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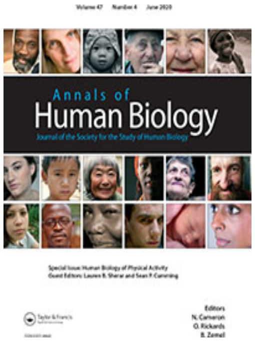

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RESEARCH PAPER

Accuracy of maturity prediction equations in individual elite male football players

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ABSTRACT

Background: Equations predicting age at peak height velocity (APHV) are often used to assess somatic maturity and to adjust training load accordingly. However, information on the intra-individual accuracy of APHV in youth athletes is not available.

Aim: The purpose of this study is to assess the accuracy of predication equations for the estimation of APHV in individual youth male football players.

Subjects and methods: Body dimensions were measured at least every three months in 17 elite youth male football players (11.9 ± 0.8 years at baseline) from the 2008–2009 through the 2011–2012 seasons. APHV was predicted at each observation with four suggested equations. Predicted APHV was compared to the player's observed APHV using one-sample-t-tests and equivalence-tests. Longitudinal stability was assessed by comparing the linear coefficient of the deviation to zero.

Results: Predicted APHV was equivalent to the observed APHV in none of the players. A difference with a large effect size (Cohen's $d > 0.8$) was noted in 87% of the predictions. Moreover, predictions were not stable over time in 71% of the cases.

Conclusions: None of the evaluated prediction equations is accurate for estimating APHV in individual players nor are predictions stable over time, which limits their utility for adjusting training programmes.

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Growth; maturation; soccer; peak height velocity; adolescent spurt

Introduction

Puberty is an important phase in the development of young athletes. Neuroendocrine alterations associated with pubertal maturation initiate rapid changes in body size, physique, appearance and composition (Marceau et al. 2011), in addition to improvements in strength, power, speed and aerobic and anaerobic fitness (Malina et al. 2004; Goswami et al. 2014; Leyhr et al. 2018). The timing of peak gains in body mass, strength and power occur, on average, after peak height velocity (PHV), while peak gains in aerobic fitness coincide with PHV (Beunen and Malina 1988; Philippaerts et al. 2006). Moreover, the timing and tempo of growth and maturation vary among individuals and are predominantly a result of heritable traits (i.e. genes), though susceptible to environmental and behavioural factors (Marceau et al. 2011). Accordingly, the development of physical and physiological characteristics may show fluctuating, non-linear patterns over time.

Identification, selection, transfer and development of youth athletes are related, in part, to individual differences in biological maturity status among high-level youth athletes (Meylan et al. 2010; Malina et al. 2015). Moreover, puberty often coincides with a stage of player development when emphasis is on player selection or de-selection, and the physical demands and intensity of training and competition increase (Tierney et al. 2016). A selection bias towards male football players advanced in maturation emerges from approximately 11 years of age and increases with age (Johnson et al. 2017). In contrast, late maturing players are underrepresented in youth football (Johnson et al. 2017), although numbers may vary depending upon method of maturity status assessment (Malina et al. 2007).

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Predicted age at PHV, based on several anthropometric dimensions (Mirwald et al. 2002; Moore et al. 2015; Fransen et al. 2018), is increasingly used in studies of youth athletes. The original Mirwald et al. (2002) equation predicts maturity offset, from chronological age (CA), height, weight, sitting height and estimated leg length; age at PHV is derived by subtraction (CA minus offset). The equation has since been modified (Moore et al., 2015) with two options for males, the first including CA and sitting height (Moore 1) and the second including CA and height (Moore 2). More recently, the original linear prediction equation has been extended to a polynomial prediction equation estimating a maturity ratio (Fransen et al. 2018).

The original equations have an error margin of about one year in boys (Mirwald et al. 2002; Moore et al. 2015). Application of the original (Malina and Kozieł 2014a, 2014b; Malina et al. 2016; Kozieł and Malina 2018) and modified equations (Kozieł and Malina 2018) to longitudinal samples for whom ages at PHV were available noted major limitations of the equations. Predicted ages at PHV increased, on average, with CA at prediction. The prediction equations of Mirwald et al. (2002) and Moore et al. (2015) had major limitations with early and late maturing youth defined by observed ages at PHV and noted significant intra-individual variation in predicted ages at PHV. At best, the prediction equation may be useful within a narrow CA band among average maturing boys. Consistent with the validation studies, an increase in the average predicted age at PHV was noted in a sample of elite football players 9 and 15 years of age (Rommers et al. 2019). Moreover, maturity status classifications based on skeletal age and predicted age at PHV in youth football players 11–12 and 13–14 years indicated poor concordance (Malina et al. 2012).

The preceding observations question the utility of the maturity offset or age at PHV prediction equations for individuals and have implications in the context of individualising training protocols, identifying player potential and assessment of injury risk. Hence, the accuracy of predicted ages at PHV in individual youth football players during the interval of adolescence merits attention. The aim of this study is to investigate the accuracy and longitudinal stability of predicted ages at PHV in elite youth male football players who were measured at least every three months during adolescence.

Subjects and methods

Participants

The players were followed longitudinally, and the data were collected during the 2008–2009 through the 2011–2012 seasons in a professional youth football academy in the Netherlands. Players were selected by the academy based on estimated potential in terms of technical, tactical, social and physical skills. All players in the academy were measured on a regular basis. Seventeen boys ($n = 17$; of European ancestry $n = 10$, African $n = 5$, Middle Eastern $n = 2$) were longitudinally followed over at least two seasons. To ensure a high temporal follow-up around the adolescent growth spurt, only players with at least 15 observations over an interval that spanned at least two years around the age of PHV were included in this study. After medical examinations, all participating players were healthy and had no known growth problems.

Procedures

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

Anthropometric assessment

Body dimensions were measured on a regular basis (range 1 to 6 months) by trained movement scientists prior to a training session in the controlled environment of the dressing rooms. Following the protocol described in Lohman et al. (1988), height was measured (Seca 213i) to the nearest 0.1 centimetre. Sitting height was measured (Seca 213i) with the player sitting on a stool of standardised height. Sitting height was subtracted from standing height to estimate leg (sub ischial) length. Weight was measured (Seca 803) to the nearest 0.1 kilogram.

Age at peak height velocity

Age at PHV was predicted using the original Mirwald et al. (2002), the two modified equations of Moore equation of et al. (2015) and the maturity ratio of Fransen et al. (2018) for boys (Table 1). The first three equations predicted maturity offset; age at PHV was estimated as CA minus predicted offset. With the maturity ratio protocol, CA was divided by the maturity ratio to estimate age at PHV.

Analyses

Descriptive statistics of the first measurement of each player are presented as means with corresponding standard deviations. Age at PHV for individual players was then estimated

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

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

with Preece-Baines model I (Preece and Baines 1978). The height records of seventeen players were successfully modelled and were used in the analysis.

The deviation between observed age at PHV and predicted ages at PHV with each of the four prediction equations (predicted age at PHV minus observed age at PHV) was calculated at each observation for individual players. The observed and the predicted ages at PHV were then compared in each player using one sample t-tests. Subsequently, tests of equivalence using Cohen's d as an effect size, 90% confidence intervals, and pre-determined upper and lower equivalence bounds of ± 0.25, were calculated to evaluate if the differences were sufficiently sizeable for practical consideration (Lakens et al. 2018). Effect sizes were interpreted as small when Cohen's *d* was > 0.2, as moderate when Cohen's *d* was > 0.5 and as large when Cohen's *d* was > 0.8 (Cohen 1988).

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

Table 2. Baseline characteristics of the players.

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

y: years; cm: centimetre; kg: kilogram; APHV: age at peak height velocity.

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

Results

Predicted and observed APHV

Anthropometric characteristics at baseline are summarised in Table 2. Observed ages at PHV based on Preece-Baines model I ranged from 12.55 to 15.18 years with a mean of 13.8 ± 0.7 years (Table 3). Average predicted ages at PHV based on the four prediction equations ranged from 13.2 to 15.5 years (Mirwald), from 13.3 to 15.3 years (Moore 1), from 12.9 to 14.8 years (Moore 2) and from 13.2 to 15.1 years (Fransen). The range of the predicted ages at PHV with each of the four prediction equations for individual players are summarised in Table 3.

Ranges of predicted ages at PHV with each equation for individual players are presented relative to observed age in Table 3. With the Mirwald equation, none of the players showed a mean age of predicted PHV that was equivalent to and not statistically different from the observed age at PHV. There were no instances in which predicted ages at PHV were equivalent to the observed age at PHV. In 87% of the predictions, predicted ages at PHV were not equivalent to observed age at PHV with the effect size indicating a large effect. In seven players, two predictions were earlier than observed age at PHV, while in most players, predicted ages at PHV were later than observed age at PHV.

Longitudinal stability of the predicted ages at PHV

The stability of the deviation of the predicted ages at PHV from observed age at PHV over time is shown for each prediction equation in four randomly selected players in

Table 3. Observed age at PHV (years) compared to predicted ages at PHV (years) for individual players with four equations.

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]**

PHV: peak height velocity; 90% CI: 90% confidence interval; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

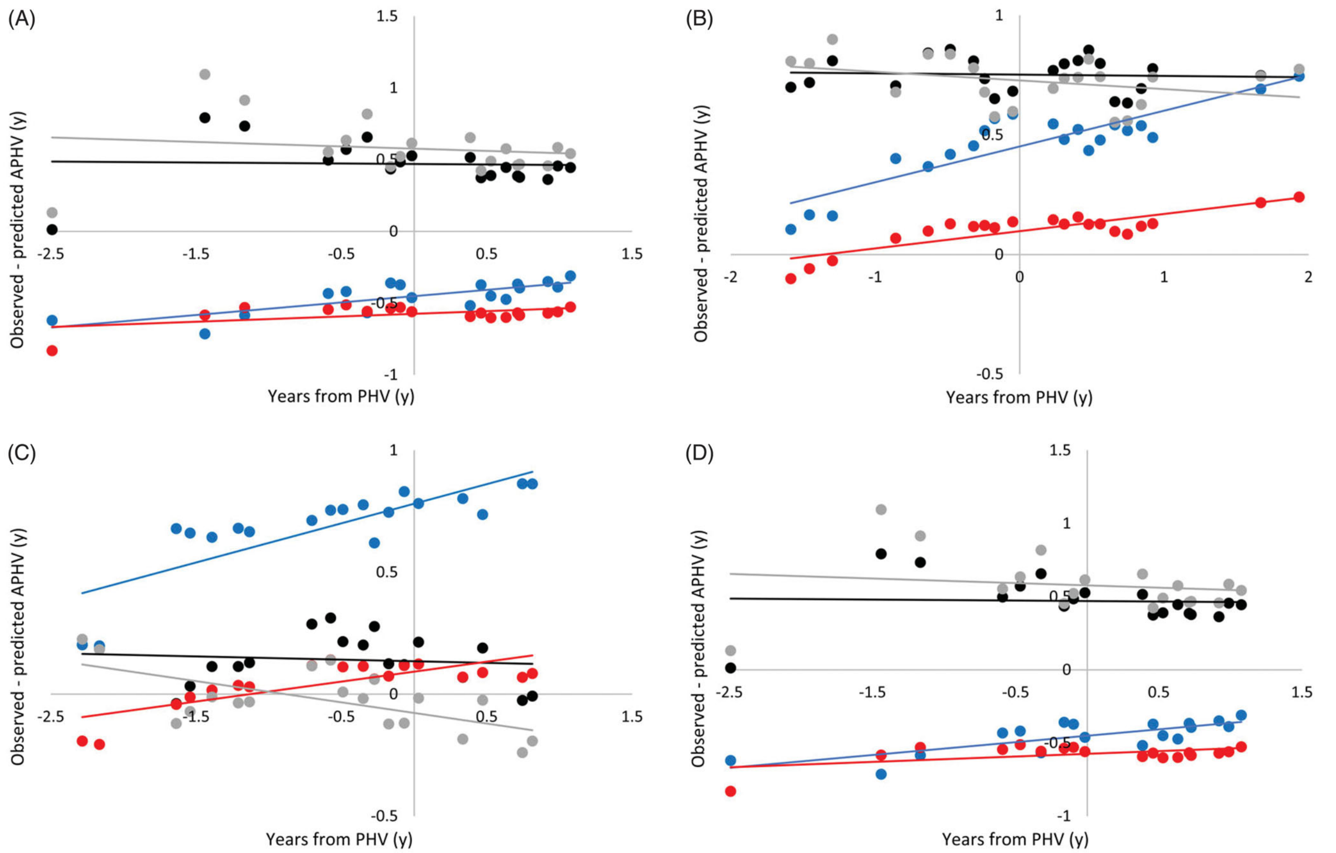

Figure 1. Deviation between observed ages at PHV and predicted age at PHV (years) in four randomly selected players by years from PHV at prediction with each of the four equations.
Black: Mirwald equation, Blue: Moore 1 equation, Red: Moore 2 equation, Grey: Fransen equation

Figure 1. The regression lines depict the deviation of predicted ages at PHV from observed age at PHV over the interval of observation by years from observed PHV at prediction; a horizontal line indicates stable predictions over time. Table 4 shows the range of the deviation for each prediction equation and the linear coefficients of the regression lines for each individual player. None of the four equations has a stable prediction over time in more than 45% of the players. The Mirwald et al. (2002) and Fransen et al. (2018) predictions have more stable predictions than the simplified Moore equations. Overall, the results indicate that a maximum of three predicted ages at PHV in a single individual show relative stability over CA ranges represented in the sample. For most players, predicted ages at PHV with only one or two equations show stability, but stable predicted ages at PHV with a specific equation over time vary within and among individuals.

Discussion

Predicted ages at PHV based on four prediction equations in a longitudinal sample of elite youth football players differed significantly from, and were not equivalent to, age at PHV estimated with Preece-Baines model I for individual players. Moreover, the majority of players' predicted ages at PHV demonstrated marked variation across the chronological age span represented.

Comparison to other studies

Validation studies of the original prediction equation (Mirwald et al. 2002) in longitudinal samples of Polish (Malina and Kozieł 2014a) and American (Malina et al. 2016) boys and of the modified equations (Moore et al. 2015) in the Polish boys (Kozieł and Malina 2018) showed, on average, reduced variation in predicted compared to observed ages at PHV. The validation studies also showed later than predicted observed ages at PHV in early maturing boys and earlier than predicted observed ages at PHV in late maturing boys. Cross-sectional studies of elite football players have indicated advanced skeletal and sexual maturity status compared to the general population (Malina 2011; Malina et al. 2012), although there is variation with the Tanner-Whitehouse method of skeletal age assessment (Malina et al. 2018). Nevertheless, allowing inter-individual differences in biological maturity status and timing, intra-individual variation in predicted ages at PHV was considerable and relatively few predictions approximated observed ages at PHV (Kozieł and Malina 2018).

The initial study on the Mirwald et al. (2002) equation in Polish boys showed, on average, a stable deviation between predicted and observed ages at PHV in *average* maturing boys between 13 and 15 years of age (Malina and Kozieł 2014a). This was not consistent with observations for 15 of the 17 boys in the present sample who had an observed age at PHV that could be classified as average. A possible

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 in individual players.

	Mirwald			Moore 1			Moore 2			Fransen		
Observed age at PHV	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

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

explanation for the greater observed variance between predicted and true age at PHV is the frequency of measurements in the present study compared to annual observations in the study of Polish boys (Malina and Kozieł 2014a; Kozieł and Malina 2018). A potential confounder, however, may be measurement variability in height, weight and sitting height across observations in addition to seasonal fluctuations in growth in height and weight. Growth in height is generally more rapid in the spring/summer and slower in the fall/winter, while growth in weight shows the opposite season pattern (Cole 1998). Seasonal variation in growth may affect predictions made across the football season. It has also been suggested that growth in height occurs in mini-spurts followed by intervals of no increment (Lampl and Johnson 1993). As the prediction equation of Fransen et al. (2018) was validated in a mixed-longitudinal sample of elite youth football players, it was expected that the prediction equation would yield more valid results. This, however, was not the case in the present study.

Strengths and limitations

The potential strength or limitation of this study is the frequency of measurements during the interval of the growth spurt. Whereas more frequent measures of growth throughout the pubertal growth spurt may permit a more accurate estimate of true age at PHV, any gains in accuracy are equally dependent on the reliability and consistency of the measures (i.e. inter- and intra-observer error) in direct (height, sitting height, weight) and derived (estimated leg length) variables. As noted, other potential confounding factors are diurnal and seasonal variation in growth. Estimates of growth rates over short intervals also have a larger variance (Tanner et al. 1966; Roche and Himes 1980). In addition, the Preece-Baines model I has an associated error margin. The PB-1 model, however, provides a clear estimate of the age at PHV, which is not the case, for example, with cubic splines that may show several peaks in some individuals (see Figure 2).

Although the majority of players in the sample were of European ancestry, players of different ethnicities were included. This variation in ethnicity is representative for contemporary elite-level youth football teams. It is also relevant as the prediction equations and the Preece-Baines model were based on samples of European ancestry. Ethnic variation in the proportion of leg length to stature is also well documented (Malina et al. 2004). As such, care is warranted in generalising the observations, although they were consistent with previous validation studies of the maturity offset/predicted age at PHV protocol. Finally, this study comprised only boys, in order to confirm the results for girls, further research is needed.

Practical recommendations for training and future directions

Although puberty is a critical period in talent development (Lloyd et al. 2014; Malina et al. 2015), it is characterised by

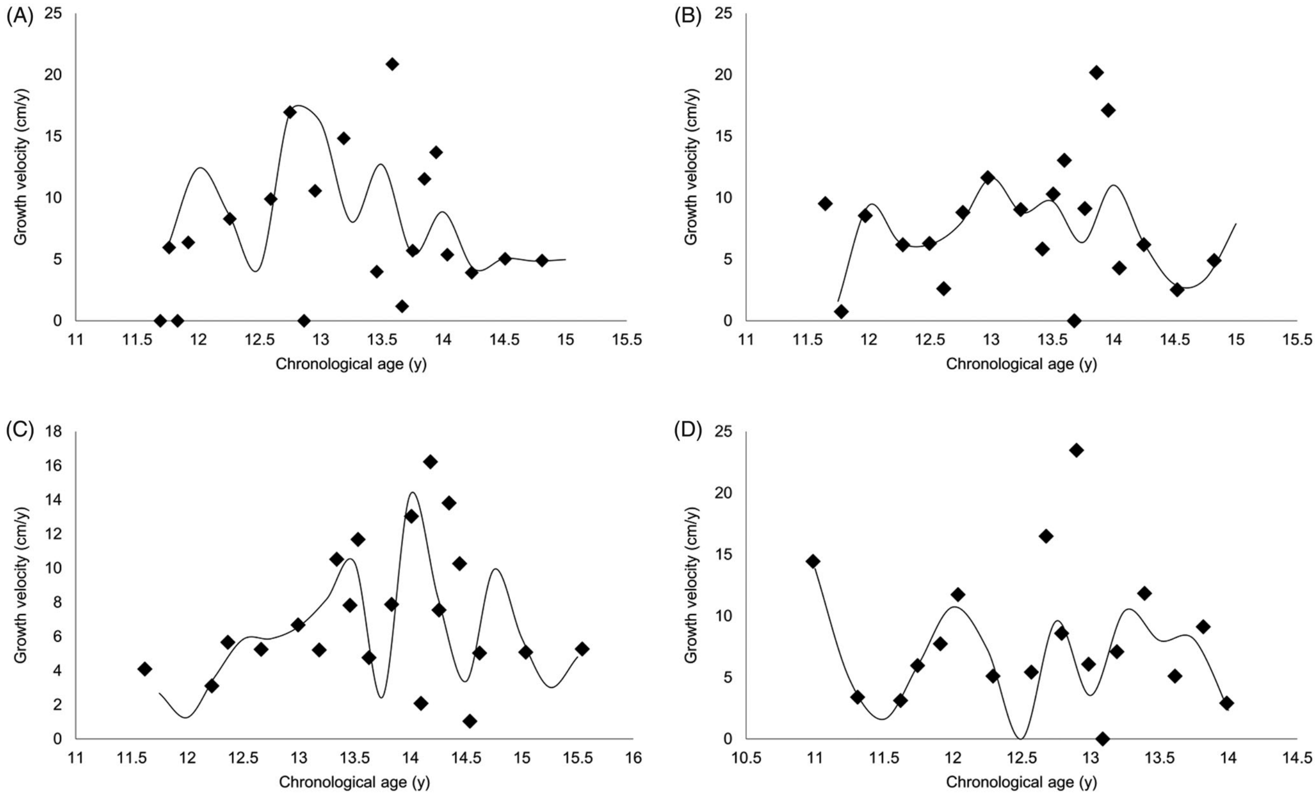

Figure 2. Growth velocity of individual players modelled by cubic splines in four randomly selected players (same players as in Figure 1).

considerable inter-individual variation in the timing of the growth spurt in body size, mass and indicators of fitness – strength, explosive power and aerobic power in male athletes and non-athletes (Philippaerts et al. 2006).

Some evidence also indicates a peak incidence of injury around the predicted time of PHV (van der Sluis et al. 2015; Read et al. 2018; Bult et al. 2018). It is also common to decrease workload and adjust exercises during the interval of PHV and to focus on individualised training protocols (Lloyd and Oliver 2013; Lloyd et al. 2016). For optimal management of training load and in order to maximise athlete development during the interval of PHV, the importance of continuous assessment of growth of youth athletes during the pubertal period has been suggested (Lloyd et al. 2014). Given the non-invasiveness, time and cost efficiency, and immediate outcome, predicted maturity offset and/or age at PHV is attractively simple and is increasingly, if not uncritically, used to individualise training and competition programmes (Cumming et al. 2017). However, as the present results indicate, the individual accuracy of all four prediction equations for estimating age at PHV for individual players is questionable and use of the prediction equations in this context is not recommended.

Growth in height during adolescence varies considerably among individuals. This individuality of somatic growth emphasises the need to closely monitor growth status in order to establish training goals. In this context, it has been recommended that youth players be measured at three-month intervals in order to establish meaningful changes and to minimise the influence of daily fluctuations and measurement variability (Lloyd et al. 2014). Estimating growth velocity across measurement intervals is relatively easy and has the advantage that it considers the non-linear characteristic of growth. Nevertheless, attention to measurement variability and potential seasonal variation should not be overlooked.

Future research may consider adapting training goals and modalities relative to estimated velocities of growth in height during the interval of the adolescent spurt and specific stage of pubertal development (pubic hair, genital) in an effort to individualise training. Moreover, more frequent assessments of growth have the potential of identifying 'mini-growth-spurts' (Figure 2), and perhaps make it possible to adjust training programmes accordingly (i.e. intensity, volume and training forms/activities). If 'mini-growth-spurts' are confirmed in subsequent studies of youth athletes, they may be potentially useful in the context of bio-banding (Cumming et al. 2017), i.e. modify bands defined by percentage of predicted adult height relative to rate of growth. Moreover, use of estimated growth velocities for height may be an option in assessing growth changes during puberty in the context of designing athlete development programmes and assessing injury risk. Growth rates over six months are available for American children and youth in the Fels Longitudinal Study (Baumgartner et al. 1986). Nevertheless, this potential approach presents challenges associated with extrapolations of frequent growth measurement for future growth, and the identification of specific growth rates that are useful for coaches in adjusting individual training protocols. Although potentially audacious, such an approach may assist coaches in guiding individual athletes during the adolescent transition, keeping in mind that all will eventually reach adulthood.

Conclusion and practical implications

Results of this longitudinal study of elite youth male football players indicate that none of the four equations for predicting age at PHV provide an accurate prediction in individuals. The stability of predictions within individuals was also poor. By inference, the utility of the prediction equations has major limitations. As such, the use of the prediction equations to prescribe individualised training programmes or to assess injury risk in youth football players is not recommended. Future studies may consider the evaluation of the reliability of repeated measurements of growth (growth tracking) in order to identify potential 'mini-growth-spurts' in the context of training and injury risk.

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References

Baumgartner RN, Roche AF, Himes JH. 1986. Incremental growth tables: supplementary to previously published charts. Am J Clin Nutr. 43(5): 711–722.

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

Bult HJ, Barendrecht M, Tak I. 2018. Injury risk and injury burden are related to age group and peak height velocity among talented male youth soccer players. Orthop J Sports Med. 6(12):232596711881104.

Cohen J. 1988. Statistical power analysis for the behavioral sciences, 2nd ed. Hillsdale, NJ: Lawrence Erlbaum.

Cole T. 1998. Seasonality of growth. In: Ulijaszek SJ, Johnston FE, Preece MA, editor. The cambridge encyclopedia of human growth and development. Cambridge: Cambridge University Press.

Cumming SP, Lloyd RS, Oliver JL, Eisenmann JC, Malina RM. 2017. Bio-banding in sport. Strength Cond J. 39(2):34–47.

Fransen J, Bush S, Woodcock S, Novak A, Deprez D, Baxter-Jones ADG, Vaeyens R, Lenoir M. 2018. Improving the prediction of maturity from anthropometric variables using a maturity ratio. Pediatr Exerc Sci. 30(2):296–307.

Goswami B, Roy AS, Dalui R, Bandyopadhyay A. 2014. Impact of pubertal growth on physical fitness. AJSSM. 2(5A):34–39.

Johnson A, Farooq A, Whiteley R. 2017. Skeletal maturation status is more strongly associated with academy selection than birth quarter. Sci Med Football. 1(2):157–163.

Kozieł SM, Malina RM. 2018. Modified maturity offset prediction equations: validation in independent longitudinal samples of boys and girls. Sports Med. 48(1):221–236.

Lakens D, Scheel AM, Isager PM. 2018. Equivalence testing for psychological research: a tutorial. Adv Methods Practices Psychol Sci. 1(2): 259–269.

Lampl M, Johnson ML. 1993. A case study of daily growth during adolescence: a single spurt or changes in the dynamics of saltatory growth? Ann Hum Biol. 20(6):595–603.

Leyhr D, Kelava A, Raabe J, Honer O. 2018. Longitudinal motor performance development in early adolescence and its relationship to adult success: An 8-year prospective study of highly talented soccer players. PloS One. 13(5):e0196324.

Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, Micheli LJ, et al. 2016. National strength and conditioning association position statement on long-term athletic development. J Strength Cond Res. 30(6):1491–1509.

Lloyd RS, Oliver J. 2013. The impact of growth and maturation on physical performance. In Strength and conditioning for young athletes. New York, NY: Routledge. p. 25–40.

Lloyd RS, Oliver JL, Faigenbaum AD, Myer GD, De Ste Croix MB. 2014. Chronological age vs. biological maturation: implications for exercise programming in youth. J Strength Cond Res. 28(5):1454–1464.

Lohman TG, Roche AF, Martorell R. 1988. Anthropometric standardization reference manual. Champaing, IL: Human Kinetic Books.

Malina RM, Bouchard C, Bar-Or O. 2004. Growth, maturation, and physical activity. Champaign, IL: Human kinetics.

Malina RM, Chamorro M, Serratosa L, Morate F. 2007. TW3 and Fels skeletal ages in elite youth soccer players. Ann Hum Biol. 34(2):265–272.

Malina RM, Choh AC, Czerwinski SA, Chumlea WC. 2016. Validation of maturity offset in the Fels longitudinal study. Pediatr Exerc Sci. 28(3): 439–455.

Malina RM, Coelho E, Figueiredo AJ, Carling C, Beunen GP. 2012. Interrelationships among invasive and non-invasive indicators of biological maturation in adolescent male soccer players. J Sports Sci. 30(15):1705–1717.

Malina RM, Coelho E, Figueiredo AJ, Philippaerts RM, Hirose N, Pena Reyes ME, Gilli G, et al. 2018. Tanner-Whitehouse skeletal ages in male youth soccer players: TW2 or TW3? Sports Med. 48(4):991–1008.

Malina RM, Kozieł SM. 2014a. Validation of maturity offset in a longitudinal sample of Polish boys. J Sports Sci. 32(5):424–437.

Malina RM, Kozieł SM. 2014b. Validation of maturity offset in a longitudinal sample of Polish girls. J Sports Sci. 32(14):1374–1382.

Malina RM, Rogol AD, Cumming SP, Coelho e Silva MJ, Figueiredo AJ. 2015. Biological maturation of youth athletes: assessment and implications. Br J Sports Med. 49(13):852–859.

Malina RM. 2011. Skeletal age and age verification in youth sport. Sports Med. 41(11):925–947.

Marceau K, Ram N, Houts RM, Grimm KJ, Susman EJ. 2011. Individual differences in boys' and girls' timing and tempo of puberty: modeling development with nonlinear growth models. Dev Psychol. 47(5): 1389–1409.

Meylan C, Cronin J, Oliver J, Hughes M. 2010. Talent identification in soccer: the role of maturity status on physical, physiological and technical haracteristics. Int J Sports Sci Coaching. 5(4):571–592.

Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. 2002. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc. 34(4):689–694.

Moore SA, McKay HA, Macdonald H, Nettlefold L, Baxter-Jones AD, Cameron N, Brasher PM. 2015. Enhancing a somatic maturity prediction model. Med Sci Sports Exerc. 47(8):1755–1764.

Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, Bourgois J, et al. 2006. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci. 24(3):221–230.

Preece MA, Baines MJ. 1978. A new family of mathematical models describing the human growth curve. Ann Hum Biol. 5(1):1–24.

Read PJ, Oliver JL, De Ste Croix MBA, Myer GD, Lloyd RS. 2018. An audit of injuries in six english professional soccer academies. J Sports Sci. 36(13):1542–1547.

Roche AF, Himes JH. 1980. Incremental growth charts. Am J Clin Nutr. 33(9):2041–2052.

Rommers N, Mostaert M, Goossens L, Vaeyens R, Witvrouw E, Lenoir M, D'Hondt E. 2019. Age and maturity related differences in motor coordination among male elite youth soccer players. J Sports Sci. 37(2):196–203.

Tanner JM, Whitehouse R, Takaishi M. 1966. Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children, 1965. I. Arch Dis Child. 41(219):454–471.

Tierney PJ, Young A, Clarke ND, Duncan MJ. 2016. Match play demands of 11 versus 11 professional football using Global Positioning System tracking: variations across common playing formations. Hum Mov Sci. 49:1–8.

van der Sluis A, Elferink-Gemser MT, Brink MS, Visscher C. 2015. Importance of peak height velocity timing in terms of injuries in talented soccer players. Int J Sports Med. 36(04):327–332.