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Methods for estimating biological maturation in developing and growing athletes: A literature review

Métodos de estimación de la maduración biológica en deportistas en etapa de desarrollo y crecimiento: Revisión bibliográfica

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Abstract

The indicators related to biological maturation have been studied for decades. The changes produced by maturation have a significant effect on the performance of young athletes. The aim of this literature review was to analyze the most commonly used methods of estimating biological maturation in sports science. Four main methods were identified that address different indicators of biological maturation: radiographic methods, which estimate biological age through bone development; anthropometric methods, which estimate the rate of biological maturation through changes in growth velocity and proportionality; sexual maturation methods, based on the manifestation of male and female sexual characteristics; and dental maturation methods, which estimate biological age through tooth development. The "gold standard" for estimating the maturational state are the methods based on radiography of the hand and wrist; however, their limitations mean that their use in the assessment of young athletes is conditioned. Widely-used alternatives are anthropometric methods, which, although not free of limitations, have been shown to have sufficient reliability and validity. Sexual or tooth maturation do not seem to be as applicable in this field.

Keywords: Puberty, growth, physical exercise, maturational development, performance.

Resumen

Los indicadores relacionados con la maduración biológica han sido estudiados desde hace décadas. Los cambios que produce la maduración afectan de forma trascendental al rendimiento de los jóvenes deportistas. El objetivo de esta revisión bibliográfica fue analizar los métodos de estimación de la maduración biológica más empleados en ciencias del deporte. Se han identificado cuatro métodos principales que abordan indicadores de la maduración biológica distintos: los métodos radiográficos, que estiman la edad biológica a través del desarrollo óseo; métodos antropométricos, que estiman el ritmo de la maduración biológica a través de cambios en la velocidad de crecimiento y la proporcionalidad; métodos de maduración sexual, basados en la manifestación de los caracteres sexuales masculinos y femeninos; y métodos de maduración dental, que estiman la edad biológica a través del desarrollo dental. El "gold standard" para estimar el estado madurativo son los métodos basados en radiografía de la mano y muñeca, sin embargo, sus limitaciones hacen que su empleo en la valoración de deportistas jóvenes se encuentre condicionado. Una alternativa muy utilizada son las antropométricas, que aunque no están exentas de limitaciones, han mostrado tener suficiente fiabilidad y validez. La maduración sexual o dental parecen no ser tan aplicables en este ámbito.

Palabras clave: Pubertad, crecimiento, ejercicio físico, desarrollo madurativo, rendimiento.

Introduction

Conceptual approach to the term maturation, chronological age, biological age and peak height velocity.

Maturation, in relation to human growth, refers to the time and process of change from childhood to reach the adult maturational state (Malina & Bouchard, 1991). These processes have been extensively studied in their different stages, but special attention has been traditionally paid to the endocrine, structural, physiological and psychological changes that occur during adolescence, due to the rapidity with which they occur around puberty (Malina & Bouchard, 1991).

For both boys and girls, the onset of puberty is associated with increased activity of the sex, adrenal and thyroid glands, resulting in increased production of the hormones that catalyze pubertal changes (Beunen et al., 2006). More specifically, in the case of boys, there is a dramatic increase in testosterone concentration, becoming 30 times higher than the values of previous stages, which favors the development of sexual characteristics, the increase in bone structure, influenced by the growth hormone (GH), as well as the increase mostly in body mass and muscle mass (Handelsman et al., 2018; Malina & Bouchard, 1991). In contrast, the onset of puberty in girls is associated with an increase in estrogen concentrations, which is closely associated to the adipose tissue present before the onset of this stage and to its distribution in later stages, and to the development of female sexual characteristics as well (Biro et al., 2014; Garnett et al., 2004).

However, differences according to sex are observed, with the onset of the prepubertal stage having been identified between the ages of 8.2-10.3 years in girls, while in boys it was found between 10.3 and 12.1 years of age, with the age at peak height velocity (APHV) observed at 11.4-12.2 and 13.8-14.4 years respectively (Beunen & Malina, 1988; Beunen et al., 2006; Malina & Bouchard, 1991). The APHV has been defined as the age at which there is a dramatic increase in the rate of growth in terms of adolescent height and body mass (Malina & Bouchard, 1991). It is characterized by an increase in height at a rate of approximately 9 cm/year and 10.3 cm/year, and an increase in body mass of 8.3 kg/year and 9 kg/year in girls and boys, respectively (Kelch & Beitins, 1994; Tanner, 1990).

Maturation, growth and development are often compared with the chronological age of the individual, understood as the time elapsed from birth to a specific day (Lloyd et al., 2014), but not all individuals with the same chronological age manifest the changes associated with maturation simultaneously, there being evidence of different maturation rates among individuals (Marshall & Tanner, 1968, 1969, 1970). On the other hand, biological age has been defined as the age corresponding to the changes observed during the development of biological maturation (Malina & Bouchard, 1991), being able to give rise to differences between chronological age and biological age. It is the gap between biological age and chronological age that lead to different maturation rates.

Factors associated with maturation

These biological maturation processes and the indicators that are manifested during their development have been shown to have a high level of dependence on genetics (Thomis & Towne, 2006), but there are also factors that can favor variations in the time in which maturation occurs (Beunen et al., 2006). Nutrition is one of the factors that can affect the rate of maturation, and it has been observed that adequate nutrition does not have an important effect on the maturation process, but that malnutrition can delay skeletal development in adolescents (Malina & Bouchard, 1991). Another factor that could modify the rate of maturation is the amount of adipose tissue present before the pubertal stage, as a relationship has been observed between overweightness and obesity with an earlier onset of maturation, with this relationship being more marked in girls (Beunen et al., 2006).

There is a great debate about the influence of the systematic practice of physical exercise as a modifier of the rate of maturation. In this sense, while on the one hand it has been observed that elite female athletes in aesthetic disciplines tend to show a later maturational process, which could be associated with low levels of adipose tissue and low energy availability over long periods of time (Beunen & Malina, 1996), most authors conclude that there is no evidence that the systematic and continuous practice of physical exercise has a relevant effect on the rate of maturation of children and adolescents (Beunen & Malina, 1996).

Influence of biological maturation on athletic performance

In sports science, the study of biological maturation in relation to sports performance has aroused the interest of both coaches and the scientific community for decades, due to the influence it has on variables directly related to performance (Albaladejo-Saura et al., 2021).

In the different sports modalities, when it comes to training stages, athletes have been grouped according to their chronological age to try to create a standard training process and a competition system that is equitable for all participants (Gutiérrez-Díaz del Campo, 2013). In spite of this, the differences in the pace of individual maturation have led to the observation that more mature athletes have higher values in anthropometric variables such as height, body mass, and variables related to bone structure and muscle mass, as well as better results in physical performance variables such as upper and lower body strength and power, movement speed or agility, in different individual and collective sports disciplines, such as soccer, basketball, volleyball, handball, canoeing or tennis, (Albaladejo-Saura et al. , 2022a; Albaladejo-Saura et al., 2022b; Albaladejo-Saura et al., 2021; Carvalho et al., 2017; Matthys et al., 2012; Söğüt et al., 2019).

The differences caused by different maturation rates have been shown to create an advantage in competitions and selection processes during the adolescent stage for more mature athletes with respect to their peers of the same age category, although these differences tend to equalize towards the end of the maturational process (Dugdale, McRobert et al., 2021; Dugdale, Sanders et al., 2021; Vaeyens et al., 2008). This is why an increasing number of sports talent identification programs are advocating for the inclusion of biological maturation variables, such as APHV or maturity offset with respect to chronological age, as part of the characteristics to be assessed in athletes (Johnston et al., 2018), although there is no consensus on which method should be used for their assessment.

Introduction to methods for estimating biological maturation

Due to this interest in knowing the differences in biological maturation, numerous methods have been developed to estimate the biological maturation gap with respect to chronological age or to identify the maturational stage in which the individual is found (Malina et al., 2015). Among the most commonly used methods, we find those based on the development of secondary sexual characteristics, giving rise to classifications according to the stage of sexual maturation (Marshall & Tanner, 1969, 1970); those based on skeletal development during childhood and adolescence, to establish a classification of skeletal age (Greulich & Pyle, 1959; Tanner et al., 1975); those that use anthropometric measures to estimate APHV as a measure of somatic maturation (Mirwald et al., 2002; Moore et al., 2015); or the study of dental maturation to assess the stage at which the individual is found (Demirjian & Goldstein, 1976; Demirjian et al., 1973).

As a result, there is an extensive debate about the suitability of these different methods for estimating biological maturation in the field of study of sport sciences. Therefore, the aim of the present research is to carry out a literature review of the most commonly used methods of estimating biological maturation in sport sciences.

Methods for the evaluation of maturation

In order to evaluate biological maturation, different indicators that undergo changes in the course of maturation can be used. Among the most commonly used indicators in sports science are skeletal maturation, assessed by radiographic methods; somatic maturation (based on growth velocity), assessed by anthropometric methods; sexual maturation, assessed by methods of secondary sexual characteristics development; and dental maturation, assessed by dental radiographs.

Study of skeletal maturation

The assessment of skeletal age is one of the most widely used indicators for the study of biological maturation. These methods are based on the taking of radiographs at different points in bones considered of interest and the comparison of these radiographs with pre-established reference models, governed by the principle of progressive calcification of the epiphyses of the bones studied, in the course of maturation (Greulich & Pyle, 1959; Roche et al., 1988; Tanner et al., 1975).

In this regard, there are three models that have been the most widely used over the years:

1. *Greulich & Pyle method*: The method described by Greulich and Pyle (1959) is a method based on an atlas of standardized reference images, taken from a population of Caucasian boys and girls, at different stages of maturation from birth to adult skeletal development, separated from each other in time periods of a year or half a year. This method involves radiographing the individual's left hand and wrist and then comparing them to reference images to determine their skeletal age. Thus, if the radiograph taken coincides with a skeletal age higher than the individual's chronological age, he or she will be categorized as an early maturer, while if it coincides with a lower chronological age, he or she will be categorized as a late maturer. This method is still used according to the protocol originally described, and was validated in a population of Caucasian American children (Greulich & Pyle, 1959).
2. *Tanner-Whitehouse 1, 2 & 3*: The method proposed by Tanner & Whitehouse (1975) is based on the radiographic assessment of the left hand and wrist, and the categorization of 13 or 20 bones in different regions of interest. Afterwards, a series of criteria are applied related to the description and shape of the bones analyzed. Finally, a skeletal age value is obtained, resulting from the assessments of the maturation of each individual bone, which is then compared to the chronological age of the individual assessed. Thus, if the skeletal age result is greater than the chronological age of the individual, he or she will be classified as early maturing, while if it is less, he or she will be classified as late maturing. This method, which has been revised three times (TW1, TW2 and TW3), has been validated in a population of children of British origin (TW1 and TW2) and in European, South American, North American and Japanese populations (Tanner et al., 1975; Tanner et al., 2001).
3. *Fels study protocol:* This method, proposed by Roche et al. (1988), is based on radiography of the left hand and wrist, with reference indicators in the ulna, radius, carpus, metacarpus and phalanges of the first and fifth fingers. In this method, a graduation is attributed to each bone according to the age and sex of the participants, including ratios between the length and width of the long bones and the ossification of the measured bones. These values are used to estimate the skeletal age of each individual, and then, when compared with the chronological age, to classify individuals as early or late maturers. This method is still used according to the protocol originally described, and was validated in a population of Caucasian American children who were followed longitudinally for different maturational indicators (Roche et al., 1988).

Study of somatic maturation

Another of the most commonly used indicators for assessing biological maturation is the study of somatic maturation. This is based on the identification of the peak height velocity (PHV) resulting from the increase in the concentration of GH, thyroid hormone, and androgens, and the changes they cause in height, weight, and proportionality of the different body segments (Malina & Bouchard, 1991). These methods are characterized by the possibility of directly observing the onset of PHV in longitudinal studies, characterized by a growth of approximately 9 cm/year in girls and 10.3 cm/year in boys, through continuous anthropometric measurements and their comparison with reference values (Kelch & Beitins, 1994). However, in cases in which cross-sectional designs make it impossible to take repeated measurements, there is the possibility of estimating APHV by means of anthropometric measurements, which are subsequently introduced into regression formulas. Among the methods of estimation using anthropometric measurements, the most commonly used are:

1. *Mirwald et al. method*: the method proposed by Mirwald et al. (2002) is based on the different growth ratios that exist between the trunk-encephalic height and lower limb length, as well as the effect of this growth on the total height of the individual, and the body mass around the PHV. Thus, two equations differentiated by sex were created in which chronological age, body mass, height, and sitting height of the individual, and the length of the lower limb are introduced as variables for the calculation. These formulas result in the biological maturation offset , which, subtracted from the chronological

age, provides an estimate of the APHV. The prediction equations were developed in the population included in the Saskatchewan Pediatric Bone Mineral Accrural Study (113 boys and 115 girls) (Mirwald et al., 2002).

2. *Moore et al. method:* The method proposed by Moore et al. (2015) is based on the same principles that identify the change in velocity of the growth rate of adolescents, by studying the proportionality between trunk and lower limb in increasing anthropometric variables, to create regression equations for the estimation of APHV. In it, two formulas differentiated by sexes were proposed, in which age and sitting height in the case of boys , and age and height, in the case of girls, were included as independent variables to estimate biological maturation offset and subsequently the APHV . The validity of the formulas was compared with populations from two external studies , the Harpenden Growth Study (419 British boys and 282 British girls) and the HBS -III study (515 Canadian boys and 556 Canadian girls) (Moore et al., 2015).

The resulting formulas for each method can be observed in Table 1.

Table 1. Methods of estimating maturation by studying the age at which the peak height velocity occurs through anthropometric variables

Authors	Equation (maturity offset)	Validity indicators	Validation population
Mirwald et al. (2002)	Boys = -9.232+0.0002708*(LLL*SH)-0.001663*(Age*LLL)+0.007216*(Age*SH)+0.02292*(BM/H)	R^2 = .891 *SEE* = 0.592	228 participants for the Saskatchewan Pediatric Bone Mineral Accrural Study (113 Boys; 115 Girls)
	Girls = -9.37+0.0001882*(LLL*SH)-0.0022*(Age*LLL)+0.005841*(Age* SH)-0.002658*(Age*BM)+0.07693*(BM/H)	R^2 = .890 *SEE* = 0.569	
Moore et al. (2015)	Boys = -8.128741+(0.0070346*(Age*SH))	R^2 = .906 *SEE* = 0.514	1071 participants for the HBS-III study (515 Boys; 556 Girls)
	Girls = -7.709133+(0.0042232*(Age*H))	R^2 = .898 *SEE* = 0.528	

LLL: Lower limb length; SH: sitting height; H: height; BM: body mass; SEE: standard estimated error.

Study of sexual maturation

The evaluation of sexual maturation as an indication of biological maturation is based on the gradual development of male and female secondary sexual characteristics that begin with the increase in sex hormones produced during the prepubertal stage (Marshall & Tanner, 1969, 1970).

Within the study of sexual maturation, the most widely used is the one proposed by Marshall and Tanner (1969, 1970). In it, a classification of five stages was made based on two scales for each sex, focused on the development of pubic hair in both boys and girls, genital development in the case of boys and the development of breast tissue in the case of girls, with images and description of each of the stages and the proposed scales. This methodology has been proposed to be utilized during a physical examination or to be self-completed by the subjects (Marshall & Tanner, 1969, 1970).

Study of dental maturation

The study of dental maturation has also been considered as an indicator of biological maturation due to the different stages through which the development of permanent teeth pass through, from their calcification, which marks the beginning of maturation, until the apical end of the dental root canal is completely closed, which marks its end (Demirjian & Goldstein, 1976; Demirjian et al., 1973).

In this sense, Dermirjian & Goldstein (1976) developed a classification system using panoramic radiography for dental maturation, dividing the process into eight phases that can be applied to each tooth. In this methodology, each tooth is classified according to a scale of eight values to subsequently calculate a joint index among all the teeth analyzed, in which the maximum sum of the values is 100. By means of this value, the subject is attributed a biological age based on his or her dental maturation, which is subsequently compared with the chronological age to establish the maturational gap. For this, they include both images and a description of the characteristics that the teeth should have in order to be included in each of the proposed groups. This method was developed with a sample of 1446 Canadian boys and 1482 Canadian girls.

Considerations for the use of biological maturation assessment methods with adolescent athletes.

It should be noted that all the methods described above have been developed and validated in the first instance in a clinical context, in populations of different ages and not specifically athletes. A summary of the main characteristics and the advantages and disadvantages of each method can be found in Table 2.

Table 2. Summary of the characteristics of the main methods for estimating biological maturation and their suitability for the field of study of sports science

Kind of method	Measuring speed	Economic cost	Ease of implementation	Suitability to the field of sports science	
				Advantages	Disadvantages
Skeletal maturation: X-ray of hand and wrist according to Greulich & Pyle (1969)	*	***	*	Considered the "gold standard" for the estimation of biological maturation in sports science, in contexts where access is available.	It cannot be adapted to field research, the need for specialized personnel, the time and cost of its application and the radiation exposure of participants.
Skeletal maturation: X-ray of hand and wrist according to Tanner & Whitehouse (1975)	*	***	*	Considered the "gold standard" for the estimation of biological maturation in sports science, in contexts where access is available.	It cannot be adapted to field research, the need for specialized personnel, the time and cost of its application and the radiation exposure of participants.
Skeletal maturation: X-ray of hand and wrist according to Roche et al. (1988)	*	***	*	Considered "gold standard" for the estimation of biological maturation in sports science, in contexts where access is available.	It cannot be adapted to field research, the need for specialized personnel, the time and cost of its application and the radiation exposure of participants.
Somatic maturation: Anthropometric measurements according to Mirwald et al. (2002)	**	**	**	Easy to implement, adaptable to field work and requiring little training for researchers.	Its limitations should be taken into account in order to avoid introducing excessive error in the estimation, it may underestimate or overestimate the value of the maturity offset in early or late maturers respectively, and its use is advised for classifying athletes according to their maturation rate.
Somatic maturation: Anthropometric measurements according to Moore et al. (2015)	**	**	**	Easy to implement, adaptable to field work and requiring little training for researchers.	Its limitations should be taken into account in order not to introduce excessive error in the estimation, it may underestimate or overestimate the value of the maturity offset in early or late maturers respectively, and its use is advised for classifying athletes according to their maturation rate.
Somatic maturation: Anthropometric measurements according Sherar et al. (2005)	**	**	***	Easy to implement, adaptable to field work and requiring little training for researchers.	It requires repeated anthropometric measurements over a period of three to 18 months over several years and subsequent individual analysis of the growth curves to obtain the result of the APHV.
Sexual maturation: Sexual characteristics according to Marshall & Tanner (1969, 1970)	***	*	***	It is an easy to implement method that does not require specific facilities, has a low cost, is quick to perform and can be self-completed by the subject.	It may be considered invasive for the privacy of the individual, decontextualized from the clinical setting. It may lose reliability when it is self-completed by the subjects.
Dental maturation: Dental radiography according to Demirjian & Goldstein (1976)	*	***	*	It has similar reliability and validity to hand and wrist radiographic methods for assessing the subject's biological maturation.	It is extremely specific in terms of the fields of study covered. It cannot be adapted to field research, requires highly specialized personnel and exposes its participants to radiation.

*: low; **: medium; ***: high.

Methods based on skeletal maturation

Methods based on radiographs have been widely used in athlete populations (Carling et al., 2012; Figueiredo et al., 2009; Gouvea et al., 2016; Söğüt et al., 2019; Valente-Dos-Santos et al., 2014). In them, the objective is to obtain the value of the subject's biological age at the time of measurement, using skeletal maturation as an indicator of the subject's biological maturation, which will later be compared with the chronological age, to find the maturational offset . These methods have been considered the "gold standard " for the estimation of biological maturation, due to the large amount of data available, the reproducibility of the methods, the possibility of performing the study from infancy to late adolescence or adulthood, and the consistency in the results with respect to the developmental curves observed in longitudinal studies (Malina et al., 2015). However, due to differences in the skeletal maturation assessment criteria used to analyze biological maturation, these methods have their own advantages and disadvantages, making it impossible to identify one of them as the "gold standard" among the different skeletal maturation methods (Malina et al., 2015). On the other hand, none of the three methods described in this review can be underlined as the most utilized in sports science, as these methods have been used to assess the biological maturation of young athletes regardless of the sports discipline (Albaladejo-Saura et al., 2021; Malina, 2011).

These methods have been used both to analyze the biological maturation of participants descriptively, and to classify them as early , on-time, or late maturers , using the difference between skeletal age and chronological age (Carling et al., 2012). When attempting to classify adolescent athletes based on the biological age assessed by these methods, the most common procedure is to subtract skeletal maturation - chronological age, and use the result to establish a range of ±1 year (difference from >-1 to < +1) to classify athletes whose maturation is considered on- time , while if the difference is positive and greater than one year (difference >+1) they would be considered early maturers , and if the difference is negative and greater than one year (difference <-1), late maturers (Carling et al. , 2012 ; Figueiredo et al., 2009). There are other proposals for the classification of biological maturation based on skeletal age, such as classi fication into more mature or less mature , without on-time maturers group, depending if the result of the subtraction between skeletal age and chronological age is positive or negative , although these methods are less employed (Söğüt et al., 2019).

Despite the benefits of radiography-based methods, it should be noted that they are not without limitations. The three most employed methods, proposed by Greulich & Pyle (1959), Tanner & Whitehouse (1975) and Roche et al. (1988) are based on the same principles to categorize bone maturation, but due to differences in the methodology used to obtain skeletal maturation, they are not considered to be interchangeable with each other (Malina et al., 2015).

On the other hand, they are expensive, time-consuming to implement and not adaptable to measurements outside the laboratory context, which limits their use in the context of sports science (Malina et al., 2015; Towlson et al., 2021). Furthermore, these methods need to be employed by specialized personnel with the necessary qualifications to perform them, otherwise their validity and reliability decreases (Lloyd et al., 2014; Towlson et al., 2021). As these methods are based on the use of X-rays, some authors argue that they are invasive methods whose use is not justified in adolescents, since they consider that radiation should only be applied to growing individuals in the context of a clinical diagnosis, not being justified in sports science research (Gómez-Campos et al., 2013). However, other authors do advocate its use, justifying that, with current techniques and instruments, the radiation to which the individual is subjected during the assessment is minimal, and would not involve an amount that is considered harmful to health (Malina et al., 2015). These limitations make it an accessible method mainly for sports with a high level of economic income or access to adequate facilities, as is the case of football (Carling et al., 2012; Figueiredo et al., 2009; Gouvea et al., 2016; Valente-Dos-Santos et al., 2014).

Methods based on somatic maturation

Somatic maturation estimation methods based on anthropometric measurements are among the most widely used in the assessment of adolescent athletes due to their low invasiveness, ease of use, the possibility of performing measurements in both laboratory and field investigations, the low cost of the equipment needed for their implementation, and the relatively little training needed by the researchers (Albaladejo-Saura et al., 2022a, 2022b, 2022c; Arede et al., 2019; Guimarães et al., 2019; Hammami et al., 2018). In them, the indicator of biological maturation is the growth rate and the age at which the increase in growth velocity occurs, compared to the chronological age of the subject. These methods do not allow estimating the subject's biological age at the time of measurement, but are indicative of the rate of biological maturation (Drenowatz et al., 2010; Drenowatz et al., 2013).

These methods, similarly to radiological methods, have been used descriptively in populations of adolescent athletes (Albaladejo-Saura et al., 2022c) or to classify them as early, on-time, or late maturers (Albaladejo-Saura et al., 2022a; Albaladejo-Saura et al., 2022b; Arede et al., 2019; Guimarães et al., 2019; Hammami et al., 2018).

In this case, there are some remarkable differences between the methods based on PHV observation and those that perform their estimation through formulas. In the case of the PHV observation method, several measurement sessions, spaced between 3 and 18 months apart, are necessary to establish the growth rate of the individual, over the years in which the PHV is theoretically produced in order to identify it in relation to the observed growth curves (Kelch & Beitins, 1994; Malina & Bouchard, 1991; Sherar et al., 2005; Tanner, 1990).

However, this method also has limitations. The main limitation found is that it is available only for longitudinal experimental designs of long duration, due to the need to space the measurements over a long period of time (Kelch & Beitins, 1994; Malina & Bouchard, 1991; Sherar et al., 2005; Tanner, 1990). On the other hand, due to the methodology used, the age range in which this method is applicable is reduced to the years around the PHV, and an individualized study of the growth curve must be carried out due to individual variations (Sherar et al., 2005).

In contrast, in the formulas developed by Mirwald et al. (2002) and Moore et al. (2015), it is only necessary for anthropometric measurements to be assessed only once, since, in the proposed formulas, one of the prediction variables is the chronological age of the subject at the time of assessment. These formulas give as a result the time in years remaining until the individual assessed reaches the PHV (if the result is negative) or the time in years that has passed since the individual passed the PHV (if the result is positive), called the maturity offset. The maturity offset, subtracted from the individual's chronological age is used to calculate the APHV (APHV = chronological age - maturity offset) (Mirwald et al., 2002; Moore et al., 2015). This value can be used directly to categorize athletes into early, on-time or late maturers, according to different criteria.

Traditionally, the ranges indicated by Malina & Bouchard (1991), in which PHV is typically observed, 11.4-12.2 years of age for girls and 13.8-14.4 for boys, have been used to classify athletes as early maturers, when their APHV was within the indicated range; early maturers when their APHV was below the indicated range; and late maturers when their APHV was above the indicated range. However, this evaluation criterion has the limitation that the estimation of APHV can be altered by chronological age, as observed in recent research (Malina, Coelho-E-Silva, et al., 2021; Towlson et al., 2021), so it would only be valid for populations in a reduced age range, which was around the theoretical APHV.

Currently, due to the heterogeneity that could be found in the groups of adolescents evaluated in sports science in terms of chronological age, the most widely used classification methods base their criteria for the calculation of the APHV, establishing ranges that define the groups as early maturers, on-time, or late maturers, on the mean and standard deviation (SD) of the group with respect to this variable (Figueiredo et al., 2009; Hammami et al., 2018; Mirwald et al., 2002; Moore et al., 2015). Thus, some authors propose a range of ±1 year in APHV with respect to the mean of the group, into which the athletes whose APHV is considered on-time would be placed, while if the APHV has a difference greater than one year both below and above that of the mean, would be considered early and late maturers, respectively (Hammami et al., 2018; Mirwald et al., 2002; Moore et al., 2015). The establishment of the criterion of a range of ±1 year with respect to the group's APHV to classify athletes into the different maturation groups is because the samples used to validate the formulas by Mirwald et al. (2002) and Moore et al. (2015) showed a *SD* ≈ 1 year when their biological maturation was assessed by radiography. But the establishment of this range has certain limitations when the samples are homogeneous. If the *SD* of the group's APHV is less than 1 year, almost all the athletes would be classified as maturing on time. That is why when the *SD* of the APHV of the group is less than 1 year, some authors have proposed the use of ranges of ±0.5 years of the APHV, with those within this range considered on-time maturers, below that range early maturers and above that range, late maturers (Albaladejo-Saura et al., 2022a, 2022b; Arede et al., 2019; Drenowatz et al., 2010; Guimaraes et al., 2019; Wickel & Eisenmann, 2007).

However, the APHV estimation formulas also have limitations that should be taken into account. On the one hand, despite being widely used methods in sports science and having good validity indices (R. = .896 - .890) (Albaladejo-Saura et al., 2021; Mirwald et al., 2002; Moore et al., 2015), it has been observed that they usually introduce a certain degree of error that limits their use at certain times since they are based on regression equations (standard error= 0.542-0.569 years) (Malina et al., 2016; Malina, Coelho-E-Silva, et al., 2021). On the other hand, it has been observed that the equations tend to underestimate the value of the maturation lag for early maturers, while overestimating it for late maturers (Towlson et al., 2021). Because of these limitations, some authors have recommended using these methods only in adolescent populations, limiting their use in child populations (Malina, Coelho-E-Silva, et al., 2021; Towlson et al., 2017; Towlson et al., 2021), to control for the effect of chronological age on the estimates, as it has been observed that the estimation of somatic maturation changes in a stable manner with advancing age. Further recommendations have also been made for using anthropometry-based methods to classify athletes into early, time or late maturers, rather than as a descriptive measure of biological maturation, as they indicate the rate of maturation, and allow for the comparison between individuals, but not the calculation of biological age (Malina, Coelho-E-Silva, et al., 2021). Despite these limitations, its use has been recommended on the adolescent athlete population when the "gold standard" method is impossible to use (Towlson et al., 2021).

Methods based on sexual maturation

Methods based on the development of secondary sexual characteristics have also been used in studies conducted in the athlete population (Figueiredo et al., 2009; Matta et al., 2014). In these methods, the indicator of biological maturation is the degree of development of the secondary sexual characteristics as compared to the scale proposed at the time of assessment. However, they are less used than methods based on skeletal or somatic maturation (Albaladejo-Saura et al., 2021). The method described by Marshall & Tanner (1962) classifies the development of secondary sexual characteristics into five stages, with stage 1 being attributed to a time before puberty (prepubertal), stages 2-4 are considered pubertal development, and stage 5 adult development (Gómez-Campos et al., 2013). The stages of sexual maturation have also been related to other indicators of biological maturation, such as the "gold standard" (Figueiredo et al., 2009). Thus, it was observed that participants classified as late maturers aged between 11 and 12 years old were mostly classified in the pre-pubertal stage (88%) from the method described by Marshall and Tanner (1969, 1970), while those classified as early and on time maturers aged 13 and 14 years old of chronological age were found between stages 3 and 4 of the aforementioned method.

This method has the advantage of being easy to apply, since it based on the use of a set of images with which to compare the current state of the individual's characteristics, as well as the possibility of the subject himself carrying out the evaluation (Marshall & Tanner, 1969, 1970).

The specific characteristics of the evaluation of sexual maturation make it necessary to take into account the possible drawbacks when intending to use this methodology. It should be considered that its use is limited to the prepubertal and pubertal stages, since no categories are detailed for the classification of the characteristics of individuals outside that range (Marshall & Tanner, 1969, 1970). On the other hand, one of the main limitations when its use is intended in the field of sports science is that it is an invasive technique for the participant due to the aspects that are assessed for classification, for which ethical and cultural aspects must be taken into account (Gómez-Campos et al., 2013). This is because this methodology was originally developed for the clinical context, for the physical examination of the patient by health personnel (Marshall & Tanner, 1968). To try to solve this problem, it has sometimes been advocated for self-assessment by the participant, a fact that could decrease the validity and reliability of the instrument (Gómez-Campos et al., 2013).

Methods based on dental radiographs

Methods based on dental maturation are widely used in clinical, dental, forensic, and anthropological contexts (De Donno et al., 2021), with the most widely used being the one proposed by Demirjian & Goldstein (1976), while in sports assessment contexts its use is less widespread (Albaladejo-Saura et al., 2021; Beunen et al., 2006; Johnston et al., 2018; Malina, Martinho, et al., 2021). This method uses tooth development as an indicator of biological maturation. It shares the advantages of skeletal age estimation methods, counting on a high reproducibility, a wide range of implementation ages from infancy to adulthood, and consistency in the results with respect to observed growth curves (De Donno et al., 2021; Demirjian & Goldstein, 1976; Demirjian et al., 1973; Gómez-Campos et al., 2013).

However, it also has similar limitations. They use X-rays for assessment, which implies radiation exposure that would not be justified in sports science studies (Gómez-Campos et al., 2013), their use requires a lot of time, specific facilities, qualified personnel, and entails a high economic expense (De Donno et al., 2021; Malina et al., 2015), reasons why their use in studies in young athletes could be scarce.

Limitations and future lines of research

The present research is not without limitations. Within it, the methods most commonly used in the assessment of different indicators of biological maturation in the sports context were reviewed. However, there are other methods for assessing biological maturation that were not analyzed, such as radiographic methods of bone structures other than the hand and wrist, or methods based on the analysis of hormone concentration, which are more commonly used in the clinical context. On the other hand, methods that are less commonly used or lack sufficient validation have not been analyzed either.

Future reviews of biological maturation estimation methods could address the inclusion of the different methods regardless of the context in which they are used.

The lines of research derived from the present review could be aimed at analyzing the validity, reliability and adequacy of the different estimation methods with respect to the developmental growth curves observed in longitudinal studies, as well as the inclusion of variables related to performance and health that may be affected by individual differences in maturational development.

Conclusions

In the field of sports, when evaluating growing athletes, it is essential to take into account their maturational state, due to the great influence of biological maturation on numerous variables directly associated with performance. Many methods for estimating maturation exist that have been proven to be useful tools for assessing the maturation process in adolescents, such as bone, somatic, sexual and dental maturation. In this sense, the method endorsed by the scientific literature as the "gold standard" for the estimation of biological maturation in populations of adolescent athletes is the bone maturation method, which is based on the performance of hand and wrist radiographs. However, it has many limitations, among which we find the economic cost, the time and facilities required for its implementation, the need for highly qualified evaluators, and the radiation to which the subjects are exposed. All of these limitations may condition its use in most situations applicable to studies in sports science. In the event that the use of the radiographic method is not possible, the assessment of somatic maturation through formulas that use anthropometric variables for its calculation are a widely used, as they have been proven to be reliable and valid options, and are easy to use and adapt to field research. However, it should be taken into account that these methods can introduce a certain error in the estimation, leading to the underestimation or overestimation of the value of the maturity offset in early or late maturers respectively. Also, their use is advisable to only classify athletes according to their rate of maturation, since the methods for estimating somatic maturation based on anthropometry can only indicate the rate of biological maturation, but not of biological age, which is one of their main limitations. Finally, the assessment of sexual characteristics and dental development are less used methods for estimating maturation in sports science, mainly because of their clinical nature, the ethical implications, and the difficulty in their application.

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