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Correlation of skeletal age by Greulich-Pyle atlas, physiological age by body development index, and dental age by London Atlas and modified Demirjian's technique in children and adolescents of an Eastern Indian population

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Abstract

Background Forensic age estimation using multiple maturity indicators necessitates investigation of correlation between various techniques. This study intended to compare and evaluate the correlation between skeletal age using Greulich-Pyle atlas, dental age by Acharya's modification of Demirjian's technique and London Atlas method of Tooth Development, and age estimated by body developmental index with chronological age. Orthopantomograms and left hand-wrist radiographs of one hundred seventy-four subjects (64 males and 70 females) in the age group of 8–20 years were evaluated by age estimation methods. Physical parameters including height, weight, biacromial breadth, and biliospinale breadth were measured. The data were entered in the SPSS software (Version 27.0). Comparison between age estimation methods was done using Student's *t*-test for paired samples. Unpaired *t*-test was utilized for gender-wise comparison of age. Pearson's correlation coefficient was calculated to assess correlation between the various methods.

Results Significant mean differences were noted between the chronological age and all the age estimation methods when Greulich-Pyle atlas method (−0.43), modified Demirjian's method (−0.31), London Atlas Method (−0.62), and body developmental index (−0.51) were employed respectively. Inter-group comparison between all methods yielded no significant differences except for modified Demirjian's method and London Atlas method (mean difference = 0.31). All the age estimation techniques showed strong correlation with chronological age; the best was provided by the Greulich-Pyle method ($r = 0.92$).

Conclusion All the assessed age estimation techniques show strong correlation with chronological age. Acharya's modified Demirjian's method (dental age) and Greulich-Pyle atlas method (skeletal age) showed good accuracy and strong correlation with chronological age, suggesting that these methods can be used simultaneously and/or interchangeably for age assessment in children and adolescents of Eastern Indian population.

Keywords Age estimation, Modified Demirjian's method, London Atlas method, GP Atlas, Body developmental index

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Background

Age estimation in living persons assumes paramount significance when the chronological age (CA) of an individual is unknown or disputed (Mansour et al. 2017). Age assessment in children and adolescents is essential to answer a variety of legal questions including issues of status of majority and criminal liability as per which trial is conducted in adult or juvenile justice court (Jayaraman 2018). Data indicates that the number of juveniles in conflict with the law under the Indian Penal Code section alone had increased to 31,618 in 2020 (NCRB- Crime in India 2020). Eligibility for sports participation also mandates estimation of age to ensure fair play and equality of opportunity (National Code against Age Fraud in Sports, cited on 2022 January 15).

According to the recommendation made in the Study Group on Forensic Age Diagnostics (AGFAD) 2000 guidelines, a forensic age estimate requires a physical examination of the subject, a hand X-ray, and a dental examination that documents the dentition status and assesses an orthopantomogram (OPG) (Mansour et al. 2017). In India, the Ministry of Youth Affairs and Sports authorizes physical examination of the subject by a panel of doctors including dental surgeon, preferably from Government hospitals to address age fraud in sports. Sports Authority of India (SAI) specifically advises *evaluation of both hand wrist radiographs/other radiographs as per requirement and dental orthopantomograms* (National Code against Age Fraud in Sports, cited on 2022 January 15).

The Atlas of Greulich and Pyle 1959 (GP) is a well-established method to evaluate skeletal age (SA) from left hand-wrist radiographs by comparing with reference radiographs having age specific standards (Greulich and Pyle 1959).

However, dental development being less influenced by nutritional and hormonal imbalances is deemed a far more precise age predictor (AlQahtani et al. 2010, Santoro et al. 2012). Among the dental age estimation (DAE) methods, Demirjian's technique is well accepted in children and adolescents owing to its well-defined stages and objective evaluation (Demirjian et al. 1973). Due to reported underestimation or overestimation, researchers have suggested adapting the technique for use in specific populations (Eid et al. 2002). Acharya et al. improvised Demirjian's 8-teeth method with Indian cubic functions for use in the multi-ethnic Indian population (Acharya 2011, Kumar et al. 2011). Recently, AlQahtani developed a comprehensive evidence-based London Atlas of Human Tooth Development and Eruption that has shown good age prediction outcome among juvenile subjects (AlQahtani et al. 2010).

Body development index (BDI), a physiological method, crucial in detecting illnesses and developmental disorders, that takes the physical parameters of the individual into consideration also aids in age estimation particularly in younger individuals (Wutschrk 1973). It is imperative to check whether the results of skeletal and tooth age determination correspond with the development of the whole organism. In fact, SAI reserves BDI as an optional method for age estimation in individuals below the age of 18 years (National Code against Age Fraud in Sports, cited on 2022 Jan 15).

Age estimation considering multiple somatic, skeletal, and dental maturity indicators is superior to a single technique. Especially in the context of sports in India, since guidelines advocate the utilization of multiple radiographic techniques for skeletal and dental age estimation, when a combination of two or more methods is used, it is important to find out the correlation between them (Kumar et al. 2011). There is limited research in the diverse multi-ethnic Indian population evaluating the correlation between techniques employing various maturity indicators (Sharma et al. 2015).

Thus, the present study compared CA and dental age (DA) assessed by London Atlas and Acharya's modification of Demirjian's technique and SA assessed by GP Atlas in individuals who reported for age ascertainment for the purpose of participation in sports. The correlation of CA with DA, SA, and age from BDI was further evaluated. The outcome of such study may be a step forward in assessing and proposing suitable biological age estimation techniques (that may be used in tandem) for applicability in the field of sports.

Methods

Study design

A cross-sectional observational study was conducted in the period between November 2019–2021 in subjects who were referred for biological age assessment to the Department of Forensic Medicine & Toxicology and Department of Oral and Maxillofacial Pathology that receive requests from courts of law and sports organizations. The category of sports persons who submitted a legal document of age proof (government-approved identity card) but nevertheless reported for compulsory age estimation as per mandatory protocol issued by sports regulatory bodies in India was included in the study.

Study sample

From a total of 210 reported cases, 134 (70 females, 64 males) subjects fulfilled the requisite inclusion criteria like the presence of all left mandibular and maxillary teeth, good quality left hand-wrist radiographs, and orthopantomogram (OPG). Those with skeletal or dental abnormality, gross caries, jaw pathology, retained deciduous teeth, and history of any systemic or metabolic disease that affects normal growth were excluded.

Methodology

SA estimation

The left hand-wrist radiographs were evaluated by two independent observers using GP Atlas by matching the X-rays with radiographic representation of bones for various reference standards (Gilsanz and Ratib 2005). Corresponding age was assigned after comparing the ossification status and appearance of various bones.

DA estimation

Tooth development stages of 8 left permanent mandibular teeth were assessed on OPG employing Acharya's modification of Demirjian's method (MDA) and assigned scores which was totaled to generate a formula-based age (Acharya 2011).

The London Atlas method (LAM) assessed the development and eruption of left side maxillary and mandibular teeth and compared it to a tooth development chart. DA was calculated with available software using the website: http://www.atlas.dentistry.qmul.ac.uk (McCloe et al. 2018).

The observers were blinded to the CA of the subjects as well as age interpretation by each other throughout execution of the various methods. The radiographs were reassessed at a 15-day interval to verify intra and inter-observer variance.

Physiological age estimation

In employing the BDI method, general physical examination of the subject was performed, and height and weight were recorded. Bony land marks such as acromion process and iliac spine were marked, and the biacromial breadth (BAB) and biliospinale breadth (BISB) were measured from the above landmarks respectively using a digital caliper (DIVINEXT Aerospace 300 mm). Forearm circumference (FAC) was measured in the middle third of the arm using a measuring tape. The data were substituted in specific formulae to yield the physiological age (Wutschrk 1973). The proposed formula for calculating BDI is as follows:

$$\text{BDI}\frac{\text{Middle breadth} \times 2\ \text{forearm circumference (corrected)}}{\text{Body height} \times 10}$$

$$\text{Middle breadth}\frac{\text{Biacromial breadth} + \text{Biliospinale breadth}}{2}$$

Forearm circumference (corrected) = forearm circumference given − Rohrer index (RI) (corrected)

$$\text{Rohrer index}\frac{\text{Body weight(kg)}}{\text{Body height } 3 \times 10} = \frac{\text{kg}}{\text{M3} \times 10}$$

Corrected Rohrer index = corresponding corrected value to the calculated Rohrer index (correlate with Supplementary file 1: Table S1).

Biological age = corresponding age to the BDI value (correlate with Supplementary file 1: Table S2).

Statistical analysis

The data obtained was entered into Microsoft Excel Worksheet and analyzed (SPSS, IBM Corp. Released 2020; IBM SPSS Statistics for Windows, Version 27.0; Armonk, NY: IBM Corp.). The chronological age (CA) of the individual was ascertained by subtracting the date of birth (recorded from documented proof of age) from date on which the radiographs were taken.

The normal distribution of data was confirmed using Shapiro–Wilk's test, and appropriate parametric statistics was employed. Mean and standard deviations including standard error were computed for continuous variables. Frequencies and proportions were calculated for categorical variables.

Comparison of continuous variables between age estimation methods was done using Student's *t*-test for paired samples. The mean difference (M.D), i.e., bias, was calculated by subtracting the estimated age from the CA; a positive value indicated underestimation, and a negative value indicated overestimation of age. Unpaired *t*-test was utilized for gender-wise comparison of age. Pearson's correlation coefficient was calculated to assess correlation between the various estimation methods. Inter-observer agreement was assessed using Kappa statistics, and it ranged from score 0.72 (GP) to 0.98 (LAM) ($p < 0.001$) which displayed a substantial agreement between the two evaluators. A $p < 0.05$ was considered significant for all statistical inferences.

Ethical considerations

The study received institutional ethical committee approval (IEC/SCBDCH/077/2020) and was conducted as per prescribed norms and regulations. Informed consent was obtained from the adult participants and parents/guardians of children aged 10–17 years.

Results

The purpose of age estimation in the study group was verification for sports participation in different age groups as per protocol of sports regulatory bodies. Majority of the 134 cases were in the reported age range of 10–15 years (y) (75.4%) followed by 22.3% cases in the 16–20 years category (Table 1).

Table 1 Gender-wise distribution of study sample in different age ranges

Age range	N = 134 n (%)	Male N = 64 n (%)	Female N = 70 n (%)
< 10 years	2 (1.4)	1 (50)	1 (50)
10–15 years	101 (75.4)	52 (51.5)	49 (48.5)
16–20 years	30 (22.4)	11 (36.7)	19 (63.3)
> 20 years	1 (0.8)	0	1 (100)

N total number of subjects, *n* no of subjects in respective category

The mean ± S.D (S.E.) CA of the entire sample was 13.95 ± 2.44 (0.21) years. Significant mean differences were noted between the CA and DA when MDA ($p = 0.02$) and LAM ($p < 0.001$) were employed respectively. SA as assessed by the GP Atlas method was found to be 14.38 ± 2.4 (0.21) years which showed significant difference ($p < 0.001$) between the two. Age estimated by the BDI method also revealed significant mean differences from CA (M.D − 0.51, $p = 0.008$). All the methods indicated a consistent overestimation of age showing minimum M.D with MDA (Table 2).

Inter-group comparison between the biological age estimation methods revealed no significant differences between age estimated by MDA and GP Atlas method ($p = 0.4$) as well as BDI method ($p = 0.3$). However, a significant difference (M.D − 0.31, $p = 0.009$) was noticed between MDA and mean age by LAM (14.56 ± 2.71 years). Inter-group comparison between any of the other methods yielded no significant differences in age (Table 3).

Gender-wise analysis (Table 4) revealed significant differences in MDA between CA and age estimated by LAM ($p = 0.01$) and BDI ($p = 0.03$) in males, while in females, all the methods exhibited significant differences with CA except age estimated by BDI method ($p = 0.1$).

Furthermore, in the overall sample, a strong positive correlation was exhibited between CA and age estimated by methods of GP ($r = 0.92$), LAM ($r = 0.89$), MDA ($r = 0.83$), and BDI ($r = 0.76$) which were significant ($p < 0.001$). Likewise, significant positive correlation of CA with all applied methods also emerged in independent analysis of male and female groups (Table 5).

Discussion

Forensic practice entails the use of most scientifically accurate methodology to estimate age from the available data (Schmeling et al. 2010, Pavlovic et al. 2017, Schmeling et al. 2004). Forensic age estimation in athletes participating in competitive sports divides athletes based on their age to ensure competition between similarly

Table 2 Comparison of mean chronological age with mean estimated age by dental, skeletal, and BDI methods

CA
Mean ± SD (SE)
13.95 ± 2.44 (0.21)

Method	Mean ± SD (SE)	Mean difference	95% CI	t	p
MDA	14.25 ± 2.78(0.24)	− 0.31	− 0.57 to 0.04	− 2.28	0.02
GP	14.38 ± 2.4(0.21)	− 0.43	− 0.6 to 0.26	− 5.12	< 0.001
LAM	14.56 ± 2.71(0.23)	− 0.62	− 0.83 to 0.4	− 5.73	< 0.001
BDI	14.46 ± 3.31(0.28)	− 0.51	− 0.88 to 0.14	− 2.7	0.008

CA chronological age, *SD* standard deviation, *SE* standard error, *CI* class interval, *MDA* Acharya's modified Demirjian method, *GP* Greulich-Pyle, *LAM* London Atlas method, *BDI* body development index

Table 3 Comparison of mean age estimated by various methods of dental, BDI, and skeletal age estimation

Method (mean ± SD)	Comparison	Mean ± SD	Mean difference	t value	95% CI	p value
MDA 14.25 ± 2.78	**GP skeletal**	14.38 ± 2.4	− 0.12	− 0.94	− 0.38 to 0.14	0.4
	LAM	14.56 ± 2.71	− 0.31	− 2.64	− 0.54 to − 0.08	0.009
	BDI	14.46 ± 3.31	− 0.19	− 0.96	− 0.61 to 0.21	0.3
GP skeletal 14.38 ± 2.4	**LAM**	14.56 ± 2.71	− 0.18	− 1.4	− 0.45 to 0.07	0.15
	BDI	14.46 ± 3.31	− 0.07	− 0.4	− 0.44 to 0.29	0.7
LAM 14.56 ± 2.71	**BDI**	14.46 ± 3.31	0.11	0.54	− 0.29 to 0.52	0.6

SD standard deviation, *SE* standard error, *CI* class interval, *MDA* Acharya's modified Demirjian method, *GP* Greulich-Pyle, *LAM* London Atlas method, *BDI* body development index

Table 4 Gender-wise comparison of chronological age with dental and skeletal age estimated by various methods

Chronological age	Methods	Mean ± SD (SE)	Mean difference	95% CI	*t*	*p*
Male 13.56 ± 2.31 (0.29)	**MDA**	13.59 ± 2.73 (0.34)	− 0.03	− 0.4 to 0.36	− 0.16	0.87
	GP	13.7 ± 2.48 (0.31)	− 0.14	− 0.33 to 0.05	− 1.44	0.15
	LAM	13.95 ± 2.78 (0.35)	− 0.39	− 0.7 to − 0.07	− 2.47	0.01
	BDI	14.28 ± 3.35 (0.42)	− 0.72	− 0.93 to 0.19	− 2.17	0.03
Female 14.3 ± 2.51 (0.3)	**MDA**	14.86 ± 2.71 (0.32)	− 0.56	− 0.92 to 0.19	− 3.06	0.003
	GP	15.0 ± 2.16 (0.25)	− 0.7	− 0.95 to 0.44	− 5.48	< 0.001
	LAM	15.12 ± 2.53 (0.3)	− 0.83	− 1.12 to 0.54	− 5.71	< 0.001
	BDI	14.61 ± 3.28 (0.39)	− 0.31	− 0.7 to 0.07	− 1.61	0.1

SD standard deviation, *SE* standard error, *CI* class interval, *MDA* Acharya's modified Demirjian method, *GP* Greulich-Pyle, *LAM* London Atlas method, *BDI* body development index

Table 5 Correlation of chronological age with dental, BDI, and skeletal age estimated by various methods

Chronological age			
Methods	**Male**	**Female**	**Overall**
MDA	0.82*	0.83*	0.83*
LAM	0.89*	0.88*	0.89*
GP	0.95*	0.91*	0.92*
BDI	0.69*	0.88*	0.76*

MDA Acharya's modified Demirjian method, *GP* Greulich-Pyle, *LAM* London Atlas method, *BDI* body development index

* $p < 0.001$, Pearson's correlation coefficient

aged individuals and to prevent age falsification. It also ensures less risk of injury to other athletes by excluding overage athletes particularly in contact sports like football, judo, and wrestling. Conversely, the principal reason for excluding underage athletes from adult competition is to protect their physical and mental health (Timme et al. 2017 Jan). In India, the athletes usually compete in under-14, under-17, and under-19 age categories in badminton, football, judo, swimming, cricket, and other competitive sports (All India Football Federation, 2018). The Ministry of Youth affairs and Sports and SAI advocate guidelines for age estimation that mandate the evaluation of multiple bones and teeth by radiological techniques, to ascertain if the CA as stated by the athlete corroborates with estimated biological age to prevent age fraud (National Code against Age Fraud in Sports, cited on 2022 January 15).

The objective of age estimation methods must be to remove the methodologic variations as much as possible, leaving only the necessary individual variability.

Radiological age assessment methods are procedurally advantageous being easily reproducible and less invasive (Jayaraman 2018). SA parameters considered physiologically stable traditionally form the gold standard for accurate forensic age estimation in which the use of left hand-wrist radiographs prevails due to its close association with predicting pubertal growth (Gilsanz and Ratib 2005, Garamendi et al. 2005). Since past studies in the preadolescent and adolescent subjects that employed GP Atlas have demonstrated good correlation with mean CA, it was preferred in our current age sample of sportspersons that fell under age categories like under-14, under-17, and under-19.

From the standpoint of forensic age estimation, dental maturity indicators may be a superior parameter as compared to skeletal parameters as developing teeth are more resistant to environmental influences and dental hard tissues exhibit high durability to withstand post-mortem destruction (Nelson 2019).

To overcome the limitations of the original Demirjian's technique, the MDA method that has performed better in various subsets of Indian population and also covers the period of late adolescence was employed (Kiran et al. 2015, Periyakaruppan et al. 2018).

The LAM bestowed with its clear-cut stages of development and eruption and integrating software assistance in age calculation (Sharma and Wadhwan 2020) has been proven to be fairly accurate in age prediction among the Iranian and Brazilian population (Alshiri et al. 2015, Gelbrich et al. 2020) and was adopted for the current study.

There are however obvious problems in assessing age when using a system designed to measure maturity (Santoro et al. 2012). Biological age (i.e., sexual, dental, or skeletal) does not always correspond to CA (i.e., legal) and is dependent on the method applied to the specific population being studied. Considering a country like India with a population of over 1.4 billion, the range of biological variations is vast, and therefore, the discrepancy between biological age and legal age may be further accentuated.

The use of a single biological parameter and/or a single technique has resulted in lower accuracy in few studies, while a combination of methods/multiple maturity indicators has been proved superior

(Garamendi et al. 2005, Gelbrich et al. 2020). Therefore, studies have emphasized the need for combined analysis of the methods mentioned above to reduce the margin of error; the results of each of the tests performed should be recorded separately (Schmeling et al. 2004, Garamendi et al. 2005). The age variables of SA, DA, and age by BDI considered in the current study were meant to assess the physical, skeletal, and dental development of the individual as a whole since a single parameter may not be sufficient for precisely determining age of the subject. In order to ameliorate diagnostic accuracy and identification of age-related developmental disorders, multiple age estimation techniques should be performed on each individual (Santoro et al. 2012). We resorted to various methods suitable in the adolescent age group and, wherever possible, used population-specific formulas (MDA). In this context, it is of utmost importance to find the degree of correlation between them. A good correlation between tested methods would improve the accuracy of age prediction, bringing it closer to the CA when the methods are simultaneously applied.

Age assessment studies have recorded basic anthropometric measurements like height, weight, and body mass index (BMI) and correlated the same with other maturity indicators (Garamendi et al. 2005). Although anthropometric variables may be more influenced by environmental factors, we included BDI as it is advised as an optional method by Sports Authority of India and may also be considered as per AGFAD guidelines (National Code against Age Fraud in Sports [cited 2022 January 15]).

Although various age assessment methods have given high degrees of reliability, ethnic differences between various population groups were found to affect the accuracy. Various studies for assessing the DA, SA, and their correlation have ben predominantly conducted in the western population with exception of a few (Santoro et al. 2012, Garamendi et al. 2005, Pinchi et al. 2016, Balla et al. 2019). A similar assessment has been lacking for Indian children and adolescents particularly in the field of sports. Hence, the present study was designed to determine whether the standards of dental maturation given by Demirjian et al. (MDA) and LAM and Atlas of GP's skeletal maturation and BDI method were applicable to our population. Previous correlation studies have assessed SA and DA parameters, but no studies have thus far explored or correlated the BDI method. The present correlation study determining the association between CA, SA, DA, and age by BDI method is most likely the first of its kind in the literature and in living individuals of the Eastern part of India.

The CA of majority of our study group ranged between 8 and 20 years similar to the age sample in Balla et al. (2019)'s study of child laborers and commercial sex workers that ranged between 8 and 19.4 years.

The overall mean CA in the current study was 13.95 years and showed a small mean difference (M.D) of 0.31 years from age estimation by MDA. This corroborates with low M.D seen in few Indian studies that have tested MDA (0.87 years (Acharya 2011), 0.89 years (Periyakaruppan et al. 2018), and 1.18 years (Kumar and Gopal 2011)).

Our study employing LAM experienced an overestimation of 0.62 years which was significant ($p < 0.001$). Our findings were in line with those of McCloe et al. who found an overestimation in 38% of a Hispanic population and Al Shiri et al. who found an overestimation (within 12 months of CA) in 65.5% of his study population (McCloe et al. 2018, Alshihri et al. 2015).

LAM determines DA with a precision of 1 year, while few others produce ages with decimal values. Therefore, when the difference between DA and CA is calculated using the London Atlas, there is an inherent error generated even when the radiograph is assigned to the correct age interval (McCloe et al. 2018).

Significant M.D of 0.43 was seen between CA and estimated age by GP Atlas. This was in accordance with results of few other studies that showed a very low M.D (0.1 years) (Mohammed et al. 2015). The overestimation in our age groups may be owing to environmental factors such as the socioeconomic status, nutrition, and dietary habits that also vary in different population groups (Schmeling et al. 2000).

BMI basically is an indicator of nutritional status of an individual and a widely used marker of obesity in children and adults. Few studies have shown correlation of BMI with anthropometrical variables determining body frame like BAB, BISB, and maximum FAC (Henneberg and Ulijaszek 2010). Integrating the aforementioned variables along with height and weight into a standardized formula, BDI is calculated. The current study thus assessed age from BDI which showed an M.D of 0.51 years from CA. No previous studies on BDI could be elicited.

In the comparison between various age estimation methods, since no significant difference arose except for the M.D between MDA and LAM (M.D $= -0.31$) which was statistically significant ($p = 0.009$), it implies that the methods can be used interchangeably. More so, DAE techniques of MDA and LAM may be substituted for GP since SA estimation methods are considered as gold standard for forensic age estimation. However, LAM and MDA may not be used interchangeably in our population.

Gender-wise analysis revealed negligible M.D of 0.03 years between CA and age estimated by MDA in males but significant M.D ($p = 0.003$) in females. Similar findings of significant M.D in females as opposed to males was found between SA by GP method and CA. This corroborated with results of Mohammed et al.'s study (0.02 years) (Mohammed et al. 2015).

Though age estimation by LAM registered significant M.D from CA in both males and females, the age estimate outcome was higher in females (0.83 years) as compared to males (0.39 years) which is in concordance with few studies (McCloe et al. 2018, Alshihri et al. 2015, Gelbrich et al. 2020). Underlying the overestimation in females may be the hormonal changes during growth or puberty that affect the tooth formation stages.

The "r" value was close to 1 for all the pairs in the overall sample, suggesting a strong positive correlation between SA and CA and high positive correlation between MDA/LAM/BDI and CA.

The mean CA showed a strong positive correlation ($r=0.83$) with DA estimated by MDA in consonance with other studies ($r=0.88$) (Sharma et al. 2015). A similarly strong correlation of DA by LAM and CA ($r=0.89$) was in concordance with findings of Gelbrich et al. (2020), showing higher accuracy and correlation with the CA. A study by Sharma et al. (2020) also favors the use of LAM in an Indian population owing to good correlation.

A very high positive correlation ($r=0.92$, $p<0.001$) was observed between the mean CA and estimated SA by GP Atlas method for the overall population. This scenario was also seen in few studies ($r=0.86$, $M=0.84$, $F=0.89$) (Mohammed et al. 2015). In developing countries such as India, age estimation by observing the appearance and fusion of ossification centers on conventional radiography is still considered one of the most accurate and reliable methods for age estimation among sportspersons which is affirmed by our study findings.

While using the BDI method, we discerned a high positive correlation ($r=0.76$) for the overall population, and in males and females, it was 0.62 and 0.88 respectively which was statistically significant ($p<0.001$). Literature search revealed no prior studies correlating CA with age from BDI.

To summarize the observations from our study, all the age estimation techniques showed excellent intra- and inter-observer kappa agreement with a slight overestimation from CA, with M.D of less than 1 year. The mean absolute difference (M.A.D) between CA and estimated age was lowest for MDA method, inferring that it best predicted the CA in our sample. Gender-wise analysis revealed negligible M.D of 0.03 years by MDA method in males showing very good accuracy with CA. All the skeletal, dental, and biological age estimation techniques showed strong correlation with CA in our sample of sportspersons; the best was shown by GP Atlas.

Conclusions

Age estimation in living individuals of unknown or disputed age manifests as an integral part of forensic casework. As standard guidelines recommend performing radiological tests for skeletal and dental age assessment in sportspersons, it is imperative to delve into the correlation between these techniques and the CA. Our study appraised the same and found the MDA method (dental age) and GP Atlas method (skeletal age) to show good accuracy and strong correlation with the CA. In fact, the MDA method may be substituted for GP Atlas method as there is less radiological exposure to subjects for age assessment in children and adolescents of Odisha. Considering the positive correlation revealed by all the techniques, these may be used simultaneously for forensic age assessment in the aforementioned population. Future studies on the age estimation of sportspersons with greater sample sizes are necessary to validate the findings of the present study in the Indian scenario. This may further help in detecting cases of age fabrication and ensuring fair opportunities for every sportsperson.

Abbreviations

CA	Chronological age
AGFAD	Study Group on Forensic Age Diagnostics
OPG	Orthopantomogram
SA	Skeletal age
GP	Greulich and Pyle
DAE	Dental age estimation
BDI	Body development index
DA	Dental age
MDA	Acharya's modification of Demirjian's method
LAM	London Atlas method
BAB	Biacromial breadth
BISB	Biliospinale breadth
FAC	Forearm circumference
M.D	Mean difference
BMI	Body mass index
MAE	Mean absolute error

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41935-023-00359-w.

Additional file 1: Supplementary file 1. National code against age fraud in sports. **Table S1.** Rohrer index and corrected value. **Table S2.** Mean values of body development index of GDR children (WUTSCHRK, 1973).

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Authors' contributions
CKB and RR interpreted the dental radiographic examinations and were the major contributors for this manuscript; SND, RR, and CKB contributed to the methods and discussion of this manuscript. GS and CKB interpreted the hand-wrist radiographic examinations. GS analyzed and interpreted the results statistically. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study received institutional ethical committee approval (IEC/SCB-DCH/077/2020) and was conducted as per prescribed norms and regulations. Informed consent was obtained from the adult participants and parents/guardians of children aged 10–17 years.

Consent for publication
Informed participant/guardian's consent was obtained from each subject before body parameter measurements as well as other demographics were taken after explaining the protocols to them. Consent was obtained from participants whose radiographic images were used as a sample for measurement of physical and dental parameters.

Competing interests
The authors declare that they have no competing interests.

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