Ultrasound Imaging-Based Methods for Assessing Biological Maturity

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Bone maturity is an indicator for estimating the biological maturity of an individual. During adolescence, individuals show heterogeneous growth rates, and thus, differences in biological maturity should be considered in talent identification and development. Radiography of the left hand and wrist is considered the gold standard of biological maturity estimation. The use of ultrasound imaging (US) may be advantageous; however, its validity and reliability are under discussion.

Keywords: ultrasonography ; bone age ; biological maturity

1. Introduction

Bone maturity is an indicator that estimates the biological maturity of an individual [1][2] and may differ from chronological age, which is calculated using the current date minus the date of birth. During childhood, but more particularly during puberty, individuals may show very heterogeneous growth rates, and the physiological and psychological changes that occur during the transition from adolescence to adulthood are rapid and pronounced [3][4]. Pediatricians and researchers use bone maturity (maturity stages) or bone age (decimal bone age) estimation to evaluate the growth process for various purposes, for example, defining when treatment can take place, or to estimate age for legal purposes [2][5]. In sports, biological maturity affects physical and cognitive skills. There is evidence that talent selection processes are distorted by differences in biological age [6][7]. Especially in sports where physical components influence performance outcomes, differences in biological maturity must be considered in talent development and identification processes to ensure fairness and equality of chances [7][8][9][10]. In addition, cut-off dates based on chronological age indicate whether an athlete is eligible to compete or enter a category. In the absence of birth certificates or to avoid abuse of the system, bone age estimation can serve as an assessment tool [11][12]. Furthermore, estimates of biological maturity, e.g., age at peak height velocity and predicted adult height, can be estimated, with a certain margin of error, using an equation based on weight, as well as sitting and standing height [13][14][15][16]. Using this information, it is possible to define whether an athlete is an early, normal, or late developer, compared to the average of a specific population. This makes it possible to assess whether certain sports favor the selection and support of athletes at a particular stage of development, or to put systems in place that promote equality and fairness [17].

Doyle et al.’s [18] standards and guidelines provide a broad overview of the existing methods to estimate bone maturity. Currently, the assessment of bone age by the Greulich and Pyle or Tanner and Whitehouse methods using radiography of the left hand and wrist, i.e., the estimation of decimal bone age, are considered the gold standard of imaging techniques. However, even though the radiation dose received during an X-ray is minimal [19], researchers and physicians tend to favor other non-ionizing techniques to avoid the ethical problem posed by radiation. In addition, in many western countries (e.g., Germany and Switzerland) it is a legal requirement to select the method with the lowest radiation intensity from several available methods (Strahlenschutzgesetz (StSG, SR 814.50)). Despite being a non-ionizing technique with validated accuracy, MRI is expensive, time consuming, and less accessible [20]. Therefore, the field of auxology is currently studying sonography, focusing on two different techniques. Ultrasound imaging of bone structure relies on the production of images through high multi-frequency linear transducers that allow one to visualize the composition of growth areas, e.g., the presence of cartilage or ossification centers [21][22]. Imaging of bone anatomy allows the direct visualization of the bony epiphyses and, furthermore, the monitoring of the closing of the growth plate, a crucial diagnostic element for bone maturity estimation. Quantitative ultrasound is another technique by which the properties of bone tissue are analyzed quantitively, for example, by the speed of sound or distance attenuation factor [23][24]. These two sonographic procedures rely on gold standard methods, on existing staging systems, or have been newly developed [25][26]. From a practical, ethical, and economic point of view, ultrasonography seems to present many advantages in various fields of application. However, to date, no ultrasound method has been accepted as the gold standard yet and its clinical utility is still being discussed [20]. Some studies have developed reference values for cartilage thickness in healthy children, mainly to detect juvenile idiopathic arthritis [27][28][29][30][31][32]. However, these measurements were not directly applicable to bone maturity estimation at the publication time.

2. Validity, Reliability, and Acceptance

One of the most significant advantages of using ultrasonography is the absence of ionization. According to human research and age estimation procedure legislations, the risks and intrusiveness must be reduced to a strict minimum and the technique used must prioritize a lack of radiation [33][34]. Although adult radiation exposure is minimal in an X-ray of the extremities, i.e., 0.001 mSv compared to 0.27 mSv for one year of terrestrial radiation [19][35], repeated measurements for longitudinal growth monitoring should be avoided. Thus, ultrasonography would be advantageous for biological maturity estimation, as long as the accuracy of the measurements is higher than other non-invasive methods such as anthropometric measurements. MRI is a technique that has been validated but is not generally considered a reference yet, as its usefulness has to be confirmed, and further studies with higher numbers of participants are needed [20][36]. In addition, its high costs and time consumption hinder the implementation in the field of sport, particularly in youth sport.

Of all the methods presented in the studies, 70% were considered to be acceptable, with relatively high validity and reliability. The comparison to the gold standard showed positive perspectives, although in two cases (femoral head thickness and maturation stages of clavicular epiphysis), the agreement was statistically unsatisfactory. To be accepted, the staging systems have to achieve the precision required by the goal of the assessment (e.g., the limit of age or growth monitoring). However, an estimation of decimal bone age by US imaging is lacking. For greater accuracy, the estimation of bone maturity could be combined with additional measurements of other body regions or include anthropometric parameters to prevent unprobeable deviations of results [37].

The US-based skeletal maturity score method developed by Wan et al. [22][26][38] provides interesting results. Measurements at the wrist and knee allowed them to reach values corresponding to the chronological age of healthy subjects. Furthermore, the method was also tested on subjects with growth disorders with valid results compared to the gold standard of hand radiographs and estimation by the Tanner-Whitehouse 3 and Greulich–Pyle methods. Despite the restricted classification of the maturity stages (n = 3), the study by Herrmann et al. [25] suggests the development of an atlas using the ultrasound scanning technique of the knee joint. Indeed, the creation of five images per zone (medial distal and lateral distal femoral physis, medial proximal and lateral proximal tibial physis, and lateral proximal fibular physis) provides a fairly complete overview of the zone.

Currently, the accuracy of US measurements depends heavily on the examiner's expertise and anatomical knowledge. The focus of future research in this area should therefore be the good standardization of the procedure and the objectification of the image analysis. In this sense, the aim must be to improve inter- and intra-rater reliability and simplify the procedure for researchers through good standardization.

3. Usability, Practicability, and Economy

Several areas of research were identified in the various studies. From a pediatric, legal, or sporting point of view, there is interest in developing a non-ionizing technique to assess biological maturity. Furthermore, orthodontic support, monitoring of idiopathic scoliosis during adolescence, and growth monitoring require repeated measurements, and as such, would profit from a non-ionizing and cheap technique. In this context, it could be shown that four different analytical procedures exist in the literature. In addition, knowledge of the biological age is a crucial component for fair selection and the implementation of bio-banding. Furthermore, existing methods could be found to be too inaccurate (e.g., anthropometric measurements), too expensive (e.g., MRI), or too radiation-intensive (e.g., X-ray). In the field of sports, the organization of systems based on biological age, such as the right to participate in competitions or bio-banding, does not represent a need for medical diagnosis per se, and therefore, it may be more difficult to allow ionizing technologies from a legal point of view. A valid method of estimating biological maturity by ultrasound would thus be a beneficial alternative.

More specifically, in the field of sport [9][12], the distribution of athletes into chronological age classes often creates imbalances between competing adolescents. Thus, the overrepresentation of early maturers and relative age effects are very common, i.e., children born at the beginning of the year are overrepresented in competitive sport compared to those born at the end of the same year [6][39][40]. This effect progressively lessens closer to the end of growth. In addition, at the onset of puberty, a disparity in performance capacity linked to the biological development of the athletes arises. For example, studies show that among soccer national team players under the age of 15, early developers are faster, more powerful, more likely to win duels, and have higher chances of being selected for talent development programs [41][42]. Conversely, late developers selected for superior teams often show superior technical abilities [42][43]. Bio-banding is a form of play in which players are divided into teams according to their biological maturity in order to mitigate differences associated with maturity status and ensure equality [43]. If the estimation of biological maturity by ultrasound proves to be more accurate than anthropometric methods, it could support such systems to ensure fairness between young athletes during competitions and selection. Monitoring growth throughout the puberty period would also help to improve and individualize training and possibly reduce the risk of injuries, especially around peak age velocity [44][45].

Depending on the field in which the method is used, the need for precision in the estimate may differ. In forensic medicine, for example, the method should be most accurate for determining a chronological age representing the majority, which is crucial for law application [33]. In the field of sport, however, growth velocity (tempo) and age at peak height velocity (timing) are the most interesting for defining the biological status of an athlete [46]. The key is to be able to categorize players showing a normal, fast, or slow growth velocity, or to define their developmental stage in order to adapt loads, restrict overloading of growth areas, and thus, possibly reduce the risk of injuries (Morbus Scheuermann, Osgood–Schlatter, Sever’s disease), and organize adjusted competition categories.

Many studies have developed methods that define a growth stage rather than a precise bone age (76.7% estimates for the VG and 100% in the RG). The number of growth stages ranged from a minimum of 3 to a maximum of 7. If you consider the age range of 8 to 23 years, which is the maximal range in which normal puberty and ossification processes occur, the theoretical maximum number of growth stages would divide the individuals into delimited categories of 2.1 years. In only two studies was the number of stages bigger than the age span of the participants, allowing the authors to reach a precision smaller than one year for bone age estimation [47][48]. Given that classification into biological developmental stages can be performed by anthropometrical measurements within an age range of one year [15] and that biological age can be estimated on a 0.1 year-scale, most ultrasound methods have to be refined to reach at least the same precision. In youth sport, this precision is particularly necessary because differences in performance can already be observed between athletes born 6 months apart [49].

In addition to the great diversity in methods, the aspect of different ethnicities must also be considered when incorporating anatomical variability and growth differences in the estimates [50][51]. The most promising methods should then be tested on different ethnic groups to generalize the results.

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