Biology of Sport

Original paper

AGES AT PEAK HEIGHT VELOCITY IN MALE SOCCER PLAYERS 11-16 YEARS: Relationships with Skeletal Age and Comparisons among Longitudinal Studies

Keywords
Adolescent spurt, Youth athletes, Maturity timing, Skeletal age, Talent

Abstract

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The study compared two estimates of ages at take-off (TO) and at peak height velocity (PHV) n a longitudinal sample of male soccer players, and evaluated maturity status based upon ages at PHV and skeletal age (SA). It also compared estimated ages at PHV in 13 longitudinal samples of soccer players.

Material and methods
Heights of 58 soccer players of European ancestry followed longitudinally across five seasons (11-16 years) were modeled with Superimposition by Translation and Rotation (SITAR) and Functional Principal Component Analysis (FPCA) to estimate ages at TO and PHV. SAs at observations 1, 3 and 5 were assessed with the Fels method. Ages at PHV in 13 longitudinal samples of soccer players (Europe 7, Japan 6) were evaluated with meta-analysis.

Results
The SITAR and FPCA estimates for ages at TO were, respectively, 11.2±0.8 and 11.0±0.8 years, while corresponding estimates for age at PHV were, respectively, 13.62±0.90 and 13.66±0.88 years. An earlier age at PHV was associated with advanced skeletal maturity status. The systematic analysis indicated a north (later) - south (earlier) gradient in ages at PHV among players in Europe, which were later than ages at PHV among players in Japan.

Conclusions
In summary, ages at TO and PHV were similar with SITAR and FPCA, and ages at PHV were most strongly correlated with SA at ~14 years. Ages at PHV showed a north-south geographic gradient in European studies, and were later compared to Japanese studies.

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Running title:

Age at PHV and Skeletal Age

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INTRODUCTION

Acceleration in rate of growth in height in late childhood/early adolescence marks the onset or take-off (TO) of the adolescent growth spurt. The rate of growth accelerates until it reaches a peak (peak height velocity, PHV) and then decelerates until growth in height ceases in late adolescence or young adulthood. Ages at TO and at PHV are estimated from longitudinal height records. Parameters of the adolescent spurt in earlier studies were based on graphic analysis of heights attained at a given CA and estimated velocities of growth based on increments between measurements. Mathematical modeling of longitudinal height records for individuals facilitated estimation of the parameters. Most models provide estimates of age at PHV (years), PHV (cm/year) and height at PHV (cm), while some provide estimates of age, velocity of growth and height at TO, and of adult height. The procedures provide a convenient means for comparing individual and/or group differences in parameters of the adolescent spurt in height [1-3].

Ages at PHV derived from longitudinal growth records of individual youth should not be confused with estimates based on predicted maturity offset defined as the time before PHV, and predicted age at PHV estimated as CA minus predicted maturity offset [4-5]. Although predicted maturity offset and age at PHV are increasingly used in studies of youth athletes, the estimates are not equivalent with those based on longitudinal observations [6-10].

Ages at PHV for youth athletes based on longitudinal data spanning adolescence are not extensive [11, 12]. This is in part a function of difficulties inherent in longitudinal studies *per se*, and the selectivity of sport, differential persistence and cessation of participation in a sport (drop out, injury, motivation, changing interests), player changes in teams or clubs, among other considerations. Nevertheless, coaches and trainers are increasingly interested in monitoring growth rates in height and weight of youth players over relatively short intervals in an effort to individualize training and to reduce the risk of injury during the adolescent growth spurt [13, 14]. In this context, further information on variation in the timing and intensity of growth at TO and PHV among youth athletes is important.

The purposes of this study are threefold: first, to compare two methods for estimating parameters of the adolescent growth spurt in a longitudinal sample of male youth soccer players 11-16 years; second, to evaluate maturity classifications based on age at PHV, an indicator of maturity timing, and on SA, an indicator of maturity status at the time of observation; and third, to systematically compare estimated ages at PHV in longitudinal samples of soccer players.

MATERIAL AND METHODS

Participants

Data for the present study were part of the [redacted], which followed the guidelines established by the *Declaration of Helsinki* [15]. Formal approval was obtained from the [redacted] and included agreements with the Presidents of the respective soccer clubs. Written consent was obtained from parents or legal guardians of the players, and players were informed that participation was voluntary and that they could withdraw from the study at any time.

The baseline sample included 87 U13 players (11-12 years) from five clubs in the [redacted]; the players were classified as *infantiles* in the [redacted]. All players except one were of European ancestry. At baseline, the sample had 1-6 years of experience in soccer (median 3 years), and participated in 3-5 training sessions (~90 minutes) and one game per week, usually on Saturday.

Heights and weights, among other anthropometric dimensions, were measured within a two week interval in December at baseline; players who persisted at the respective clubs were subsequently measured within the same two week interval in December over the next five seasons. All measurements were taken by a single observer (MJC) at the University of Coimbra. Heights, with shoes removed, were measured to the nearest 0.1 cm using a stadiometer (Harpenden 98.603, Holtain Ltd, Croswell, UK). Weight was measured to the neared 0.1 kg using a SECA scale (model 770, Hanover, MD, US). Intra-observer technical errors of measurement were 0.27 cm for height and 0.47 kg for weight. CA at each observation was calculated as the difference between date of birth and date of a hand-wrist radiograph (see below) for observations one, three and five, and between date of birth and date of measurement for observations two and four.

Over the five years, 59 players had four or five annual height measurements. The longitudinal sample did not differ significantly from their 28 teammates at baseline: respectively, CA, 11.9±0.5 and 11.7±0.5 years; SA, 12.0±1.4 and 11.8±1.6 years; height, 144.8±6.9 and 144.3±6.5 cm; and weight, 37.6±6.0 and 38.8±7.0 kg; the distribution of players by pubic hair status also did not significantly differ.

Parameters of the Adolescent Spurt

The longitudinal height records of 58 players of European ancestry were successfully modeled with two methods to estimate parameters of the adolescent spurt: Superimposition by Translation and Rotation (SITAR) and Functional Principal Component Analysis (FPCA). The heights of one player of non-European ancestry limited to four observations were not successfully modeled.

The SITAR procedure [16, 17] available in the R package *sitar* 18] was used. The model fits the raw data for all players with a curve (defined as a B-spline), superposes the curves of all cases, averages the curves and then back-projects the average curve into the original data as a growth model through uniform transformations: translation and rotation. A total of 269 measurements were available for the 58 players. Visual inspection of the model based on running plots with the raw data showed that the model fit the data very well. The mean residual was 0.0 cm by definition; the standard deviation of the residuals was 0.47 cm and the mean absolute value of the residuals was 0.36 cm.

The FPCA growth model [19] is based on a combination of general Functional Data Analysis (FDA) and FCPA [20, 21]. The complete postnatal growth curves of individual boys in the Brno Growth Study were the training set, which was fit by the B-spline curves of the raw data for all soccer players. The splines were modeled with the FPCA procedure; 12 Principal Components (6 for phase and 6 for amplitude of the growth curves) were then used as a generative model to fit the newly analyzed data based on the Levenberg–Marquardt optimization algorithm. Details of the specific calculations and functions of the model are available in the R package *growthfd* [19, 22]. The mean of the 269 model residuals was 0.04 cm and the standard deviation of the residuals was 0.44 cm; the mean absolute value of the residuals was 0.33 cm.

Both methods provided estimates of age, velocity of growth and height at TO and at PHV for each player. Descriptive statistics for each variable were calculated. Each player was also classified as late (delayed), on time (average) or early (advanced) maturing based on estimated ages at PHV with the SITAR and FCPA models. A band of plus/minus 1.0 year of the respective mean ages at PHV for the total sample defined on time or average maturity status. An age at PHV greater than +1.0 year of the respective means indicated late maturity status, while an age at PHV less than –1.0 year of the respective means indicated early maturity status. A band of plus/minus one year was used as standard deviations for ages at PHV generally approximate about 1 year; the band also reflects variation in ages at PHV *per se* and variation associated with the different methods of estimation [6].

Skeletal Age

Posterior-anterior radiographs of the left hand-wrist of players were taken at observations one, three and five. The Fels method [23] method was used to estimate skeletal age (SA), an indicator of maturity status at the time of observation. The method utilizes specific criteria for the radius, ulna, carpals, adductor sesamoid of the first metacarpal and the first, third and fifth metacarpals and phalanges, and ratios of linear measurements of epiphyseal and metaphyseal widths the first, third and fifth metacarpals and phalanges. The ratings are entered into the Felshw 1.0 Software program to derive an SA and its standard error. The mean difference between independent assessments of SAs of 20 radiographs by two individuals and the inter-observer technical error of measurement were, respectively, 0.03±0.04 years and 0.12 years; the inter-observer intra-class correlation was 0.99. Standard errors for SA assessments at observations one, three and five ranged, respectively, from 0.27 to 0.30 year (median 0.29), from 0.29 to 0.49 year (median 0.35), and from 0.30 to 0.48 (median 0.37) year.

Based on SA and CA at each observations, the skeletal maturity status of each player was classified as average (on time), SA within ± 1.0 year of CA; delayed (late), SA younger than CA >1.0 year; or advanced (early), SA older than CA by >1.0year. The ±1.0 year band approximates standard deviations for SAs within specific CA groups, allows for error associated with assessments, and provides for broad range of youth who are classified as average in maturity status [24]. Four players were skeletally mature at observation five and an SA is not assigned. At observation five, 42 players had radiographs, but three did not have a measure of height and weight; of the 40 players with a measure of height and weight, one player did not have a radiograph.

Statistics

Descriptive statistics (means and standard deviations) at each observation for the longitudinal sample were calculated for CA, height and weight, and for SA and SA minus CA at the three observations. Corresponding statistics were calculated for estimates ages at TO and PHV (years), velocities of growth at TO and at PHV (cm/year), and heights at TO and at PHV (cm) based on the SITAR and FPCA methods. The differences between parameters of the growth spurt with the two methods were evaluated with paired sample t-tests and tests of equivalence using 90% equivalence boundaries representative of a moderate effect (±0.5 of Cohen's d). Correlations between parameters of the growth spurt and the difference of SA minus CA at observations one and three with ages at PHV were also calculated, and the concordance of maturity status classifications based on the two estimates of age at PHV and on skeletal maturity status at observations one, three and five were evaluated with chi square and unweighted Cohen's Kappa coefficients.

Systematic Comparisons among Samples of Soccer Players

Ages at PHV based on a variety of methods for 12 longitudinal samples of soccer players from Europe and Japan were compiled from the literature: six samples from Europe: Wales [25], Denmark [26], Belgium [27], Spain [28-30], England [31], and the Netherlands [32], and six samples from central Japan [33-37]. Several studies including the present study reported estimated ages at PHV based on two or three methods, while three studies provided estimates for subsamples of players from the same club. Excluding estimates based on graphic and incremental methods [25, 31], and the FPCA method (present study), and limiting the estimate for Spanish players to the one based on the largest sample [30], ages at PHV in 13 samples of soccer players from Europe and Japan were subjected to a meta-analysis using methods available in the R-Package *metaphor*[38]. Sample size, mean and standard deviation for age at APHV in each of the 13 samples were used as estimates of effect size. The Random Effect Model was used because it can be reasonably assumed that the population with the same grand mean age at PHV was not sampled in the different studies of soccer players (i.e., the populations actually differed in ages at PHV). The restricted maximum likelihood method (REML estimator) was used to estimate the between-sample variance (τ^2, tau-squared).

RESULTS

Descriptive statistics for CA, height and weight at each observation and for SA at observations 1, 3 and 5 in the longitudinal sample are summarized in Table 1. Corresponding statistics for parameters of TO and PHV are summarized in Table 2.

[Table 1 about here]

[Table 2 about here]

Parameters of the Adolescent Growth Spurt

Estimated mean ages based on SITAR and FPCA are statistically different and not equivalent with each other for age at TO, 11.2±0.8 years and 11.0±0.8 years, respectively ($t=2.73$, $p<0.01$; Cohen's $d=0.36$), and for age at PHV, 13.6±0.9 years and 13.7±0.9 years, respectively ($t=2.60$, $p=0.01$; Cohen's $d=0.34$). Mean estimated heights at TO, 141.1±5.7 cm (SITAR) and 140.2±6.0 cm (FPCA), differ significantly ($t=2.06$, $p<0.05$) but are equivalent (Cohen's $d=0.27$); mean estimated heights at PHV, 157.9±5.6 cm (FPCA) and 157.1±5.7 cm (SITAR), also differ significantly but are not equivalent ($t=3.80$, $p<0.01$, Cohen's $d=0.50$). Velocities of growth in height at TO, 4.6±0.5 cm/year (SITAR) and 4.6±0.4 cm/year (FPCA), do not differ statistically ($t=0.56$, $p>0.05$) and are equivalent (Cohen's $d=.07$). Velocities of growth in height at PHV, 9.7±1.3 cm/year, (SITAR) and 9.8±1.3 cm/year (FPCA), also do not differ statistically between methods and can be considered equivalent (Cohen's $d=0.11$).

Although the differences between estimated ages and heights at TO and at PHV with the SITAR and FCPA methods are statistically significant, they are quite small. The estimated ages at PHV and heights at PHV with the two methods are highly correlated, 0.99 and 0.98 (p<0.001), respectively, while the correlation for estimated PHVs with the two methods is slightly lower, 0.77 (p<0.001). Estimated ages and heights at TO with the two methods are correlated to a lesser extent, 0.62 and 0.84 (p<0.001), while the correlation for estimate velocity of growth at TO with the two methods is lower, 0.48 (p<0.001).

The cross-tabulation of maturity classifications based on each age at PHV is summarized in Table 3. Overall, 90% of the players are classified as having the same maturity status based on ages at PHV with the SITAR and FPCA models. Four of the six players who are misclassified have estimated ages at PHV close to the plus/minus one year cut-offs, and the differences in ages at PHV with the two methods (SITAR minus FPCA) are negligible, 0.08, 0.07, 0.05 and 0.08 year. The differences between ages at PHV for the other two players are somewhat larger, 0.35 and -0.35 year.

[Table 3 about here]

Maturity Based on SA and Age at PHV

Spearman correlations (rho) between maturity classifications based on the difference of SA minus CA and on age at PHV are moderate in early adolescence (~12 years, observation one), -0.53 (SITAR, p<0.01) and -0.54 (FPCA, p<0.001), but are higher in mid-adolescence (~14 years, observation three), -0.76 (SITAR, p<0.001) and -0.77 (FPCA, p<0.001). Negative correlations indicate an earlier age at PHV among players with a positive difference of SA minus CA, i.e., an SA in advance of CA.

Maturity classifications (late, average or early) based on ages at PHV with SITAR and FPCA and on the difference of SA minus CA at each observation are summarized in Table 4. Classifications at observations one and three, respectively, are concordant in 59% and 71% of the players for SITAR ages at PHV and in 62% and 74% of the players for FPCA ages at PHV. The Kappa coefficients are relatively low at observation one and moderate at observation three. Allowing for small numbers at observation five (~16 years), maturity classifications are concordant in 57% (SITAR) and 60% (FPCA) of the players, and the Kappa coefficient is moderate. Two of the four skeletally mature players at observation five are classified as on time and two as early maturing based on the ages at PHV. Mean ages at PHV for the four skeletally mature players are similar with SITAR (12.57±0.38 years) and FPCA (12.65±0.37 years), and the respective means are earlier than mean ages at PHV among early maturing CA peers who are not skeletally mature, SITAR (12.90±0.65 years) and FPCA (12.94±0.66 years), respectively.

[Table 4 about here]

Ages at PHV in Studies of Soccer Players

Ages at PHV reported in the 13 studies of soccer players are summarized in Table 5. Mean ages based on different methods of estimation within the same samples do not differ, while the mean ages at PHV for Portuguese soccer players estimated with SITAR and FPCA are within the range of mean ages at PHV in the six longitudinal samples of soccer players in Europe, 12.9 to 14.2 years. The earliest estimated mean age at PHV, 12.9 years (standard deviation not reported), is for a sample of 33 Spanish players 10+ years measured on four to six occasions [28]. Two estimates for larger samples from the same soccer club (n=110 and 124) and with 10 or more observations beginning at 10-11 years are later, 13.4±0.8 years [29] and 13.5±0.9 years [30]. The analysis of the small sample used a two level polynomial, while the later analyses used the SITAR model. The differences likely reflect both sampling and methodological variation; the more recent estimates are also based on a larger number of height measurements for each player.

[Table 5 about here]

The estimated mean ages at PHV for players from professional clubs in Europe are somewhat earlier than those for players from a school and local club.

With the exception of one subsample of club players in Spain [28], means ages at PHV for club soccer players in Europe tend to be later than estimates for players at a professional club in Japan, 12.6 to 12.9 years (Table 5). The latter, in turn, are earlier than estimates for school and recreational league players in Japan.

Results of the meta-analysis of ages at PHV in the 13 samples of soccer players from Europe and Japan indicate significant heterogeneity (Q [df, 12]) = 103.45, p <0.0001) while I^2 for the model of all studies is relatively high (93.3%), By inference, a systematic effect among samples is suggested. The effect of geographic location (Japan and Southern, Northern and Western Europe) as a moderator of age at PHV was then evaluated. The Mixed Effect Model indicates a statistically significant moderator effect (Q_M [df , 2] = 22.33, p <0.0001); ages at PHV differ significantly among the geographic groups (Figure 1). Age at PHV is latest for players from Northern and Western Europe, earlier for players from Southern Europe, and earliest for players from Japan. Heterogeneity among samples in Northern and Western Europe (professional and local clubs and schools combined) is not significant (Q [df, 4] = 5.46, p = 0.2433), while heterogeneity among the samples of professional clubs in Europe (Southern, Northern and Western Europe together) is significant (Q [df, 4] = 15.4260, p = 0.0039). By inference, geographic distribution appears to be a more significant factor than level of competition; note, however, sample sizes in Northern and Western Europe are relatively small which may have reduced the statistical significance of differences among samples.

[Figure 1 about here]

DISCUSSION

Differences in estimated mean ages at TO and PHV and estimated mean PHVs based on the SITAR and FPCA models in the sample of 58 Portuguese soccer players (Table 2), though statistically significant, were very small in practical terms. Estimated mean ages at TO (11.2 and 11.0 years) and at PHV (13.6 and 13.7 years) among the soccer players were also within the ranges of reported mean ages in longitudinal samples of European boys spanning the 1970s through the present: 10.4 to 11.8 years for 21 estimates of mean age at TO, and 13.0 to 14.5 years for 64 estimates of mean age at PHV. Mean PHVs among the soccer players (9.7 and 9.8 cm/year) were also within the range of estimates in the general population: 27 estimates ranged from 7.8 to 11.5 cm/year [6, the reference includes the citations for the studies reporting the respective means].

Estimated mean ages at PHV for the 58 Portuguese soccer players based on SITAR and FPCA were also within the range of mean ages at PHV estimated with different methods in six longitudinal samples of soccer players in Europe (Table 5). Though limited to a relatively small number of studies, results of the systematic analysis of ages at PHV in 13 samples of soccer players from Europe and Japan suggested earlier ages among players in Southern compared to Northern and Western Europe, while mean ages at PHV for Japanese club players, largely from Central Japan, tended to be earlier than corresponding ages in European players (Figure 1). The trend towards earlier ages at PHV among soccer players in Japan compared to players in Europe was consistent that with noted for ages at PHV in the general populations of youth in both regions [6].

The preceding discussion was largely focused on mean ages at PHV. Variation in ages at PHV *among individual players* also merits attention. Ages at PHV among players in five of the European clubs ranged from 11.8 to 15.9 years (Table 5) were within the range noted in several longitudinal samples of European boys, 11.3 to 17.3 years [6, 7, 10]. Of potential relevance, the range among soccer players may have been somewhat restricted by relatively the late CAs at initial observation and limited duration of several studies. Studies in Japan are unique in that they commonly use serial height records of players measured annually at their respective schools; beginning at 7 years of age, heights of school children in Japan are measured annually in April [33]. In several instances, school records were complemented by measurements taken at the leagues and soccer clubs.

Estimated ages at TO of the adolescent spurt among the Portuguese players spanned 8.6 to 13.0 years (Table 2) and were largely in the range of ages at TO in three longitudinal samples of European boys, 9.0 to 15.0 years [8, 39, 40]. Corresponding estimates are lacking for the other longitudinal samples of soccer players. Nevertheless, the range in estimated ages at TO in soccer players highlights the importance monitoring the growth status of players from an earlier age. The Growth and Maturation Screening Programme implemented by the English Premier League, for example, now measures the heights and weights of all registered academy players 9 years and older every three to four months [13]. Along with corresponding observations for fitness and an academy-wide injury audit, the data provide a potentially unique opportunity to better understand the impact of the adolescent spurt upon fitness and performance and also on the incidence and burden of injury. Note, however, taking height measurements at relatively close intervals requires attention to inter- and intra-examiner measurement variability, diurnal variation in measurements, and seasonal variation in growth [6]. Heights also should not be measured after a period of physical activity as in training programs and scrimmages.

Concordance of maturity classifications (late, average or early) based on ages at PHV (maturity timing) and on SA minus CA (maturity status at the time of observation) was modest at initial observation, 11.9±0.5 years, but was higher at the third observation, 13.9±0.5 years (Table 4). The observations were consistent with relationships among indicators of maturity timing close to the time of PHV among 111 boys in the Wrocław Growth Study [41]. Correlations between estimated ages at attaining SAs of 12.0 and 14.0 years and age at PHV were, respectively, 0.42 and 0.81. Correlations between the two estimates of age at PHV and the difference of SA minus CA in the 58 soccer players were similar at observations one (-0.54) and three (-0.77), i.e., advanced skeletal maturity status at 12 and 14 years was related with an earlier age at PHV, and the association was stronger closer to the time of PHV.

Inter-individual variation in estimated rates of growth in height (cm/year) at TO and at PHV in the longitudinal series of soccer players has implications for those working with youth athletes. Ranges for estimated rates of growth at PHV (Table 2) spanned 6.7 to 13.6 cm/year (SITAR) and 7.0 to 14.5 cm/year (FCPA). Based on monthly measurements of heights and weights of soccer players 11-19 years during the course of a season (September through April), estimated monthly increments of $\geq$0.6 cm/month in height and of $\geq$0.3 kg/m^2/month in the BMI, and an estimated monthly decline of $\geq$0.4 kg/m^2/month in the BMI were associated with an increased risk of injury [42]. Extending the monthly increments in height through a year, it was suggested that an estimated velocity of growth in height ≥7.2 cm/year was indicative that a player was within his growth spurt [14, 42]. The range of estimated PHVs in the sample of 58 soccer players (Table 2) suggests that some players with rates of growth <7.2 cm/year were in their growth spurts.

Epidemiological data suggest enhanced susceptibility to injury during the interval of the growth spurt, especially conditions associated with rapid growth, i.e., Osgood-Schlatter and Sever's disease [43. 44], and overuse [45]. Management of training load and use of developmentally appropriate training protocols (activities emphasizing core strength, balance, coordination, mobility, and limiting accelerations and decelerations) may serve to mitigate injury risk during this interval of rapid growth [46]. Some athletes may also experience temporary disruptions or regressions in motor performances during the interval of the growth spurt, commonly labeled as adolescent awkwardness [6]. Of potential relevance, recent evidence suggests that coach evaluations of match performances of youth soccer players tend to decline through the growth spurt, but return to pre-spurt levels at the cessation of the spurt [47]. By inference, it is essential that coaches and others working with youth athletes are aware of the details of growth and maturation during the interval of the adolescent spurt, specifically individual differences in timing and tempo, when evaluating youth athletes, for example, delaying decisions until after the growth spurt, reviewing game film/player performance metrics prior to the onset and during the spurt, and/or allowing a player to play down an age group while they adjust to changes associated with the adolescent spurt [48].

CONCLUSIONS

Mean ages at PHV based on two methods of estimation in the longitudinal sample of 58 Portuguese soccer players were 13.6±0.9 years and 13.7±0.9 years, and were within the range of observed means and standard deviations for ages at PHV in studies of the general population and of soccer players in Europe. Concordance of maturity classifications based on age at PHV and the difference of SA minus CA was moderate, but was strongest close the age at PHV (observation 3, about 14 years). Systematic analysis of ages at PHV in 13 longitudinal samples of European and Japanese soccer players suggested a geographic gradient: northern Europe > southern Europe > Japan. The gradient was consistent with that observed in the general population of adolescents in Europe and Japan.

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CONFLICT OF INTEREST:

The authors declare no conflict of interest.

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TABLES

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Table 3. Frequencies and cross-tabulations of maturity status classifications (late, on time, early)[1] based on ages at PHV with the SITAR and FPCA models, percentage agreement, Chi square (χ^2) and Cohen's Kappa (κ); means and standard deviations for ages at PHV in the respective maturity groups are also indicated.

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Table 5. Ages at PHV (years) and PHV (cm/year) in longitudinal samples of adolescent male soccer players in Europe (including the present study) and Japan.

FIGURES

Figure 1. Aggregation of ages of PHV (years) in samples of male soccer players based on meta-analysis, including the subgroup analysis. Q: Cochran's Q-statistic (weighted sum of squares), Q_M: Cochran's Q-statistic for subgroups, I^2: percentage of variability in effect sizes which is not due sampling error, τ^2: between-study variance in a given set of samples (years squared); plots: means and 95% CIs of individual studies; diamonds: width represents 95% CI for each model aggregated by subsample and for all studies (below).

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Table 1. Means (M) and standard deviations (SD) for chronological age (CA), skeletal age (SA), height and weight for the longitudinal sample by observation.

Obs	N	CA, yrs		SA, yrs		Height, cm		Weight, kg	
		M	SD	M	SD	M	SD	M	SD
1	58	11.9	0.5	12.0	1.4	144.9	6.9	37.6	6.0
2	58	12.9	0.5			151.7	7.9	42.3	7.3
3	58	13.9	0.5	14.2	1.1	159.2	7.7	48.7	8.4
4	55	14.9	0.5			165.5	6.7	54.9	7.9
5[a]	40	15.9	0.5			169.3	5.3	60.1	6.3
5[b]	35	15.8	0.5	16.3	1.1	169.2	5.4	59.7	6.2
5[c]	4	16.8	0.2			171.5	5.0	64.9	6.1

Obs (servations); CA (chronological age); SA (skeletal age); [a]Total sample of players with measures of height and weight at observation five; one player did not have a radiograph; [b]Not skeletally mature; [c]Skeletally mature

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Table 2. Estimated parameters for take-off (TO) and peak height velocity (PHV) of the adolescent spurt based on the SITAR and FPCA methods applied to the longitudinal height records of 58 soccer players and differences between the respective estimates (SITAR minus FPCA) with the two methods (M, mean; SD, standard deviation).

Parameters	SITAR			FPCA			SITAR - FPCA	
	M	SD	Range	M	SD	Range	M	SD
Age at TO, yrs	11.24	0.79	9.94-13.00	10.99	0.82	8.55-12.81	0.25	0.70
TO, cm/yr	4.62	0.52	3.37-6.06	4.58	0.36	3.85-5.67	0.03	0.47
Height at TO, cm	141.1	5.7	130.0-153.8	140.2	6.0	125.0-153.0	0.90	3.32
Age at PHV, yrs	13.62	0.90	11.92-15.59	13.66	0.88	11.90-15.49	-0.04	0.12
PHV, cm/yr	9.71	1.26	6.69-13.56	9.81	1.33	6.97-14.53	-0.10	0.87
Height at PHV, cm	157.1	5.7	145.9-169.7	157.9	5.6	147.7-170.1	-0.51	1.02

Table 3. Frequencies and cross-tabulations of maturity status classifications (late, on time, early)[1] based on ages at PHV with the SITAR and FPCA models, percentage agreement, Chi square (χ^2) and Cohen's Kappa (κ); means and standard deviations for ages at PHV in the respective maturity groups are also indicated.

Age at PHV: FPCA, yrs			**Age at PHV: SITAR**, yrs			
			Late	On time	Early	Total
			14.92±0.35	13.54±0.53	12.37±0.20	
Late	14.98±0.27		**8**	1	0	9
On Time	13.69±0.52		3	**36**	0	39
Early	12.36±0.26		0	2	**8**	10
		Total	11	39	8	58

Agreement 90% χ^2 = 77.29* κ = 0.79*

* (p<0.01); [1]On time (average) is an age at PHV within ±1.0 year of the mean age at PHV for the total sample of 58 players with SITAR (13.62±0.90 years); late is a PHV >14.56 years; early is a PHV <12.72 years; corresponding on time classification with FPCA is (13.66±0.88 years); late is a PHV >14.54 years; early is a PHV <12.78 years

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Table 4. Frequencies and cross-tabulations of maturity status classifications based on ages at PHV with the SITAR and FPCA models and on Fels skeletal ages (SA – CA) at observations 1, 3 and 5, percentage agreement, Chi square (χ^2) and Cohen's Kappa (κ); means and standard deviations for SA – CA differences in the respective maturity groups are also indicated.

Skeletal Maturity Groups	Skeletal Age[2]	Maturity Groups							
		Age at PHV SITAR[1]				Age at PHV FPCA[1]			
		Late	On time	Early	Total	Late	On time	Early	Total
Observation 1									
Late	(-1.98±0.98 yrs)	**3**	6	0	9	**3**	6	0	9
On Time	(-0.02±0.59 yrs)	6	**25**	2	33	4	**26**	3	33
Early	(1.76±0.62 yrs)	2	8	**6**	16	2	7	**7**	16
Total	(0.16±1.38 yrs)	11	39	8	58	9	39	10	58
		Agreement 59%, χ^2 =11.60**, κ = 0.25*				Agreement 62%, χ^2 =13.49**, κ = 0.31*			
Observation 3									
Late	(-1.48±0.33 yrs)	**5**	3	0	8	**4**	4	0	8
On Time	(0.18±0.46 yrs)	5	**29**	1	35	4	**30**	1	35
Early	(1.66±0.54 yrs)	1	7	**7**	15	1	5	**9**	15
Total	(0.33±1.07 yrs)	11	39	8	58	9	39	10	58
		Agreement 71%, χ^2 = 28.75*, κ = 0.45*				Agreement 74%, χ^2 =33.45**, κ = 0.51*			
Observation 5									
Late	(-1.76±0.38 yrs)	**5**	0	0	5	**3**	2	0	5
On Time	(0.00±0.72 yrs)	2	**14**	0	16	1	**15**	0	16
Early	(1.71±0.41 yrs)	0	12	**5**	17	0	10	**7**	17
Mature		0	2	2	4	0	2	2	4
Total	(0.53±1.33 yrs)	7	28	7	42	4	29	9	42
		Agreement 57%, χ^2 = 36.90*, κ = 0.45*				Agreement 60%, χ^2 = 27.17*, κ = 0.37*			

*(p<0.01); [1]See Table 3 for ages at PHV in the respective maturity groups; On time - SA within ±1.0 year of CA; late - SA behind CA by >1.0 year; early - SA advance of CA by > 1.0 year

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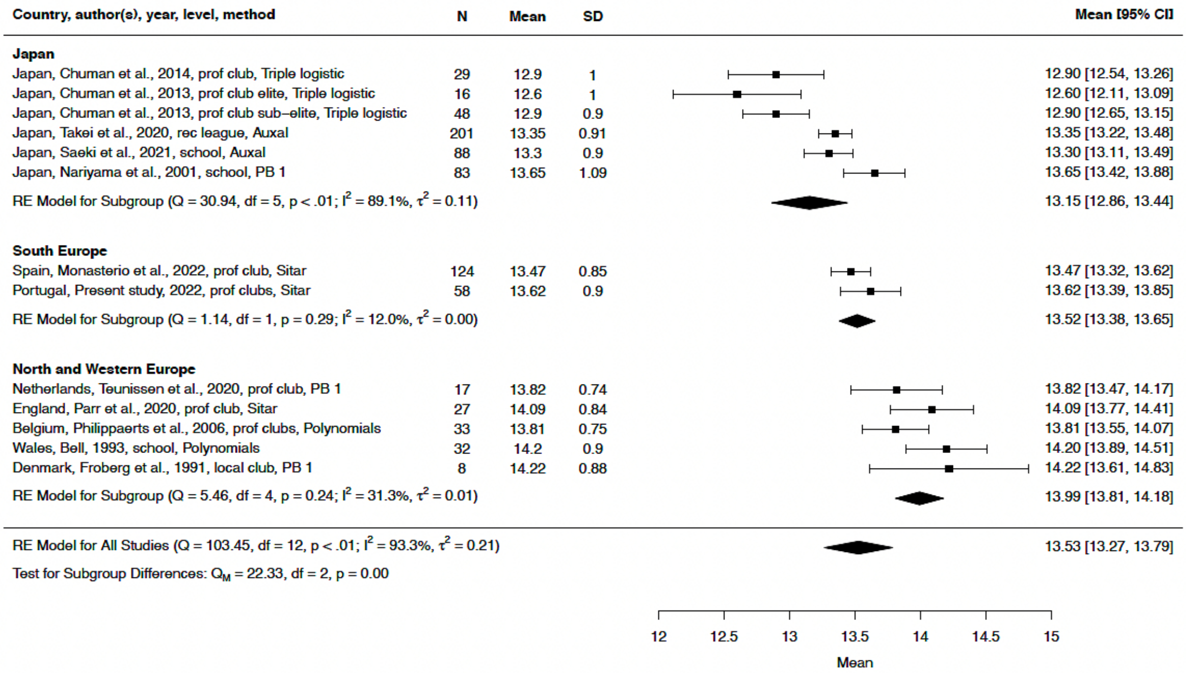
Table 5. Ages at PHV (years) and PHV (cm/year) in longitudinal samples of adolescent male soccer players in Europe (including the present study) and Japan.

			Competitive			APHV yrs			PHV cm/yr	
Country	Study	Method	Level	Observations (obs)	N	M	SD	Range, yrs	M	SD
EUROPE										
Portugal	Present study	Sitar	prof clubs	11-12/15-16 yrs, 4-5 annual obs, 2003-2008	58	13.6	0.9	11.9-15.6	9.7	1.3
		FPCA			58	13.7	0.9	11.9-15.5	9.8	1.3
Wales	Bell (1993)[25]	Graphic	school	12-15 yrs, 4 annual obs, 1981-1984	32	14.2	0.8		9.6	1.8
		Moving incr				14.1	0.8		9.3	1.5
		Polynomials				14.2	0.9		9.5	1.5
Denmark	Froberg et al. (1991)[26]	PB 1	local club	11-16 yrs, semi-annual obs over 6 yrs, 1980s	8	14.2	0.9	12.6-15.7		
Belgium	Philippaerts et al. (2006)[27]	Polynomials	prof clubs	10-13/14-17yrs, annual obs 1996-2000	33	13.8	0.8			
Spain (same club)	Carvalho et al. (2017)[28]	Polynomials	prof club	10-16 yrs, 4 obs 2009-2014	33	12.9		11.8-15.5*	8.1	
	Monasterio et a. (2021, 2022)[29,30]	Sitar	prof club	10-11 yrs-16-18 yrs, ≥10 obs, 2000-2020	110	13.4	0.8		9.9	1.8
					124	13.5	0.9		10.1	2.0
England	Parr et al. (2020)[31]	Sitar	prof club	5 seasons 12.4±0.6 yrs baseline, 17-20 obs, 2013-2017	27	14.1	0.8	12.6-15.5	9.8	
		Graphic			27	14.2	0.8			
Netherlands	Teunissen et al. (2020)[32]	PB 1	prof club	4 seasons 11.9±0.8 yrs baseline, 16-25 obs, 2008-2012	17	13.8	0.7	12.6-15.2		
JAPAN										
Fukui Prefecture	Nariyama et al. (2001)[33]	PB 1	school	school records, 1970-1987, 6-18 yrs	83	13.7	1.1		8.8	1.1
Saitama	Saeki et al. (2021)[34]	Auxal	school	school records 7-12 yrs + obs JHS	88	13.3	0.9			
Tokyo	Takei et al. (2020)[35]	Auxal	rec league	school records + 6 obs over 2 yrs 2011-2016	201	13.4	0.9			
Shizouka	Chuman et al. (2013)[36]	Triple logistic	prof club	school record: 7-12yrs, club obs at 13 yrs — sub-elite	48	12.9	0.9			
				elite	16	12.6	1.0			
Shizouka	Chuman et al. (2014)[37]	Triple logistic	prof club	school records, club 6 obs, 7-15 yrs, 2008-2010	29	12.9	1.0			

*(estimated 95% credible interval)



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Figures

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