Tanner-Whitehouse Skeletal Ages in Male Youth Soccer Players: TW2 or TW3?

Published version:

DOI:10.1007/s40279-017-0799-7

(Article begins on next page)

Tanner-Whitehouse Skeletal Ages in Youth Soccer Players: TW2 or TW3?

Robert M. Malina,[1] Manuel J. Coelho-e-Silva,[2] António J. Figueiredo,[2]

Renaat M. Philippaerts,[3] Norikazu Hirose,[4] Maria Eugenia Peña Reyes,[5] Andrea Benso,[6]

Roel Vaeyens,[7] Dieter Deprez,[7] Luiz F. Guglielmo,[8] Rojapon Buranarugsa[9]

[1]Department of Kinesiology and Health Education, University of Texas at Austin, USA

[2]CIDAF (uid/dtp/04213/2006), Faculty of Sport Science and Physical Education, University of Coimbra, Portugal

[3]Club Brugge KV, Brugge, Belgium

[4]Faculty of Sports Sciences, Waseda University, Saitama, Japan

[5]Instituto Nacional de Antropologia e Historia, Mexico, D.F., Mexico

[6]Endocrinology, Diabetology and Metabolic Unit, Department of Medical Sciences, University of Turin, Turin, Italy

[7]Department of Movement and Sport Sciences, Ghent University, Ghent, Belgium

[8]Human Performance Research Group, Center for Health and Sport Science, Santa Catarina State University (CEFID/UDESC), Florianópolis, Santa Catarina , Brazil

[9]Department of Physical Education, Faculty of Education, Khon Kaen University, Khon Kaen, Thailand,

Corresponding author:

Robert M. Malina
10735 FM 2668
Bay City, TX 77414 USA
rmalina@1skyconnect.net
979 240-3446

E-mail contacts for other authors:

Manuel J. Coelho-e-Silva, mjcesilva@hotmail.com

António J. Figueiredo, afigueiredo@fcdef.uc.pt

Renaat M. Philippaerts, renaat.philippaerts@telenet.be

Norikazu Hirose, toitsu_hirose@Waseda.jp

Maria Eugenia Peña Reyes, eugeniapere@prodigy.net.mx

Andrea Benso, andrea.benso@unito.it

Roel Vaeyens, roel.vaeyens@ugent.be

Dieter Deprez

Luiz F. Guglielmo, luizguilherme@cds.ufsc.br

Rojapon Buranarugsa, rojapon@hotmail.com

Abstract

Background. The Tanner-Whitehouse radius-ulna-short bone protocol (TW2 RUS SA) is a widely used indicator of maturity status. The scale for converting ratings to an SA has been revised (TW3 RUS SA) which may have implications for studies of youth athletes.

Objectives. To compare TW2 and TW3 RUS SAs in an international sample of youth soccer players and to compare distributions of players by maturity status defined by each SA

Methods. SA assessments with the TW RUS method were collated for 1831 soccer players 11-17 years from 8 countries. RUS scores were converted to TW2 and TW3 SAs using the appropriate tables. SAs were compared within chronological age (CA) groups. The difference of SA minus CA with each method was used to classify players as late, average or early maturing. Concordance of maturity classifications with TW2 and TW3 SAs was evaluated with Cohen's Kappa coefficients.

Results. For the same RUS score, SAs were systematically and substantially reduced with TW3 compared to TW2; mean differences ranged, on average, from -0.97 to -1.16 years. Kappa coefficients indicated fair concordance of maturity classifications based on TW2 and TW3 SAs.

Conclusion. TW3 SAs were systematically lower than corresponding TW2 SAs in youth soccer players. The differences between scales have major implications for the classification of players by maturity status, which is central to many talent development programs.

Key Words: maturation, bone age, talent development, secular change, youth athletes

Introduction

Skeletal age (SA) is a commonly used indicator of maturity status in clinical contexts [1-3] and in studies of growth *per se* [4-7], of growth and performance, and of youth athletes [8-10]. Three methods are commonly used to estimate SA: Greulich-Pyle [GP, 11], which was based on the earlier protocol of Todd [12], Tanner-Whitehouse [TW, 13-16], and Fels [17]. The methods are similar in principle: a hand-wrist radiograph of a youngster is matched to a set of criteria; however, criteria, procedures and reference samples for each method differ. The GP and Fels methods were developed on reasonably well-off American children in the state of Ohio, while the TW method was developed on a sample of healthy British children [10,18]. Modifications of the three methods have been developed, but are less widely used with youth athletes [7,18-21].

The TW method provides several estimates of SA and has been revised on two occasions. The original version provided an SA based on maturity indicators for 20 bones – the radius, ulna, 11 metacarpals and phalanges of the first, third and fifth digital rays, and 7 carpals excluding the pisiform [13]. The first revision, TW2 [15], did not modify criteria for maturity indicators and assigned scores, but provided for three SAs based, respectively, on the 20 bones (TW2 20 Bone SA), the 7 carpals (TW2 Carpal SA) and the radius, ulna and short bones (TW2 RUS SA). The second revision, TW3 [16,22], retained the RUS SA (TW3 RUS) and Carpal SA (TW3 Carpal), but eliminated the 20 Bone SA. The criteria for maturity indicators and assigned scores for each bone were not modified. Tables for converting the sum of maturity scores for the seven carpal bones to an SA were also not modified, while tables for converting the sum of the maturity scores for the radius, ulna and short bones (RUS maturity score) to an SA were modified with TW3. British children were the reference for the first two versions of the TW method and for TW3 Carpal SA, but reference values for

TW3 RUS SA were based on a composite of Belgian (Flemish), Italian, Spanish, Argentine, Japanese and “for the most part” American children and adolescents surveyed between 1969 and 1995 [16, p. 19]. The American sample, followed 1985-1995, was of European ancestry (White) and from a well-off community in the Houston region in the state of Texas [22].

Two modifications in the TW3 revision merit attention. First, TW3 RUS SAs were scaled downward beginning at about 10 years of age, and second, ages at attaining skeletal maturity (RUS score of 1000) were lowered from 18.2 to 16.5 years in boys and from 16.0 to15.0 years in girls [16].

The potential utility of SA in sport was indicated early last century and was labeled “anatomic age” [23]. All methods, including the earlier protocol of Todd, GP, Fels and different versions of TW, have been applied to youth athletes [10]. GP and TW SAs have also been used to verify chronological age (CA) in youth sport competitions [10].

Observations for youth soccer players have been based on TW2 20 bone, TW2 RUS, GP and Fels SAs [10], and to a lesser extent TW3 RUS SAs. TW3 SAs were consistently lower than Fels SAs in elite Spanish soccer players [24], while comparisons of TW2 SAs using specific tables for Japanese youth and TW3 SAs varied with CA among elite Japanese players [25]. Among 14 year old Serbian players, selection tended to favor later maturing players based on TW3 SAs [26], while among 14 year old elite Swiss players, 21% of players were classified as late and 20% as early maturing with TW3 SAs [27]. The latter results [26,27] contrasted maturity distributions in studies of 14 year old soccer players using TW2, Fels and GP SAs [10,28].

The purposes of this study are twofold, first, to compare TW2 and TW3 RUS SAs in an international sample of youth soccer players 11-17 years of age, and second, to evaluate the influence of changes in TW3 SAs on the classification and distribution of players by maturity status. The latter is of relevance as maturity status is central to development and selection protocols in soccer [29,30], to individualizing training protocols [31,32], and to efforts aimed at equalizing competitions within and among CA groups of youth [33,34].

Methods

TW2 and/or TW3 RUS SAs were available for 1831 soccer players 10.93 to 17.94 years of age from eight countries (Table 1):

(a) two series from Portugal, 139 players 11-17 years from national and regional youth teams surveyed in 1997-1998 [35,36] and 315 players 11-17 years from clubs in the Aveiro and Coimbra regions surveyed 2003-2007 [37,38];

(b) two series from Belgium, a mixed-longitudinal sample of 572 players 11-17 years from several clubs in Flanders surveyed 1996-2001 [29,38] and 57 players 11-16 years from clubs the Ghent region surveyed in 2013 [39];

(c) 40 players 12-15 years from an elite club in Madrid, Spain, surveyed 2001-2002 [24];

(d) 51 players 11-12 years from an elite club in Torino, Italy, surveyed in 2002 [10];

(e) two series J league youth players in Japan, 287 players 11-16 years surveyed 1997-1999 and 167 players 11-16 years surveyed 2000-2005 [25,40,41];

(f) 62 players from a sport school for soccer in, Khon Kaen, Thailand, 12-16 years, surveyed in 2009 [42];

(g) 46 players 11-17 years from clubs in two cities in the northern states of Durango and Nuevo Leon, Mexico surveyed in 1982 [43]; and

(h) 88 players 11-15 years from clubs in the Minas Gerais, Brazil surveyed in 2011 [44].

The majority of players participated at the club level; many players 13 years and older were members of both club and regional teams, and included a number of regional and national selections. The Thailand sample competed regionally and nationally.

Standard radiographs of the left hand-wrist were taken in all studies and evaluated with the TW RUS method by experienced assessors in the respective studies. Radiographs of players in the Portuguese A and B, Spanish, Belgian B, Mexican and Brazilian series were assessed by the first author (RMM) or several students whom he supervised and taught the protocols (MEPR, MJC, AJF); radiographs in the Italian, Belgian A, Japanese A and B, and Thai series were read by experienced assessors. Accordingly, stages and associated scores were assigned to each of 13 bones: radius, ulna and metacarpals and phalanges of the first, third and fifth digit rays. The scores were summed (RUS score) and converted to a TW2 RUS SA and a TW3 RUS SA using the appropriate tables [15,16]. They are subsequently labeled as TW2 SA and TW3 SA.

As noted, the criteria for specific maturity indicators and assigned scores for each bone were the same with TW2 and TW3, but the tables for converting the sum of the maturity scores for the radius, ulna and short bones (RUS maturity score) to SAs were modified with TW3. If necessary, the conversion of a TW2 SA to its RUS score and subsequent conversion of the RUS score to a TW3 SA was straightforward using the respective tables. An SA was not assigned to individuals with a RUS score of 1000 (maturity). The players were mature at the time of observation; the specific CA at which each player reached maturity was not known. The number of mature players is indicated by CA group in the results.

Procedures for obtaining ethical approval varied among countries. Within each country, the studies were approved by the appropriate university committees or agencies, participating clubs and schools. Parental and athlete consent was obtained directly and/or through the club at which the youth trained. In several studies, parents were informed of the objectives and procedures of the respective studies, and both parents and son provided informed consent, while in others, informed consent was obtained from parents/guardians and also from the players when they entered a club/school. By way of background, institutional review boards were not established in the United States until after the 1979 Belmont Report from the Department of Health, Education, and Welfare [45]. The establishment of formal institutional review committees was variable in timing and scope among countries and universities.

Sample sizes and descriptive statistics for CA, RUS score and TW2 and TW3 SAs for non-skeletally mature players and CA of mature players in each series of players are summarized by whole year CA groups (i.e., 11.0 to 11.99 years, etc.) in Supplemental Table 1. The 11 series were combined for subsequent analyses. Descriptive statistics (means, standard deviations, also medians for SA variables) for non-mature players were calculated for CA, RUS score, and TW2 and TW3 SAs. Corresponding statistics were also calculated for the difference between SA and CA (SA minus CA) with TW2 and TW3 SAs, and for the difference of TW3 SA minus TW2 SA. Differences between TW2 and TW3 SAs and the differences of SA minus CA with each method were compared within CA groups with paired t-tests.

The difference of SA minus CA for TW2 and TW3 was used to classify players by maturity status with each method as follows: average (on time), SA ± 1.0 year of CA; late (delayed), SA younger than CA by > 1.0 year; and early (advanced), SA older than CA by > 1.0 year. Skeletally mature players were simply noted as such. The classification criteria were the same as used in earlier

[46,47] and more recent [10] studies of athletes. The band of ±1.0 year approximated standard deviations of SA within single year CA groups of boys 11-17 years in the general population, e.g., 0.92 to 1.41 years in a national sample of American boys 12-17 years [48], 0.86 to 1.28 years in boys from the Harvard School of Public Health Study [49], and 0.96 to 1.24 years in boys 12-16 years of the Fels study [17]. Standard deviations of about one year were indicated for TW2 and TW3 SAs among boys 5 to 16 years, but specific values were not reported [15,16]. Nevertheless, the band of ±1.0 year was somewhat arbitrary; a band of ±2.0 years is commonly used to define "normal" in the clinical context.

Narrower ranges have also been used to define maturity groups, e.g., a band of ±3 months among adolescent boys and girls [50] and a band of ±0.5 year in elite soccer players 14 years of age [26]. The narrower bands may be within the range of standard errors of SA assessments; however, only Fels assessments provide a standard error for assigned SAs. Standard errors ranged from 0.27 to 0.42 year (median 0.30) in 159 soccer players 11-14 years [37], 0.27 to 0.47 year (median 0.34) in 38 players 12-16 years [24], and 0.27 to 0.70 year (median 0.35) in players 11-17 years [35]. Higher standard errors were noted in youth approaching skeletal maturity. The band of one year thus allows for errors associated with assessments.

Concordance of maturity status classifications based on TW2 and TW3 SAs by CA group and in the total sample was evaluated with Cohen's Kappa coefficient. Descriptive statistics for the CA, SA, height and weight of players who remained in the same maturity classification with TW2 and TW3 SAs and who changed classification were also calculated. Heights and weights of players of contrasting maturity status were compared with ANOVA.

Results

Mean TW2 and TW3 SAs for players in each series (Supplementary Table 1) are plotted by mean CAs in Figures 1 and 2, respectively. In instances of small samples, adjacent age groups were combined. SAs are limited to non-mature players, which influences SA relative to CA among players 15-17 years. The plot of mean TW3 SAs versus mean TW2 SAs shows the systematic reduction of TW3 relative to TW2 SAs (Figure 3).

Sample sizes and descriptive statistics for CA and the RUS score of non-mature players and for CA of mature players are summarized for the combined sample by age group in Table 2. The same players are identified as mature by TW2 and TW3, i.e., RUS score = 1000. Mature players range in CA from 13.30 to 17.94 years and numbers increase with age: 13 years (n=6, 1%), 14 years (n=18, 5%), 15 years (n=85, 32%), 16 years (n=65, 55%), 17 years (n=20, 65%).

Corresponding statistics for TW2 and TW3 SAs, SA minus CA (SA-CA) with each method and the difference of TW3 minus TW2 SAs are summarized by CA group in Table 3. The difference between TW3 and TW2 SAs in each CA group is significant ($p<0.001$). TW3 SAs are, on average, systematically less than TW2 SAs by about one year or more. The small sample size of non-mature players at 17 years of age (n=11) should be noted.

TW3 SA lags behind CA in players 11-13 years, is equivalent to CA at 14 years, and lags behind CA at 15 and 16 years, while TW2 SA is in advance of CA from 11 through 15 years and then approaches zero (Figure 4). The SA-CA difference for TW2 and TW3 within each CA group is significant ($p<0.001$). SA-CA differences among players 15 to 17 years are influenced by the upper limit of assigned SAs with each protocol and the increasing number of mature players.

Absolute and relative frequencies of players classified as late, average and early maturing with TW2 and TW3 SAs are summarized in Table 4. Percentages of players classified as late maturing with TW 2 decline with age, while percentages of players classified as early maturing and mature increase with age. The highest proportion of players classified as average with TW2 SA occurs at 11 years, and is reasonably constant at about 40% between 12 and 15 years. In contrast, percentages of players classified as late maturing with TW3 SA in each CA group are consistently higher than corresponding percentages with TW2 SA across the age range. Compared to TW2 SA, percentages of players 11-14 years classified as average with TW3 SA increase, and percentages of players 11 to 15 years classified as early maturing with TW3 SA decrease. Across all ages and excluding mature players, 10%, 44% and 46% of players are classified, respectively, as late, average and early maturing with TW2, while 28%, 55% and 17% are classified, respectively, as late, average and early maturing with TW3.

Concordance of maturity status classifications based on TW2 and TW3 SAs (excluding mature players) ranges from 45% (13 years) to 62% (16-17 years), and is 52% in the total sample (Table 5). Kappa coefficients range from 0.06 (15 years) to 0.33 (14 years), and is 0.23 for the total sample; all are significant ($p<0.01$) except at 15 years. The magnitude of the coefficients, however, suggests at best fair concordance [51].

Frequencies of players who had the same and who had a different maturity status classification based, respectively, on TW2 and TW3 SAs are summarized in Table 6. Given the systematically lower TW3 SA assigned for the same RUS score compared to TW2 SA, the direction of changes is systematic. Across the age range, 42% (307 of 725) of players classified as average with TW2 are classified as late with TW3, and 64% (479 of 752) of players classified as early with TW2 are classified as average with TW3

Discussion

As expected with the modification in assigning SAs for RUS scores in the most recent version of the TW RUS method [16], TW3 SAs were, on average, lower than TW2 SAs in youth soccer players 11-17 years. Mean and median differences of TW3 minus TW2 SAs ranged, respectively, from -0.97 to -1.16 years and from- 0.97 to -1.20 years (Table 3). For the same RUS score, SAs of youth soccer players were systematically and substantially reduced with the TW3 compared to the TW2 version of the method.

TW3 SAs were reported for 48 elite Serbian soccer players, 14.5±0.3 years [26] and 119 elite Swiss soccer players, 14.0±0.3 years of age [27]. TW3 SAs were 14.7 years in Serbian players (estimated from mean SAs for early, average and late maturing players), and 13.9±1.1 years in Swiss players ; corresponding TW2 SAs in the two samples were, respectively, 15.5 years and 15.0 years. The estimates were consistent with observed differences between TW3 and TW2 SAs in 13 and 14 year old players in the present analysis (Table 3). Similar differences between TW3 and TW2 SAs were noted in studies of non-athletes [52-54].

Why TW3? The rational for assigning lower SAs for the same RUS score with TW3 compared to TW2 was to accommodate secular change:

> "In nearly all industrialized countries there has been a trend toward *earlier maturity*, as well as *increased height*. Accordingly, we present here new SMS Bone Age norms; originally called 'EA90', to stand for Europe/European Americans (as well as other European-derived populations) in recent years, and here renamed TW3" [16, p. 19, italics ours).

The modifications in SAs assigned to the same RUS maturity scores (lower SA for the same maturity score with TW3) in boys were only apparent beginning with SAs of about 10 years. Of interest, secular changes in height are apparent early in childhood and continue through puberty [6,7,16,55]. Moreover, secular increases in height are not necessarily associated with accelerated maturation as noted between 1960 and 1980 in Belgium [56,57] and between 1980 and 1997 in the Netherlands [58].

Two questions, and perhaps others, of relevance to the rational for the systematic change in SAs assigned to RUS scores (TW3 SAs) merit attention. First, what is the magnitude of secular change in indicators of maturity status and maturity timing, and in height over the past 50 years or so? And second, what is the evidence for corresponding secular changes in maturity status and timing and in height of youth soccer players?

Maturity Timing. SA provides an estimate of maturity status at the time of observation, and must be distinguished from maturity timing, the CA at which a specific maturational event occurs, e.g., age at peak height velocity (PHV) or age at menarche. Estimated ages at which specific RUS scores were attained by the European samples used to develop the TW3 reference declined from the original English reference sample (labeled 1960) to the Belgian sample surveyed in the 1970s, but appeared to be relatively stable in the Spanish sample of the 1980s and the Italian sample of the 1990s [16, Table 7, p. 19]. In contrast, estimated ages at which specific RUS scores were attained by the American sample of 1985-1995 were earlier than in the European samples. The decline in ages at reaching specific RUS scores was especially apparent between 12 and 15 years in boys, the interval during which PHV ordinarily occurs in boys.

Though related, maturity timing and status are not equivalent, and variation in SA at the time of PHV can be considerable. Estimated age at PHV and TW2 RUS SA at PHV were, on average, similar in Polish boys (Wroclaw Growth Study), 14.1±1.1 and 14.0±1.0 years, respectively, but SAs at PHV ranged from about 12.5 to 15.5 years, and CAs at PHV ranged from <12.0 to >16.5 years [59].

Evidence for secular change in mean ages at PHV in European and North American longitudinal studies was inconsistent over the past two generations [6,7,60]. A decline in estimated mean ages at PHV among Danish youth born in the 1930s through the 1960s, 12.5 to 12.0 years in girls and 14.5 to 14.2 years in boys, was recently reported [61]. Ages at PHV did not differ among boys and girls in the Fels Longitudinal Study born in the 1960s, 1970s and 1980s [62], while ages at PHV among Japanese youth born in the 1960s through early 1980s changed negligibly [63,64].

Estimates of age at PHV in soccer players are limited. Two earlier studies were focused on active and less active boys; the former were regularly involved in soccer although level of competition was not indicated. The studies included 32 Welsh players followed from 12 to 15 years [65] and 8 Danish players followed from 11 to 16 years [66]. Mean ages at PHV were identical in both studies, 14.2±0.9 years. The players were born in the 1970s and the mean ages at PHV were identical with estimated mean age at PHV for Danish boys born in the 1960s [61].

A mean age at PHV of 13.8±0.8 years was more recently reported for 33 Belgian club players [67]. The 33 players represented 43% of a sample of 76 players followed for 4-5 years. The 33 players had a TW2 SA (12.4±1.3 years) slightly in advance of CA (12.1±0.7 years) at initial observation. Age at PHV could be not estimated for 43 players (57%). Plots of heights for individual boys suggested that PHV was attained before or early in the study by 25 players and was not attained during the study 18 players. At initial observation, SA was advanced (13.5±1.2 years) relative to CA (12.6±0.5 years) in the former, and somewhat delayed (11.1±1.1 years) relative to CA (11.5±0.8 years) in the latter [67].

The mean ages at PHV for the three studies were within the range of ages at PHV noted in longitudinal studies of European boys [7]. The studies of soccer players also highlight a limitation of many longitudinal studies of athletes; they often start too late and conclude too early [68]. Sampling variation per se and differential persistence and dropout in a sport are additional important considerations.

Estimated ages at PHV based on the application of Preece-Baines model 1 [69] to cross-sectional mean heights of soccer players 9-18 years in two time periods, 1978 to 1999 and 2000 to 2015, differed negligibly between the intervals, 13.01 years and 12.91 years, respectively [70], and were earlier than the preceding studies [65-67]. The estimated ages at PHV were in the range of mean ages at PHV for early and average maturing boys in longitudinal samples of Polish boys, early 12.57±0.41 years and average 13.97±0.52 years [71] and American boys, early 12.15±0.43 years and average 13.75±0.54 years [62]. Allowing for limitations of modeling cross-sectional data, the negligible change in estimated ages at PHV across time likely reflected two features of talent development in soccer: first, the persistence and/or systematic selection and retention of players of average and advanced maturity status beginning at about 12-13 years, and second, the differential dropout, either voluntary or systematic as in “cutting”, of later and probably some average maturing players beginning at the same ages [70]. The estimated ages at PHV of players based on the cross-sectional data were generally consistent with distributions of players based on maturity status defined by Fels and GP SAs [7]. In the present analysis (Table 4), the distribution of players by TW2 SA maturity status indicated proportionally more average and early maturing than late maturing players 11-15 years, while the distribution of players by TW3 SA maturity status was reversed, i.e., proportionally more late and average maturing players and markedly fewer early maturing players.

Maturity Status. Samples used to develop the TW3 RUS reference were surveyed between 1969 and 1995 [16]. Data addressing secular variation in SA in the general population are limited. A comparison of Japanese children 7-16 years in 1986 and 1996 indicated no changes in heights and TW2 RUS maturity scores over the decade [72]. Of interest, RUS scores for Japanese boys (7-18 years) and girls (7-16 years) in 1963 did not differ, on average, from those of boys and girls in 1986 and 1996 [72]. Among Portuguese boys and girls 8-14 years from Madeira, height showed, on average, a small but consistent increase across the age range between 1996-1998 and 2006, while RUS scores and TW3 SAs varied inconsistently [73].

Studies reporting the skeletal maturity status of youth soccer players date to the1980s. Studies of Belgian [74], Japanese [75,76] and Mexican [43] players 10-12 years in the early 1980s, indicated mean TW2 20 bone SAs that approximated mean CAs. However, SAs were in advance of CA in Mexican players 13-14 years. Among players at an elite Spanish club in the late 1980s/early 1990s, mean SAs, based on a modification of the original TW method [77], approximated CAs at 12 and 13 years, were in advance of CAs at 14 and 15 years, and approximated CA at 16 and 17 years [78]. It was not indicated, however, if any players in the older CA groups were skeletally mature. Players 14-16 years were also advanced in stage of genital development and testicular volume.

Among Italian players in the late 1980s [79] and Portuguese players in the late 1990s [36], mean GP SAs approximated mean CAs among players 11-13 years, and were in advance of CAs among players 14-15 years. The advanced SAs in older players was consistent with advanced genital maturation, testicular volume in the Italian [80] and stage of genital and pubic hair in the Portuguese [36] players. The observations for pubic hair stages were consistent with other samples of adolescent soccer players [68], and those for testicular volume [78,80] were consistent with short-term longitudinal observations of testicular volume and serum testosterone in elite and non-elite players ~11 to ~14 years of age [81].

Mean GP SAs of youth players ~13 years on entry to a select club in France between 1992 and 2003 did not differ significantly across the decade [82]. Overall, SA was, on average, slightly in advance of CA.

Though limited and allowing for variation among methods, the data for youth soccer players showed little change in SAs from the early 1980s through the 1990s. SA approximated CA among players 10-12 years, and a pattern of advanced SA emerged among players 13-14 years. The same trend was apparent in a compilation of Fels SAs for Portuguese, Spanish and Mexican youth players [10].

Samples used in the present analysis of SA, with one exception (Mexican players, n=46), were surveyed from the mid-1990s through 2013. The overlap among mean SAs, respectively, for TW2 and TW3, in players of the ten series from eight countries suggested negligible changes in skeletal maturity status over about 20 years (Figure 1). However, TW2 and TW3 SAs differed significantly; TW3 SAs were delayed relative to TW2 SAs by about one year across the age range (Table 3). TW2 SAs were, on average, in advance of CA by about 0.5 year at 11 years; the difference increased systematically with age reaching 1.1 years at 14 years and then declined to 0.6 year at 15 years (Figure 3). In contrast, TW3 SAs were, on average, slightly delayed relative to CA at

11-12 years, approximated CA at 13-14 years, and were then delayed relative to CA. The increasing number of mature players 15-17 years limits interpretations of SA-CA differences at these ages.

The SAs of players 15-17 years should also be viewed in the context of the criterion for the final stage of maturation of the ulna and radius: "…fusion of the epiphysis and metaphysis has begun" [16, p. 63, 65). The interval between onset and completion of fusion or union is not considered. Thus, a number of youth are classified as mature (fusion has begun), even though the epiphysis and diaphysis of the ulna or radius, especially the radius, is still in the process of fusing. It is thus possible that significant numbers of players 15-17 years classified mature with TW would be classified otherwise by the Fels and GP methods, both of which consider the interval from beginning through complete union of the radius and ulna. Fels SAs were available for a subsample of players in the current analysis. Among players 13 (n=106) and 14 (n=84) years, 1 and 2, respectively, were classified as mature with TW but not with Fels. Among players 15 (n=112), 16 (n=70) and 17 (n=27) years, 35, 23 and 8, respectively, were classified mature with TW but not with Fels, while only 9, 14 and 10, respectively, were classified mature by both methods (Malina, unpublished).

Height. Secular gains in heights of European youth were marked for several decades after World War II, but have since slowed or stopped in many countries [7,83-85]. Similar trends were apparent in Japan; heights increased after WW II but have leveled since the 1990s [63] . Median heights also have not changed appreciably among national samples of U.S. youth since the 1960s [86,87].

The comparison of heights of soccer players (largely from Europe and the Americas) 9-18 years in two time intervals, 1978 to 1999 and 2000 to 2015, indicated secular gains of about 2 cm between 9 and 12 years, about 3 cm between 13 and 16 years, and about

2.5 cm at 17 and 18 years [70]. In addition to general health and nutrition, improved conditions in soccer clubs over time and the selectivity of talent development programs, specifically during the adolescent transition, are perhaps primary factors underlying the secular gains.

Implications of Changes with TW3. The maturity status of youth soccer players is a significant factor in talent identification, development and selection. Individual differences in biological maturation *per se* and more importantly size and performance advantages associated with advanced maturity status in boys, specifically measures of strength, power and speed [7], may influence immediate success in soccer and/or may influence perceptions of adults who make decisions on the fates of youth players.

Given the systematically lower TW3 SA assigned for the same RUS score compared to TW2 SA [16], adoption of TW 3 would systematically influence maturity classifications of players (Table 4). Across the age range 11-17 years and excluding skeletally mature players, 42% of players (307/725) classified as average with TW2 were classified as late with TW3, and 64% of players (479/752) classified as early with TW2 were classified as average with TW3 (Table 6).

Characteristics of players who had the same maturity status classification (Late [L-L], Average [A-A], Early [E-E]) with both SAs and a different classification with TW3 (TW2 Average, TW3 Late [A to L]; TW2 Early, TW3 Average [E to A]) are summarized in Supplementary Tables 2 and 3, respectively. There was no clear pattern in mean CAs and mean differences of TW3 minus TW2 SAs by maturity groups within CA groups, while heights and weights differed significantly ($p<0.001$). Overall, players 11-15 years whose maturity status changed from Average to Late had mean heights and weights that were intermediate between players classified as L-L and A-A with both SA methods. Players 11-13 years whose status changed from Early to Average had mean heights and weights that were intermediate between players classified as A-A and E-E with both SA methods. Contrasts among maturity groups at 14, 15 and 16 years were more variable, which likely reflected the exclusion of skeletally mature players. The latter had heights and weights similar to early maturing players of the same CA. Allowing for small numbers, 17 year old mature players were, on average, shorter and lighter than players in other maturity groups; this likely reflected the catch-up of late and average maturing players in late adolescence, consistent with the general growth literature [7].

Maturity status is also indicated as significant in efforts to individualize training and to identify intervals of readiness and trainability [28-32,88]. Coaches, however, are likely not familiar with methods of maturity assessment and are dependent upon medical and training personnel for information on the maturity status of individual players that may be relevant to decisions regarding training load and injury risk. Variable maturity classifications provided by TW2 and TW3 SAs are likely to present a dilemma for coaches and may lead to confusion and potentially erroneous decisions on when to start specific training protocols and/or to adjust training loads. Among players 11-14 years, for example, strength training protocols may focus on core stability and basic strength for late maturing players but may focus on joint and muscle flexibility and coordination drills for early maturing players. As such, accurate estimates of maturity status are central to such decisions.

Potential relationships between skeletal maturity status and injury risk in soccer are not firmly established, although data are limited. Fels and GP SAs *per se* were not associated with the incidence of injury in elite players 9-16 years [89] and elite U-14, U-16 and U-18 players [90]. Pubertal status also was not related with the incidence of injury in a mixed-longitudinal sample of youth players 8-15 years [91].

Size and maturity characteristics of youth athletes are often indicated as risk factors for injury, but relatively little is known about the growth and maturity status of youth who present with injuries. Among 200 youth players training and competing at the club level, 22 presented with epiphyseal lesions during the course of a season [92]; complete records including SA [21] and stages of pubic hair and genital development were available for 11 of the players who ranged in CA from 12.2 to 15.7 years. As a group, players presenting with epiphyseal injuries were delayed in skeletal and pubertal maturation. In 9 of the 11 players, SAs ranged from 12 to 27 months less than their respective CAs, which would categorize them as late maturing. In the study of players 9-16 years noted above, skeletal maturity status, playing time and training time accounted for 48% of the variance in the incidence of injury [89], which highlights the potential interactions among maturity status, training load and playing time in the risk of injury in soccer.

The adolescent growth spurt is often indicated as a risk factor for injury. The adolescent spurt, however, is not a single point in time. It begins with acceleration in growth rate at take-off of the spurt, continues with an increase in rate until maximum velocity is reached (age at PHV), and then decelerates until growth in height ceases. What is unique about the spurt that renders a youngster at risk for injury? Moreover, body segments (foot and leg length, sitting height), bone area and bone mineral, muscle mass and muscular strength and power differ in the timing of their respective growth spurts [7]. Behavioral changes during adolescence may also be a related factor in injury risk [88].

The present discussion focuses on SA, an indicator of maturity status at the time of observation, and not on the timing of the growth spurt. Data relating injury among youth soccer players to the growth spurt are limited. For example, two inflammatory conditions, Sever's disease (inflammation of the growth plate of the calcaneus) and Osgood-Schlatter's disease (inflammation of the patellar tendon of the anterior quadriceps muscle at the tibial tuberosity) occurred most frequently among U-10 to U-14 (~84%) and U-12 to U-16 (~87%) soccer players, respectively [93]. The authors emphasized "…the importance to football clubs of identifying the onset of these growth spurts to start early effective treatment and management and even prevention of these injuries" [93, p. 469-470]. The specific growth spurts were not identified, although these inflammatory conditions are often attributed to rapid growth of the foot, lower leg (tibia) and thigh (femur), which occurs early in the male adolescent spurt [7].

Maturity status based on predicted age at PHV was related to injuries among 26 soccer players, 11.9±0.84 years at initial selection, who were followed for three years [94]. Mean numbers of traumatic and overuse injuries per player were lower among pre-PHV players, but did not differ between players at PHV and post-PHV. A subsequent analysis suggested an increase in overuse injuries among players with an older age at PHV [95]. Although potentially interesting, the results need to be evaluated in the context of limitations of the equations for the prediction of age at PHV [62,71,96].

The issue of ethnic variation in skeletal maturation also merits consideration. Although observations for Japanese youth are included among the reference values for TW3, the new norms for converting RUS scores to TW3 SAs were "…originally called 'EA90', to stand for Europe/European -Americans (as well as other European-derived populations) … and (were) here renamed 'TW3'" [16, p. 19]. The chronological ages at which specific RUS scores were attained by Japanese boys from Tokyo [97] were similar to the European and European-American samples for RUS scores of 400 and 500 but were in advance of these samples for RUS scores of 600 through 950. Although there was considerable overlap among samples in the present study, mean SAs of the youth soccer players 12-15 years from Japan and Thailand were often in advance of corresponding means for players from European and Latin American countries (Figures 1 and 2, Supplementary Table 1).

Potential variation associated with ethnicity is, however, a sensitive issue. Studies of youth soccer players increasingly do not indicate the ethnicity of players, while laws in some countries do not permit ethnic identification [98]. Moreover, given the use of GP and TW3 SAs with "…children of different nationalities, races and ethnicities … The appropriateness of these two methods explicitly needs testing as a priority, and new standards need to be developed if these data are found to be inadequate" [99, p. R69].

The systematic reduction in TW3 compared to TW2 SAs has implications for the use of SA to verify CA in youth competitions [10]. A RUS score of 427, for example, would be assigned an SA of 13.4 years with TW2 and an SA of 12.0 years with TW3, while a RUS score of 740 would be assigned an SA of 16.0 years with TW2 and an SA of 15.0 years with TW3 [15,16]. The range of SAs within a given CA group, of course, can exceed three or four years. Such inter-individual variability precludes use of SA as a valid tool for verification of CA for age-group competitions. Cut-off dates for competitions imply greater precision, whereas SA provides a crude approximation of CA with a large margin of error.

Nevertheless, TW3 RUS SAs were used to verify CA at the U15 Asian Cricket Championship in Nepal in 2007. Accordingly,

> "Each participating country consists of 14 squad-members. In the instances where more than two players in each squad have been found to be over-age, those teams have been disqualified from the competition [100]. …eight of the ten competing sides had earlier been disqualified for fielding over-age players, and so Singapore and Kuwait contested the final as they were the only teams remaining in the competition [101]."

One can wonder how many age-eligible players were disqualified on the basis of SA, and given the systematic reduction of TW3 SAs some over age players may be noted as CA-eligible based on SA. Potential ethnic variation is an additional concern.

Both GP and TW3 SAs have been labeled as the "current gold standards" for assessing skeletal maturity [99], while others refer to TW3 as the "gold standard" [102]. TW3 rather than TW2 has been recommended for use clinically [54] and as the "method of first choice" [52]. The issue of which method is more appropriate, however, is not settled [2,103]. The utility of TW3 for height predictions has also been questioned; based on a comparison of predictions with TW2 and TW3 RUS SAs, the authors concluded: "TW3 does not represent any real progress" [104, p. 221]. Discussions of methods of SA assessment of the hand-wrist generally focus on the GP and TW methods, while the Fels method surprisingly receives relatively little consideration.

Conclusion

TW3 SAs were, on average, lower than corresponding TW2 SAs in youth soccer players 11-17 years. For the same RUS score, SAs were systematically and substantially reduced with the TW3 compared to the TW2 version of the method. Mean differences of TW3 minus TW2 SAs ranged from -0.97 to -1.16 years. The lower TW3 SA assigned for the same RUS score compared to TW2 SA has major implications for the classification of players by maturity status, which is central to many talent development programs. Across the age range 11-17 years, maturity classifications varied with method: 42% of players classified as average with TW2 were classified as late with TW3, while 64% of players classified as early with TW2 were classified as average with TW3.

Observations based on TW3 SAs and specifically the shift from average-to-late and from early-to-average status classifications contrasted observations and maturity classifications based on Fels and GP SAs which provided results more consistent with TW2 SAs in youth soccer players. Given the secular change in the heights with negligible change in estimated age at PHV of youth soccer players, negligible changes in SA-CA relationships among players 11-15 years using a variety of assessment protocols in studies spanning the early 1980s through 2013, and the selectivity of the sport in favor of more mature players during adolescence, the TW2 RUS SA is the method of choice *for those using the TW protocol* with youth soccer players.

Acknowledgments

We thank Dr. Alan Rogol for a critical reading of the manuscript and for his constructive comments.

No funding was provided for this analysis.

Each of authors declares that he has no conflict of interest.

References

1. Martin DD, Wit JM, Hochberg Z, et al. (2011). The use of bone age in clinical practice – Part 1. Hormone Res Paediatr. 2011a; 76:1-9.
2. Martin DD, Wit JM, Hochberg Z, et al. (2011). The use of bone age in clinical practice – Part 2. Hormone Res Paediatr. 2011b; 76:10-6.
3. Satoh M. Bone age: Assessment methods and clinical applications. Clin Pediatr Endoc. 2015; 24:143-52.
4. Tanner JM. Growth at Adolescence, 2nd edition. Oxford: Blackwell, 1962.
5. Acheson RM. Maturation of the skeleton. In Falkner F, editor. Human Development. Philadelphia: Saunders, 1966; p. 465-502.
6. Roche AF, Sun S. Human Growth: Assessment and Interpretation. Cambridge: Cambridge University Press, 2003.

7. Malina RM, Bouchard C, Bar-Or O. Growth, Maturation, and Physical Activity, 2nd edition. Champaign, IL: Human Kinetics, 2004.
8. Malina RM. Biological maturity status of young athletes. In RM Malina, editor, Young Athletes: Biological, Psychological and Educational Perspectives. Champaign, IL: Human Kinetics, 1988; p. 121-40.
9. Malina RM. Physical growth and biological maturation of young athletes. Exerc Sports Sci Rev. 1994; 22:389-433.
10. Malina RM. Skeletal age and age verification in youth sport. Sports Med. 2011; 41:925-47.
11. Greulich WW, Pyle SI. Radiographic Atlas of Skeletal Development of the Hand and Wrist, 2nd edition. Stanford, CA: Stanford University Press, 1959.
12. Todd TW. Atlas of Skeletal Maturation. St. Louis: Mosby, 1937.
13. Tanner JM, Whitehouse RH, Healy MJR. A New System for Estimating Skeletal Maturity from the Hand and Wrist, with Standards Derived from a Study of 2,600 Healthy British Children. Paris: International Children's Centre, 1962.
14. Tanner JM, Whitehouse RH, Marshall WA, et al. Assessment of Skeletal Maturity and Prediction of Adult Height (TW2 Method). New York: Academic Press, 1975.
15. Tanner JM, Whitehouse RH, Cameron N, et al. Assessment of Skeletal Maturity and Prediction of Adult Height, 2nd edition. New York: Academic Press, 1983.
16. Tanner JM, Healy MJR, Goldstein H, et al. Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 Method), 3rd edition. London: Saunders, 2001.

17. Roche AF, Chumlea WC, Thissen D. Assessing the Skeletal Maturity of the Hand-Wrist: Fels Method. Springfield, IL: CC Thomas, 1988.

18. Malina RM. Assessment of biological maturation. In Armstrong N, van Mechelen W, editors, Oxford Textbook of Children's Exercise Science and Medicine. Oxford: Oxford University Press, 2017; p. 3-11.

19. Roche AF. The measurement of skeletal maturation. In Johnston FE, Roche AF, Susanne C, editors, Human Physical Growth and Maturation: Methodologies and Factors. New York: Plenum Press, 1980; p. 61-82.

20. Roche AF. Bone growth and maturation. In Falkner F, Tanner JM, editors, Human Growth. Volume 2. Postnatal Growth, Neurobiology. New York: Plenum, 1985; p. 25-60.

21. Sempé M. Analyse de la Maturation Squelettique. A Pediatrie au Quotidien. Paris: Les Editions INSERM, 1987.

22. Tanner J, Oshman D, Babbage F, Healy M. Tanner-Whitehouse bone age reference values for North American children. J Pediatr. 1997; 131:34-40.

23. Rotch TM. Chronological and anatomical age early in life. J Am Med Assoc. 1908; 51:1197-205.

24. Malina RM, Chamorro M, Serratosa L, Morate F. TW3 and Fels skeletal ages in elite youth soccer players. Ann Hum Biol. 2007; 34:265-72.

25. Hirose N, Hirano A. The bias toward biological maturation through the talent selection in Japanese elite youth soccer players. Int J Sport Hlth Sci. 2012; 10:30-8.

26. Ostojic SM, Castagna C, Calleja-Gonzalez J, et al. The biological age of 14 year old boys and success in adult soccer: Do early maturers predominate in the top-level game. Res Sports Med Int J. 2014; 22:398-407.

27. Romann M, Javet M, Fuchslocher J. Coache's eye as a valid method to assess biological maturation in youth elite soccer. Talent Dev Excellence. 2017; 9:3-13.

28. Malina RM, Coelho-e-Silva MJ, Figueiredo AJ. Growth and maturity status of youth players. In Williams AM, editor, Science and Soccer: Developing Elite Performers, 3rd edition. Abington, UK: Routledge, 2013; p. 307-32.

29. Vaeyens R, Malina RM, Janssens M, et al. A multidisciplinary selection model for youth soccer: the Ghent Youth Soccer Project. Br J Sports Med. 2006; 40:928-33

30. Coelho-e-Silva MJ, Figueiredo AJ, Simões F, et al. Discrimination of U-14 soccer players by level and position. Int J Sports Med. 2010; 31:790-6.

31. Meylan CM, Cronin JB, Oliver JL, Hughes M. Talent identification in soccer: The role of maturity status on physical, physiological and technical characteristics. Int J Sports Sci Coach. 2010; 5:571-92.

32. Lloyd RS, Oliver JL, Faigenbaum AD, et al. Chronological age vs. biological maturation: Implications for exercise programming in youth. J Strength Cond Res. 2014; 28:1454-64.

33. Malina RM, Beunen G. Matching of opponents in youth sports. In Bar-Or O, editor The Child and Adolescent Athlete. Oxford, UK: Blackwell Science, 1986; p. 202-13.

34. Cumming SP, Lloyd RS, Oliver JL, et al. Bio-banding in sport: Applications to competition, talent identification, and strength and

conditioning of youth athletes. Strength Cond J. 2017; 39:34-47.

35. Malina RM, Peña Reyes ME, Eisenmann JC, et al. Height, mass, and skeletal maturity of elite Portuguese soccer players 11-16 years of age. J Sports Sci. 2000; 18:685-93.

36. Horta L. Factores de predicão do rendimento desportivo em atletas juvenis de futebol. Doctoral thesis, Faculty of Medicine, University of Porto, Portugal, 2003.

37. Figueiredo AJ, Gonçalves CE, Coelho-e-Silva MJ, Malina RM. Youth soccer players, 11-14 years: Maturity, size, function, skill and goal orientation. Ann Hum Biol. 2009; 36:60-73.

38. Philippaerts RM, Vaeyens R, Cauwelier D, et al. De jeugdvoetballer beter begeleiden/Ghent Youth Soccer Project. Ghent University: Publicatiefonds voor Lichamelijke Opvoeding, 2004.

39. Deprez S. Anthropometrical, physical fitness and maturational characteristics in youth soccer: Methodological issues and a longitudinal approach to talent identification and development. Doctoral thesis (Health Sciences), Ghent University, Belgium, 2015.

40. Hirose N. Relationships among birth-month distribution, skeletal age and anthropometric characteristics in adolescent elite soccer players. J Sports Sci. 2009; 27:1159-66.

41. Hirose N, Hirano A, Fukubayashi T. Biological maturity and choice reaction time in Japanese adolescent soccer players. Res Sports Med. 2004; 12:45-58.

42. Buranarugsa R. Biological maturation and response to complex strength training in adolescent Thai soccer players. Doctoral

thesis, Faculty of Sport, University of Porto, Portugal, 2012.

43. Peña-Reyes ME, Cardenas-Barahona E, Malina RM. Growth, physique, and skeletal maturation of soccer players 7-17 years of age. Humanbiologia Budapestinensis. 1994; 25:453-58.

44. Teixeira AS, Valente-dos-Santos J, Coelho-E-Silva MJ, et al. Skeletal maturation and aerobic performance in young soccer players from professional academies. Int J Sports Med. 2015; 36:1069-75.

45. Gunsalus CK, Bruner EM, Burbules NC, et al. Mission creep in the IRB world. Science. 2006; 312:1441.

46. Krogman WM. Maturation age of 55 boys in the Little League World Series, 1957. Res Q. 1959; 30:54-6.

47. Rochelle RH, Kelliher MS, Thornton R. Relationship of maturation age to incidence of injury in tackle football. Res Q. 1961; 32:78-82.

48. Roche AF, Roberts J, Hamill PVV. Skeletal maturity of youths 12-17 years, United States. Vital and Health Statistics, Series 11, no 160. Hyattsville, MD: Department of Health Education and Welfare, National Center for Health Statistics, DHEW Publication Number (HRA) 77-1642, 1976.

49. Pyle SI, Reed RB, Stuart HC. Patterns of skeletal development in the hand. Pediatrics. 1959; 24:886-903.

50. Kemper HCG, Verschuur R, Ritmeester RM. Longitudinal development of growth and fitness in early and late maturing teenagers. Pediatrician 1987; 14:219-25.

51. Viera AJ, Garrett JM. Understanding interobserver agreement: The Kappa statistic. Fam Med. 2005; 37:360-3.

52. Kuchyňková I, Krásničanová H. Methods of skeletal maturity assessment – some clinical aspects. Anthropologie, 2004; 42:115-19

53. Vignolo M, Naselli A, Magliano P, et al. Use of the new US90 standards for TW-RUS skeletal maturity scores in youths from the Italian population. Hormone Res. 1999; 51:168-72.

54. Ahmed ML, Warner JT. TW2 and TW3 bone ages: Time to change? Arch Dis Child. 2007; 92:371-72.

55. Meredith HV. Change in stature and body weight of North American boys during the last 80 years. In Lipsitt LP, Spiker CC, editors. Advances in Child Development and Behavior. New York: Academic Press, 1963; p. 69-114.

56. Hauspie RC, Vercauteren M, Susanne C. Secular changes in growth and maturation: an update. Acta Paediatr, suppl. 1997; 424:20-7.

57. Wellens R, Malina RM, Beunen G, et al. Age at menarche in Flemish girls: Current status and secular change in the 20^{th} century. Ann Hum Biol. 1990; 17:145-52.

58. Mul D, Fredriks AM, van Buuren S, et al. Pubertal development in The Netherlands 1965-1997. Pediatr Res. 2001; 50:479-86.

59. Hauspie R, Bielicki T, Koniarek J. Skeletal maturity at onset of the adolescent growth spurt and at peak velocity for growth in height: a threshold effect. Ann Hum Biol. 1991; 18:23-9.

60. Beunen GP, Rogol AD, Malina RM. Indicators of biological maturation and secular changes in biological maturation. Food Nutr Bull. 2006; 27:S244-56.

61. Aksglaede L, Olsen LW, Sørensen TIA, Juul A. Forty years trends in timing of pubertal growth spurt in 157,000 Danish school children. PLoS One. 2008; 3 (7):e2728.

62. Malina RM, Choh AC, Czerwinski SA, Chumlea WC. Validation of maturity offset in the Fels Longitudinal Study. Pediatr Exerc Sci. 2016; 28:439-55.

63. Kouchi M. Secular change and socioeconomic difference in height in Japan. Anthropol Sci. 1996; 104:325-40.

64. Ali MDA, Lestrel PE, Ohtsuki F. Secular trends for takeoff and maximum adolescent growth for eight decades of Japanese cohort data. Am J Hum Biol. 2000; 12:702-12.

65. Bell W. Body size and shape: A longitudinal investigation of active and sedentary boys during adolescence. J. Sports Sci. 1993; 11:127-38.

66. Froberg K, Andersen B, Lammert O. Maximal oxygen uptake and respiratory functions during puberty in boy groups of different physical activity. In Frenkl R, Szmodis I, editors. Children and Exercise: Pediatric Work Physiology XV. Budapest: National Institute for Health Promotion, 1991; p. 265-80.

67. Philippaerts RM, Vaeyens R, Janssens M, et al. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci. 2006; 24:221-30.

68. Malina RM, Rogol AD, Cumming SP, et al. Biological maturation of youth athletes: Assessment and implications. Br J Sports Med. 2015; 49:852-59.

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

70. Malina RM, Figueiredo AJ, Coelho-e-Silva MJ. Body size of male youth soccer players: 1978-2015. Sports Med. 2017; in press.

71. Malina RM, Kozieł SM. Validation of maturity offset in a longitudinal sample of Polish boys. J Sports Sci. 2014; 32:424-37.

72. Matsuoka H, Sato K, Sugihara S, Murata M. Bone maturation reflects the secular trend in growth. Hormone Res. 1999; 52:125-30.

73. Freitas D, Malina RM, Maia J, et al. Short-term secular change in height, body mass and Tanner-Whitehouse 3 skeletal maturity of Madeira youth, Portugal. Ann Hum Biol. 2012; 39:195-205.

74. Vrijens, J., Pannier JL, Van Cauter C. Voetbal, groei en ontwikkeling Werken van de Belgische Vereniging voor Sportgeneeskunde en Sportwetenschappen. 1981-1982; 30;66-75.

75. Atomi Y, Fukunaga T, Yamamoto Y, Hatta H. Lactate threshold and VO_2 max of trained and untrained boys relative to muscle mass and composition. In Rutenfranz J, Mocellin R, Klimt F, editors. Children and Exercise XII. Human Kinetics, Champaign, IL, 1986; p. 53-8.

76. Satake T, Okajima Y, Atomi Y, et al. Effect of physical exercise on physical growth and maturation. J Phys Fit Japan. 1986; 35:104-10.

77. Marti-Henneberg C, Patois E, Niiranen A, et al. Bone maturation velocity. In Compte Rendu de la XII^{e} Reunión des Équipes Chargées des Études sur la Croissance et le Développement de l'Enfant Normal. Paris, Centre International de l'Enfance, Paris, 1974; p. 107-12.

78. Feliú Rovira A, Albanell Pemán A, Bestit Cartasona C, et al. Predicción de la capacidad física de deportistas durante la pubertad: Análisis en futbolistas de alto rendimiento. Anales Españoles de Pediatria. 1991; 35:323-26.

79. Mazzanti L, Tassinari D, Bergamaschi R, et al. Hormonal, auxological and anthropometric aspects in young football players. In Bierich JR, Cacciari E, Raiti S, editors, Growth Abnormalities. Raven Press, New York, 1989; p. 363-69.

80. Cacciari E, Mazzanti L, Tassinari D, et al. Effects of sport (football) on growth: Auxological, anthropometric and hormonal aspects. Eur J Appl Physiol. 1990; 61:149-58.

81. Hansen L, Bangsbo J, Twisk J, Klausen K. Development of muscle strength in relation to training level and testosterone in young male soccer players. J Appl Physiol. 1999; 87:1141-47.

82. Carling C, Le Gall F, Malina RM. Body size, skeletal maturity, and functional characteristics of elite academy soccer players on entry between 1992 and 2003. J Sports Sci. 2012; 30:1683-93.

83. Bodzsár ÉB, Susanne C. Secular growth changes in Europe: Do we observe similar trends? Considerations for future research. In Bodzsar ED, Susanne C, editors. Secular Growth Changes in Europe. Budapest: Eötvös University Press, 1998; p. 369-81.

84. Ong KK, Ahmed ML, Dunger DB. Lessons from large population studies on timing and tempo of puberty (secular trends and relation to body size): The European trend. Mol Cell Endoc. 2006; 254-255:8-12.

85. Gohlke B, Woelfle J. Growth and puberty in German children: Is there still a secular trend? Dtsch Arztebl Int. 2009; 106:377-82.

86. OgdenCL, Fryar CD, Carroll, MD, et al. Mean body weight, height, and body mass index, United States 1962-2002. Advance Data from Vital and Health Statistics, no 347. Hyattsville, MD: National Center for Health Statistics, 2004.

87. McDowell MA, Fryar CD, Ogden CL, et al. Anthropometric reference data for children and adults: United States, 2003-2006. National Health Statistics Reports, no 10. Hyattsville, MD: National Center for Health Statistics, 2008.

88. Malina RM, Cumming SP, Coelho-e-Silva MJ, Figueiredo AJ. Talent identification and development in the context of "growing up". In: Baker J, Cobley S, Schorer J, Wattie N, editors. Routledge Handbook of Talent Identification and Development in Sports. New York: Routledge, 2017; p. 150-68.

89. Johnson A, Doherty PJ, Freemont A. Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: Prospective study. Br Med J. 2009; 338:b490 (doi: 1136/bmj.b490).

90. Le Gall F, Carling C, Reilly T. Biological maturity and injury in elite youth football. Scand J Med Sci Sports. 2007; 17:564-72.

91. Baxter-Jones ADG, Maffulli N, Helms P. (1993) Low injury rates in elite athletes. Arch Dis Child. 1993; 68:130-2.

92. Vidalin H. Football. Traumatismes et âge osseux. Étude prospective de 11 cas. Médecine du Sport. 1988 ; 62 :195-7

93. Price RJ, Hawkins RD, Hulse MA, et al. The Football Association medical research programme: An audit of injuries in academy youth football. Br J Sports Med. 2004; 38:466-71.

94. van der Sluis A, Elferink-Gemser MT, Coelho-e-Silva MJ, et al. Sport injuries aligned to peak height velocity in talented pubertal soccer players. Int J Sports Med. 2014; 35:351-55.

95. van der Sluis A, Elferink-Gemser MT, Brink MS, et al. Important of peak height velocity timing in terms of injuries in talented soccer players. Int J Sports Med. 2015; 36:327-32.

96. Kozieł SM, Malina RM. Modified maturity offset prediction equations: Validation in independent longitudinal samples of boys and girls. Sports Med. 2017; in press.

97. Ashizawa K, Asami T, Anzo M, et al. Standard RUS skeletal maturation of Tokyo children. Ann Hum Biol. 1996; 23:457-69.

98. Malina RM. Ethnicity and biological maturation in sports medicine research. Scan J Med Sci Sports. 2009; 19:1-2.

99. Hochberg Z. On the need for national-, racial-, or ethnic-specific standards for the assessment of bone maturation. Eur J Endoc. 2016; 175:R65-70.

100. Asian Cricket Council. U-15 ACC elite age-verification program results issued. 2007a. (http://www.asiancricket.org/h_1207_u15eageverification.cfm, accessed 15 January 2008).

101. Asian Cricket Council. Eight teams expelled in Asian age row. 2007b; (http://content-uk.cricinfo.com/other/content/story/323637.html, accessed 15 January 2008).

102. Caldas MdeP, Ambrosano GMB, Haiter-Neto F. Use of cervical vertebral dimensions for assessment of children growth. J Appl Oral Sci. 2007; 15:144-7.

103. de Sanctis V, di Maio S, Soliman AT, et al. Hand X-ray in pediatric endocrinology: Skeletal age assessment and beyond. Indian J Endoc Metab. 2014; 18(suppl 1):s63-71.

104. Bertiana C, Stasiowska B, Benso A, Vannelli S. Is TW3 height prediction more accurate than TW2? Preliminary data. Hormone Res. 2007; 67:220-23.

Captions for Figures:

Figure 1. Mean TW2 RUS skeletal ages plotted relative to mean chronological ages by age group in each of the eleven samples.

Figure 2. Mean TW3 RUS skeletal ages plotted relative to mean chronological ages by age group in each of the eleven samples.

Figure 3. Mean TW3 skeletal ages (y-axis) plotted relative to mean TW2 RUS skeletal ages (x-axis) in each of the eleven samples.

Figure 4. Mean differences and standard deviations for skeletal age minus chronological age with TW2 and TW3 SAs by chronological age groups. The number and percentage of skeletally mature players by chronological age group are also included.

Table 1. Distribution of players in each of the series by chronological age (CA) group

CA	Portugal		Belgium							Japan		
Group	A	B	A	B	Spain	Italy	Mexico	Brazil	Thailand	A	B	Total
11	9	62	55	9	-	33	9	13	-	55	45	290
12	20	25	141	10	6	18	10	20	9	72	45	376
13	6	80	140	13	7	-	13	39	17	70	35	420
14	22	46	114	11	13	-	3	15	18	60	31	333
15	37	59	82	10	10	-	6	8	12	29	9	262
16	30	35	36	4	4	-	1	-	8	1	2	119
17	15	8	4	-	-	-	4	-	-	-	-	31
Total	139	315	572	57	40	51	46	95	62	287	167	1831

Table 2. Total sample size, and sample sizes and descriptive statistics for chronological age (CA) and the RUS score of non-skeletally mature players and for CA of skeletally mature players by CA group

		RUS Score <1000 (not mature)						RUS Score =1000 (mature)		
CA			CA, years		RUS Score				CA, years	
Grp	N	n	M	SD	M	SD	Md	n	M	SD
11	290	290	11.55	0.28	382	74	365			
12	376	376	12.54	0.27	456	113	428			
13	420	414	13.53	0.29	568	148	546	6	13.70	0.23
14	333	315	14.51	0.30	697	171	661	18	14.60	0.26
15	262	177	15.48	0.30	758	139	762	85	15.62	0.27
16	119	54	16.39	0.29	809	129	833	65	16.53	0.31
17	31	11	17.42	0.29	923	94	971	20	17.43	0.30

Table 3. Descriptive statistics for chronological age (CA), TW2 and TW3 RUS skeletal ages (SA), the differences between SA and CA with each method, and the differences between TW3 and TW2 SAs by CA group among non-skeletally mature players

CA		CA years		TW2 SA years			TW3 SA years			TW2 SA-CA years			TW3 SA-CA years			TW3 minus TW2 SA, years				
Grp	n	M	SD	M	SD	Md	M	SD	Md	M	SD	Md	M	SD	Md	M	SD	Md	Min	Max
11	290	11.5	0.3	12.1	1.5	12.1	11.1	1.1	11.0	0.55	1.43	0.51	-0.42	1.12	-0.51	-0.97	0.36	-1.06	-1.46	0.00
12	376	12.5	0.3	13.3	1.6	13.4	12.2	1.4	12.0	0.75	1.49	1.00	-0.38	1.34	-0.43	-1.13	0.28	-1.20	-1.50	-0.04
13	414	13.5	0.3	14.6	1.3	14.7	13.4	1.4	13.4	1.05	1.28	1.15	-0.11	1.35	-0.04	-1.16	0.17	-1.16	-1.50	-0.64
14	315	14.5	0.3	15.6	1.2	15.5	14.5	1.3	14.4	1.10	1.17	1.14	0.01	1.27	-0.11	-1.09	0.17	-1.08	-1.42	-0.80
15	177	15.5	0.3	16.1	0.9	16.1	15.0	1.0	15.1	0.59	0.96	0.66	-0.43	1.02	-0.31	-1.02	0.13	-1.00	-1.42	-0.80
16	54	16.4	0.3	16.4	0.8	16.5	15.4	0.8	15.6	0.01	0.90	0.09	-0.99	0.91	-0.82	-1.00	0.12	-0.97	-1.26	-0.80
17	11	17.4	0.3	17.2	0.7	17.5	16.1	0.6	16.4	-0.24	0.61	-0.18	-1.32	0.57	-1.12	-1.07	0.17	-1.11	-1.32	-0.85

Table 4. Absolute and relative frequencies of players classified as late, average and early maturing on the basis of SA minus CA with TW2 and TW3 SAs. Frequencies and percentages of skeletally mature players are the same with each method.

		TW2 RUS SA						TW3 RUS SA							
Age		Late		Average		Early		Late		Average		Late		Mature	
Group	N	n	%	n	%	n	%	n	%	n	%	n	%	n	%
11	290	39	13.4	147	50.7	104	35.9	86	29.7	178	61.4	26	9.0	0	-
12	376	51	13.6	144	38.3	181	48.1	128	34.0	174	46.3	74	19.7	0	-
13	420	36	8.6	146	34.8	232	55.2	102	24.3	236	56.2	76	18.1	6	1.4
14	333	15	4.5	133	39.9	167	50.2	64	19.2	167	50.2	84	25.2	18	5.4
15	262	7	2.7	110	42.0	60	22.9	58	22.1	106	40.5	13	5.0	85	32.4
16	119	11	9.2	35	29.4	8	6.7	21	17.6	33	27.7	0	-	65	54.6
17	31	1	3.2	10	32.3	0	-	8	25.8	3	9.7	0	-	20	64.5
Total	1831	160	8.7	725	39.6	752	41.1	467	25.5	897	49.0	273	14.9	194	10.6

Table 5. Cross-tabulation of maturity status classifications based on TW2 and TW3 SAs, percentage agreement and Cohen's Kappa coefficients by CA group. Skeletally mature players (n=194) are excluded; numbers of mature players are indicated in ( ).

Maturity Status Classification TW3 RUS SA		Maturity Status Classification TW2 RUS SA L	A	E	Total	Agreement* %	Kappa
11 yrs	L	**39**	47	-	86		
	A	-	**100**	78	178		
	E	-	-	**26**	26		
	Total	39	147	104	290	57	0.30*
12 yrs	L	**51**	77	-	128		
	A	-	**67**	107	174		
	E	-	-	**74**	74		
	Total	51	144	181	376	51	0.28*
13 yrs	L	**36**	66	-	102		
	A	-	**80**	156	236		
	E	-	-	**76**	76		
	Total	36	146	232	414 (6)	46	0.21*
14 yrs	L	**15**	49	-	64		
	A	-	**84**	83	167		
	E	-	-	**84**	84		
	Total	15	133	167	315 (18)	58	0.33*
15 yrs	L	**7**	51	-	58		
	A	-	**59**	47	106		
	E	-	-	**13**	13		
	Total	7	110	60	177 (85)	45	0.06
16+17 yrs	L	**12**	17	-	29		
	A	-	**28**	8	36		
	E	-	-	-	-		
	Total	12	45	8	64 (85)	62	0.28*
Total sample	L	**160**	307	-	467		
	A	-	**418**	479	897		
	E	-	-	**273**	273		
	Total	160	725	752	1637 (194)	52	0.23*

*p<0.01

Table 6. Frequencies of players who had the same maturity status classification based on TW2 and TW3 SAs (Late, Average, Early) and who had a different classification (TW2 Average, TW3 Late; TW2 Early, TW3 Average). Skeletally mature players (n=194) are excluded.

		Maturity Status Classifications					
	TW2:	Late-	Average-	Average-	Early-	Early-	
CA	TW3:	Late	Late	Average	Average	Early	Mat Status
Group	N	n	n	n	n	n	% change
11	290	39	**47**	100	**78**	26	43%
12	376	51	**77**	67	**107**	74	49%
13	414	36	**66**	80	**156**	76	54%
14	315	15	**49**	84	**83**	84	42%
15	177	7	**51**	59	**47**	13	55%
16	54	11	**10**	25	**8**	-	33%
17	11	1	**7**	3	**-**	-	
Total	1637	160	**307**	418	**479**	273	**48%**
% of Total:		10%	**19%**	26%	**29%**	17%	

Supplementary Materials

Supplementary Table 1. Sample size per age group, and sample sizes and descriptive statistics for chronological age (CA), RUS score, TW2 SA and TW3 SA of non-skeletally mature players and for CA of skeletally mature players by age group in each series of youth soccer players

			RUS Score <1000 (not mature)								RUS Score =1000 (mature)		
CA			CA, years		RUS Score		TW2 SA		TW3 SA			CA, years	
Grp	N	n	M	SD	M	SD	M	SD	M	SD	n	M	SD
Portugal A													
11	9	9	11.7	0.2	425	112	12.9	1.5	11.8	1.4			
12	20	20	12.6	0.3	470	104	13.6	1.4	12.4	1.3			
13	6	6	13.7	0.3	760	135	16.1	0.8	15.1	0.9			
14	22	21	14.6	0.3	793	137	16.3	0.9	15.3	0.9	1	14.7	
15	37	22	15.6	0.3	875	95	16.8	0.6	15.8	0.6	15	15.7	0.3
16	30	11	16.3	0.2	947	45	17.3	0.4	16.2	0.2	19	16.6	0.3
17	15	5	17.7	0.2	976	5	17.6	0.1	16.4	0.0	10	17.6	0.2
Portugal B													
11	62	62	11.5	0.3	397	77	12.4	1.4	11.4	1.1			
12	25	25	12.5	0.2	431	96	13.0	1.6	11.9	1.4			
13	80	80	13.6	0.3	574	131	14.7	1.1	13.5	1.2			
14	46	46	14.5	0.3	669	158	15.4	1.1	14.3	1.2			
15	59	42	15.5	0.3	753	129	16.0	0.8	15.0	0.9	17	15.6	0.3
16	35	21	16.4	0.3	779	119	16.2	0.7	15.2	0.8	14	16.6	0.3
17	8	4	17.2	0.1	941	35	17.2	0.4	16.2	0.2	4	17.1	0.1
Belgium A													
11	55	55	11.6	0.3	366	59	11.8	1.4	10.9	1.0			
12	141	141	12.5	0.3	406	70	12.7	1.3	11.6	1.1			
13	140	140	13.5	0.3	476	92	13.7	1.2	12.5	1.1			
14	114	112	14.5	0.3	592	145	14.9	1.2	13.7	1.3	2	14.3	-
15	82	69	15.5	0.3	688	131	15.6	0.8	14.6	0.9	13	15.6	0.2
16	36	14	16.5	0.3	747	130	16.0	0.8	15.0	0.8	22	16.6	0.2

17	4	2	17.3	-	754	-	16.1	-	15.1	-	2	17.3	-
Belgium B													
11	9	9	11.6	0.1	414	46	13.0	0.9	11.8	0.7			
12	10	10	12.5	0.3	431	37	13.4	0.6	12.1	0.5			
13	13	13	13.6	0.3	459	45	13.7	0.6	12.4	0.6			
14	11	11	14.6	0.2	632	138	15.2	1.0	14.1	1.2			
15	10	10	15.5	0.3	768	113	16.1	0.7	15.1	0.8			
16	4	4	16.6	0.2	825	83	16.5	0.5	15.5	0.5			
Spain													
12	6	6	12.8	0.2	532	55	14.5	0.5	13.3	0.6			
13	7	7	13.5	0.4	585	154	14.9	1.0	13.7	1.2			
14	13	13	14.7	0.3	820	111	16.4	0.7	15.5	0.7			
15	10	2	15.7	-	883	146	17.0	-	15.9	-	8	15.6	0.3
16	4	1	16.0	-	833	-	16.5	-	15.3	-	3	16.0	0.04
Italy													
11	33	33	11.5	0.3	360	36	11.8	0.9	10.9	0.6			
12	18	18	12.5	0.2	381	71	12.1	1.4	11.1	1.1			
Mexico													
11	9	9	11.4	0.4	409	158	12.1	2.2	11.3	2.0			
12	10	10	12.5	0.3	458	119	13.3	1.6	12.2	1.5			
13	13	12	13.6	0.3	646	118	15.3	1.0	14.2	1.1	1	13.3	-
14	3	2	14.3	-	788	-	16.3	-	15.3	-	1	14.7	-
15	6	2	15.4	-	788	-	16.3	-	15.3	-	4	15.8	0.1
16	1										1	16.3	-
17	4										4	17.4	0.2
Brazil													
11	13	13	11.6	0.2	388	51	12.4	1.2	11.3	0.9			
12	20	20	12.6	0.2	495	99	14.0	1.0	12.8	1.1			
13	39	38	13.6	0.2	620	119	15.1	0.9	14.0	1.1	1	13.6	-
14	15	12	14.4	0.2	771	144	16.1	0.9	15.1	1.0	3	14.6	0.1

15	8	5	15.2	0.1	787	119	16.2	0.7	15.3	0.8	3	15.2	0.1
Thailand													
12	9	9	12.6	0.2	587	71	14.9	0.6	13.8	0.7			
13	17	17	13.3	0.2	629	151	15.1	1.3	14.0	1.4			
14	18	17	14.4	0.3	778	119	16.2	0.8	15.2	0.8	1	14.3	-
15	12	8	15.2	0.3	799	107	16.3	0.6	15.4	0.7	4	15.5	0.3
16	6	2	16.0	-	696	-	15.7	-	14.7	-	4	16.2	0.1
Japan 1													
11	45	45	11.6	0.3	374	72	11.9	1.6	11.0	1.2			
12	45	45	12.6	0.3	551	112	14.4	1.3	13.3	1.3			
13	35	34	13.5	0.3	613	145	15.0	1.2	13.8	1.3	1	13.9	-
14	31	28	14.4	0.3	752	122	16.0	0.8	15.0	0.8	3	14.8	0.1
15	9	6	15.2	0.3	776	142	16.2	0.9	15.2	1.0	3	15.6	0.2
16	2										2	16.1	-
Japan 2													
11	55	55	11.6	0.3	380	76	12.0	1.6	11.0	1.3			
12	72	72	12.6	0.3	490	145	13.5	1.8	12.4	1.7			
13	70	67	13.5	0.3	674	167	15.4	1.2	14.3	1.3	3	13.8	0.1
14	60	53	14.6	0.3	813	167	16.4	1.2	15.3	1.2	7	14.6	0.3
15	29	11	15.3	0.3	887	106	16.9	0.8	15.9	0.6	18	15.6	0.2
16	1	1	16.0	-	923	-	17.0	-	16.1	-			

Supplementary Table 2. Chronological age (CA), TW2 RUS and TW3 RUS skeletal ages (SA), and the difference of TW3 minus TW2 SAs of players who had the same maturity status classification (Late, Average, Early) and a different classification (TW2 Average, TW3 Late; TW2 Early, TW3 Average) with the two methods. Skeletally mature players (n=194) are excluded.

CA Group		Late-Late n	Late-Late M	Late-Late SD	Average to Late n	Average to Late M	Average to Late SD	Average-Average n	Average-Average M	Average-Average SD	Early to Average n	Early to Average M	Early to Average SD	Early-Early n	Early-Early M	Early-Early SD
11	CA	39	11.58	0.30	47	11.62	0.24	100	11.49	0.30	78	11.57	0.27	26	11.58	0.31
	TW2 SA		9.84	0.66		11.01	0.40		11.88	0.53		13.35	0.48		14.59	0.55
	TW3 SA		9.50	0.50		10.30	0.28		10.89	0.35		12.00	0.43		13.36	0.67
	TW3 – TW2		-0.34	0.18		-0.71	0.12		-0.99	0.18		-1.35	0.08		-1.23	0.13
12	CA	51	12.47	0.27	77	12.51	0.27	67	12.50	0.25	107	12.55	0.30	74	12.63	0.24
	TW2 SA		10.57	0.68		12.20	0.44		13.11	0.44		14.10	0.48		15.27	0.45
	TW3 SA		10.00	0.47		11.11	0.30		11.79	0.35		12.77	0.56		14.18	0.53
	TW3 – TW2		-0.57	0.21		-1.10	0.14		-1.32	0.10		-1.33	0.09		-1.09	0.08
13	CA	36	13.50	0.32	66	13.54	0.28	80	13.55	0.26	156	13.50	0.31	76	13.56	0.28
	TW2 SA		11.89	0.46		13.37	0.46		14.26	0.30		15.01	0.41		16.34	0.64
	TW3 SA		10.90	0.31		12.01	0.40		12.95	0.36		13.87	0.50		15.37	0.65
	TW3 – TW 2		-1.00	0.15		-1.35	0.08		-1.31	0.06		-1.14	0.09		-0.97	0.11
14	CA	15	14.59	0.26	49	14.46	0.27	84	14.45	0.30	83	14.51	0.31	84	14.58	0.29
	TW2 SA		12.97	0.56		14.17	0.45		15.10	0.29		15.96	0.43		17.08	0.50
	TW3 SA		11.68	0.43		12.85	0.51		13.98	0.33		14.99	0.51		16.05	0.36
	TW3 – TW2		-1.29	0.13		-1.32	0.08		-1.11	0.06		-0.97	0.09		-1.02	0.19
15	CA	7	15.81	0.08	51	15.53	0.27	59	15.51	0.30	47	15.45	0.30	13	15.06	0.09
	TW2 SA		14.56	0.42		15.12	0.30		16.11	0.41		16.87	0.36		17.42	0.31
	TW3 SA		13.31	0.51		14.00	0.35		15.15	0.48		15.95	0.29		16.30	0.11
	TW 3 – TW2		-1.25	0.09		-1.12	0.06		-0.95	0.08		-0.93	0.10		-1.13	0.20

16	CA	1116.56	0.29	1016.38	0.29	2516.39	0.29	816.17	0.05	-
	TW2 SA	15.29	0.29	15.83	0.40	16.73	0.33	17.58	0.11	
	TW3 SA	14.21	0.34	14.84	0.47	15.83	0.32	16.40	0.03	
	TW3 – TW2	-1.08	0.05	-0.99	0.07	-0.90	0.05	-1.18	0.08	
17	CA	117.33		717.54	0.28	317.16	0.18	-		-
	TW2 SA	15.60		17.30	0.43	17.41	0.41			
	TW3 SA	14.55		16.23	0.28	16.31	0.18			
	TW3 – TW2	-1.05		-1.07	0.17	-1.09	0.24			

Supplementary Table 3. Heights and weights of players who had the same maturity status classification with TW2 and TW3 (late, average, early, mature) and a different maturity status classification with each method (TW2 average, TW3 late; TW2 early, TW3 average).[†]

		Maturity Status Classifications															
Age		Late-Late			Average to Late			Average-Average			Early to Average			Early-Early			Ma…
Grp		n	M	SD	n	M	SD	n	M	SD	n	M	SD	n	M	SD	n
Height, cm																	
11	289	39	141.1	6.1	47	143.3	5.3	100	145.7	5.8	78	149.6	6.1	25	151.6	7.5	
12	370	51	145.2	5.7	74	150.3	5.4	65	152.0	5.4	107	155.7	6.4	73	162.4	5.6	
13	418	35	151.7	7.3	66	154.9	5.9	80	158.6	6.0	155	163.1	7.2	76	166.7	6.9	6 16…
14	333	15	156.5	5.3	49	162.4	8.0	84	167.5	6.6	83	170.9	7.0	84	171.0	6.5	18 17…
15	259	7	164.8	4.7	51	170.3	7.8	58	172.7	5.5	46	174.6	5.7	13	171.4	4.9	84 17…
16	118	11	172.7	6.6	10	172.6	9.2	25	174.8	6.8	8	174.9	4.9		-		64 17…
17	31	1	175.2	-	7	179.3	6.8	3	178.1	4.2		-			-		20 17…
Weight, kg																	
11			33.4	3.0		35.0	4.4		37.3	4.9		40.0	5.7		43.4	5.4	
12			36.1	4.7		39.4	5.2		40.9	5.2		44.9	6.2		51.5	6.0	
13			39.4	4.3		42.6	6.4		45.6	5.5		51.0	7.0		56.9	7.4	6…
14			42.1	3.9		48.5	7.9		54.2	6.9		59.0	8.0		61.4	7.4	6…
15			50.5	3.8		56.2	8.5		60.5	7.0		65.1	7.2		62.3	6.9	6…
16			58.6	6.2		58.8	12.0		65.7	7.6		64.5	4.5		-		6…
17			58.8	-		67.9	8.7		73.2	4.8		-			-		6…

[†] Numbers per maturity group are the same as in Table 5 with the exception that height and weight were not available for 13 players: 11 yrs (1), 12 yrs (6), 13 yrs (2), 15 yrs (3), 16 yrs (1).