 \times \text{age}) + (0.001450825199 \times \text{age}^2) + (0.004518400406 \times \text{weight}) - (0.000034086447 \times \text{weight}^2) - (0.151951447289 \times \text{height}) + (0.000932836659 \times \text{height}^2) - (0.000001656585 \times \text{height}^3) + (0.032198263733 \times \text{leg length}) - (0.000269025264 \times \text{leg length}^2) - (0.000760897942 \times (\text{height} \times \text{age}))$

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403 **Table 2.** Baseline characteristics of the players

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	Mean	SD	Range	
Age (y)	11.9	0.8	10.9 – 14.1	405
Height (cm)	149.7	6.2	139.5 – 165.5	
Weight (kg)	38.9	5.9	33.0 – 56.0	406
Sitting Height (cm)	75.8	2.8	70.7 – 82.1	
Observed APHV (y)	13.8	0.7	12.6 – 15.2	407
Number of measurements	19.8	2.3	16 – 25	408

410 y: years, cm: centimetre, kg: kilogram, APHV: age at peak height velocity

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412 **Table 3.** Observed age at PHV (years) compared to predicted ages at PHV (years) with four equations

413

Observed age at PHV	Mirwald		Moore 1		Moore 2		Fransen	
	Range	Cohen's d [90% CI]	Range	Cohen's d [90% CI]	Range	Cohen's d [90% CI]	Range	Cohen's d [90% CI]
12.6	13.3 : 13.7	7.5 [5.2 : 9.5]***	13.5 : 14.0	9.5 [6.7 : 12.2]***	13.2 : 13.3	10.9 [7.6 : 13.9]***	13.1 : 13.6	4.3 [3.0 : 5.5]***
13.0	13.5 : 14.4	3.3 [2.4 : 4.2]***	13.6 : 14.2	4.7 [3.4 : 6.0]***	13.4 : 13.6	9.9 [7.2 : 12.4]***	13.4 : 14.7	2.1 [1.4 : 2.7]***
13.2	13.2 : 13.5	1.5 [0.9 : 2.0]***	13.4 : 14.1	3.8 [2.6 : 4.8]***	13.0 : 13.4	0.5 [0.1 : 0.9]*	13.0 : 13.4	0.1 [-0.3 : 0.5]
13.3	13.4 : 14.0	3.8 [2.8 : 4.8]***	13.5 : 14.2	3.6 [2.7 : 4.6]***	13.1 : 13.7	0.8 [0.4 : 1.2]**	13.4 : 14.3	2.3 [1.6 : 3.0]**
13.4	13.6 : 14.2	3.1 [2.2 : 4.0]***	13.9 : 14.6	4.3 [3.1 : 5.4]***	13.5 : 13.8	3.9 [2.8 : 5.0]***	13.4 : 14.2	2.1 [1.4 : 2.7]***
13.4	13.4 : 13.8	1.9 [1.2 : 2.5]***	13.4 : 13.9	2.2 [1.5 : 2.9]***	13.0 : 13.3	2.0 [1.3 : 2.7]***	13.3 : 14.0	0.7 [0.3 : 1.1]**
13.4	13.8 : 14.1	6.5 [4.7 : 8.3]***	13.4 : 13.9	2.4 [1.7 : 3.1]***	13.3 : 13.5	0.5 [0.1 : 0.8]	13.8 : 14.3	3.7 [2.6 : 4.7]**
13.5	13.6 : 14.2	1.5 [0.9 : 2.1]***	14.0 : 14.7	4.9 [3.4 : 6.4]***	13.7 : 13.8	6.1 [4.2 : 7.8]***	13.4 : 14.2	0.9 [0.4 : 1.4]**
13.6	13.0 : 13.4	3.3 [2.3 : 4.2]***	13.2 : 13.5	4.0 [2.9 : 5.1]***	12.8 : 13.1	9.9 [7.1 : 12.5]***	13.1 : 14.2	0.5 [0.1 : 0.9]*
13.7	13.7 : 14.6	4.2 [3.1 : 5.3]***	13.8 : 14.5	2.7 [1.9 : 3.5]***	13.3 : 14.0	0.9 [0.5 : 1.3]***	13.8 : 14.6	4.4 [3.2 : 5.6]**
14.1	14.1 : 14.5	1.2 [0.7 : 1.8]***	13.9 : 14.2	0.1 [-0.3 : 0.5]	13.6 : 13.8	11.5 [7.8 : 14.8]***	14.1 : 14.6	1.5 [0.9 : 2.1]***
14.1	13.1 : 13.7	3.7 [2.6 : 4.8]***	13.3 : 14.1	0.9 [0.4 : 1.3]**	13.1 : 13.4	6.9 [4.9 : 8.8]***	13.0 : 13.6	4.7 [3.4 : 6.0]***
14.1	13.0 : 13.9	2.7 [1.8 : 3.5]***	14.2 : 14.7	3.0 [2.0 : 4.0]***	13.4 : 13.7	7.5 [5.2 : 9.7]***	13.0 : 13.8	3.5 [2.4 : 4.5]**
14.6	14.6 : 15.4	2.6 [1.7 : 3.4]***	13.8 : 14.3	4.6 [3.2 : 5.9]***	13.7 : 14.0	9.0 [6.3 : 11.4]***	14.7 : 15.7	2.6 [1.7 : 3.4]***
14.6	13.9 : 14.7	0.6 [0.3 : 1.0]**	14.0 : 14.8	0.6 [0.3 : 1.0]**	13.5 : 14.1	4.8 [3.6 : 6.0]***	14.0 : 14.7	1.1 [0.7 : 1.5]***
15.2	14.6 : 15.1	2.3 [1.6 : 2.9]***	14.4 : 15.4	0.4 [0.0 : 0.7]	14.1 : 14.6	4.0 [2.9 : 5.0]***	14.5 : 14.8	5.7 [4.2 : 7.2]***
15.2	15.2 : 15.6	3.2 [2.3 : 4.0]***	15.2 : 15.5	1.0 [0.6 : 1.5]***	14.6 : 14.8	11.4 [8.3 : 14.3]***	15.0 : 15.3	0.8 [0.4 : 1.2]**

428 PHV: peak height velocity, 90% CI: 90% confidence interval, *: p<0.05, **p<0.01, ***: p<0.001

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Table 4. Range of deviation between observed and predicted ages at PHV (years) and slopes of regression lines of predictions over time with each of the four prediction equations.

Observed age at PHV	Mirwald			Moore 1			Moore 2			Fransen		
	Deviation range	Linear coefficient [95% CI]	p-value	Deviation range	Linear coefficient [95% CI]	p-value	Deviation range	Linear coefficient [95% CI]	p-value	Deviation range	Linear coefficient [95% CI]	p-value
12.6	0.73 : 1.13	-0.07 [-0.12 : -0.01]	0.031	0.98 : 1.5	0.13 [0.1 : 0.15]	0.000	0.56 : 0.8	0.05 [0.03 : 0.07]	0.001	0.55 : 1.08	-0.16 [-0.21 : -0.1]	0.000
13.0	0.50 : 1.40	-0.26 [-0.31 : -0.2]	0.000	0.53 : 1.21	0.17 [0.13 : 0.22]	0.000	0.38 : 0.53	-0.01 [-0.03 : 0.01]	0.415	0.33 : 1.63	-0.38 [-0.47 : -0.29]	0.000
13.2	-0.04 : 0.31	-0.01 [-0.07 : 0.04]	0.637	0.2 : 0.86	0.16 [0.1 : 0.22]	0.000	-0.21 : 0.14	0.08 [0.05 : 0.12]	0.000	-0.24 : 0.23	-0.09 [-0.14 : -0.03]	0.004
13.3	0.14 : 0.71	0.03 [-0.02 : 0.08]	0.228	0.2 : 0.86	0.12 [0.1 : 0.15]	0.000	-0.2 : 0.36	0.07 [0.05 : 0.1]	0.000	0.06 : 1.03	0.12 [0.06 : 0.18]	0.001
13.4	0.22 : 0.83	-0.12 [-0.18 : -0.07]	0.000	0.54 : 1.21	0.2 [0.16 : 0.24]	0.000	0.16 : 0.44	0.05 [0.03 : 0.08]	0.001	0.08 : 0.81	-0.16 [-0.22 : -0.1]	0.000
13.4	0.06 : 0.44	-0.1 [-0.13 : -0.06]	0.000	0.01 : 0.52	0.03 [-0.04 : 0.11]	0.374	-0.34 : -0.01	-0.03 [-0.06 : 0.01]	0.154	-0.02 : 0.6	-0.05 [-0.14 : 0.03]	0.213
13.4	0.41 : 0.72	-0.05 [-0.09 : -0.01]	0.019	0 : 0.52	0.14 [0.08 : 0.19]	0.000	-0.16 : 0.07	0.04 [0.02 : 0.07]	0.004	0.34 : 0.88	-0.11 [-0.17 : -0.05]	0.002
13.5	0.11 : 0.75	-0.29 [-0.35 : -0.24]	0.000	0.58 : 1.26	0.25 [0.21 : 0.28]	0.000	0.21 : 0.36	0.01 [-0.02 : 0.04]	0.379	-0.02 : 0.74	-0.33 [-0.39 : -0.28]	0.000
13.6	-0.57 : -0.13	-0.09 [-0.13 : -0.04]	0.002	-0.39 : -0.08	0.05 [0.02 : 0.09]	0.005	-0.75 : -0.51	-0.01 [-0.04 : 0.03]	0.583	-0.47 : 0.58	0.25 [0.17 : 0.33]	0.000
13.7	-0.03 : 0.86	0.08 [0.01 : 0.15]	0.026	0.05 : 0.75	0.15 [0.12 : 0.18]	0.000	-0.42 : 0.24	0.11 [0.08 : 0.14]	0.000	0.09 : 0.9	0.04 [-0.03 : 0.11]	0.224
14.1	-0.01 : 0.39	-0.12 [-0.19 : -0.04]	0.005	-0.18 : 0.15	0.04 [-0.03 : 0.11]	0.241	-0.44 : -0.31	-0.03 [-0.05 : 0]	0.062	0.08 : 0.48	0 [-0.1 : 0.1]	0.998
14.1	-0.93 : -0.33	-0.01 [-0.1 : 0.09]	0.855	-0.7 : 0.06	0.2 [0.12 : 0.28]	0.000	-0.99 : -0.63	0.1 [0.05 : 0.14]	0.000	-1.06 : -0.48	0.01 [-0.08 : 0.1]	0.771
14.1	-1.1 : -0.15	-0.29 [-0.37 : -0.21]	0.000	0.14 : 0.68	0.13 [0.11 : 0.16]	0.000	-0.61 : -0.37	-0.05 [-0.08 : -0.03]	0.001	-1.04 : -0.28	-0.2 [-0.28 : -0.12]	0.000
14.6	0.01 : 0.79	-0.01 [-0.1 : 0.09]	0.879	-0.71 : -0.31	0.09 [0.05 : 0.13]	0.000	-0.83 : -0.51	0.04 [0 : 0.07]	0.031	0.13 : 1.09	-0.03 [-0.15 : 0.08]	0.571
14.6	-0.73 : 0.04	0.01 [-0.05 : 0.07]	0.728	-0.64 : 0.16	0.19 [0.16 : 0.22]	0.000	-1.14 : -0.56	0.1 [0.07 : 0.13]	0.000	-0.62 : 0.02	-0.03 [-0.08 : 0.03]	0.294
15.2	-0.59 : -0.09	0.12 [0.09 : 0.16]	0.000	-0.75 : 0.19	0.28 [0.22 : 0.34]	0.000	-1.12 : -0.53	0.19 [0.16 : 0.22]	0.000	-0.68 : -0.35	0.07 [0.04 : 0.09]	0.000
15.2	0.08 : 0.42	0.02 [-0.04 : 0.07]	0.472	-0.01 : 0.32	0.09 [0.04 : 0.15]	0.002	-0.52 : -0.35	0.05 [0.04 : 0.06]	0.000	-0.15 : 0.11	-0.03 [-0.05 : 0.05]	0.909

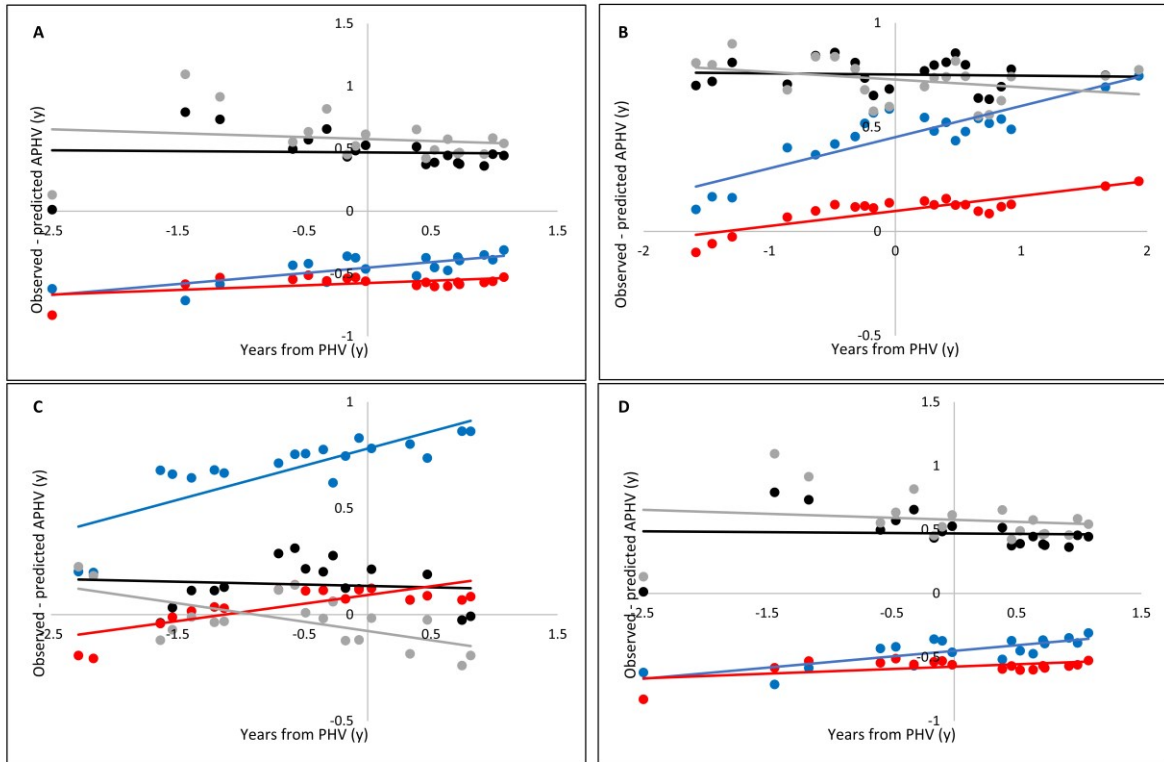
431 PHV: peak height velocity, 95% CI: 95% confidence interval

432 **Figure 1.** Deviation between observed ages at PHV and predicted age at PHV (years) in four randomly
433 selected players by years from PHV at prediction with each of the four equations.

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435 Black: Mirwald equation, Blue: Moore 1 equation, Red: Moore 2 equation, Grey: Fransen equation

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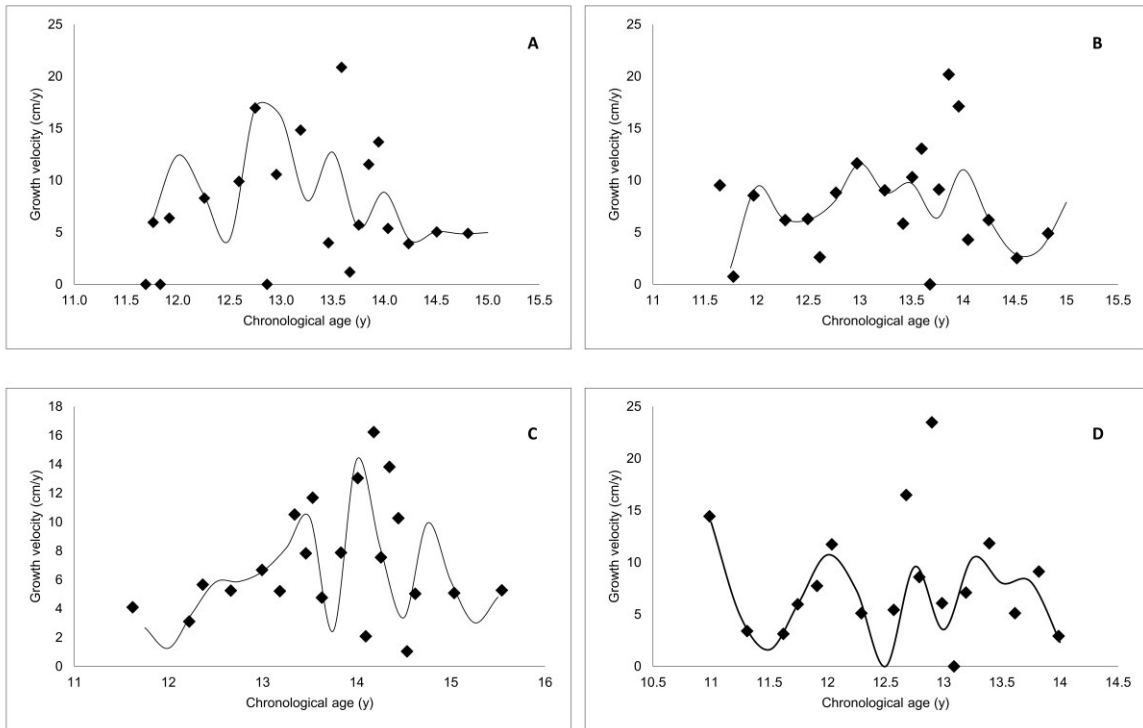
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458 **Figure 2.** Growth velocity of individual players modelled by cubic splines in four randomly selected
459 players (same players as in figure 1).
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