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Exploratory comparison of TW2, TW3, and FELS methods for assessing bone maturity in Cuban youth basketball and beach volleyball players

Comparación exploratoria de los métodos TW2, TW3 y FELS para evaluar la madurez ósea en jugadores cubanos juveniles de baloncesto y voleibol de playa

Comparação exploratória dos métodos TW2, TW3 e FELS na avaliação da maturidade óssea em jogadores cubanos juvenis de basquetebol e voleibol de praia

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Abstract

This study aimed to compare the Tanner-Whitehouse II (TW2) method with the more contemporary methods, Tanner-Whitehouse III (TW3) and FELS, to determine their relevance and accuracy in the current Cuban context, among school athletes playing basketball and beach volleyball. The sample included 44 young athletes (22 male and 22 female), aged 11 to 15 years, representative of a multi-ethnic population, predominantly of African ancestry and mestizo backgrounds. Each X-ray was evaluated three times, using each method, with the two closest values averaged to determine the final result. Additionally, anthropometric variables such as body mass and height were measured following the methodology of the International Society for the Advancement of Kinanthropometry. Results showed a high level of agreement between TW2 and TW3, indicating that both methods are interchangeable despite modifications made to TW3 to account for secular growth trends and ethnic diversity. TW3 exhibited greater precision during intermediate stages, while FELS showed a tendency to overestimate skeletal maturity in athletes nearing final development, with greater variability in its estimates. Although the sample size limits the generalization of the findings, the results align with international studies, emphasizing the importance of validating these methods in local contexts. This study provides a basis for optimizing sports evaluation and selection strategies in Cuba. Rev Arg Antrop Biol 28(1), e116, 2026. https://doi.org/10.24215/18536387e116

Keywords: basketball; bone age; human development; skeletal maturation; volleyball beach

Resumen
Este estudio tuvo como objetivo comparar el método Tanner-Whitehouse II (TW2) con métodos más contemporáneos, Tanner-Whitehouse III (TW3) y FELS, para deter-minar su relevancia y precisión en el contexto cubano actual, en deportistas escolares de baloncesto y voleibol de playa. La muestra incluyó 44 atletas jóvenes (22 masculi-nos y 22 femeninos), con edades cronológicas entre 11 y 15 años, representativos de una población multiétnica, principalmente de ancestralidad africana y mestiza. Cada radiografía fue evaluada tres veces por cada método, utilizando los dos valores más cercanos para calcular el promedio. Además, se midieron variables antropométricas como masa corporal y estatura, siguiendo la metodología de la Sociedad Internacio-nal para el Avance en Cineantropometría. Los resultados mostraron un alto nivel de concordancia entre TW2 y TW3, indicando que ambos métodos son intercambiables, a pesar de las modificaciones realizadas en TW3 para reflejar tendencias seculares del crecimiento y diversidad étnica. TW3 presentó mayor precisión en etapas inter-medias, mientras que FELS mostró una tendencia a sobreestimar la maduración ósea en atletas cercanos al desarrollo final, con mayor variabilidad en sus estimaciones. Aunque el tamaño de la muestra limita la generalización, los resultados coinciden con estudios internacionales, subrayando la importancia de validar estos métodos en contextos locales. Este estudio establece una base para optimizar las estrategias de evaluación y selección deportiva en Cuba. Rev Arg Antrop Biol 28(1), e116, 2026. https://doi.org/10.24215/18536387e116

Palabras Clave: baloncesto; edad ósea; desarrollo humano; maduración ósea; voleibol de playa

Resumo
Este estudo teve como objetivo comparar o método Tanner-Whitehouse II (TW2) com métodos mais contemporâneos, Tanner-Whitehouse III (TW3) e FELS, para determinar sua relevância e precisão no contexto cubano atual, em atletas escolares de basquete e vôlei de praia. A amostra incluiu 44 atletas jovens (22 do sexo masculino e 22 do sexo feminino), com idades entre 11 e 15 anos, representativos de uma população multiétnica, predominantemente de ancestralidade africana e mestiça. Cada radiografia foi avaliada três vezes por cada método, utilizando os dois valores mais próximos para calcular a média. Além disso, foram medidas variáveis antropométricas como massa corporal e estatura, seguindo a metodologia da Sociedade Internacional para o Avanço da Cineantropometria. Os resultados mostraram um alto nível de concordância entre TW2 e TW3, indicando que ambos os métodos são intercambiáveis, apesar das modificações realizadas no TW3 para refletir tendências seculares de crescimento e

diversidade étnica. O TW3 apresentou maior precisão em estágios intermediários, enquanto o FELS mostrou tendência de superestimar a maturação óssea em atletas próximos ao desenvolvimento final, c om m aior v ariabilidade e m s uas e stimativas. Embora o tamanho da amostra limite a generalização, os resultados estão alinhados com estudos internacionais, destacando a necessidade de validar esses métodos em contextos locais. Este estudo estabelece uma base para otimizar estratégias de avaliação e seleção esportiva em Cuba. Rev Arg Antrop Biol 28(1), e116, 2026. https://doi. org/10.24215/18536387e116

Palavras-chave: basquetebol; idade óssea; desenvolvimento humano; maturação óssea; vôlei de praia

The assessment of bone age has been widely recognized as an essential indicator of biological maturity, with applications spanning public health, pediatric endocrinology, forensic sciences, and sports contexts (Coelho-E-Silva *et al*., 2022; Freitas *et al*., 2024; Martín-Pérez *et al*., 2023; Pinchi *et al*., 2014). The Greulich and Pyle method, introduced in 1959, provided an early alternative by utilizing a visual atlas to compare radiographs with reference standards (Greulich & Pyle, 1959). Although popular for its simplicity, its reliance on subjective evaluations limited its applicability in scientific and clinical contexts that demanded higher precision, prompting the development of more quantitative systems such as Tanner-Whitehouse (Tanner *et al*., 1962; Tanner *et al*., 1975; Tanner *et al*., 2001).

The evolution of methods for assessing biological maturity has been continuous since the initial development of the Tanner-Whitehouse I (TW1) system. Introduced in the 1960s, TW1 was pioneering in offering a quantitative system based on scoring specific features in radiographs of the wrist and hand (Tanner *et al*., 1962). This method was later replaced by TW2, which incorporated improvements such as the exclusion of bones with high variability in maturation and the updating of standards based on new population data (Tanner *et al*., 1975). In 2001, TW3 emerged, reducing the number of evaluated stages to simplify the process and again updating references based on recent European population data. These revisions responded to the need to increase precision, reduce evaluation time, and adapt to generational changes in growth patterns (Tanner *et al*., 2001).

Through the evolutionary development of bone age assessment methods, one of the most popular approaches originating in North America is the FELS method. Unlike traditional methods such as Tanner-Whitehouse or Greulich and Pyle, this method employs a different statistical approach based on 98 indicators of bone maturity obtained from radiographs of the wrist and left hand, ensuring highly accurate and objective evaluations (Roche *et al*., 1988). Specialized literature has demonstrated its value in bone age assessment (Furdock *et al*., 2022; Martinho *et al*., 2023; Sinkler *et al*., 2024; Sousa-E-Silva *et al*., 2023), although some studies have highlighted its lack of agreement with other methods (Martinho *et al*., 2022).

In Cuba, the evaluation of bone age gained greater relevance in the 1970s during the National Growth and Physical Development Study (1972-1974), led by Professor José Jordán, with advisory support from renowned international researchers like James Tanner (Jordán *et al*., 1975). This project facilitated the development of the first specific standards for Cuba using the Tanner-Whitehouse II (TW2) method, a tool that has served as a national reference since the 1980s (Jiménez-Hernández *et al*., 1986; Jordán *et al*., 1980).

In the sports field, bone age has been employed for talent selection and biomedical monitoring of youth athletes, as evidenced by studies conducted with tennis players, footballers, and other young sports groups (Coelho-E-Silva *et al*., 2022; Cumming *et al*., 2024; Freitas *et al*., 2024; Martinho *et al*., 2023). Nevertheless, these applications are not exempt from limitations, as discrepancies between methods can influence the classification of biological maturity, with direct implications for development and sports ethics (Martinho *et al*., 2022). In particular, methods like TW3 tend to systematically classify youths as less mature compared to the FELS method, which may affect talent programs and sports development due to the risk of athletes being misclassified as false positives or false negatives (Malina, 2011; Malina *et al*., 2007; Malina *et al*., 2018).

In Cuba's sports population, the study of bone maturation gained significant interest during the 1980s, largely due to the scientific revolution initiated by the first National Growth Investigation (Jiménez-Hernández *et al*., 1986). Using Cuban population-specific standards based on the TW2 method, Siret *et al*. (1991) identified correlations between bone age and the Body Development Index of young Cuban athletes, which led to the creation of specific equations that have facilitated age determination without the invasive X-ray method in several Latin American countries (García-Avendaño *et al*., 2001; Flores-Esteves *et al*., 2008; Sellés *et al*., 2016; Villamarín-Menza *et al*., 2021).

Given the growing challenges surrounding the evolution of bone maturation methods, the need arises to evaluate whether the TW2 method remains representative of the biological maturity characteristics of Cuban school athletes, particularly youth athletes practicing sports such as basketball and beach volleyball. Therefore, this study aims to compare traditional and contemporary bone age estimation methods to determine their relevance and precision in the current Cuban context, where population-specific standards based on TW2 (Jiménez-Hernández *et al*., 1986) and the equations proposed by Siret *et al*. (1991) are still employed. This analysis will not only provide key evidence on the applicability of TW2 but also offer perspectives for improving biological maturity assessment in specific sports populations.

This study should be considered exploratory in nature, given the limited but complete sample of athletes available within the provincial high-performance sports system of Havana. In elite sports contexts, access to participants is inherently restricted due to the selective and hierarchical structure of athlete development. Therefore, the findings offer contextualized insights rather than aiming for broad generalization.

MATERIALS AND METHODS

Study design and sample

This research was conducted as an exploratory descriptive observational study focusing on the assessment of bone maturation in youth athletes engaged in competitive sports. The study included a total of 44 individuals, evenly distributed by sex (22 females and 22 males), who practiced basketball (n = 31) and beach volleyball (n = 13). Participants were between 11.2 and 14.8 years old and were in the competitive preparation stage.

The sample universe comprised all available athletes from the competitive age categories 11-12 and 13-15 years belonging to the "Escuela de Iniciación Deportiva Escolar (EIDE)" in the province of La Habana, Cuba. It is important to clarify that this universe does not represent all school athletes in Cuba within these age ranges, but specifically those with the highest performance levels in the capital province, which is recognized as the leading region in Cuba for competitive results in basketball and beach volleyball.

Athlete selection for these competitive categories follows a structured pathway within the Cuban sports development system. Young athletes are first identified through school-based physical education programs and municipal competitions. Those who demonstrate exceptional performance in provincial championships or exhibit outstanding physical attributes for the sport are selected by talent scouts. These athletes are then invited to join specialized training centers such as EIDE, where they undergo systematic development. Ultimately, they form the teams that represent La Habana province in national championships.

Since the study included the entire accessible population within this high-performance context, no inclusion or exclusion criteria were applied. This design supports the internal validity of the findings while acknowledging the exploratory nature of the research.

The studied population included athletes of diverse ancestral backgrounds, as determined through self-identification: five individuals of European ancestry, nineteen of African ancestry, and twenty of mixed/mestizo ancestry. To ensure accuracy and respect for individual identity, participants were asked to define their ancestry based on personal and familial history, following contemporary best practices in population-based biological research.

This classification approach allows for a more precise evaluation of biological diversity and is particularly relevant in Cuba, where ancestry-based distinctions have long been used in anthropological and biological studies to assess variations in growth and skeletal maturation patterns (Jiménez-Hernández *et al*., 1986; Jordán *et al*., 1980). These distinctions have contributed to the development of population-specific biological norms, which are essential for interpreting bone age assessments in multi-ethnic athletic populations.

Previous research has shown that genetic and geographical background can influence skeletal maturation estimates (Grgic *et al*., 2020; Martín-Pérez *et al*., 2023), underscoring the importance of considering ancestry when evaluating the applicability of bone age methods. In this study, such distinctions are particularly important for understanding how traditional techniques such as Greulich-Pyle and TW2, and contemporary approaches like TW3 and FELS, perform in a diverse Cuban youth athlete population.

All participants and their legal guardians read, approved, and provided written informed consent for participation and publication. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki for research involving human subjects (World Medical Association, 2025) and adheres to the ethical standards established for case studies.

By incorporating self-identification as the primary criterion for ancestry classification, complemented by historical and familial data, this study followed contemporary best practices in population-based biological research. This approach ensured a respectful and scientifically rigorous evaluation of biological diversity, avoiding racialized markers and enhancing the contextual relevance of the findings.

The research protocol, illustrated in Figure 1, was structured into two main phases:

Phase 1 (Day 1):

- Initial interview: Conducted with athletes and their parents to collect personal and developmental information, including birth weight.
- Radiograph of the left hand: Performed using an LG DXD X-ray detector with a 16-bit image processing and a pixel pitch of 140 µm, ensuring high-resolution and distortion-free imaging.

- Measurement of body weight and height: Taken using a SECA 514/515 body composition analyzer with an integrated stadiometer. These parameters were recorded as essential indicators for characterizing growth and development.

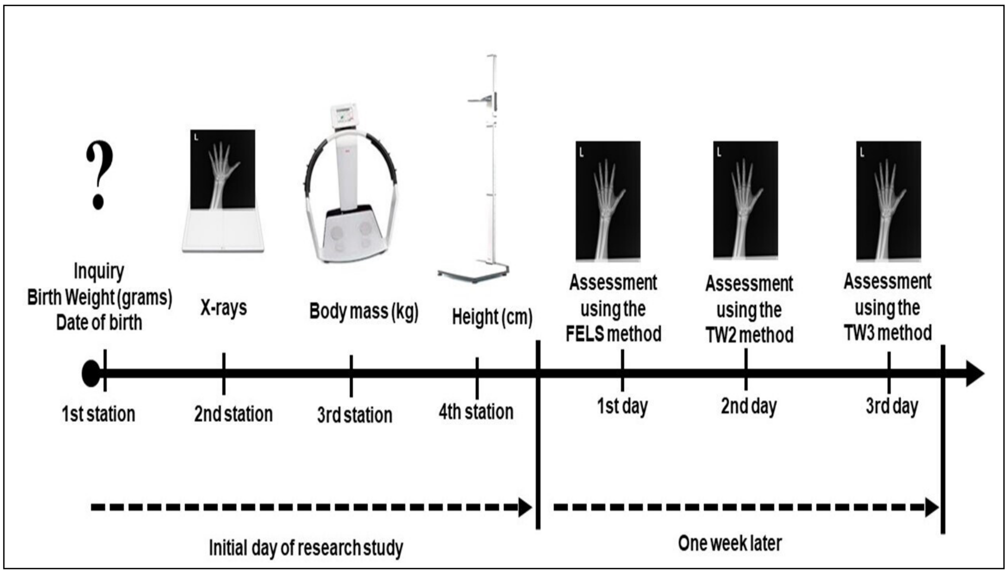

FIGURE 1. Flowchart of the research process, structured in two phases: Phase 1 (initial day) with four stations and Phase 2 (one week later) with radiographic assessments over three consecutive days.

Phase 2 (Two weeks later): Bone age was assessed in three independent sessions using the following methods:

- TW2 Method (Tanner *et al*., 1975): This method involved the evaluation of 20 bones in the left hand and wrist. Each bone was assigned a specific maturity score, and the total score was compared with reference tables to determine skeletal age. In this study, Cuban reference scores were used (Jiménez-Hernández *et al*., 1986) instead of the original English standards to ensure cultural and developmental relevance. These Cuban scores were derived from a nationally representative sample and revealed consistent differences in skeletal age percentiles (3rd, 50th, and 97th) compared with the British reference. The curve between the 3rd and 97th percentiles was notably wider in the Cuban sample, likely due to ethnic, socioeconomic, and methodological factors. While the British standards were based on institutionalized urban children, the Cuban scores reflect a broader and more diverse population, enhancing their applicability in national sports contexts.
- TW3 Method (Tanner *et al*., 2001): The updated TW3 protocol was applied, maintaining the assessment of the same 20 bones. Each bone was classified into one of five maturity stages (I to V), and skeletal age was derived from the cumulative score using standardized reference tables.
- FELS Method (Roche *et al*., 1988): The FELS method was implemented according to its original protocol, which evaluates 22 bones of the hand and wrist. Each bone was scored on a continuous scale based on its degree of ossification. Skeletal age was then calculated using sex-specific regression equations provided by the authors.

Skeletal maturation was categorized into three groups —Late, Average, and Early— based on the difference between the estimated bone age and the chronological age of each subject (Carling *et al*., 2012).

Late: bone age was more than 1 year below chronological age.

Average: bone age was within ± 1 year of chronological age.

Early: bone age was more than 1 year above chronological age. These thresholds were applied consistently across all assessment methods (TW2, TW3, and FELS) to ensure comparability of maturation status classifications.

For all methods, three independent readings were conducted per participant by trained observers. The two closest values were averaged to determine skeletal age. Intra-observer differences ranged from .03 ± .02 to .09 ± .03 years, while inter-observer discrepancies ranged from .17 to .24 years, with standard deviations between .01 and .02 years, resulting in coefficients of variation below 10%. All observers had between two and 20 years of experience in the field, ensuring consistency and reliability across assessments.

Anthropometric measurements were performed by a certified team composed of one ISAK Level 3 anthropometrist and two Level 2 anthropometrists, following the international standards established by the International Society for the Advancement of Kinanthropometry (ISAK) (Esparza-Ross *et al*., 2019). The intra-observer technical error of measurement (TEM) for stature remained well below the accepted threshold of 1%, with a reliability coefficient (R) exceeding 99.1%.

Data analysis

Statistical analyses were performed using MedCalc software (version 2024) to evaluate the agreement, consistency, and reliability among the three bone age assessment methods (TW2, TW3, and FELS) applied to Cuban youth athletes practicing basketball and volleyball. Descriptive statistics—including mean, standard deviation, minimum, and maximum values—were calculated for skeletal age estimates obtained by each method and stratified by sex.

To assess intra-method reliability**,** the intraclass correlation coefficient (ICC) for single measures was calculated for each method independently. Additionally, standard errors of estimate (SEE) were computed for the FELS method to quantify its precision, addressing reviewer concerns regarding its reporting. SEE values ranged from .29 to .47 years**,** indicating acceptable predictive accuracy.

Inter-method consistency was examined using repeated-measures analysis of variance (ANOVA), with bone age method as a within-subjects factor and sex as a between-subjects factor. When the assumption of sphericity was violated, Huynh-Feldt corrections were applied to adjust degrees of freedom. Post hoc comparisons with Bonferroni adjustments were conducted to identify statistically significant differences between methods.

To further evaluate absolute agreement and potential systematic bias, Bland-Altman plots were generated for each pairwise comparison between methods. These plots allowed for visual inspection of agreement limits and the identification of any consistent over- or underestimation trends.

A significance level of $p < .05$ was established for all statistical tests, ensuring robust and interpretable results. All procedures were designed to meet the standards of methodological rigor expected in skeletal age validation studies.

RESULTS

The data presented in Table 1 provides a comparative overview of the sample's descriptive characteristics, divided by sex (female and male). Key variables include decimal age, body mass, height, birth weight, bone age estimated by the TW2, TW3, and FELS methods, and the difference between bone age and decimal age for each method.

TABLE 1. Descriptive characteristics of the sample.

	Female				Male			
	M	**SD**	**Min**	**Max**	**M**	**SD**	**Min**	**Max**
Decimal age (years)	13.6	1.02	11.2	14.8	13.7	.8	12.3	14.8
Body Mass (kg)	56.4	9.59	42.3	85.1	57.6	9.5	40.1	74.9
Height (cm)	170.7	8.67	150	188.4	174.7	10.7	157	195
Birth weigh (lb)	7.4	1.33	3.7	9.5	8	1.3	5.1	10.4
Bone age (years)								
TW2	13.7	.84	12.6	15	13.9	.8	12.5	15
TW3	13.6	.9	12.2	14.7	13.9	.7	12.3	14.9
FELS	14.1	.97	12.6	16.6	14.6	1.1	12.5	17.4
Bone age-decimal age (years)								
TW2	.12	.38	-.4	1.4	.17	.4	-.9	1
TW3	.05	.48	-.7	1.2	.2	.39	-.6	.8
FELS	.56	.85	-1.36	2.22	.87	.75	-.19	2.85

TW2: Tanner-Whitehouse II; **TW3:** Tanner-Whitehouse III; **M:** mean; **SD:** standard deviation, **Min:** minimum; **Max:** maximum

Females and males show similar decimal ages, with averages of 13.6 years and 13.7 years, respectively, indicating minimal variation between groups. Differences emerge in body mass, where males exhibit a slightly higher average of 57.6 kg compared with 56.4 kg in females. A similar pattern is observed for height: males average 174.7 cm, whereas females average 170.7 cm, reflecting expected adolescent growth differences.

Birth weight also shows a modest sex-associated trend, with males reporting higher averages (8 lb) than females (7.4 lb). Regarding bone age, males surpass females across all methods: TW2 (males: 13.9 years, females: 13.7 years), TW3 (males: 13.9 years, females: 13.6 years), and FELS (males: 14.6 years, females: 14.1 years). These patterns indicate slightly accelerated skeletal maturation in males compared to females.

The difference between bone age and decimal age further emphasizes sex-based disparities. Across all methods, males show larger differences, suggesting more advanced skeletal maturity relative to their chronological age. For instance, in TW2, males have an average difference of .40 years, whereas females show only .12 years. A similar pattern appears in TW3, where males average .39 years compared with .05 years for females. The largest gap is observed in FELS, with males exhibiting a difference of .87 years and females averaging .56 years.

In summary, although both sexes exhibit comparable chronological ages, males show higher averages in body mass, height, bone age, and the difference between bone age and decimal age, reflecting subtle variations in growth and development during adolescence.

The data in Table 2 present the absolute and relative frequencies of skeletal maturation status by sex and assessment method (TW2, TW3, and FELS). Maturation status is categorized into three groups: Late, Average, and Early, providing insights into the distribution of skeletal maturity across sexes and methods.

For females, the majority exhibit an average maturation status across all methods. Specifically, 95.5% fall into this category for both TW2 and TW3, while 72.7% are categorized as average under the FELS method. A small proportion (4.5%) demonstrate Late maturation in the FELS method, and 22.7% are classified as Early. Notably, neither the TW2 nor TW3 methods identified Late-maturing females.

TABLE 2. Absolute (No) and relative (%) frequencies of skeletal maturation status by sex and methods of assessment.

		TW2		TW3		FELS	
		No	**%**	**No**	**%**	**No**	**%**
Female	Late	0	0	0	0	1	4.5
	Average	21	95.5	21	95.5	16	72.7
	Early	1	5	1	5	5	22.7
	Total	22	100	22	100	22	100
Male	Late	0	0	0	0	0	0
	Average	22	100	22	100	15	68.2
	Early	0	0	0	0	7	31.8
	Total	22	100	22	100	22	100
Total	Late	0	0	0	0	1	2.3
	Average	43	97.7	43	97.7	31	70.5
	Early	1	2.3	1	2.3	12	27.3
	Total	44	100	44	100	44	100

TW2: Tanner-Whitehouse II; **TW3:** Tanner-Whitehouse III

Among males, all subjects are classified as having an average maturation status under both the TW2 and TW3 methods (100% for each). In contrast, under the FELS method, a larger proportion (31.8%) are classified as Early matures, while 68.2% fall into the average category. Interestingly, no males were identified as Late matures in any of the methods.

When combining sexes, average maturation status remains predominant across all methods, accounting for 97.7% under both TW2 and TW3 and 70.5% under FELS. The FELS method additionally identifies 2.3% Late matures and a relatively larger proportion of Early matures (27.3%), indicating greater variability in maturation assessment compared with TW2 and TW3.

In summary, the TW2 and TW3 methods consistently classify nearly all subjects into the average maturation category, regardless of sex. The FELS method, however, identifies a more varied distribution of maturation statuses, with notable proportions of Early matures and a small presence of Late matures, particularly among females.

The scatter plots in Figure 2 illustrate the correlation between decimal age and bone age estimated by the TW2, TW3, and FELS methods, stratified by sex (females represented by red squares and males by blue circles). Each plot visually highlights the relationship between decimal age and skeletal maturity assessment, offering insights into the reliability and agreement of each method.

In the TW2 method (Fig. 2A), the correlation coefficients are $r = .937$ for females ($p < .001$) and $r = .878$ for males ($p < .001$), indicating a strong positive association for both sexes. The data points are clustered tightly along the diagonal line, suggesting a high level of agreement between decimal age and TW2 bone age estimates. The slightly higher correlation for females indicates that TW2 provides more consistent results for this group compared with males, although both sexes exhibit a reliable alignment between decimal and skeletal age.

The TW3 method (Fig. 2B) also demonstrates strong correlations, with coefficients of $r = .882$ for females ($p < .001$) and $r = 0.886$ for males ($p < .001$). Similar to TW2, the scatter plots reveal a close alignment of points along the diagonal line, reinforcing the robustness of TW3 in estimating bone age for both sexes. Unlike TW2, the correlation strength between females and males is nearly identical, suggesting that the TW3 method is equally effective across both groups.

In contrast, the FELS method (Fig. 2C) exhibits weaker correlations compared with TW2 and TW3, with coefficients of $r = .637$ for females ($p < .01$) and $r = .758$ for males (p < .001). The scatter plots show greater variability, particularly among females, with data points scattered more broadly around the diagonal line. This pattern reflects a lower level of agreement between decimal age and FELS-derived bone age estimates. Males display higher correlation values, indicating that the FELS method yields more reliable results for this group compared with females.

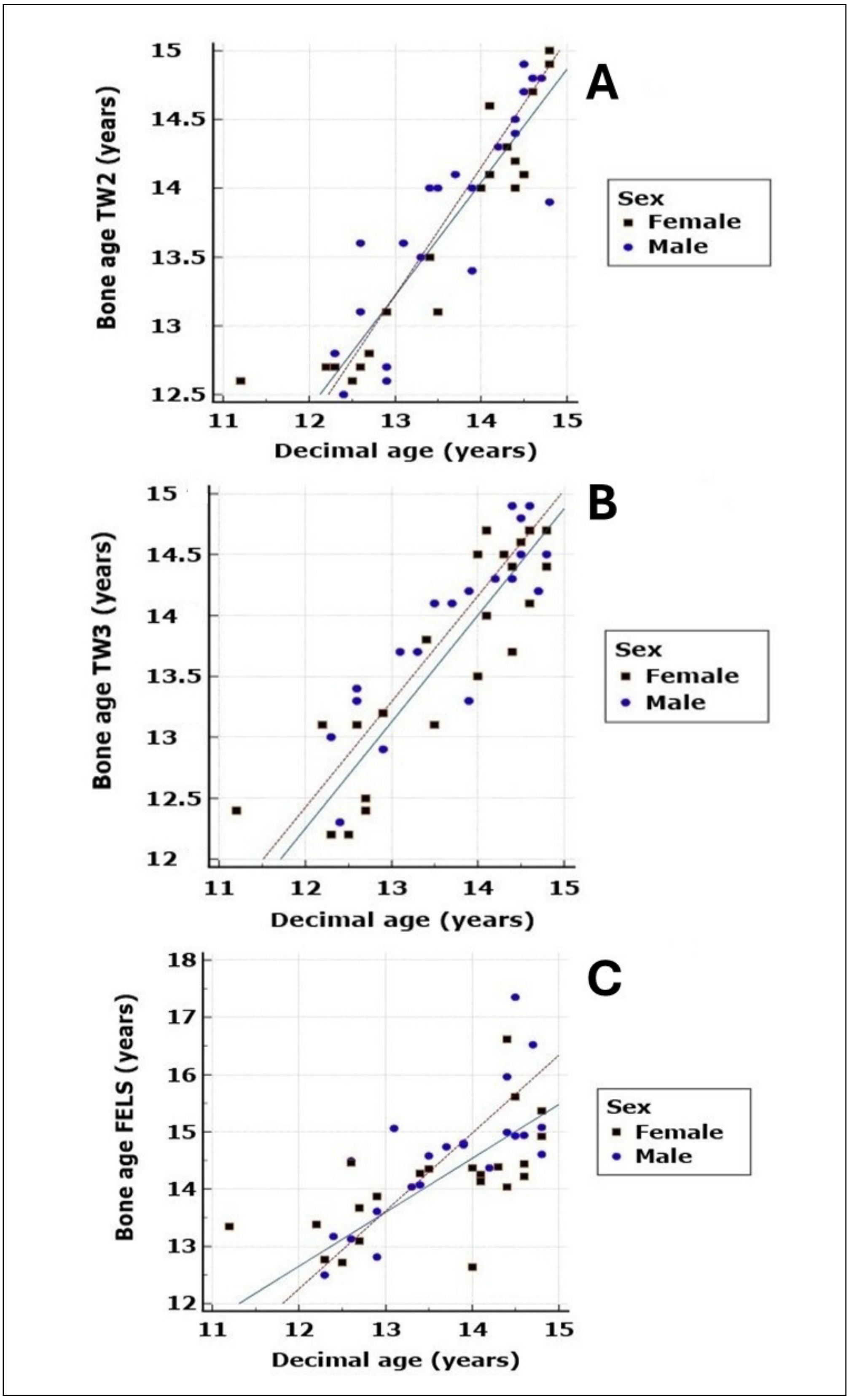

FIGURE 2. Scatter plot showing correlation between decimal age and bone age for each method.

Across methods, TW2 and TW3 demonstrate strong correlations and tightly clustered data points, indicating high reliability in estimating bone age relative to decimal age for both sexes. In contrast, the FELS method shows greater variability and weaker correlations, especially among females, suggesting limitations in its consistency compared with TW2 and TW3.

The Bland-Altman plots in Figure 3 extend the analysis presented in Figure 2 by offering a detailed comparison of the differences between bone age and decimal age for the TW2, TW3, and FELS methods. These plots help visualize the agreement between each bone age method and decimal age, highlighting any systematic biases and the range of variability in their estimations. The plots are stratified by sex, with black squares representing females and blue circles representing males.

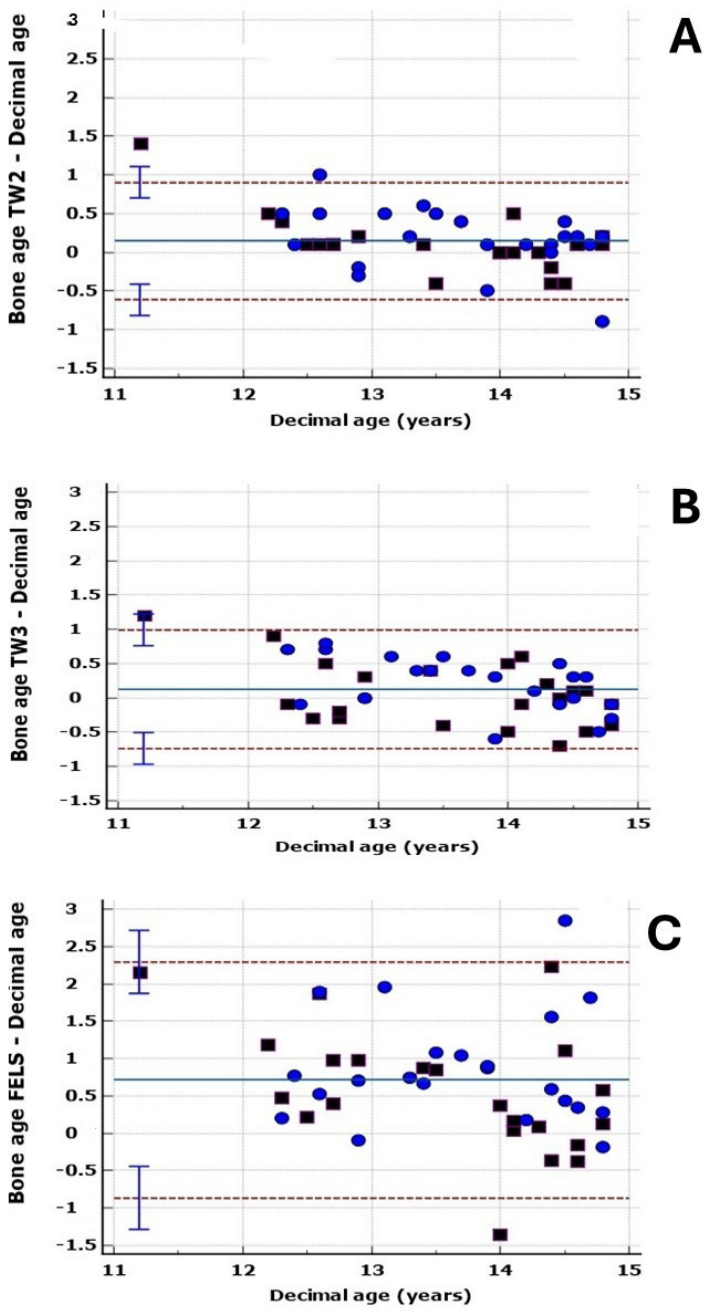

FIGURE 3. Bland-Altman plot comparing bone age methods Tanner-Whitehouse II (TW2), Tanner-Whitehouse III (TW3) and FELS, against decimal age.

In Figure 3A (TW2 vs. decimal age), the data points are closely distributed around the mean difference, indicating a high level of agreement between TW2 bone age and decimal age for both sexes. The limits of agreement are relatively narrow, demonstrating consistent estimations across the analyzed age range (11-15 years). The clustering of points within these limits suggests that TW2 provides reliable estimates with minimal systematic bias. However, slight variability is observed in the extreme ends of age range, particularly among males.

Figure 3B (TW3 vs. decimal age) shows a pattern similar to that observed for TW2, with data points evenly distributed around the mean difference and narrow limits of agreement. This reinforces the reliability of the TW3 method for estimating bone age in relation to decimal age. Both sexes exhibit comparable distributions, although females tend to show slightly greater variability within the limits, particularly at the lower end of the age range.

In Figure 3C (FELS vs. decimal age), greater variability is evident compared with the previous methods. The data points are more widely dispersed, with broader limits of agreement, particularly among females. This suggests that the FELS method demonstrates less consistency in its estimations of bone age relative to decimal age. Additionally, the plot indicates a slight systematic bias, with FELS tending to overestimate bone age, especially in younger participants. The variability is more pronounced for females, highlighting potential limitations of the FELS method for this subgroup.

Overall, the Bland-Altman plots emphasize the superior agreement and reliability of the TW2 and TW3 methods in assessing bone age relative to decimal age.

The results presented in Table 3 analyze the level of agreement among the bone age assessment methods, TW2, TW3, and FELS, usingIntraclass correlation coefficients (ICC) categorized by sex. For females, the TW2 and TW3 methods demonstrated excellent agreement, with an ICC of .908 and 95% confidence interval ranging from .795 to .96. Moderate agreement was observed between TW2 and FELS (ICC = .533, CI = .152 to .776) and between TW3 and FELS (ICC = .55, CI = .143 to .791). In contrast, for males, TW2 and TW3 achieved excellent agreement (ICC = .936, CI = .853 to .973), while TW2 versus FELS (ICC = .613, CI = .077 to .854) and TW3 versus FELS (ICC = .562, CI = .037 to .817) showed moderate agreement.

TABLE 3. Intraclass correlation coefficient (ICC) for agreement between bone age methods.

Sex		ICC	95% IC	Consistency Level
Female	TW2 vs. TW3	.908	.795 - .96	Excellent
	TW2 vs. FELS	.533	.152 - .776	Moderate
	TW3 vs. FELS	.55	.143 - .791	Moderate
Male	TW2 vs. TW3	.936	.853 - .973	Excellent
	TW2 vs. FELS	.613	.007 - .854	Moderate
	TW3 vs. FELS	.562	.037 - .817	Moderate

TW2: Tanner-Whitehouse II; **TW3:** Tanner-Whitehouse III

Before examining differences between bone age estimation methods, it was necessary to evaluate whether sex influenced the results. The main effect of sex was not statistically significant ($F = 1.03$, $p = .316$, $\eta^2 = .02$), indicating that bone age estimates did not differ substantially between male and female participants. Similarly, the interaction between method and sex was non-significant ($F = 1.06$, $p = .370$, $\eta^2 = .02$), suggesting that the relative performance of the methods remained consistent across sexes. These findings support the validity of subsequent method comparisons without stratifying or adjusting for sex.

Table 4 presents the results of a repeated-Measures ANOVA assessing bone age across different methods (TW2, TW3, and FELS) and sex (female and male). The table also includes post hoc comparisons between methods using Bonferroni correction, highlighting key findings regarding agreement and interaction effects.

TABLE 4. Results of repeated-measures ANOVA for bone age by methods and sex. Post hoc comparisons between methods (Bonferroni correction).

Effect	F-value	p-value	Partial Eta-Squared(η^2)	df	Bonferroni Correction
Method	23.6	< .001	.36	1.796	TW2 = TW3 ≠ FELS*
Sex	1.03	.316	.02	1	
Method x Sex	1.06	.37	.02	1.796	

TW2: Tanner-Whitehouse II; **TW3:** Tanner-Whitehouse III; **df:** degrees of freedom

The main effect of the method was statistically significant ($F = 23.6$, $p < .001$, $\eta^2 = .36$) indicating that the methods differ meaningfully in their estimation of bone age. Post hoc comparisons with Bonferroni correction show that TW2 and TW3 are equivalent (TW2 = TW3), while both differ significantly from FELS (TW2 ≠ FELS; TW3 ≠ FELS). This suggests that TW2 and TW3 provide closely aligned assessments, whereas FELS produces substantially different bone age estimates.

These results, taken together with the findings from Figure 2 and Figure 3, underscore the reliability of TW2 and TW3 in yielding comparable bone age estimates and highlight the distinctiveness of FELS relative to these methods. While sex does not appear to contribute to differences in bone age assessments, the choice of method plays a pivotal role in determining outcomes.

Figure 4 illustrates the effect of sex on estimated bone age across the three methods (TW2, TW3, and FELS) and highlights comparative differences between males and females. The bar plot provides a clear visualization of mean bone age values for each method, stratified by sex (black squares for females and blue circles for males).

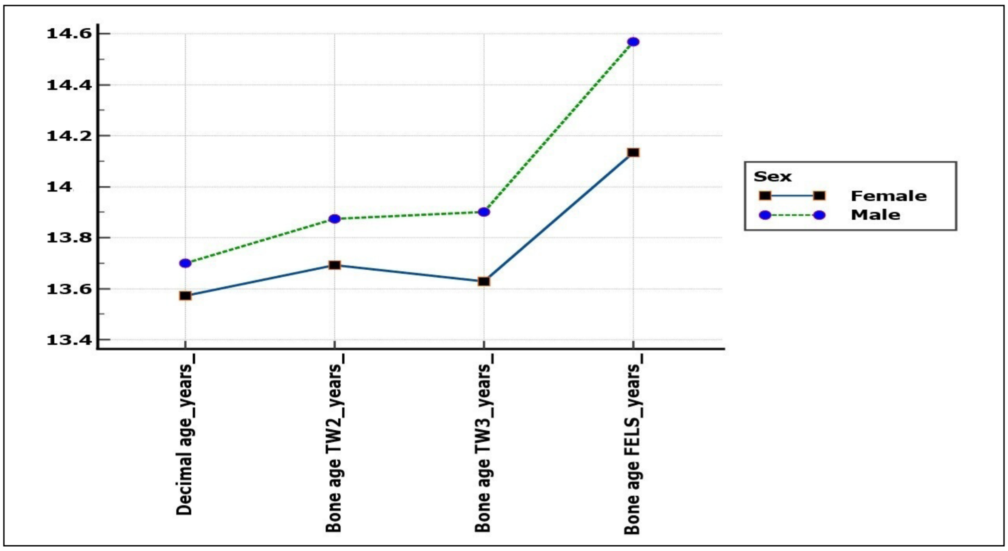

FIGURE 4. Bar plot of mean bone age by method and sex.

Males consistently exhibited higher mean bone age values than females across all methods. TW2 and TW3 show modest but consistent sex-based differences in skeletal maturation estimates. The largest difference is observed in the FELS method, where males display notably higher mean bone ages than females. This suggests that the FELS method is more sensitive to sex-based variation in skeletal maturation. The overall range of differences across methods underscores the importance of considering sex as a contextual factor when interpreting bone age assessments.

DISCUSSION

This study explores the methodological reliability of the Tanner-Whitehouse 2 (TW2) method in comparison with more recent approaches, including Tanner-Whitehouse 3 (TW3) and FELS, for assessing skeletal maturation in Cuban youth athletes participating in beach volleyball and basketball. Given the critical role of accurate biological age classification in school-based sports programs, the findings offer a nuanced evaluation of each method's strengths and limitations within this specific population. Despite the modest sample size, the results provide valuable insights into the practical implications of bone age assessment for talent identification, training periodization, and long-term athlete development in Cuba —where localized standards and resource constraints may influence methodological choices—.

An important dimension of this study concerns ethnicity and population specificity. To date, no published studies have validated bone maturation methods in athletes from the Caribbean Islands —including the Greater and Lesser Antilles— particularly within targeted populations such as provincial basketball and beach volleyball players from Havana. The validity of bone age assessment methods is known to be influenced by ethnic and socioeconomic factors, as these methods were originally developed using reference samples from predominantly white, middle-class populations. For example, the Greulich and Pyle (1959) method was based on children from Cleveland, Ohio; TW2 on British children from the 1950s and 1960s (Tanner *et al*., 1975); FELS on youth from south-central Ohio (Roche *et al*., 1988); and TW3 on samples from Europe, Argentina, Texas, and Japan (Tanner *et al*., 2001).

Recent studies have highlighted the limitations of applying these methods across diverse populations. Kowo-Nyakoko *et al*. (2023) found TW3 to be more accurate than Greulich and Pyle in Zimbabwean youth, while Martín-Pérez *et al*. (2023) reported that Greulich and Pyle was reliable in Caucasian and Hispanic children but less so in Asian and Arab populations, where both Greulich and Pyle and TW3 tended to overestimate bone age near adulthood, a pattern also observed in our study with the FELS method. Khadilkar *et al*. (2004) further demonstrated that sensitivity varies across age segments, with TW2 and TW3 showing greater deviation in younger Indian children.

Our findings reflect the characteristics of a Caribbean population composed predominantly of individuals of African ancestry and mestizo heritage, whose biological diversity presents specific challenges for skeletal age estimation. In this context, the TW3 method provided coherent and consistent estimations, showing strong correlations with decimal age and reduced variability in younger age groups, particularly among females. These patterns suggest that TW3 responds effectively to the morphological heterogeneity observed in Cuban youth athletes. Although TW2 was applied using localized reference scores developed in the 1970s, TW3 incorporates more recent and multi-ethnic standards, which may offer greater adaptability to contemporary populations. Rather than replacing TW2, TW3 complements it as a robust alternative for assessing skeletal maturation in mixed-ancestry cohorts. These preliminary findings support the need to validate skeletal age methods in regionally distinct populations and encourage further research aimed at refining their applicability in educational and athletic settings.

Concordance between methods

The present study found a high degree of concordance between TW2 and TW3 in the evaluated sample of Cuban youth athletes, with intraclass correlation coefficients (ICC) exceeding 0.90. This suggests that TW2 remains a reliable method within this population, despite its older reference standards. These findings contrast with those of Malina *et al*. (2018), who reported substantial reclassification between TW2 and TW3 in young footballers, and with Pinchi *et al*. (2014), who found TW2 to be the least reliable method in forensic applications, particularly when compared to Greulich and Pyle and TW3.

Since the 1980s, Cuba has employed a localized scoring system for TW2 (Jiménez-Hernández *et al*., 1987), developed from a nationally representative sample. This system revealed notable differences in skeletal age percentiles (3rd, 50th, and 95th) compared with the original British sample used by Tanner *et al*. (1975). These differences —attributable to ethnic, socioeconomic, and methodological factors— may explain the strong agreement observed between TW2 and TW3 in this study. Moreover, TW3's reference data, derived from multi-ethnic populations across Europe, Argentina, Texas, and Japan, may better reflect the morphological diversity of Cuban athletes than the original TW2 reference.

FELS, by contrast, tended to classify a higher proportion of athletes —particularly males— as "mature," suggesting greater sensitivity to advanced skeletal development in competitive contexts such as beach volleyball and school basketball. This pattern aligns with findings from Coelho-E-Silva *et al*. (2022), who reported that early-maturing athletes are more likely to be retained in sports requiring greater body mass and stature. Similarly, Martinho *et al*. (2022) found that FELS classified 19% more football players as mature compared to Greulich and Pyle, while Lolli *et al.* (2023) observed discrepancies of up to three years between TW2 and FELS in Qatari youth athletes.

A key limitation of the present study is the absence of age group stratification due to sample size constraints and uneven age distribution. Nevertheless, exploratory analyses indicated that individuals classified as advanced by FELS also presented higher overall maturation levels. This trend is consistent with Martinho *et al*. (2022), who noted that agreement between Greulich and Pyle and FELS declined with increasing chronological age.

The variability observed in FELS estimates —particularly for athletes with average maturation— raises concerns about its reliability in school-based settings. As noted by Sousa-E-Silva *et al*. (2023), FELS is more dependent on evaluator expertise, which may introduce uncertainty when assessing individuals with ambiguous skeletal development. In the Cuban context, where precise classification is essential for sports selection and training decisions, this variability may limit the method's practical applicability.

Limitations of FELS and sport-specific implications

The FELS method consistently classified a greater proportion of athletes —particularly males— as "maturely advanced" compared with TW2 and TW3, raising concerns about the relative sensitivity of the latter methods in detecting advanced maturation stages. This trend is especially relevant in school-based sports, where physical demands are elevated and accurate biological classification is crucial. These findings align with Vignolo *et al*. (1992), who reported that FELS may overestimate skeletal maturity in adolescents with more developed physical characteristics.

However, discrepancies observed in younger athletes (ages 9-12) suggest that FELS may be less suitable for assessing early maturation stages. This limitation has been corroborated by recent studies (Celis-Moreno *et al*., 2025), which emphasize the importance of tailoring bone age assessment methods to both the age range and the sport-specific context of the target population.

The discrepancy between TW3 and FELS further underscores the need for caution in school sports settings, where decisions based on skeletal age carry ethical and competitive implications. As Malina *et al*. (2011) warned, none of these methods should be used as a direct substitute for chronological age due to the risk of misclassification and its potential impact on athlete development and selection.

In the disciplines analyzed, TW2 remains a practical and reliable tool, especially for younger athletes or contexts in which skeletal age is expected to closely mirror chronological age. Conversely, FELS demonstrated greater sensitivity in identifying advanced maturation stages, which may be relevant for talent identification in beach volleyball, a sport where physical development strongly influences performance outcomes. In school basketball, where athletes often show heterogeneous maturation profiles due to the influence of body size on motor skills and positional demands, TW3 may offer advantages by capturing more nuanced distinctions in skeletal maturity.

Although the sample size limits broader generalizations, these findings nonetheless provide valuable preliminary insights into the differential behavior of bone age assessment methods in Cuban youth athletes. They offer a foundation for future research aimed at validating skeletal maturation tools in ethnically diverse and sport-specific contexts, and underscore the importance of developing localized protocols that reflect the unique characteristics of Caribbean athletic populations.

Response to the research question

In addressing the central question of this study —the comparative reliability of TW2, TW3, and FELS for assessing skeletal maturation in Cuban youth athletes— the findings suggest that TW2 remains a consistent and practical method, particularly in school-based sports contexts. TW3 demonstrated additional sensitivity in identifying advanced maturation stages, which may enhance its applicability in competitive environments where physical development is a key performance factor.

Conversely, the FELS method exhibited greater variability and a tendency to classify athletes as more maturely advanced, especially among males. This raises concerns about its precision in populations with heterogeneous maturation profiles and underscores the importance of further validation in ethnically and sport-specific cohorts.

Methodological contributions, contextual limitations, and future challenges

One of the key strengths of this study lies in its contextual specificity: by examining skeletal maturation methods in a Caribbean athletic population with predominantly African and mestizo ancestry, it contributes to addressing a critical gap in the literature regarding ancestral diversity in bone age assessment. The inclusion of three internationally recognized methods —TW2, TW3, and FELS— enabled a multidimensional evaluation of their performance in a sport-specific setting, offering insights into their relative sensitivity and practical utility.

It is important to note that this study applied Cuban reference scores for the TW2 method, unlike most Latin American research, which relies on the original British standards. This methodological distinction introduces a qualitative advantage, as the Cuban scores were developed from a nationally representative sample and reflect the ancestral, socioeconomic, and developmental characteristics of the local population (Jiménez-Hernández *et al*., 1986). In Latin America, only Venezuela has undertaken a similar effort by producing a national atlas of skeletal maturation based on its own population data. In contrast, studies in Brazil (e.g. Ortega *et al*., 2006) and Mexico (e.g. Ramos Rodríguez *et al*., 2020) have compared TW2 and TW3 using international references. While the Brazilian study recommended TW3-RUS due to its lower overestimation of chronological age, the Mexican study —conducted in an indigenous Mixtec population— found TW3 to be more aligned with chronological age but did not reach definitive conclusions. In this context, the present study contributes original evidence grounded in national standards and a specific athletic cohort, reinforcing the need for regionally adapted references in skeletal age assessment.

The methodological design, which incorporated repeated measures and cross-method comparisons, adds analytical depth and supports the internal consistency of the findings. Moreover, the alignment of several results with international studies reinforces their relevance, while highlighting areas where population-specific differences may emerge.

While the findings provide valuable insights into a specific athletic cohort, generalization across the broader national sports system requires caution. Cuba's high-performance pyramid encompasses a wide spectrum of morphological profiles, maturational tempos, and ancestral compositions, shaped by decades of mestizaje and regional diversity. This biological heterogeneity presents both a challenge and an opportunity: it demands that skeletal age assessment methods be critically evaluated not only for statistical robustness but also for their adaptability to the nuanced realities of Cuban athlete development.

Future research must therefore move beyond isolated group analyses and engage with the full complexity of the Cuban sports structure. This includes examining how different methods perform across disciplines with distinct physical demands, and how they respond to the variability observed in early and late maturers. Talent identification strategies are not uniform: some sports prioritize explosive strength and favor early maturers, while others value technical refinement and long-term progression, often associated with late maturation (Lehnert *et al*., 2024). As Cuban research since the 1980s has shown, skeletal age correlates with physical development, but its interpretation must be contextualized within sport-specific, ethical, and developmental frameworks (Siret *et al*.,1991). Expanding future investigations to include broader age ranges, multiple disciplines, and diverse training environments will be essential to refine the application of skeletal age estimation and to ensure that athlete selection and development strategies are both equitable and scientifically grounded.

Recent findings by Lehnert *et al*. (2024) reinforce this perspective by demonstrating that the impact of biological maturation on performance varies depending on the type of motor skill assessed. Their study showed that early maturers tend to excel in sprinting and jumping, while late maturers may perform better in change-of-direction tasks and technical execution. These differences highlight the importance of aligning assessment tools and selection criteria with the specific demands of each sport and stage of development.

In a system as diverse and structured as Cuba's, skeletal age estimation must therefore be approached with methodological flexibility and contextual sensitivity, ensuring that no athlete is disadvantaged by a one-size-fits-all model.

Nonetheless, the study is not without limitations. The modest sample size (n = 44) constrains statistical power and limits extrapolation to broader athletic populations. Additionally, the absence of longitudinal follow-up restricts the ability to capture developmental trajectories over time. Given that the reference standards for TW2 and TW3 were originally derived from predominantly Caucasian populations, there remains a possibility of methodological bias when applied to populations with distinct ancestral compositions such as the one studied here.

Despite these constraints, the research offers a valuable exploratory framework for future validation efforts and underscores the importance of developing localized skeletal age assessment protocols that reflect the morphological and developmental characteristics of diverse youth athlete populations. In doing so, it contributes to a more inclusive and contextually grounded approach to talent identification and athlete development within the Cuban sports system.

CONCLUSIONS

This study evaluated the accuracy of three skeletal age assessment methods in Cuban school athletes, emphasizing the importance of selecting appropriate tools based on the biological and contextual characteristics of the target population. Although TW2 and TW3 demonstrated high concordance, TW3 exhibited specific advantages, including greater consistency across sexes, reduced dispersion at age extremes, and improved sensitivity for identifying early or advanced maturation stages. These differences, while statistically subtle, carry practical relevance in educational and sports settings, where biological age influences planning, performance, and selection. The discrepancies observed with FELS and its tendency to classify individuals with advanced development as "mature" further reinforce the need for more precise and contextually adapted approaches.

While the scope of this study is limited, its findings provide a solid foundation for future research integrating advanced technologies and multidimensional frameworks to enhance the assessment of biological maturation. From an anthropological perspective, this work contributes to the analysis of methodological differences in biological classification and to the broader discussion on adapting standards to specific populations. Its interdisciplinary approach opens new avenues for research aimed at improving the precision and relevance of skeletal maturity evaluations in school populations with ethnic and morphological diversity.

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AUTHOR CONTRIBUTIONS

Wiliam Carvajal Veitia: Conceptualization; Data curation; Writing – original draft; Writing – review & editing. Sofía León Pérez: Methodology; Data curation; Writing – review & editing. Danays Fernández Berdallez: Supervision; Writing – review & editing; Visualization. Ramsés Raymond Yáñez: Software; Formal analysis; Validation. María del Carmen Fuentes Danger: Investigation; Data curation. Beatriz Izquierdo Jiménez: Investigation. Celia García Hernández: Investigation. Milena Duharte Hernández: Methodology.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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