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1 **Predicting the Timing of the Peak Pubertal Growth Spurt in Elite Youth Soccer**  
2 **Players: Evaluation of Methods**

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1 **Abstract**

2 **Background:** Three commonly used non-invasive [protocols](#) are implemented amongst  
3 youths to estimate the window in which PHV is most likely to occur. By being able to  
4 accurately estimate the [circumpubertal years](#) can aid practitioners to better manage  
5 training load of adolescent athletes.

6 **Aim:** Three methods for estimating the interval of the pubertal growth spurt were  
7 compared relative to observed age at PHV: an estimate of  $13.8 \pm 1.0$  years - generic  
8 age at PHV ([obtained from longitudinal measures](#)); predicted age at PHV based on the  
9 maturity offset equation, predicted age at PHV  $\pm 1.0$  year; and a window of PHV based  
10 on a percentage of predicted adult height at the time of observation between  
11 85% - 96%.

12 **Subjects & Methods:** [A final sample of 23 \(from initial sample of 28\) adolescent](#)  
13 [participants were selected from an academy belonging to a club competing in the](#)  
14 [English Premier League](#). Anthropometric measures were collected across five  
15 consecutive playing seasons; age at PHV was estimated with [Super-Imposition by](#)  
16 [Translation and Rotation](#). Using measurements at 13.0 years, predicted maturity  
17 offset, age at PHV and [circumpubertal years](#) of PHV based on percentage of predicted  
18 adult height were estimated.

19 **Results and Conclusions:** Predicted age at PHV correctly assigned 15 participants  
20 (65%) as experiencing PHV, while the percentage height window correctly assigned  
21 [the circumpubertal years of](#) 17 participants (74%). Generic age at PHV and predicted  
22 age at PHV correctly predicted observed age at PHV for 14 participants (61%), while  
23 the percentage of adult height window correctly predicted 22 participants (96%). A  
24 specific age window based on predicted maturity offset did not improve estimation of  
25 PHV compared to generic age method; however, percentage of predicted adult height  
26 window of PHV showed improvement in [performance](#).

27  
28 **Keywords:** maturity offset; adolescent spurt; predicting adult height; youth athletes; peak  
29 height velocity

## 1 Introduction

2 Characteristics associated with physical growth and biological maturation, and related changes in  
3 functional and behavioural characteristics influence the development of athletic ability (Williams and  
4 Reilly, 2000). Although the processes of growth and maturation span approximately the first two  
5 decades of life, the interval spanning the adolescent growth spurt and pubertal maturation,  
6 sometimes labelled the pubertal growth spurt, is highly individual and variable in timing and tempo  
7 (Malina et al., 2004, Malina et al., 2015). The spurt begins with acceleration in the rate of growth in  
8 height (labelled take-off), continued acceleration in growth rate until peak velocity is attained (peak  
9 height velocity, PHV), and then deceleration and eventual cessation of growth in height (Malina et  
10 al., 2004, Molinari et al., 2013). The interval of the growth spurt is of interest and often presents a  
11 challenge to those involved in the identification and development of youth athletes, including  
12 decisions regarding retention or exclusion.

13 Young athletes are traditionally grouped by chronological age (CA) for the purpose of  
14 training and competition. Youth of the same CA vary significantly in maturity status at the time of  
15 observation, e.g. skeletal age, stage of puberty, and in maturity timing, CA at the onset of puberty  
16 and at PHV (Marshall and Tanner, 1970, Beunen and Malina, 1988, Patel et al., 1998, Malina et al.,  
17 2004). Estimation of the CA at which a youngster attains specific maturational landmarks requires  
18 longitudinal observations, and inter-individual variation is substantial. For example, youth soccer  
19 players of the same CA varied by as much as five to six years in skeletal age (Johnson, 2015), while  
20 age at take-off of growth spurt varied between 8.2 – 12.7 years in boys from the Fels longitudinal  
21 study (Malina et al., 2016).

22 Individual differences in maturity status have implications for development and  
23 retention / exclusion in many sports, including youth soccer. Players advanced in maturity status  
24 have, on average, size and functional advantages (e.g. strength and power) compared to later  
25 maturing teammates of the same CA (Malina et al., 2013) and generally possess a competitive  
26 advantage (Cumming et al., 2017a). Data are lacking, however, on individual differences in size and  
27 function among soccer players relative to timing of the adolescent growth spurt (Malina et al.,  
28 2015). Data from longitudinal surveys of the general population clearly indicate higher values for  
29 stature from 10 through 15 years of age in boys who attain PHV earlier than peers and a weight  
30 advantage through adolescence (Malina et al., 2004). Of relevance to the development of youth  
31 players, those who mature early experience the adolescent growth spurt at a CA when the training  
32 load is typically lighter and fewer decisions are made regarding the retention or release of players  
33 from the academy system (Cumming et al., 2017a). To accommodate individual differences in rate of  
34 growth during the growth spurt, many soccer academies systematically monitor the growth and  
35 estimated maturity status of youth players.

36 Assessment of growth status is rather straightforward and involves measurements of height,  
37 weight and perhaps other dimensions. Assessment of maturity status is a different issue as  
38 established methods (stage of pubertal development and skeletal age) are often viewed as invasive  
39 and require expertise that may not be available at some clubs (Malina, 2017). Assays of hormonal  
40 levels are also invasive and expensive, but more importantly, may be influenced by behaviours such  
41 as sleep, stress, nutritional status and physical activity (Johnson et al., 1992, Dawes et al., 1999,  
42 Shirtcliff et al., 2009, Blakemore et al., 2010). Estimated growth velocities based on longitudinal  
43 height and weight records may be useful in identifying the growth spurt; care in estimating velocities

1 is essential and available longitudinal observations may not span the interval of the spurt. Such  
2 estimates are, nevertheless, retrospective and have limitations in the context of the needs of  
3 individual players.

4 Current interest in the application of non-invasive and predictive techniques in youth soccer  
5 and other sports to accommodate the perceived need for identifying the onset and subsequent  
6 progress of the growth spurt is considerable. Sex-specific equations based on CA, height, mass,  
7 sitting height and estimated leg length are available to predict maturity offset, defined as the time  
8 before or after PHV (Mirwald et al., 2002); CA at observation minus predicted maturity offset  
9 provides a predicted age at PHV. Predicted offset is commonly used to classify youth as pre-PHV,  
10 circa-PHV or post-PHV, while predicted age at PHV is also used to group youth into maturity  
11 categories, i.e. early, on-time or late (Sherar et al., 2007, Malina et al., 2012). The validity, reliability  
12 and accuracy of predicted ages at PHV with the maturity offset protocol have been questioned  
13 (Malina and Kozieł, 2014, Malina et al., 2016, Kozieł and Malina, 2018). In addition to dependence  
14 upon CA and body size at prediction, and reduced variation in predicted relative to  
15 estimated/observed ages at PHV (based on longitudinal data spanning late childhood through  
16 adolescence), the prediction equation has major limitations with early and late maturing boys,  
17 defined by observed ages at PHV. Further, the median error tends to be magnified considerably in  
18 children that are either 'early' or 'late' maturing, who typically are of most concern in the context of  
19 sport (Cumming et al., 2017a). Accordingly, the reliability of this method merits attention.

20 Another protocol increasingly used to estimate maturity status youth athletes is the  
21 percentage of predicted adult height attained at the time of observation; use of percentage of  
22 predicted adult height as a maturity indicator was recommended by Roche et al. (1983) and  
23 equations for the prediction of adult height without skeletal age were subsequently developed  
24 (Khamis and Roche, 1994). Concordance of classifications of maturity status based on percentage of  
25 predicted adult height at the time of observation and on skeletal age among youth participants in  
26 American football 9 – 14 years (Malina et al., 2007) and in soccer 11 – 14 years (Malina et al., 2012)  
27 were moderate, approximately 60%. Percentage of predicted adult height also had concurrent and  
28 predictive validity in samples of North American and British youth (Malina et al., 2005, Cumming et  
29 al., 2006, Malina et al., 2006, Cumming et al., 2014). In recent applications, responses of academy  
30 soccer players 11 - 14 years of age with current heights  $\geq 85.0\%$  and  $< 90.0\%$  of their predicted adult  
31 heights (Cumming, 2018, Cumming et al., 2018) and 13 – 15 years of age with current heights  $\geq$   
32  $90.0\%$  and  $< 95.0\%$  of their predicted adult heights (Thomas et al., 2017) to participation in maturity  
33 matched (i.e. bio-banded) competitions have been monitored. The studies assumed that the ranges  
34 of percentage of predicted adult height spanned the interval of the growth spurt.

35 In the context of the preceding, the purpose of the present study is to evaluate three  
36 protocols used to estimate the window in which PHV is most likely to occur for individual male  
37 soccer players at 13.0 years of age. This age was selected as it is common for soccer coaches/clubs  
38 to consider the retention or exclusion of players, and/or the option of playing a youngster "up" or  
39 "down" an age group at about this time.

#### 40 **Methods**

41 The study was approved by the Ethics Committee of the Faculty of Science and Engineering, at  
42 Manchester Metropolitan University. Parents/guardians of the participants were informed of the  
43 aim of the study, research procedures, requirements, benefits and risks, and provided written

1 informed consent. The youth also provided assent and were advised that involvement in the study  
2 was voluntary and that they could withdraw from the study at any point.

3 A sample of 28 (19 Caucasian, 9 non-Caucasian) male players from a professional soccer  
4 academy within the English Premier League was followed across five consecutive competitive  
5 playing seasons. Heights and weights were measured at two-month intervals during the respective  
6 seasons. All participants were born between 2001 and 2004, and represented one of five age groups,  
7 defined by age at the beginning of the competitive year (1<sup>st</sup> of September) and monitored during  
8 their time until they were 18 years of age.

### 9 ***Anthropometry***

10 Mass, stature (hereafter, 'height') and sitting height were measured every two months throughout  
11 each competitive playing season (six measurements per season). Participants wore a t-shirt and  
12 shorts; footwear was removed. Height (cm) and sitting height (cm) were measured using a fixed  
13 Harpenden stadiometer (Holtain Ltd., UK) to the nearest 0.10 cm. Height was measured as the  
14 distance from the standing surface to the vertex of the head. Participants were instructed to stand in  
15 the standard erect posture with weight equally spread between both feet. The head was positioned  
16 in the Frankfort horizontal plane. Sitting height was measured as the distance from a flat sitting  
17 surface (40 cm high box) to the top of the head with participants sitting in an upright position with  
18 the head in the Frankfort horizontal plane, knees together and directed straight ahead. Sitting height  
19 was subtracted from height to provide an estimate of leg length. Body mass was measured by means  
20 of a weighing scale (Tanita®, type BC-420 SMA, Japan) to the nearest 0.10 kg.

21 A sample of 15 participants was selected and measured at the same time of day on a second  
22 occasion within 4 days (after their earliest measurement date). The initial and replicate  
23 measurements were taken by two experienced observers. Inter-observer technical errors of  
24 measurement were as follows: weight (0.38 kg), height (0.24 cm) and sitting height (0.25 cm). The  
25 observed technical errors of measurement were well within the range of those reported in several  
26 small scale and national surveys of school age children and youth (Malina, 1995), and were similar to  
27 corresponding technical errors in the Wrocław Growth Study, 0.29 cm and 0.35 cm for height and  
28 sitting height, respectively (Kozielec, 1998).

### 29 ***Age at Peak Height Velocity (PHV)***

30 The longitudinal height records for the 28 individual players were fit with the  
31 Super-Imposition by Translation of Rotation (SITAR) model (Cole et al., 2010) to estimate age at PHV.  
32 Ages at initial observation ranged from 11.21 to 13.13 years (mean  $12.4 \pm 0.6$  years), while ages at  
33 final observation ranged from 14.51 to 16.43 years (mean  $15.4 \pm 0.6$  years). Frequencies of  
34 observations ranged from 13 to 20 (mean  $18.6 \pm 1.6$ ); one participant had 13 height measurements,  
35 while the number of measurements in the remainder ranged from 17 to 20. The SITAR model was  
36 successfully fit to the height records for all 28 participants, with a mean age at PHV of  $14.0 \pm 0.9$   
37 years.

38 The estimated age at PHV for one participant preceded his first observation, while four  
39 players lacked a measurement of young adult height at 18.0 years (see below). Thus, the sample for

1 analysis was reduced to 23 players (15 Caucasian, 8 non-Caucasian) with a mean age at PHV of 14.2  
2 ± 0.9 years. The height of each player at PHV was accepted as the height measured closest to age at  
3 PHV with the SITAR model.

#### 4 ***Pubertal Growth Spurt Prediction Protocols***

5 The issues associated with the pubertal growth spurt are thought to occur in a time period around  
6 the point of PHV. This is commonly referred in the literature as circumpubertal years, and in soccer  
7 academies, as the ‘window of PHV’ or ‘PHV window’. The frequency with which observed age at PHV  
8 of each participant (estimated from longitudinal data) occurred within three windows based on  
9 different protocols was examined: (1) an age band of ± 1.0 year around the estimated mean age of  
10 PHV of males of European ancestry, 12.8 – 14.8 years of age, labelled the generic age band; (2) a  
11 band of ± 1.0 year around predicted ages at PHV based on the maturity offset protocol (Mirwald et  
12 al., 2002); and (3) a window of 85% to 96% of percentage of predicted young adult height based on  
13 observations in two longitudinal studies (Sanders et al., 2017). The logic and details of each protocol  
14 are indicated subsequently.

#### 15 *Generic Age at PHV*

16 The estimated mean age at PHV in the three samples upon which the maturity offset prediction  
17 equation was developed (Mirwald et al., 2002) was 13.8 years with an estimated standard deviation  
18 of 0.9 year (Malina et al., 2012), which was similar the interval of ± 1.0 year of observed age at PHV  
19 commonly used in longitudinal studies to classify youth as late, average or early maturing (Malina et  
20 al., 2004, Malina, 2017). Observed standard deviations for estimated ages at PHV in longitudinal  
21 studies have ranged from 0.8 to 1.3 years in boys with most clustering close to 1.0 year (Malina et  
22 al., 2004). As such, a window of ± 1.0 year was used in the present study; a majority of boys should  
23 experience PHV within a window of 12.8 to 14.8 years of age. Accordingly, CA at the time of  
24 observation within this range was used as an approximate estimate of when the player was likely to  
25 experience PHV. This was labelled the generic estimate of age at PHV. Boys with a current CA within  
26 this band would be considered to be within the interval of the growth spurt, whereas boys outside  
27 the band would be considered, accordingly, as having already attained peak velocity, or not yet in  
28 the interval of peak velocity. Further, only participants whose SITAR determined age at PHV was  
29 between 12.8 – 14.8 years would have been correctly identified by using this method.

30

31

#### 32 *Predicted Age at PHV*

33 Maturity offset at the observation closest to 13.0 years of age ( $13.03 \pm 0.06$  years, range 12.93 –  
34 13.13 years) was predicted with the equation proposed by Mirwald et al. (2002):

35 
$$\text{Maturity Offset} = -9.236 + (0.0002708 \times [\text{Leg Length} \times \text{Sitting Height}]) +$$
  
36 
$$(0.001663 \times [\text{CA} \times \text{Leg Length}]) + (0.007216 \times [\text{CA} \times \text{Sitting Height}]) + (0.02292 \times$$
  
37 
$$[\text{Weight by Height Ratio} \times 100]).$$

1 Note, the need to multiply the weight by height ratio by 100 was overlooked in the original  
2 publication (Mirwald et al., 2002). The standard error of estimate for the prediction equation was  
3 0.592. CA at prediction minus maturity offset provided a predicted age at PHV (years).

#### 4 *Window of Percentage of Predicted Adult Height*

5 The adult height of each player at the observation closest to 13.0 years (see above) was predicted  
6 with age-specific equations for males of European ancestry in the Fels Longitudinal Study (Khamis and  
7 Roche, 1994). The equations require CA, height and weight of the youngster and mid-parent height  
8 (average of the heights of the player's biological mother and father). Heights of the biological parents  
9 were self-reported and, as in other studies using the protocol, self-reported heights were adjusted for  
10 overestimation using sex specific equations (Epstein et al., 1995). The median error bound between  
11 actual and predicted young adult height using the Khamis-Roche equations was  $2.2 \pm 0.6$  cm in males  
12 between 4.0 to 17.5 years of age; the estimated median error in males at 13.0 years was 2.5 cm  
13 (Khamis and Roche, 1994). The height of each player at 13.0 years was expressed (1) as a percentage  
14 of his predicted adult height and also (2) as a percentage of his young adult attained height at 18.0  
15 years of age.

16 Recent analyses of two early longitudinal studies of North American boys and girls noted  
17 that PHV occurred within a range of 85% – 96% of adult height and at a mean of approximately 90%  
18 of adult height (Sanders et al., 2017). Citing this study, the window of 85% – 96% is currently  
19 employed by a number of professional soccer academies to facilitate maturity-specific training  
20 strategies (Cumming et al., 2017b, Cumming, 2018). Of potential interest, the upper limit of 96% was  
21 noted in one of the longitudinal samples of girls (Sanders et al., 2017). Consistent with the [protocol](#)  
22 currently employed by some academies, the window of 85% – 96% of young adult height was used  
23 in the present analysis. Percentage of predicted adult height at 13.0 years and height at PHV (SITAR)  
24 expressed as a percentage of measured young adult height were compared with this window.

25 The height window was also converted into an age window. In addition to the serial  
26 longitudinal observations across five seasons, young adult height at 18 years of age was also  
27 measured in 24 players. Heights of each player across the five seasons were expressed as a  
28 percentage of his young adult height. By taking the ages when 85% – 96% of observed young adult  
29 heights were attained, individual age windows were estimated for each participant.

#### 30 **Statistical Analysis**

31 Chi-square tests were conducted in order to determine whether there was a significant difference  
32 for each of the three prediction [protocols](#) against an even chance of the prediction being correct.  
33 The Predicted Age at PHV and the Window of Percentage of Predicted Adult Height [protocols](#) were  
34 also compared with the Generic Age at PHV method to test for improvement in estimation. More  
35 specifically, if predicted APHV with maturity offset and SITAR derived APHV were between 12.8 -  
36 14.8 years ( $13.8 \pm 1.0$  years), the individual was classified as within the window. And, if percentage  
37 of predicted adult height based on height measured at 13 years and if percentage of observed young  
38 adult height based on height at SITAR derived APHV were between 85% - 96%, the individual was  
39 classified as within the window.

40 Concordance analyses (Cohen's Kappa [ $\kappa$ ] coefficients) were used to estimate the degree to  
41 which the [protocols](#) associated with predicted age at PHV and percentage of predicted adult height



1 correctly identified individuals as being within or outside the respective windows based on maturity  
2 classifications at 13.0 years of age. Higher  $\kappa$  coefficients indicate more agreement between methods,  
3 while small or negative values indicate poor or no agreement. With the maturity offset protocol, an  
4 individual with a predicted age at PHV within  $\pm 1.0$  year of observed age at PHV was considered  
5 within the PHV window. For percentage of predicted adult height, an individual whose percentage of  
6 predicted adult height was between 85% – 96% of their observed young adult height was considered  
7 to be within the window of PHV. Subsequent analyses focused on the comparison of the observed  
8 age at PHV window and each of the three predictions.

## 9 Results

10 Data for individual participants at 13.0 years of age are summarised in [Table 1](#), while descriptive  
11 characteristics of participants in consecutive competitive age groups are summarised in  
12 [\\*Participants were classified as early maturing if their age at PHV was observed more than one standard  
13 deviation \(1.0 years\) before the mean age of PHV in European boys \(13.8 years\) and classified as late if they  
14 were more than one standard deviation after the mean. Otherwise, they were classified as on-time.](#)

15 [Table 2](#). Observed ages at PHV based on the SITAR model range from 12.6 - 15.5 years with a mean  
16 of  $14.2 \pm 0.9$  years. Applying the range based on youth of European ancestry (12.8 – 14.8 years) to  
17 categorise individuals as early, on-time, or late in maturity status (based upon observed age at PHV),  
18 14 participants are classified average or on-time, 3 as early and 6 late maturing.

19 \*\*\*\*Insert [Table 1](#) near here\*\*\*\*

20 \*\*\*\*Insert [\\*Participants were classified as early maturing if their age at PHV was observed more than one  
21 standard deviation \(1.0 years\) before the mean age of PHV in European boys \(13.8 years\) and classified as late  
22 if they were more than one standard deviation after the mean. Otherwise, they were classified as on-time.](#)

23 [Table 2](#) near here\*\*\*\*

## 24 Concordance of Predictions

25 Concordance of predicted maturity status classifications of the participants are summarised in  
26 [Table 3](#). Percentage of predicted adult height at 13.0 years of age identifies 21 participants as in the  
27 interval of PHV, i.e. within the 85% – 96% window, and 2 participants as outside the window. In  
28 contrast, predicted age at PHV based on the maturity offset protocol at 13.0 years of age, shows  
29 greater variation in the classification of players within or outside the PHV window.

30 The percentage of predicted adult height method has a higher degree of concordance with  
31 classifications based on observed age at PHV based on the SITAR model; the prediction protocol  
32 correctly classified 19 of the 23 participants as being within the 85% – 96% band. Of the four  
33 misclassified participants, two are identified as outside the PHV window and two as within the PHV  
34 window.

35 \*\*\*\*Insert [Table 3](#) near here\*\*\*\*

36 Concordance of the three methods for estimating age at PHV relative to observed age at  
37 PHV based on SITAR are summarised in [Table 4](#).

38 Among the 23 participants, 14 (61%) have an observed age at PHV within the window

1 defined by generic age of PHV (12.8 – 14.8 years), while 14 (61%) have a predicted age at PHV at 13  
2 years of age within the window defined by observed age at PHV  $\pm$  1.0 year. However, only 11  
3 participants are similarly classified by the two methods. In contrast, 22 of 23 participants (96%)  
4 attain PHV within the window defined by 85% – 96% of predicted adult height at 13 years of age.  
5 Results of the Chi-square analyses are not significant for generic age at PHV and predicted age at  
6 PHV ( $\chi^2 = 1.09$ ), but that for percentage of predicted adult height is significant ( $\chi^2 = 19.17$ ).

7 \*\*\*\*Insert [Table 4](#) near here\*\*\*\*

8 Chi square and Kappa coefficients were also calculated to evaluate the concordance of the  
9 predictive methods with the generic age method, i.e. generic age at PHV method at 13.0 years of  
10 age compared with predicted age at PHV based on maturity offset at 13.0 years of age and with the  
11 percentage of predicted adult height based on height measured at 13.0 years within the 85 – 96%  
12 window. Predicted ages at PHV are concordant with the generic age method in 14 of the 23 players  
13 (61%,  $\chi^2 = 0.0$ ), but the  $\kappa$  coefficient (0.48) suggests moderate concordance. In contrast, the  
14 percentage height window method (converted to an age window) improves upon the generic age  
15 method ( $\chi^2 = 11.68$ ) and the  $\kappa$  coefficient (0.65) suggests substantial agreement. At 13.0 years of age,  
16 the percentage height window converted to an age window correctly identifies status based upon  
17 observed age at PHV in 22 of the 23 participants (96%).

## 18 Discussion

19 The degree to which CA, predicted age at PHV with the maturity offset protocol, and percentage of  
20 predicted adult height at the time of observation (13.0 years) effectively predicted the window  
21 within which PHV was likely to occur was evaluated in a sample of youth soccer participants. The  
22 majority (18 of 23, 78%) experienced PHV when their heights were between 88% and 92% of  
23 observed young adult height at 18 years of age, and all 23 participants attained PHV within the  
24 85% – 96% window ([Figure 1](#)). The latter was consistent with the observations of Sanders et al.  
25 (2017) based on two early longitudinal studies of United States youth. PHV occurred at  $90.0 \pm 2.1\%$   
26 and  $90.2 \pm 4.0\%$  of young adult height in boys from the Brush Foundation and Berkeley studies,  
27 respectively. Based on measurements taken at 13.0 years, the distribution of percentages of  
28 predicted adult heights at PHV are shown in Figure 2. Percentages of predicted adult height in 22 of  
29 the 23 participants (96%) were within the 85% – 96% window. The only participant outside the range  
30 had a percentage of predicted adult height <85%, while no percentages of predicted adult height  
31 were >96%.

32 \*\*\*\*Insert [Figure 1](#) near here\*\*\*\*

33 \*\*\*\*Insert [Figure 2](#) near here\*\*\*\*

34 Although the maturity offset prediction protocol is widely used with soccer players (Kozielec  
35 and Malina, 2018), predicted ages at PHV were not consistent with estimates based on the generic  
36 age method. Mean predicted age at PHV at 13.0 years of age was  $15.1 \pm 0.5$  years, with a range of  
37 14.0 – 16.0 years; corresponding statistics for observed age at PHV were  $14.2 \pm 0.8$  years with a  
38 range of 12.6 – 15.5 years ([Table 1](#)[Table 4](#)). Of relevance, the three early maturing players with observed  
39 ages at PHV of 12.59, 12.73 and 12.79 years had predicted ages at PHV at 13 years (based on  
40 maturity offset) that exceeded observed ages at PHV by 1.42, 1.58 and 2.50 years, respectively  
41 ([Table 1](#)[Table 4](#)). By inference, these participants would not have had training loads adjusted for the interval

1 of rapid growth. A similar trend was apparent in the 14 participants classified as on time based on  
2 observed ages at PHV; all predicted ages at PHV exceeded observed ages at PHV by >0.5 year (0.56  
3 to 1.66 years). These participants would also be identified as having PHV after their pubertal growth  
4 spurt had already occurred. On the other hand, five of the six late maturing participants had a  
5 predicted age at PHV within 0.5 year of their observed age at PHV and thus had a lower chance of  
6 such a misclassification. Results were the same for the total sample of 28 players, 4 early, 18 on-time  
7 and 6 late.

8 The results for the small samples of select soccer participants of contrasting maturity status  
9 were generally consistent with observations for males in the Wrocław, Poland (Malina and Kozieł,  
10 2014, Malina et al., 2016, Kozieł and Malina, 2018) Kozieł and Malina, 2018) and the Fels, U.S.  
11 (Malina et al., 2016) longitudinal studies classified early, average or late maturing, allowing for the  
12 age ranges in the three series and for variation associated with the different methods for estimating  
13 age at PHV in the studies, i.e. SITAR in the present study, Preece-Baines model 1 in Polish youth, and  
14 the triple logistic Bock-Thissen-du Toit model in U.S. youth. The contrast between predicted and  
15 observed ages at PHV was most apparent among early maturing youth, athletes and non-athletes.

16 Observed ages at PHV estimated with the SITAR model in the 23 participants ranged  
17 12.6 – 15.5 years. Accordingly, the generic age at PHV, i.e.  $13.8 \pm 1.0$  years, was an unreliable  
18 indicator of when PHV was likely to occur in this sample of academy soccer players. Observed ages  
19 at PHV in 9 of the 23 participants (39%) were outside the generic age window of 12.8 – 14.8 years of  
20 age.

21 As previously noted, evidence based on skeletal age and pubertal status suggests that soccer  
22 tends to select for boys who advanced in maturity status based; the selection bias emerges at about  
23 12 – 13 years, although there is variation with method of maturity assessment (Malina, 2011, Malina  
24 et al., 2013). In contrast, estimated mean age at PHV, an indicator of maturity timing, in the present  
25 sample of soccer players ( $14.2 \pm 0.9$  years) was in the range of mean ages at PHV noted in  
26 longitudinal studies (Malina et al., 2004). The corresponding mean age at PHV in the longitudinal  
27 records for the original sample of 28 players was slightly earlier,  $14.0 \pm 0.9$  years.

28 Estimated age at PHV among 33 Belgian youth soccer players,  $13.8 \pm 0.8$  years (Philippaerts  
29 et al., 2006), was slightly earlier than the present study, but was also in the range of average ages at  
30 PHV. Of relevance, however, 76 Belgian youth players were tracked annually over four or five years  
31 beginning at ages ranging from 10.4 to 13.7 years, but the growth curves were successfully modelled  
32 with non-smoothed polynomials in only 33 players (43%); at initial observation, chronological and  
33 skeletal ages in this sample approximated each other,  $12.1 \pm 0.7$  and  $12.4 \pm 1.3$  years, respectively. In  
34 contrast, the majority of players whose height records could not be successfully modelled comprised  
35 two groups: (1) 25 players had skeletal ages in advance of chronological ages at initial observation,  
36 CA =  $12.6 \pm 0.5$  and skeletal age =  $13.5 \pm 1.2$  years, and were likely early maturing; and (2) 18 players  
37 has skeletal ages somewhat delayed relative to chronological ages at initial observation, CA =  $11.6$   
38  $\pm 0.8$  and skeletal age =  $11.1 \pm 1.1$  years, and were likely late maturing (Philippaerts et al., 2006).

39 Players who experienced an earlier age at PHV were under-represented in the present study  
40 and also in the sample of Belgian youth players compared to the general population. An indicator of  
41 skeletal maturity status at 11.0 – 12.0 years was not available for the current sample. However,  
42 height at 13.0 years of age expressed as a percentage of predicted adult height was  $87.7 \pm 2.1$  % and  
43 as a percentage of observed young adult height at 18.0 years was  $88.6 \pm 2.2$ % (Table 1Table 1). Both

1 percentages were similar to the percentage of estimated adult height without skeletal age attained  
2 by boys in the Fels Longitudinal Study at 13.0 years,  $88.7 \pm 1.8\%$  (Roche et al., 1983) and to the  
3 percentage of adult height attained by boys in the Berkeley Longitudinal Study at 13.0 years,  $87.3 \pm$   
4  $3.0\%$  (Bayer and Bailey, 1959). The preceding thus suggests that the sample of players in the present  
5 study approximated average maturity status based on percentage of predicted adult height attained  
6 as the time of observation.

7 Relative to the proposed band of 85% – 96% of adult height as reflecting the window of PHV  
8 (Sanders et al., 2017), 21 of 23 players had percentages of predicted adult height at 13.0 years of age  
9 that correctly identified them as being in the window of PHV; the range of percentages, however,  
10 was somewhat narrow, 84.2% to 92.0% (Table 1). This would suggest that the percentage of  
11 predicted adult height attained at 13.0 years of age was a comparatively more accurate predictor of  
12 age at PHV.

13 Age, height and weight at SITAR derived age PHV were estimated from the longitudinal  
14 records for each participant and were used along with mid-parent height to predict adult height at  
15 this time (Khamis and Roche, 1994). Height at PHV was then expressed as a percentage of predicted  
16 adult height attained at PHV. Accordingly, the 23 players attained PHV at  $88.9 \pm 3.1\%$  of predicted  
17 adult height (range 81.1% – 93.9%). When height at PHV was expressed relative to young adult  
18 height at 18.0 years, the 23 participants attained PHV at  $91.2 \pm 2.3\%$  (range 84.9% – 95.7%). Both  
19 estimates were similar to those for boys observed by Sanders et al. (2017),  $90.0 \pm 2.1\%$  in the Brush  
20 Foundation (range 85.6% - 93.8%) and  $90.2 \pm 4.0\%$  in the Berkeley (75.3% – 94.8%) longitudinal  
21 studies. Note, however, estimated age at PHV in the present study ( $14.2 \pm 0.9$  years) was later than  
22 estimated for boys in the Brush Foundation and Berkeley studies,  $13.0 \pm 0.7$  years and  $13.4 \pm 1.4$   
23 years, respectively.

24 Predicted age at PHV is used by many English professional soccer clubs to classify players as  
25 early, on time or late maturing (Cumming et al., 2017b). Results of the present study highlight the  
26 need for caution when using maturity offset *per se* as a predictor of age at PHV and maturity timing  
27 for players. All predictions have associated errors and application to individuals, specifically select  
28 samples of adolescent athletes, requires caution. Inter-individual differences in the timing and  
29 tempo of the growth spurt need to be considered.

30 The contrast of maturity status and maturity timing (age at PHV) should be emphasised; the  
31 concepts are not equivalent. The former indicates the state of skeletal or sexual maturity, or the  
32 percentage of predicted adult height attained at the time of observation. The latter indicates the age  
33 (time) when a specific maturity event occurs, in the present study, age at PHV. It is thus possible that  
34 some youth may be selected due to their advanced maturity status, whereas equally talented youth  
35 average or delayed in biological maturity status relative to their age peers may not be selected. This  
36 may be more apparent in sports such as soccer where height, mass, velocity, power and strength are  
37 viewed as advantageous (Meylan et al., 2010). Indeed, youth soccer players tend to be, on average,  
38 advanced in sexual maturity status compared to non-athletes of the same age (Malina et al., 2010),  
39 while skeletal maturity status based on three commonly used methods of assessment, the Greulich-  
40 Pyle, Tanner-Whitehouse 2 radius-ulna-short bone (TW2 RUS) and Fels methods of skeletal age  
41 assessment (Malina et al., 2004) were consistent in showing advanced maturity status among soccer  
42 players from several countries (Malina, 2011, Malina et al., 2018). Note, however, observations of  
43 soccer players using the modified TW3 RUS method did not indicate advanced skeletal ages among  
44 youth soccer players 11.0 – 15.0 years; rather, skeletal ages with the TW3 RUS methods were, on

1 average, one year lower than corresponding skeletal ages with the TW2 RUS method at these ages  
2 (Malina et al., 2018).

3 A limitation of the present study was the small number of early maturing players based on  
4 SITAR derived ages at PHV, which likely skewed the results; as such, the sample may not be  
5 representative of male youth soccer players in general. Unfortunately, longitudinal data spanning 9  
6 years of age through adolescence are lacking for soccer players. Of potential relevance, the  
7 estimated age at PHV of youth soccer players based on the Preece-Baines model 1 applied to age  
8 group-specific grand means of heights spanning 9 through 18 years in studies reported between  
9 2000 and 2015 was 12.9 years (Malina, 2017), and was consistent with the sexual and skeletal  
10 maturity data for youth soccer players (Malina et al., 2010).

11 Further development of these protocols should consider the international and ethnically  
12 diverse makeup of soccer in general and now of elite soccer academies. The maturity offset  
13 prediction equation was established on samples of European ancestry in Canada and Belgium  
14 (Mirwald et al., 2002). Similarly, the Khamis-Roche method for the prediction of adult height was  
15 based on youth of European ancestry in the Fels Longitudinal Study (Roche et al., 1983). Ethnic  
16 variation in body proportions, specifically evident in the sitting height / standing height ratio and by  
17 inference in leg length merits attention (Malina et al., 1987, Martorell et al., 1988) and implies a  
18 need for care when applying the prediction protocol to other ethnic groups (Malina, 2009). In the  
19 present study, the non-European participants were taller and displayed a lower sitting  
20 height / height ratio than the European participants. Therefore, the evaluation of players of non-  
21 Caucasian ethnicity may need to be investigated. Considerations should also be given to the findings  
22 of Malina (2012) which indicate that in the half-century between the Berkeley and Fels longitudinal  
23 studies, there appears to have been an acceleration in the maturational process. Optimization  
24 against these two factors could improve predictions of timing of PHV.

25 Predicted maturity offset and in turn age at PHV, and the window of PHV based on  
26 percentage of predicted adult height in the present study were based on measurements taken at 13  
27 years of age. Predicted age at PHV ( $15.1 \pm 0.5$  years) was later than observed age at PHV ( $14.2 \pm 0.9$   
28 years) in the 23 soccer players; the standard deviation for the former was considerably less than that  
29 of observed age at PHV. Generic age at PHV and predicted age at PHV correctly predicted observed  
30 age at PHV for 14 participants (61%), while the percentage of adult height window correctly  
31 predicted 22 participants (96%). Generation of a specific age window based on predicted maturity  
32 offset did not improve estimation of PHV compared to the generic age method, while the  
33 percentage of predicted adult height window of PHV showed improvement in accuracy.

34 The results suggest the potential utility of the percentage of height window for PHV. While  
35 the percentage of predicted adult height performed statistically better, the Khamis-Roche equation  
36 requires the most information such that the improvement in prediction accuracy may be offset  
37 against input data reliability and potential calculation complexity. Future studies could consider  
38 improvement of existing methods in order to further constrict the age at PHV window or to consider  
39 height at PHV as an alternative for scenarios where less information is available (e.g. extrapolation  
40 from Office of National Statistics data), as the trade-off between calculation complexity and accuracy  
41 of the results must be considered.

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#### **Declaration of Interest**

The authors have no conflicts of interest.

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**Table 1: Characteristics of individual players: observed and predicted estimates (at 13.0 years).**

Participant	Observed (SITAR) age at PHV (years)	Maturity classification*	Predicted age at PHV (years) at 13 years	Predicted minus observed age at PHV (years)	Attained height at 13.0 years as a % of observed young adult height	Attained height at 13.0 years as a % of predicted adult height	% of predicted minus % of observed young adult height (cm)	Window % of Predicted Adult Height expressed as an age window
1	14.18	On-time	14.84	0.66	84.6	87.4	2.8	13.0 – 15.2
2	14.29	On-time	14.96	0.67	85.9	87.0	1.1	12.9 – 16.0
3	15.16	Late	15.07	-0.09	84.0	87.5	3.5	12.6 – 15.5
4	13.90	On-time	14.59	0.69	87.6	88.4	0.8	12.6 – 15.4
5	14.25	On-time	15.14	0.89	85.5	89.1	3.6	12.4 – 15.5
6	12.73	Early	14.31	1.58	92.2	92.0	-0.2	12.0 – 17.3
7	12.79	Early	15.29	2.50	89.3	88.4	-0.9	13.2 – 18.1
8	14.60	On-time	15.94	1.34	88.4	84.4	-4.0	14.0 – 17.3
9	12.95	On-time	14.92	1.97	89.6	84.2	-5.4	12.8 – 18.3
10	15.47	Late	16.02	0.55	88.6	85.6	-3.0	13.4 – 16.1
11	14.46	On-time	15.03	0.57	89.7	88.1	-1.6	13.2 – 15.7
12	15.09	Late	15.10	0.01	91.1	87.3	-3.8	13.2 – 15.9
13	15.49	Late	15.62	0.13	90.1	85.1	-5.0	14.9 – 18.3
14	14.84	Late	15.26	0.42	89.8	88.1	-1.7	13.0 – 16.8
15	15.03	Late	15.23	0.20	89.7	89.4	-0.3	13.0 – 15.7
16	13.73	On-time	15.05	1.32	87.0	88.2	1.2	13.1 – 16.0

17	13.87	On-time	15.53	1.66	89.2	86.7	-2.5	13.1 – 17.1
18	14.07	On-time	15.09	1.02	89.9	88.1	-1.8	12.4 – 16.6
19	14.23	On-time	14.80	0.57	89.0	87.7	-1.3	13.0 – 16.2
20	14.54	On-time	15.10	0.56	88.2	85.9	-2.3	13.4 – 17.0
21	13.68	On-time	14.80	1.12	90.1	90.6	0.5	12.5 – 15.0
22	12.59	Early	14.01	1.42	92.5	91.9	-0.6	12.1 – 16.6
23	14.73	On-time	15.37	0.64	86.2	86.9	0.7	13.7 – 16.3
Mean	14.20		15.09	0.89	88.6	87.7	-0.9	
± SD	0.87		0.45	0.65	2.2	2.1	2.5	

\*Participants were classified as early maturing if their age at PHV was observed more than one standard deviation (1.0 years) before the mean age of PHV in European boys (13.8 years) and classified as late if they were more than one standard deviation after the mean. Otherwise, they were classified as on-time.

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**Table 2. Descriptive statistics for player characteristics by competitive age groups through the 2013 – 2017 seasons.**

Variable	U13 (n=20)	U14 (n = 24)	U15 (n = 23)	U16 (n = 23)	U17 (n = 16)
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Chronological Age (years)	12.6 ± 0.3	13.5 ± 0.3	14.5 ± 0.3	15.5 ± 0.3	16.5 ± 0.3
Maturity offset (years)	-2.3 ± 0.4	-1.6 ± 0.6	-0.6 ± 0.7	0.4 ± 0.7	1.8 ± 0.4
Predicted age at PHV	14.8 ± 0.4	15.1 ± 0.5	15.1 ± 0.6	15.0 ± 0.6	14.4 ± 0.4
Predicted age minus observed age at PHV	0.9 ± 0.6	0.9 ± 0.6	0.8 ± 0.6	0.6 ± 0.7	-0.3 ± 0.6
Current height (cm)	162.2 ± 7.6	167.8 ± 8.1	175.5 ± 7.0	178.8 ± 4.6	179.2 ± 4.2
Predicted adult height (cm)	190.2 ± 4.2	188.4 ± 4.5	187.1 ± 4.7	186.2 ± 4.7	188.5 ± 2.4
Height as a percentage of predicted adult height (%) <sup>*</sup>	83.4 ± 2.6	86.1 ± 2.5	89.9 ± 2.4	93.5 ± 2.2	96.9 ± 1.2
Height as a percentage of observed young adult height at 18.0 years (%)	82.6 ± 1.9	85.8 ± 2.5	89.9 ± 2.5	93.3 ± 2.1	96.6 ± 1.1

<sup>\*</sup>Predicted adult height was calculated at 13.0 years by Khamis-Roche (1994).

**Table 3: Concordance of predicted and observed classifications of participants based on predicted age at PHV at 13.0 years and percentage of predicted adult height at 13.0 years relative to classifications based, respectively, on observed ages at PHV (SITAR) and on height at PHV (SITAR) expressed as a percentage of young adult height. Values in brackets indicate the number of correct predictions.**

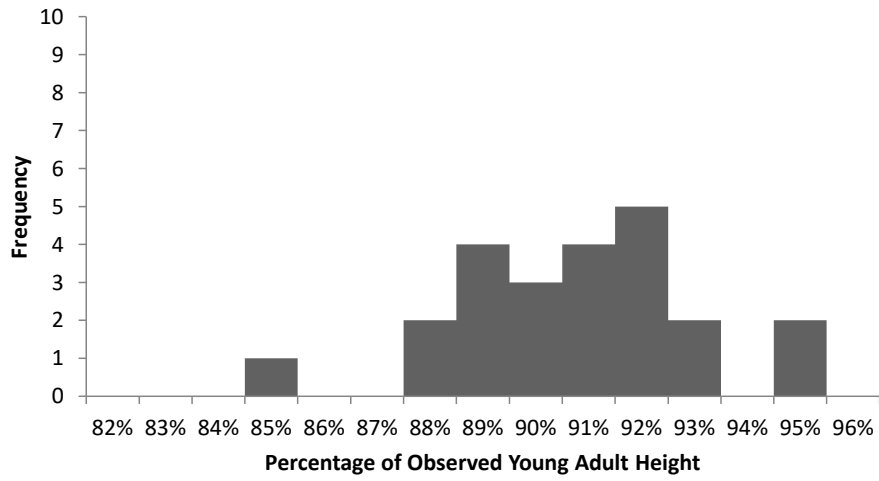
Method	Yes	No	$\kappa$
Age at PHV between 12.8 – 14.8 years:			
Predicted ages at PHV	0	23	
Observed ages at PHV	8	15	
Concordance between prediction and observation for age at PHV	0	15	0.65
Percentage of adult height 85 – 96%			
As % predicted adult height at 13.0 years	21	2	
Height at PHV as % young adult height	21	2	
Concordance between prediction and observation for height at PHV	19	0	0.83

**Table 4: Performance of each method for estimating window of age at PHV based on observed age at PHV (SITAR) and results of the chi-squared analyses.**

Method	Observed ages at PHV within the prediction window defined by each method	$\chi^2$
Generic Age at PHV	14	1.09
Predicted Age at PHV	14	1.09
Window % of Predicted Adult Height expressed as an age window	22	*19.17

\* $p < 0.01$

**Figure 1: Frequency of observed heights at PHV expressed as a percentage of observed young adult heights at 18.0 years.**





**Figure 2: Frequency of observed heights at PHV expressed as a percentage of predicted adult heights at 13.0 years.**

