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Accuracy of maturity prediction equations in individual elite football players

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Accuracy of maturity prediction equations in individual elite football players

Abstract

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

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

Subjects and methods: Anthropometric measurements were conducted at least every three months in 17 adolescent elite football players (11.9 ± 0.8 years) from seasons 2008-2009 to 2011-2012. APHV was estimated at each measurement point by four predominant prediction 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: In none of the players, predicted APHV was equivalent to the observed APHV. A difference with a large effect size (Cohen's d>0.8) was found in 87% of the cases. Furthermore, the prediction was not stable over time in 71% of the cases.

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

Keywords;

Growth, maturation, soccer, puberty, adolescence

Introduction

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

Identification, selection, transfer and development of youth athletes are related to differences in individual biological maturity status among high-level youth athletes (Meylan et al. 2010; Malina et al. 2015). Moreover, puberty coincides with a stage of player development where there is increased emphasis on player selection and de-selection and where the physical demands and intensity of training sessions 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 have been shown disproportionally represented in youth football (Johnson et al. 2017).

A commonly used indicator of maturational timing is predicted age at PHV, based on several anthropometric dimensions (Mirwald et al. 2002; Moore et al. 2015; Fransen et al. 2018). The original prediction equation (2002) estimates the maturity offset, an indicator of the time before or after the age of PHV, from chronological age (CA), height, weight, sitting height and estimated leg length. This prediction equation has since been modified (Moore 1, includes age and sitting height) and simplified by eliminating sitting height from the equation (Moore 2, includes age and height) (Moore et al. 2015). More recently, the linear prediction equation has been extended to a polynomial prediction equation estimating a maturity ratio (Fransen et al. 2018).

The authors of the original equations report error margins around one year in boys (Mirwald et al. 2002; Moore et al. 2015). In addition, several validation analyses in longitudinal samples spanning from 8 through 18 years report major limitations of the original and modified equations. Predicted ages at PHV increase, on average, with CA at prediction, have a reduced range of variation, and have major limitations with early and late maturing youth defined by observed ages at PHV (Malina and Koziel 2014a, 2014b; Malina et al. 2016; Koziel and Malina 2018). 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).

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 individualizing training prescriptions, identifying a player's 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. In this context, the aim of this study is to investigate the accuracy and longitudinal stability of predicted ages at PHV in elite youth football player who were measured at least every three months during adolescence.

Subjects and methods

Participants

Data were collected from seasons 2008-2009 through 2011-2012 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 youth academy were measured on a regular basis. Seventeen players (n=17; Caucasian n = 10, African n = 5, Middle Eastern n = 2) were longitudinally followed over at least two years. To ensure a high temporal follow-up around the adolescent growth spurt, only players with at least 15 measurement points over an interval that spanned at least two years around the age of PHV were included in this study. After medical checks all participating players were found healthy and had no known growth disorders.

Procedures

All measurements in this study were part of the regular programme of the club and 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 frequently (range every 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 standardized 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 equation for boys (2002), the two modified equations (2015) and the maturity ratio (2018) (Table 1). The first three equations predict maturity offset; age at PHV is estimated as CA minus predicted offset. With the maturity ratio protocol, CA was divided by the maturity ratio to estimate age at PHV.

*** Insert Table 1 near here ***

Analyses

Descriptive statistics of the first measurement of each player are presented as means with corresponding standard deviations (SD). Age at PHV for individual players was than estimated 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 – 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 with Cohen's d was > 0.5 and as large with 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 visualize 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.

In order to visualise the individual growth patterns of the included players, we fitted cubic splines 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 summarized in Table 2.

*** Insert Table 2 near here ***

Observed ages at PHV based on Preece-Baines model I ranged from 12.55 to 15.18 years with mean of 13.8 ± 0.7 years (Table 3). Average predicted ages at PHV based on the four prediction equations of 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 mean and SD of the predicted ages at PHV with each of the four prediction equations for individual players are summarized in Table 3.

*** Insert Table 3 near here ***

The ranges of predicted ages at PHV with each prediction equation for individual players are presented 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, the predicted ages at PHV were not equivalent to the observed age at PHV with the effect size showing a large effect. In seven players, two predictions were less than observed age at PHV, while in most players, predicted ages at PHV were higher 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 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 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 and Fransen 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.

*** Insert Figure 1 ***

*** Insert Table 4 ***

Discussion

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

Comparison to other studies

Validation studies of the original prediction equation (Mirwald et al. 2002) in longitudinal samples of Polish (Malina and Koziel 2014a) and American (Malina et al. 2016) boys and of the modified equations (Moore et al. 2015) in the Polish boys (Koziel and Malina 2018) showed, on average, reduced variation in predicted compared to observed ages at PHV, later predicted than observed ages at PHV in early maturing boys and earlier predicted than observed ages at PHV in late maturing boys. Moreover, 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). Nevertheless, allowing inter-individual differences in biological maturity status and timing, intra-individual variation in predicted ages at PHV is considerable and relatively few predictions approximated observed age at PHV (Koziel and Malina 2018).

The initial study, on the Mirwald 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 Koziel 2014a). This was not consistent with observations for 15 of the 17 boys in our sample who had an observed age at PHV that could be classified as average. A possible explanation for the difference is the frequency of measurements in the present study compared to annual observations the study of Polish boys (Malina & Koziel, (2018). On the other hand, it is possible that predictions in the present study were affected by 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 also 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 increase (Lampl and Johnson 1993).

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

Strengths and limitations

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

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

Practical recommendations for training and future directions

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

Some evidence indicates a peak incidence of injury around the predicted time of PHV (van der Sluis et al. 2015; Read et al. 2017). It is common to decrease the workload and adjust exercises during the interval of PHV and to focus on individualized training plans (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 shown in the present study, the individual accuracy of all four prediction equations for estimating a player's age at PHV 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 emphasizes the need to closely monitor growth status in order to establish training goals. In this context, it is recommended that youth players should be measured at three-month intervals in order to establish meaningful changes and to minimize the influence of daily fluctuations and measurement variability (Lloyd et al. 2014). Such measures can be taken in conjunction with estimates of maturity status to provide a more comprehensive picture of growth and maturity status. Monitoring growth velocity is relatively easy to establish in practice and has the advantage that it considers the non-linear character of growth. Nevertheless, attention to potential seasonal variation in growth should not be overlooked. Future research could focus on 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 individualize training. The authors would like to propose the hypothesis that more frequent assessments of growth will show 'mini-growth-spurts' (Figure 2), despite the limitations of the reliability of frequent measurements, and will make it possible to adjust training programs (i.e. intensity, volume and training forms/activities) accordingly. If 'mini-growth-spurts can be confirmed in future studies than we would like to suggest revising the bio-banding concept by constructing the bands around the rate of growth-velocity rather than maturity offset or percentage of adult stature. Moreover, to support the practitioner in the future with a more accurate tool to assess growth spurts during puberty for 1) the design of athlete development programmes and 2) the assessment of injury risk - a combination of the current equations and growth velocity tracking can be more a valid option. The challenges of this concept are: 1) it is not known how accurate individual extrapolations of frequently measured growth data in the past are for the growth curve ahead, and 2) no cut-off growth-velocity-rates are established by which coaches can adjust their training. Although his concept might be audacious, it might help the coach to more accurately guide individual pathways of athletes during their transition from adolescents to adults.

Conclusion and practical implications

The results of this longitudinal study in elite youth football players suggested that none of the four equations for predicting age at PHV provides 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. Therefore, we do not recommend the use of the prediction equations to prescribe individualized training programmes or to assess injury risk in youth elite level football players. Future studies could focus on the evaluation of the reliability of frequent measurements of growth (growth tracking) in order to capture possible 'mini-growth-spurts' and to assess the associated injury risk and optimal training accordingly.

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Declaration of interest statement

The authors report no conflict of interest.

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

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

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

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

	Mirwald		Moore 1		Moore 2		Fransen	
Observed age at PHV	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

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.

	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

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

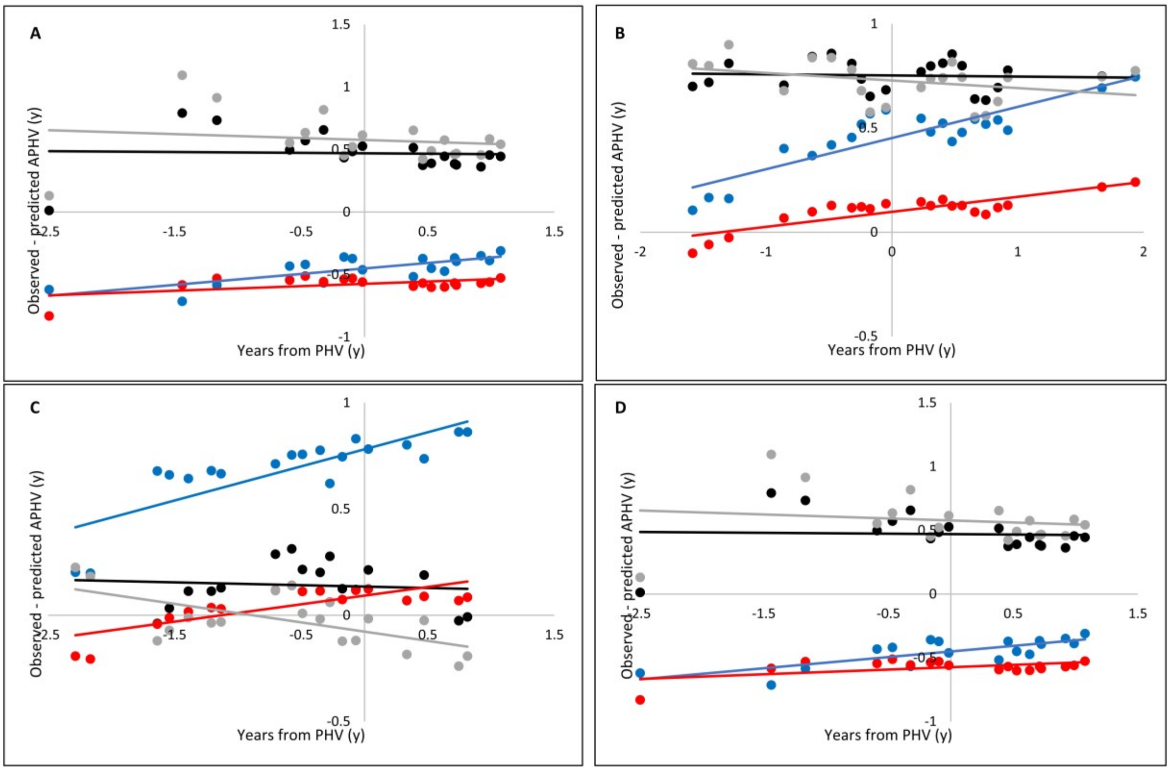

Figure 2. Growth velocity of individual players modelled by cubic splines in four randomly selected players (same players as in figure 1).