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ORIGINAL RESEARCH ARTICLE

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

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Abstract

Background The Tanner–Whitehouse radius-ulna-short bone protocol (TW2 RUS) for the assessment of skeletal age (SA) is widely used to estimate the biological (skeletal) maturity status of children and adolescents. The scale for converting TW RUS ratings to an SA has been revised (TW3 RUS) and has implications for studies of youth athletes in age-group sports.

Objectives The aim of this study was to compare TW2 and TW3 RUS SAs in an international sample of male youth soccer players and to compare distributions of players by maturity status defined by each SA protocol.

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

Results For the same RUS score, TW3 SAs were systematically and substantially reduced compared with TW2 SAs; mean differences by CA group ranged from − 0.97 to

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− 1.16 years. Kappa coefficients indicated at best fair concordance of TW2 and TW3 maturity classifications. Across the age range, 42% of players classified as average with TW2 SA were classified as late with TW3 SA, and 64% of players classified as early with TW2 SA were classified as average with TW3 SA.

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

Key Points

Skeletal ages (SA) based on the most recent version of the Tanner–Whitehouse radius, ulna, short bone protocol (TW3 RUS SA) were systematically lower than SAs with the earlier version (TW2 RUS SA) in male youth soccer players aged 11–17 years. Mean differences of TW3 minus TW2 SAs by age groups ranged from − 0.97 to − 1.16 years.

The difference between protocols has implications for player classifications by maturity status. Across the age range 11–17 years, 42% of players classified as average with TW2 SA were classified as late with TW3 SA, and 64% of players classified as early with TW2 SA were classified as average with TW3 SA.

Observations based on TW3 SAs and the shift from average to late and from early to average status contrasted with maturity classifications of male youth soccer players based on other commonly used methods of SA assessment (Fels and Greulich–Pyle), which were generally consistent with TW2 SAs.

Given the secular increase in heights of youth soccer players without a change in estimated age at peak height velocity between 1978 and 2015, a negligible change in SA–chronological age (CA) relationships among players aged 11–15 years in studies spanning the early 1980s through 2013 using the TW2, Greulich–Pyle and Fels methods, and the selectivity of the sport in favor of more mature players during adolescence, TW2 RUS SA is the method of choice for those using the TW protocol with youth soccer players.

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1 Introduction

Skeletal age (SA) is commonly used to estimate 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 for assigning an SA, 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 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 seven carpals excluding the pisiform [13]. The first revision, TW2 [14], did not modify the criteria for specific maturity indicators. However, the final stages of the radius, ulna, and several carpals were eliminated as they were viewed as difficult to rate; accordingly, the assigned scores were modified. Sex-specific scores for each bone were assigned. The revision also provided for three SAs based, respectively, on the 20 bones (TW2 20 Bone SA), the seven 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 SA) and Carpal SA (TW3 Carpal SA), but eliminated the 20 Bone SA. The criteria for maturity indicators and assigned scores for each bone were not modified with TW3. Tables for converting the sum of maturity scores for the seven carpal bones to an SA were also not modified, but 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 during 1985–1995, was of European ancestry (White) and from a well-off community in the Houston region in the state of Texas [22]. Two other modifications in the TW3 revision were made. TW3 RUS SAs were scaled downward beginning at about 10 years of age, and ages at attaining skeletal maturity (RUS score of 1000) were lowered from 18.2 to 16.5 years in boys and from 16.0 to 15.0 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].

Maturity assessments among male 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 RUS SAs were lower than Fels SAs in elite Spanish 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 with TW3 SAs [26, 27] contrasted maturity classifications of 14-year-old soccer players using TW2, Fels, and GP SAs [10, 28].

In this context, our study had two purposes: first, to compare TW2 and TW3 RUS SAs in an international sample of male youth soccer players 11–17 years of age; and, second, to compare maturity status classifications and distributions of players with each method. The latter is relevant as maturity status is central to development and selection programs in soccer among youth 11–15 years of age, an interval when inter-individual variation in maturity status is considerable [29, 30]. Inter-individual variation in maturity status is also central to individualizing training protocols [31, 32] and to efforts aimed at equalizing competitions within and among CA groups of youth [33, 34].

2 Methods

2.1 Available Series of Male Youth Soccer Players

TW2 and/or TW3 RUS SAs were available from several existing databases that included a total of 1831 male soccer players 10.93 to 17.94 years of age from eight countries (Table 1).

(a) Two series from Portugal—A: 139 players aged 11.14–17.94 years from national and regional youth teams surveyed in 1997–1998 [35, 36]; and B: 315 players aged 10.98–17.26 years from clubs in the Aveiro and Coimbra regions surveyed in 2003–2007 [30, 37].
(b) Two series from Belgium—A: a mixed-longitudinal sample of 572 players aged 11.0–17.58 years from several clubs in Flanders surveyed in 1996–2001 [29, 38]; and B: a sample of 57 players aged 11.42–16.84 years from clubs in the Ghent region surveyed in 2013 [39].
(c) Forty players aged 12.51–16.07 years from an elite club in Madrid, Spain, surveyed in 2001–2002 [24].
(d) Fifty-one players aged 10.93–12.72 years from an elite club in Torino, Italy, surveyed in 2002 [10].
(e) Two series J league players in Japan—A: 287 players aged 11.0–16.0 years surveyed in 1997–1999 [40, 41], and B: 167 players aged 11.0–16.10 years surveyed in 2000–2005 [25].
(f) Sixty-two players from a sport school for soccer in Khon Kaen, Thailand, aged 12.25–16.42 years, surveyed in 2009 [42].
(g) Forty-six players aged 10.95–17.68 years from clubs in two cities in the northern states of Durango and Nuevo Leon, Mexico, surveyed in 1982 [43].
(h) Ninety-five players aged 11.35–15.41 years from clubs in the state of Santa Catarina, Brazil, surveyed in 2011 [44].

The 11-year-old sample included four players aged 10.93–10.99 years. The majority of players participated at the club level. Many players 13 years and older were members of both club and regional teams, and a number were regional and national selections. The Thai sport school sample competed regionally and nationally.

2.2 Skeletal Age

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 the Portuguese, Spanish, Mexican, and Brazilian players and the smaller Belgian sample were assessed by the first author (RMM) and/or several students whom he supervised (MEPR, MJCS, AJF). Radiographs of the Italian and Thai players, the larger Belgian sample, and the two Japanese samples 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 referred to as TW2 SA and TW3 SA. As 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

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

CA group (years)	Portugal		Belgium		Spain	Italy	Mexico	Brazil	Thailand	Japan		Total
	A	B	A	B						A	B	
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

Sources of all samples are indicated in the "Methods" section

respective tables, and vice versa. An SA was not assigned to individuals with an RUS score of 1000 (maturity). The players were skeletally mature at the time of observation, but the CA at which maturity was reached was not known. The number of skeletally mature players is indicated by CA group in the results.

Allowing for variation in procedures for obtaining ethical approval, the appropriate university committees or agencies, participating clubs, and/or schools approved the studies from which each sample was extracted. 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 temporal 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], while the establishment of formal institutional review committees was variable in timing and scope among countries and universities.

2.3 Descriptive Statistics

Sample sizes and descriptive statistics for CA, RUS score, TW2 RUS SA (TW2 SA) and TW3 RUS SA (TW3 SA) of non-skeletally mature players and for CA of skeletally mature players in each series are provided by whole year CA groups (i.e., 12 years = 12.0 to 12.99 years, etc.) in Supplementary Table 1. The 11 series were combined for analysis; as noted, four players, 10.93–10.99 years, were included in the 11 year old sample. Descriptive statistics (means, standard deviations, also medians for SA variables) for non-mature players were calculated by CA group for the RUS score, TW2 SA and TW3 SA. Corresponding statistics were calculated for the difference of SA minus CA for both TW2 and TW3 SAs, and for the difference of TW3 SA minus TW2 SA. Differences between TW2 and TW3 SAs and of SA minus CA with each method were compared with paired *t* tests within CA groups.

2.4 Maturity Status Classification

The difference of SA minus CA with both TW2 SA and TW3 SA was used to classify players into four maturity groups as follows: average (on time), SA $\pm$ 1.0 year of CA; late (delayed), SA younger than CA by $>$ 1.0 year; early (advanced), SA older than CA by $>$ 1.0 year; and skeletally mature (simply noted as such). The classification criteria for average, late, and early maturing players were the same as used in previous [46, 47] and more recent [10] studies. The band of $\pm$ 1.0 year approximated standard deviations of SA within single-year CA groups of boys aged 11–17 years in the general population; such as 0.92–1.41 years in a national sample of American boys aged 12–17 years [48], 0.86–1.28 years in boys from the Harvard School of Public Health Study [49], and 0.96–1.24 years in boys aged 12–16 years from the Fels study [17]. Standard deviations of about 1 year were also indicated for TW2 and TW3 SAs among boys aged 5–16 years, but specific values were not reported [15, 16].

The band of $\pm$ 1.0 year, though widely used, is somewhat arbitrary. Narrower ranges have been used, such as a band of $\pm$ 3 months among adolescent boys and girls [50] and a band of $\pm$ 0.5 years in elite soccer players 14 years of age [26]. The narrower bands may be within the range of standard errors of SA assessments, but only the Fels method provides an estimate of error associated with assessments. For example, standard errors ranged from 0.27 to 0.42 year (median 0.30) in 159 soccer players aged 11–14 years [37], 0.27 to 0.47 year (median 0.34) in 38 players aged 12–16 years [24], and 0.27 to 0.70 year (median 0.35) in players aged 11–17 years [35]. Higher errors were generally noted in youth approaching skeletal maturity. The band of 1 year thus allows for errors associated with assessments. In contrast, a band of ± 2.0 years is commonly used to define 'normal' in the clinical context.

Concordance of maturity status classifications based, respectively, on TW2 and TW3 SAs within CA groups and the total sample was evaluated with Cohen's Kappa coefficient [51]. Descriptive statistics for the CA, SA, height, and weight of players who had the same maturity classification and who changed classification with TW2 SAs and TW3 SAs were calculated; heights and weights of players were compared with ANOVA.

3 Results

Mean TW2 SAs and TW3 SAs for players in each series (Supplementary Table 1) are plotted by mean CAs in Figs. 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 older players. The plot of mean TW3 SAs versus mean TW2 SAs illustrates the systematic reduction in TW3 SAs relative to TW2 SAs (Fig. 3).

Sample sizes and descriptive statistics for CA and the RUS score of non-mature players and for CA of skeletally mature players are summarized by CA group for the total sample in Table 2. Note, the same players are identified as mature with TW2 and TW3 (RUS score = 1000). Mature players range in CA from 13.30 to 17.94 years and numbers increase with CA from 13 to 17 years.

Corresponding statistics for TW2 SAs and TW3 SAs, SA minus CA (SA–CA) with each method, and the difference of TW3 SA minus TW2 SA 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 1 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 aged 11–13 years, is equivalent to CA at 14 years, and lags behind CA at 15 and 16 years. On the other hand, TW2 SA is in advance of CA from 11 through 15 years and then approaches zero (Fig. 4). The SA–CA difference for TW2 and TW3 within each CA group is significant ($p < 0.001$). SA–CA differences among players aged 15–17 years are influenced by the upper limit of assigned SAs with each method, and the increasing number of skeletally mature players with age.

Absolute and relative frequencies of players classified as late, average, and early maturing with TW2 SAs and TW3 SAs are summarized in Table 4. Percentages of players classified as late maturing with TW 2 SA decline, while percentages of players classified as early maturing and mature increase with CA. 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 with TW2 SA, percentages of players aged 11–14 years classified as average with TW3 SA increase while percentages of players aged 11–15 years classified as early maturing with TW3 SA decrease. Across all ages and excluding skeletally mature players, 10, 44, and 46% of players are classified, respectively, as late, average, and early maturing with TW2 SAs, while 28, 55, and 17% are classified, respectively, as late, average, and early maturing with TW3 SAs.

Concordance of maturity status classifications based on TW2 and TW3 SAs (excluding skeletally mature players) ranges from 45% (13 years) to 62% (16–17 years); concordance 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 indicates, at best, fair concordance [51].

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

4 Discussion

As expected with the modification in assigning SAs for RUS scores in the most recent revision of the TW RUS method [16], TW3 SAs were systematically lower than TW2 SAs in male youth soccer players aged 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 with the TW2 version of the method.

Studies of two independent samples of elite male youth soccer players applied the TW3 protocol. Among 48 Serbian players, 14.5 ± 0.3 years of age, the estimated TW3

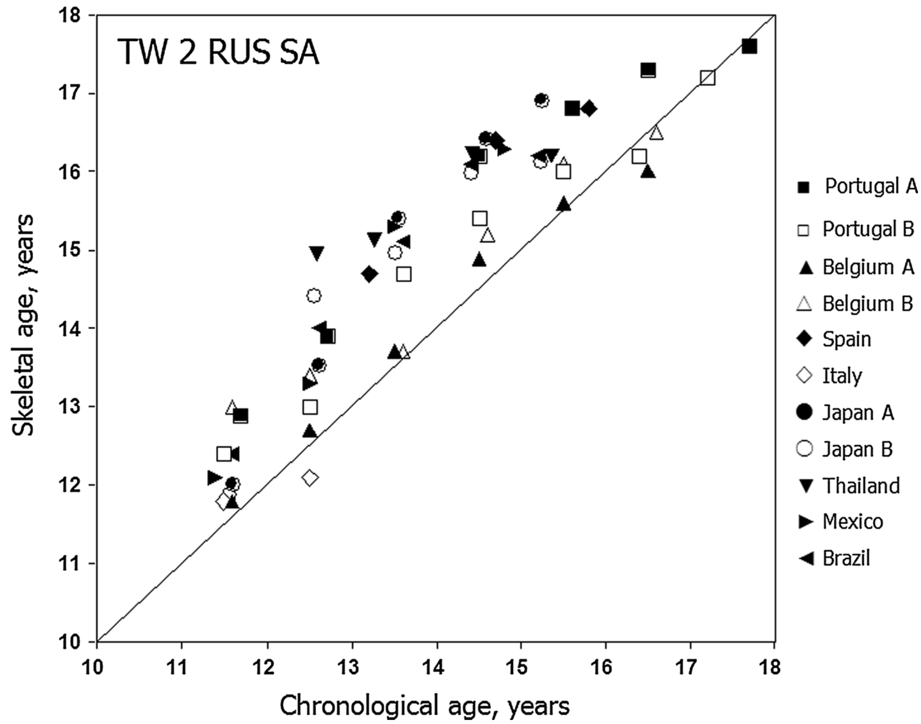

Fig. 1 Mean Tanner–Whitehouse radius-ulna-short bone protocol–first revision (TW2 RUS) skeletal ages (SAs) plotted relative to mean chronological ages by age group in each of the 11 samples

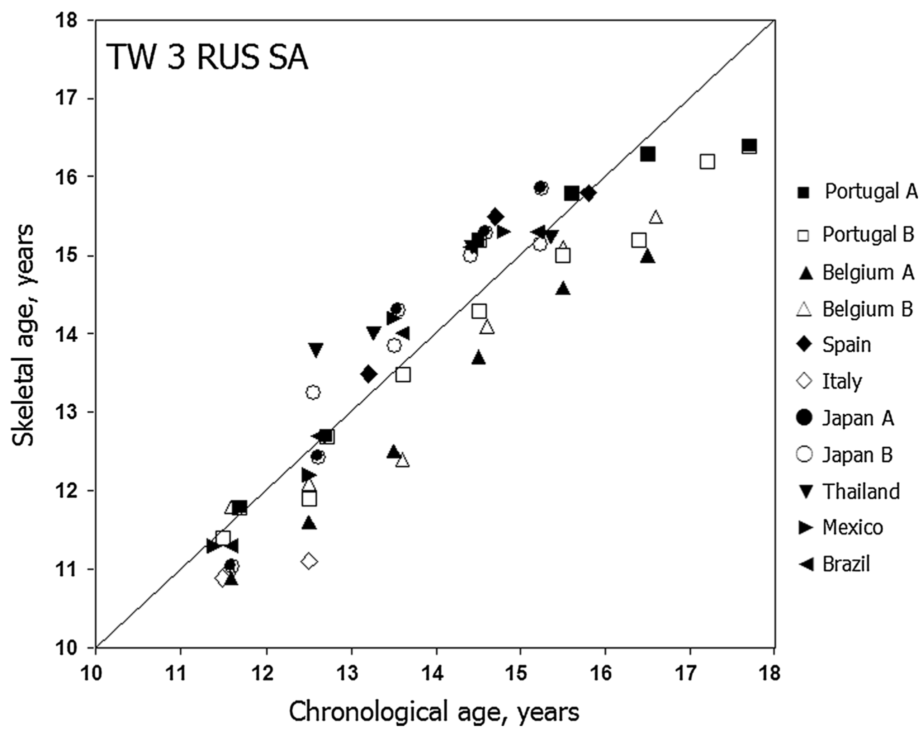

Fig. 2 Mean Tanner–Whitehouse radius-ulna-short bone protocol–second revision (TW3 RUS) skeletal ages (SAs) plotted relative to mean chronological ages by age group in each of the 11 samples

SA derived from mean SAs for early, average, and late maturing players was 14.7 years [26]. Among 119 Swiss players, mean CA and TW3 SA were, respectively, 14.0 ± 0.3 and 13.9 ± 1.1 years [27]. Converting the mean TW3 SAs to their respective RUS scores and then to TW2 SAs yielded TW2 SAs of 15.5 and 15.0 years in the Serbian and Swiss players, respectively. The results were consistent with TW3 SAs and TW2 SAs in 13- and 14-year-old players in this study (Table 3).

Similar differences (i.e., consistently lower TW3 SAs than TW2 SAs) were also noted in a sample of non-athlete boys aged between 11 and 16 years [18], and in a clinical

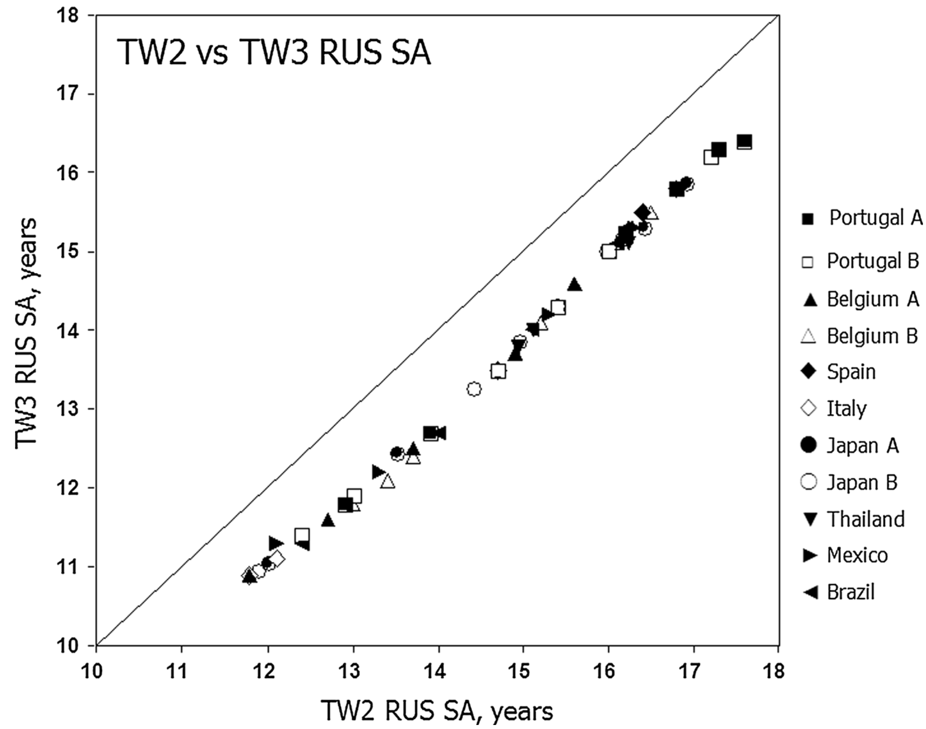

Fig. 3 Mean TW3 RUS skeletal ages (y-axis) plotted relative to mean TW2 RUS skeletal ages (x-axis) in each of the eleven samples. *RUS* radius-ulna-short bone, *SA* skeletal age, *TW* Tanner–Whitehouse protocol

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

CA group (years)	*N*	RUS score < 1000 (not mature)						RUS score = 1000 (mature)		
		n	CA (years)		RUS score			*n*	CA (years)	
			M	SD	M	SD	Md		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
Total	1831	1637	13.47	1.40				194	15.96	0.89

CA chronological age, *M* mean, *Md* median, *RUS* radius-ulna-short bone, *SD* standard deviation

series of Italian boys aged 10–16 years [52] and Brazilian boys aged 10–15 years [53]. Similar trends in mean TW3 and TW2 SA were also apparent in a clinical series of boys combined across several ages, such as early and late maturing boys aged 9–16 years [54] and boys with idiopathic short stature/constitutional growth delay (11.3 ± 0.7 years) and with congenital adrenal hyperplasia (9.9 ± 0.6 years) [55].

4.1 Why TW3?

The rationale for assigning lower SAs for the same RUS score with TW3 compared with TW2 was to accommodate secular change [16, p. 19, italics ours]:

> "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

Table 3 Descriptive statistics for CA, TW2 and TW3 RUS SAs, 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 group (years)	*N*	CA (years)		TW2 SA (years)			TW3 SA (years)			TW2 SA–CA (years)			TW3 SA–CA (years)			TW3 SA–TW2 SA (years)				
		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

CA chronological age, *M* mean, *Md* median, *RUS* radius-ulna-short bone, *SA* skeletal age, *SD* standard deviation, *TW* Tanner–Whitehouse protocol

European-derived populations) in recent years, and here renamed TW3."

Many reasons have been postulated for secular trends towards larger body size and earlier maturation; most have focused on improved living conditions reflected in environmental quality, overall public health, and nutritional circumstances [4, 7].

Although secular changes in height are evident in early childhood and continue through puberty [6, 7, 16, 56], modifications in SAs assigned to the same RUS maturity scores in boys (i.e., lower SA for the same maturity score with TW3) were only apparent beginning with SAs of about 10 years. More importantly, secular increases in height were not necessarily accompanied by accelerated maturation between 1960 and 1980 in Belgium [57, 58] and between 1980 and 1997 in the Netherlands [59].

Two questions, and perhaps others, of relevance to the rationale 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 timing and status, and in height over the past 50 years or so? And second, what is the evidence for corresponding secular changes in maturity timing and status, and in height of youth soccer players? Maturity timing refers to the CA at which a specific maturational event occurs; for example, age at peak height velocity (PHV), age at menarche, or age at attaining a specific RUS score, whereas maturity status refers to the state or level of maturation at the time of observation; for example, SA or stage of secondary sex characteristic development.

4.2 Maturity Timing

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.

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

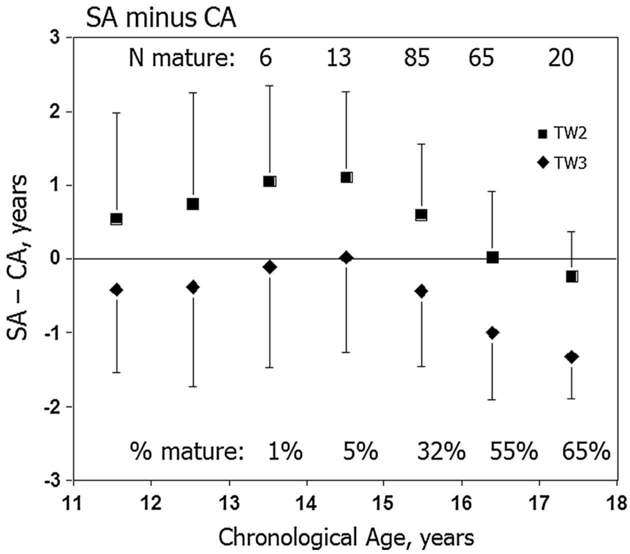

Fig. 4 Mean differences and standard deviations for skeletal age minus chronological age with TW2 and TW3 SAs by chronological age groups. The number and percentage of skeletally mature players by chronological age group are also included. *CA* chronological age, *SA* skeletal age, *TW* Tanner–Whitehouse protocol

1960s through 1980s [62], while ages at PHV among Japanese youth born in the 1960s through early 1980s changed negligibly [63, 64].

Variation in estimated SA at PHV is generally reduced compared with estimated CA at PHV. For example, means and standard deviations for estimated CA and SA at PHV in several longitudinal samples of boys were, respectively, 14.1 ± 1.1 and 14.0 ± 0.5 years (Poland, TW2 RUS SA) [65], 14.0 ± 0.9 and 13.3 ± 0.6 years (Switzerland, TW3 RUS SA) [66], 13.9 ± 1.1 and 13.4 ± 0.8 years (Switzerland, GP SA) [67], and 12.5 ± 1.1 and 12.9 ± 0.6 years (Japan, TW2 RUS SA standardized for Japanese children) [68]. SAs at PHV were generally estimated by linear interpolation. The evidence for Swiss boys also indicated an adolescent spurt in TW3 RUS SA; modeling longitudinal records for SAs of individual boys indicated a spurt in SA at an estimated CA of 14.2 ± 1.2 years [66].

Estimates of age at PHV in male soccer players are limited. Two earlier studies were focused on active and less active boys; the former were regularly active in soccer although level of competition and intensity of training were not indicated. The studies included 32 Welsh players followed 12–15 years [69] and 8 Danish players followed 11–16 years [70]. Mean ages at PHV were identical in both studies, 14.2 ± 0.9 years. The players were born in the 1970s; 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 [71]. 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 in 18 players. SA at initial observation 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 [71].

Mean ages at PHV for the three studies of soccer players were within the range of ages at PHV in longitudinal studies of European boys [7]. The studies of soccer players, however, highlight a limitation of many longitudinal studies of athletes; they often started too late and concluded too early [72]. Sampling variation per se and differential

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 RUS SAs. Frequencies and percentages of skeletally mature players are the same with each method

CA group (years)	*N*	TW2 RUS SA						TW3 RUS SA						Mature	
		Late		Average		Early		Late		Average		Early			
		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

CA chronological age, *RUS* radius-ulna-short bone, *SA* skeletal age, *TW* Tanner–Whitehouse protocol

Table 5 Cross-tabulation of maturity status classifications based on TW2 and TW3 SAs, percentage agreement and Cohen's Kappa coefficients by CA group

CA group (years)	Maturity status classification					Agreement*	
	TW3 RUS SA	TW2 RUS SA				%	Kappa
		L	A	E	Total		
11	L	**39**	47		86		
	A		**100**	78	178		
	E			**26**	26		
	Total	39	147	104	290	57	0.30*
12	L	**51**	77		128		
	A		**67**	107	174		
	E			**74**	74		
	Total	51	144	181	376	51	0.28*
13	L	**36**	66		102		
	A		**80**	156	236		
	E			**76**	76		
	Total	36	146	232	414 (6)	46	0.21*
14	L	**15**	49		64		
	A		**84**	83	167		
	E			**84**	84		
	Total	15	133	167	315 (18)	58	0.33*
15	L	**7**	51		58		
	A		**59**	47	106		
	E			**13**	13		
	Total	7	110	60	177 (85)	45	0.06
16 + 17	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*

The bold values indicate concordant classifications

Skeletally mature players ($n = 194$) are excluded; numbers of mature players are indicated in parentheses

A average, *CA* chronological age, *E* early, *L* late, *RUS* radius-ulna-short bone, *SA* skeletal age, *TW* Tanner–Whitehouse protocol

*$p<0.01$

persistence, exclusion, and/or dropout are additional important considerations.

Estimated ages at PHV based on the application of Preece–Baines model 1 [73] to cross-sectional mean heights of soccer players aged 9–18 years reported in studies from 1978 through 1999 and from 2000 through mid-2015 differed negligibly, 13.01 and 12.91 years, respectively [74]. Although earlier than available estimates for the relatively small samples of soccer players [69–71], the estimated ages at PHV were in the range of mean ages at PHV for early and average maturing boys in longitudinal studies; for example, 12.15 ± 0.43 and 13.75 ± 0.54 years, respectively, in American boys [62] and 12.57 ± 0.41 and 13.97 ± 0.52 years, respectively, in Polish boys [75]. The estimated ages at PHV of players based on the cross-sectional data were also consistent with distributions of players aged 11–15 years by maturity status based on Fels and GP SAs [10] and TW2 SAs (Table 4); that is, proportionally more average and early maturing than late maturing players. In contrast, the distribution of players by TW3 SA was reversed; that is, proportionally more late and average maturing players and markedly fewer early maturing players.

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)

CA group (years)	*N*	Protocol	Maturity status classifications					Maturity status % change
		TW2 TW3	Late Late *n*	Average Late *n*	Average Average *n*	Early Average *n*	Early Early *n*	
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
% Total			10	19	26	29	17	

Skeletally mature players ($n = 194$) are excluded

CA chronological age, *SA* skeletal age, *TW* Tanner–Whitehouse protocol

Allowing for limitations of modeling cross-sectional data, the negligible change in the estimated ages at PHV across time likely reflected two features of talent development programs in soccer beginning at about 12–13 years of age. First, the sport generally favors the persistence and/or systematic selection and retention of players of average and advanced maturity status, and second, the sport encourages the differential dropout, either voluntary or systematic as in ‘cutting’, of later and some average maturing players [74].

4.3 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 aged 7–16 years in 1986 and 1996 indicated no changes in heights and TW2 RUS maturity scores over the decade [76]. Moreover, 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 [76]. Among Portuguese boys and girls aged 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 [77].

Studies reporting the skeletal maturity status of male youth soccer players date to the 1980s. Studies of Belgian [78], Japanese [79, 80], and Mexican [43] players aged 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 aged 13–14 years [43]. Among elite Spanish club players in the late 1980s/early 1990s, mean SAs with a modification of the original TW method [81] approximated CAs at 12–13 years, were in advance of CAs at 14–15 years, and approximated CA at 16–17 years [82]. It was not indicated, however, if any older players were skeletally mature. Players aged 14–16 years were also advanced in stage of genital development and testicular volume.

Among Italian players in the late 1980s [83] and Portuguese players in the late 1990s [36], mean GP SAs approximated mean CAs among players aged 11–13 years, and were in advance of CAs among players aged 14–15 years. Advanced SAs in older players were consistent with advanced testicular volume in the Italian [84] and stages of genital and pubic hair in the Portuguese [36] players. The observations for pubic hair were consistent with other samples of adolescent players [72], while those for testicular volume [82, 84] 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 [85]. Moreover, mean GP SAs of youth players aged ~ 13 years on entry to a select club in France between 1992 and 2003 did not differ significantly across the decade [86]; SA was, on average, slightly in advance of CA.

Though limited and allowing for variation among methods and in sampling, the data for youth soccer players showed little change in skeletal maturity status from the early 1980s through the 1990s. SA approximated CA, on average, among players aged 10–12 years, and the pattern of advanced SA emerged among players aged 13–14 years. The same trend was apparent in a compilation of Fels SAs for Portuguese, Spanish, and Mexican youth players [10] and was suggested for Fels SAs in mixed-longitudinal samples of youth players from an English Premier League academy and a Middle Eastern sports academy [87].

Samples used in the present analysis, with one exception (Mexican players), were surveyed from the mid-1990s through 2013. The overlap among mean SAs, respectively, for TW2 and TW3, in players of the 10 series from seven countries suggested negligible change in skeletal maturity status over about 20 years (Figs 1 and 2). TW2 and TW3 SAs, however, differed significantly; TW3 SAs were delayed relative to TW2 SAs by about 1 year across the age range (Table 3). TW2 SAs were, on average, in advance of CA by about 0.5 years at 11 years of age; the difference increased systematically with age reaching 1.1 years at 14 years and then declined to 0.6 years at 15 years (Fig. 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 aged 15–17 years limits interpretations of SA–CA differences at these ages.

The SAs of players aged 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, some youth were classified as mature (fusion has begun), even though the epiphysis and diaphysis of the radius or ulna, especially the radius, was still in the process of fusing. It was thus possible that significant numbers of players aged 15–17 years classified as 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 soccer players aged 13 ($n = 106$) and 14 ($n = 84$) years, one and two, respectively, were classified as mature with TW but not with Fels. Among players aged 15 ($n = 112$), 16 ($n = 70$), and 17 ($n = 27$) years, 35, 23, and 8, respectively, were classified as mature with TW but not with Fels; only 9, 14, and 10, respectively, were classified as mature by both methods (Malina, unpublished). Among a sample of male non-athletes aged 14 ($n = 23$), 15 ($n = 20$), and 16 ($n = 10$) years whose SA was assessed with the GP, TW2, TW3, and Fels methods, more were classified as skeletally mature with TW (one each at 14 and 15 years, five at 16 years) compared with GP (two at 16 years) and Fels (one at 16 years) [18].

4.4 Height

Secular gains in height of European youth were marked for several decades after World War II, but have since slowed or stopped in many countries [7, 88–90]. 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 US youth since the 1960s [91, 92].

In contrast, a comparison of heights of soccer players (largely from Europe and the Americas) aged 9–18 years reported in studies from 1978 through 1999 and from 2000 through 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 [74]. In addition to improved general health and nutritional status over time, other factors contributing to secular gains in youth soccer players likely reflected improved conditions in soccer clubs and increased selectivity of the sport, specifically during the adolescent transition [74].

4.5 Implications of Changes With TW3

The maturity status of youth athletes is a significant factor in talent identification, selection, and development in soccer and other sports. Individual differences in biological maturation per se and size and performance advantages associated with advanced maturity status, specifically measures of strength, power, and speed in males [7], may influence immediate success and/or perceptions of adults who make decisions on youth players.

Given the systematically lower TW3 SA assigned for the same RUS score compared with TW2 SA, adoption of TW 3 will systematically influence classifications of player maturity status (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 classification with both SAs [Late (L–L), Average (A–A), Early (E–E)] and a different classification with TW3 [TW2 Average, TW3 Late (A–L); TW2 Early, TW3 Average (E–A)] are summarized in Supplementary Tables 2 and 3 (see ESM). Heights and weights differed significantly among groups ($p < 0.001$), but there was no clear pattern in mean CAs and differences of TW3 minus TW2 SAs. Overall, players aged 11–15 years whose maturity status changed from A to L had mean heights and weights that were intermediate between players classified as L–L and A–A. Players aged 11–13 years whose status changed from E to A had mean heights and weights that were intermediate between players classified as A–A and E–E. Contrasts among maturity groups at 14, 15, and 16 years were more variable, which reflected in part the exclusion of skeletally mature players. Heights and weights of the latter were 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 which reflected the catch-up of late and average maturing players in late adolescence, consistent with the general growth literature [7].

4.5.1 Coaching and Training Decisions

Coaches are likely not familiar with the details of maturity assessment and variation among methods. They are dependent upon medical and training personnel for information on the maturity status of individual players that may be relevant to decisions regarding player retention, training load, injury risk, and perhaps whether to play a boy ‘up’ or ‘down’ depending upon his maturity status and other developmental considerations.

Youth competitions in soccer and other sports are set within the context of specific CA limits. Modification of the rules to account for individual differences in maturity status within specific CA bands may help to overcome the size, strength, and power advantages associated with earlier maturation in adolescent boys [33, 34]. For example, having skilled, later maturing, chronologically older players compete with and against younger players of similar maturity status (i.e., ‘playing down’) may assist them to develop their potential while giving them time to catch-up biologically with their CA peers. Early maturing younger players may similarly benefit from competitions with chronologically older peers of the same maturity status (i.e., ‘playing up’). Decisions to ‘play down’ or to ‘play up’ depend upon a reliable indicator of maturity status and appropriate CA bands. In the context of the present discussion, the systematic reduction in TW3 SAs relative to TW2 SAs among youth players aged 11–17 years has major implications for maturity classifications (Tables 4 and 6).

Maturity status is often indicated as significant in efforts to individualize training and to identify intervals of readiness and trainability [28–32, 93]. Variable maturity classifications with TW3 compared with TW2 SAs present a dilemma that may lead to confusion and potentially erroneous decisions on when to start specific training protocols and/or to adjust training loads. Among players aged 11–14 years, for example, strength training protocols may focus on core stability and basic strength for late maturing players and 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.

4.5.2 Risk of Injury

Maturity status is often indicated as a potential risk factor for injury, but relationships between maturity status and injury in soccer are not firmly established. Fels and GP SAs per se were not associated with the incidence of injury in elite players aged 9–16 years [94] and elite U-14 players [95]. Pubertal status also was not related with the incidence of injury in a mixed-longitudinal sample of players aged 8–15 years [96]. Among the elite players aged 9–16 years, however, skeletal maturity status, playing time, and training time together accounted for 48% of the variance in the incidence of injury [94]. By inference, interactions among maturity status, training load, and playing time may influence injury risk in youth players. Moreover, decisions regarding training load and playing time are made by coaches and trainers who, as noted, may not be familiar with the maturity status of individual players.

Relatively little is known about the growth and maturity status of youth who are injured, although size and maturity characteristics of youth athletes are often indicated as potential risk factors for injury. Among 200 youth players training and competing at the club level, 22 had epiphyseal injuries during a season [97]; complete records including SA [21] and stages of pubic hair and genital development were available for 11 of these players aged 12.2–15.7 years. Injured players were delayed in skeletal and pubertal maturation. Nine players had SAs ranging from 12 to 27 months less than their respective CAs, which would categorize them as late maturing.

Proportionally more acute injuries were noted among male soccer camp participants classified as ‘tall and weak’ (labeled ‘skeletally mature but muscularly weak’, 24.8%) compared with players classified as ‘tall and strong’ (‘mature’, 17.3%) or ‘short and weak’ (‘immature’, 13.5%) [98]. Biological maturity status was not assessed. Height and grip strength were measured, and it was assumed that height was related to stage of puberty. The assumption does not allow for individual differences in actual maturity status, the differential timing of growth spurts in height and strength, and genotypic differences in height [7, 28].

The adolescent growth spurt is also indicated as a risk factor for injury. The spurt, however, is not a single point in time. Acceleration in growth rate marks the start of the spurt (take-off); the rate continues to increase to a maximum (age at PHV) which is followed by deceleration in rate until growth in height ceases. Body segments (foot and leg length, sitting height), bone mineral, muscle mass, muscular strength and power also have growth spurts which vary in timing relative to PHV [7]. Behavioral changes during adolescence may be a related factor in injury risk [93]. Hence, what is unique about the adolescent spurt that places some youth at risk for injury?

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 in youth soccer players to the growth spurt are limited. Among youth players, 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 the U-10 to U-14 ($\sim$ 84%) and U-12 to U-16 ($\sim$ 87%) competitive age groups, respectively [99]. 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" [99, p. 469–470]. Specific growth spurts were not identified, although the two inflammatory conditions are often attributed to rapid growth of the foot, lower leg (tibia), and thigh (femur) that occurs early in the male adolescent spurt [7].

Maturity status based on predicted age at PHV was related to injuries among 26 soccer players aged 11.9 ± 0.84 years at initial selection, followed for 3 years [100]. Numbers of traumatic and overuse injuries per player were, on average, lower among pre-PHV players, but did not differ between players at-PHV and post-PHV. Subsequent analysis suggested an increase in overuse injuries among players with an older age at PHV [101]. Although interesting, the results must be evaluated in the context of the limitations of the equations used to predict time before PHV (maturity offset) and in turn age at PHV. Predicted ages at PHV with the original and modified equations increased with CA and likely size at prediction, had a reduced range of variability, were consistently overestimated in early and underestimated in late maturing boys, and showed considerable intra-individual variation [62, 75, 102].

4.5.3 Ethnic Variation

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 European/European Americans (as well as other European-derived populations) … and (were) here renamed 'TW3'" [16, p. 19]. The CAs at which specific RUS scores were attained by Japanese boys from Tokyo [103] 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 youth soccer players aged 12–15 years from Japan and Thailand were often in advance of corresponding means for players from European and Latin American countries [Figs. 1 and 2, Supplementary Table 1 (see ESM)].

Potential variation associated with ethnicity is 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 [104]. However, 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" [105, p. R69].

4.5.4 Chronological Age Verification

Youth competitions in soccer and other sports are set within the context of specific CA limits, and SA has been used to 'verify' CAs of individual players [10]. Concern for alleged use of over-age players prompted the use of GP SAs for CA verification in a sample of players participating in the1988 Asian Junior Youth Football Tournament (U16). Of 50 randomly selected players (five per team), only five had a GP SA <15 years and six had an SA of 16 years, while the remainder had an SA ≥ 17 years; the majority of the latter were skeletally mature [106]. Relevant to the present discussion, TW3 RUS SAs were used to verify CA at the 2007 U15 Asian Cricket Championship in Nepal. Each team had 14 members; if a team had more than two over-age players, it was disqualified [107]; "…eight of the ten competing sides had earlier been disqualified for fielding over-age players…" [108].

The systematic reduction in TW3 SAs compared with TW2 SAs has implications for CA verification in youth competitions. An 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 an 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]. Cut-off dates for youth competitions imply greater precision; SA provides a crude approximation of CA with a large margin of error. The range of SAs within a given CA group can exceed three or four years. Such inter-individual variability precludes use of SA to verify CA for age-group competitions. Given the systematic reduction of TW3 compared with TW2 SAs, some over-age players may be noted as CA eligible; on the other hand, use of TW2, GP, and Fels SAs may lead to the disqualification of CA-eligible players.

4.5.5 What is the Preferred Method?

Both GP and TW3 SAs have been labeled as the 'current gold standards' for assessing skeletal maturity [105], while TW3 SA has been noted as the 'gold standard' [109]. TW3 rather than TW2 has been recommended as the 'method of first choice' [54] and for use clinically [55]. The issue of which method is more appropriate is not settled [2, 110]. Discussions of methods of SA assessment of the hand–

wrist have generally focused on only the GP and TW methods. The GP method is widely used clinically, but is not ordinarily applied in a bone-specific manner. The Fels method has surprisingly received relatively little consideration in discussions of SA assessment. Although perhaps a bit more tedious to apply, the Fels method has an advantage in providing a standard error for each assessment [17], which is lacking with the other methods.

The utility of TW3 for height prediction has also been questioned. Comparisons of predictions with the TW2 and TW3 protocols in healthy children aged 6–12 years [111] and in children with congenital renal diseases aged 10–15 years [112] suggested that the advantage of the TW3 revision compared with earlier versions of the prediction protocol was negligible. Potential sources of variation may be the different samples upon which the different protocols were developed and the samples to which the protocols were applied.

Although the literature addressing the skeletal maturity of youth athletes is reasonably extensive, the use of SA in studies of youth athletes is perceived as 'invasive' [10]. As a result, anthropometric protocols for the prediction of maturity status and of maturity timing are increasingly used [18, 34, 72, 113, 114]. The prediction protocols need validation in the general population and in youth athletes representing different sports. Concordance of maturity status classifications based on anthropometric protocols and on Fels SAs was fair at best among youth soccer players aged 11–14 years [115], but was somewhat better among youth American football players aged 9–14 years [116].

5 Conclusion

TW3 SAs were, on average, systematically lower than corresponding TW2 SAs in youth soccer players aged 11–17 years. For the same RUS score, SAs were systematically and substantially reduced with TW3 compared with TW2; mean differences of TW3 minus TW2 SAs ranged from -0.97 to -1.16 years. The reduced TW3 SA assigned for the same RUS score compared with 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, specifically the shift from average-to-late and from early-to-average status classifications, contrasted maturity classifications based on GP and Fels SAs which were consistent with TW2 SAs in youth soccer players. Moreover, SA–CA relationships among soccer players aged 11–15 years using TW 20 Bone, TW2 RUS, GP, and Fels SAs have changed negligibly in studies spanning the early 1980s through 2013, while a secular increase in heights of youth soccer players without change in estimated age at PHV was noted between 1978 and 2015. Given the preceding and also the selectivity of the sport in favor of more mature players during adolescence, TW2 RUS SA should be the method of choice for those using the TW protocol with youth soccer players.

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Compliance with ethical standards

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Conflict of interest Robert Malina, Manuel Coelho-e-Silva, Antonio Figueiredo, Renaat Philippaerts, Norikazu Hirose, Maria Eugenia Peña Reyes, Giulio Gilli, Andrea Benso, Roel Vaeyens, Dieter Deprez, Luiz Guglielmo, and Rojapon Buranarugsa declare that they have no conflict of interest.

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