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ORIGINAL ARTICLE

An evaluation of the three-component pubic symphyseal human age estimation method: a CT-based exploration in an Indian population

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Abstract
Age estimation constitutes an important facet of human identification within forensic, bioarchaeological, repatriation, and humanitarian contexts. Within the human skeletal framework, the pubic symphysis comprises one of the more commonly utilized structures for age estimation. The present investigation was aimed at establishing the applicability of the McKern–Stewart pubic symphyseal age estimation method in males and females of an Indian population, an aspect previously unreported. Three hundred and eighty clinical CT scans of the pubic symphysis were collected and scored in accordance with the McKern–Stewart method. An overall accuracy of 68.90% was obtained on applying the method to males, demonstrating a limited applicability of the method in its primal form. Subsequently, Bayesian analysis was undertaken to enable accurate age estimation from individual components in both sexes. Bayesian parameters obtained with females suggest that McKern–Stewart's components fail to accommodate for age-related changes within the female pubic bone. Improved accuracy percentages and reduced inaccuracy values were obtained with Bayesian analysis in males. With females, the error computations were high. Weighted summary age models were utilized for multivariate age estimation, and furnished inaccuracy values of 11.51 years (males) and 17.92 years (females). Error computations obtained with descriptive analysis, Bayesian analysis, and principal component analysis demonstrate the limited applicability of McKern–Stewart's components in generating accurate age profiles for Indian males and females. The onset and progression of age-related changes within the male and female pubic bone may be of interest to biological anthropologists and anatomists involved in exploring the underlying basis for aging.

Keywords Human age estimation · Computed tomography · Pubic symphyseal morphology · McKern–Stewart · Bayesian inference · Principal component analysis

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Introduction

Age estimation is vital to the process of human identification within forensic, bioarchaeological, repatriation, and humanitarian contexts (Krogman 1986). Within forensic/medico-legal settings, age estimation is of paramount importance in cases involving and not limited to illegal immigrants, assigning criminal responsibility to individuals, disaster victim identification, and missing person identification. Age estimation in an archaeological sample aids in understanding and reconstructing the life of past populations. Age estimation, and by extension, human identification, additionally aids in the repatriation of refugees and victims of war. Within a humanitarian context, estimation of age is undertaken with the primary objective of preventing human rights violations in cases involving unaccompanied minors, human trafficking victims, child labour, pedopornography, and asylum seeking refugees. In cases where human skeletal remains present for examination, ossification and fusion of bones, as well as degenerative changes transpiring within the skeletal framework, are relied on for age estimation. Previously undertaken investigations have extensively explored the role of numerous bony markers for human age estimation (Ruengdit et al. 2018; Shedge et al. 2020, 2021; Widek et al. 2021; Brooks and Suchey 1990; Warrier et al. 2022a). Amongst these markers, the human pelvis, in addition to being a robust and resilient structure, houses multiple developmental and degenerative markers (Warrier et al. 2022b; Lottering et al. 2013; Rissech et al. 2006; Buckberry and Chamberlain 2002; Bartolini et al. 2018; Zhang et al. 2016). This confers to the pelvis the ability to estimate age across a broader age cohort, as opposed to other commonly utilized age markers which remain applicable for restricted age groups alone (Shedge et al. 2020; Widek et al. 2021; Kotecha 2016) .

Within the human pelvis, the pubic symphysis constitutes one of the more commonly utilized age markers (Miranker 2016; Moraitis et al. 2014). The pubic symphysis exhibits developmental changes in younger individuals, and degenerative changes in older adults, rendering it applicable for age estimation across a broader age class (McKern and Stewart 1957). Furthermore, its resistance to activity patterns involving constant flexion and extension confers the symphyseal face added significance over other regions within the pelvis. Multiple pubic symphyseal age estimation methods have been devised over the previous century (Brooks and Suchey 1990; McKern and Stewart 1957; Todd 1920; Berg 2008; Gilbert and McKern 1973; Hanihara and Suzuki 1978; Hartnett 2010; Chen et al. 2008), each targeted towards exploiting these advantages for human identification. Amongst these, McKern and Stewart's component-based method (McKern and Stewart 1957) constitutes one of the more commonly employed methods for age estimation (Garvin and Passalacqua 2012). The method was initially developed using male pubic bones, and involves breaking down pubic symphyseal changes into three distinct components: dorsal plateau, ventral rampart, and symphyseal rim. Each component is scored on a scale of 0–5, and the obtained cumulative score (0–15) is then employed to ascertain the age of remains presenting for examination (McKern and Stewart 1957). In the years that followed the method's conception, multiple researchers have undertaken evaluations of McKern–Stewart's pubic symphyseal age estimation method using different population groups (Sinha and Gupta 1995; Sharma et al. 2008; Kumar et al. 2009; Kumar 2011; Singh et al. 2013; Prasad et al. 2015; Selvamurugan et al. 2019; Javvadi et al. 2016; Kumaran et al. 2019; Janardhan et al. 2016; Pal and Tamankar 1983; Madanraj and Suares 2021; Snow 1983; Klepinger et al. 1992; Gorchiya et al. 2020; Meindl et al. 1985). However, limited research investigations have attempted to ascertain the accuracy and precision of the method (Meindl et al. 1985; Lungmus 2009). Establishing the accuracy and error associated with different age estimation methods is of paramount significance for forensic, humanitarian, and bioarchaeological contexts. Furthermore, the applicability of McKern–Stewart's components in aging female remains has rarely been explored (Sharma et al. 2008; Singh et al. 2013; Selvamurugan et al. 2019; Lungmus 2009), with all such investigations employing under-represented female study groups.

Recent decades have witnessed the predominance of digital visualization techniques for human age estimation. 3D visualization techniques such as computed tomography enable the scrutiny of age-related morphological changes transpiring within the human skeletal framework without having to invest in the resource intensive and time-consuming maceration process. In addition to this, CT evaluations help create large-scale image databases of contemporary human populations which can then be utilized to test and appropriately modify conventionally derived age estimation methods. This is of particular significance in present day scenarios, where the lack of modern human skeletal repositories outside the USA impedes such an analysis. Previously undertaken computed tomographic assessments with pubic symphyseal age estimation methods have indicated a satisfactory reproduction of age-related morphological features on CT images (Lottering et al. 2013; Gorchiya et al. 2020; Wink 2014; Hall et al. 2019; Hisham et al. 2019; Pattamapaspong et al. 2019; Villa et al. 2013; Merritt 2018; Truesdell 2011).

The present study was aimed at ascertaining the applicability of the McKern–Stewart method through a CT-based examination of the pubic symphysis in an Indian population. The objectives of the present study were threefold: (1) establishing the accuracy and precision of the McKern–Stewart method for Indian males based on descriptives reported within the original study for males (2) ascertaining the applicability of McKern–Stewart's components in aging males, as well as females of an Indian population using Bayesian analysis, as it generates realistic age profiles while circumventing age mimicry (3) to perform multivariate age estimation using principal component analysis and weighted summary age models with the aim of garnering reliable age estimates, advantages of which have previously been demonstrated (Warrier et al. 2022c, d).

Materials and methods

Sample collection

The present prospective cross-sectional study was carried out in the Department of Forensic Medicine and Toxicology, and the Department of Diagnostic and Interventional Radiology, All India Institute of Medical Sciences, Jodhpur, India. Prior to commencement of the study, ethical approval was obtained from the Institutional Ethics Committee (Letter no. AIIMS/IEC/2019-20/1007). For this study, individuals aged 10 years and above undergoing computed tomographic examinations of the pelvis/abdomen, as per directions of their treating physicians, at the Department of Diagnostic and Interventional Radiology were approached. Such individuals/their guardians were appraised about the study parameters in detail, and their consent for voluntary participation into the study was sought. CT scans of individuals who consented to participate in the study were incorporated following proof of age verification through valid documents. Individuals who could not provide valid proof of age, and/or those with known bone injuries/deformities/pathologies within the pelvic region, or those which became apparent during CT examination were excluded from the study. Additionally, CT scans presenting with technical/patient-movement induced artefacts interfering with the analysis of interest were also excluded.

CT scans of 480 consenting individuals were collected between the study period of January 2020 and December 2021. The total study set of 480 CT scans was divided into two sub-sets: an informative prior comprising of 100 individuals, and an equally represented male and female population of 380 individuals (190 males, 190 females). All 380 CT scans were coded to blind the investigator to information capable of inducing bias. The informative prior was utilized to ascertain hazard parameters for the population under scrutiny, a pre-requisite for Bayesian analysis.

Scanning parameters

CT images of the pelvis of consenting individuals were obtained using Dual Source CT-SOMATOM Definition Flash^{TM} (Siemens Medical Solutions, Erlangen, Germany). A slice thickness of 1 mm (standardized technical parameter utilized by the healthcare centre for diagnostic purposes) was employed within all scans. Obtained CT images were processed and assessed using 3D Slicer 4.11.20200930 (RRID: SCR_005619) (https://www.slicer.org/; Fedorov et al. 2012). For analysing the pubic symphysis, the bone window was selected, following which the generated image was cropped to narrow down on the region under scrutiny. Subsequently, a 3D volume rendered reconstruction of the cropped image was created. Using the scissor tool, additional interfering bony remnants were cut out to enable a clearer visualization of the pubic bone. The obtained pubic symphyseal reconstructions were examined from multiple planes to better appreciate transpiring morphological changes.

Age estimation using the McKern–Stewart method

Age progressive morphological changes observed on 3D CT images of the male and female pubic symphysis were evaluated according to McKern–Stewart's three component method (McKern and Stewart 1957). Each component was assigned a score from 0 to 5 based on the observed morphological changes. Subsequently, a cumulative score was computed using the individual scores of all three components and this was utilized for statistical analysis. Descriptions for individual components and the associated scoring system devised by McKern and Stewart are tabulated under Table 1. 3D CT representations of the component-based scoring method are shown in Figs. 1, 2, and 3.

Statistical analysis

Statistical analysis was performed using IBM Statistical Package for Social Sciences (SPSS) v26 and R Studio (RStudio Team (2022). RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/). R scripts and codes for specific statistical tests were obtained from previously undertaken studies (Konigsberg and Frankenberg 2013; Lyle W 2022 Konigsberg's webpage: http://faculty.las.illin

Table 1 Scoring method employed in the present study (devised by McKern–Stewart)

Score	Morphological features pertaining to the dorsal plateau	Morphological features pertaining to the ventral rampart	Morphological features pertaining to the symphyseal rim
0	Dorsal margin absent	Ventral bevelling absent	Symphyseal rim absent
1	Slight margin formation first appears in middle third of the dorsal border	Ventral bevelling present only at superior extremity of border	Partial dorsal rim present; round and smooth, elevated above surface
2	Dorsal margin extends along entire dorsal border	Bevel extends inferiorly along ventral border	Dorsal rim complete; ventral rim beginning to form
3	Filling in of grooves and resorption of ridges to form a beginning plateau in middle third of dorsal demiface	Ventral rampart begins by means of bony extensions from either or both extremities	Symphyseal rim complete; surface is finely-grained, irregular and undulating
4	Plateau extends over most of dorsal demiface with vestiges of billowing	Rampart is extensive but gaps evident on earlier ventral border, especially upper two-thirds	Rim breakdown, rim is sharp rather than round, with lipping at ventral edge
5	Billowing disappears completely; surface of demiface becomes flat and granulated	Rampart complete	Further breakdown of rim and rarefaction of symphyseal face; erratic ossification along ventral rim

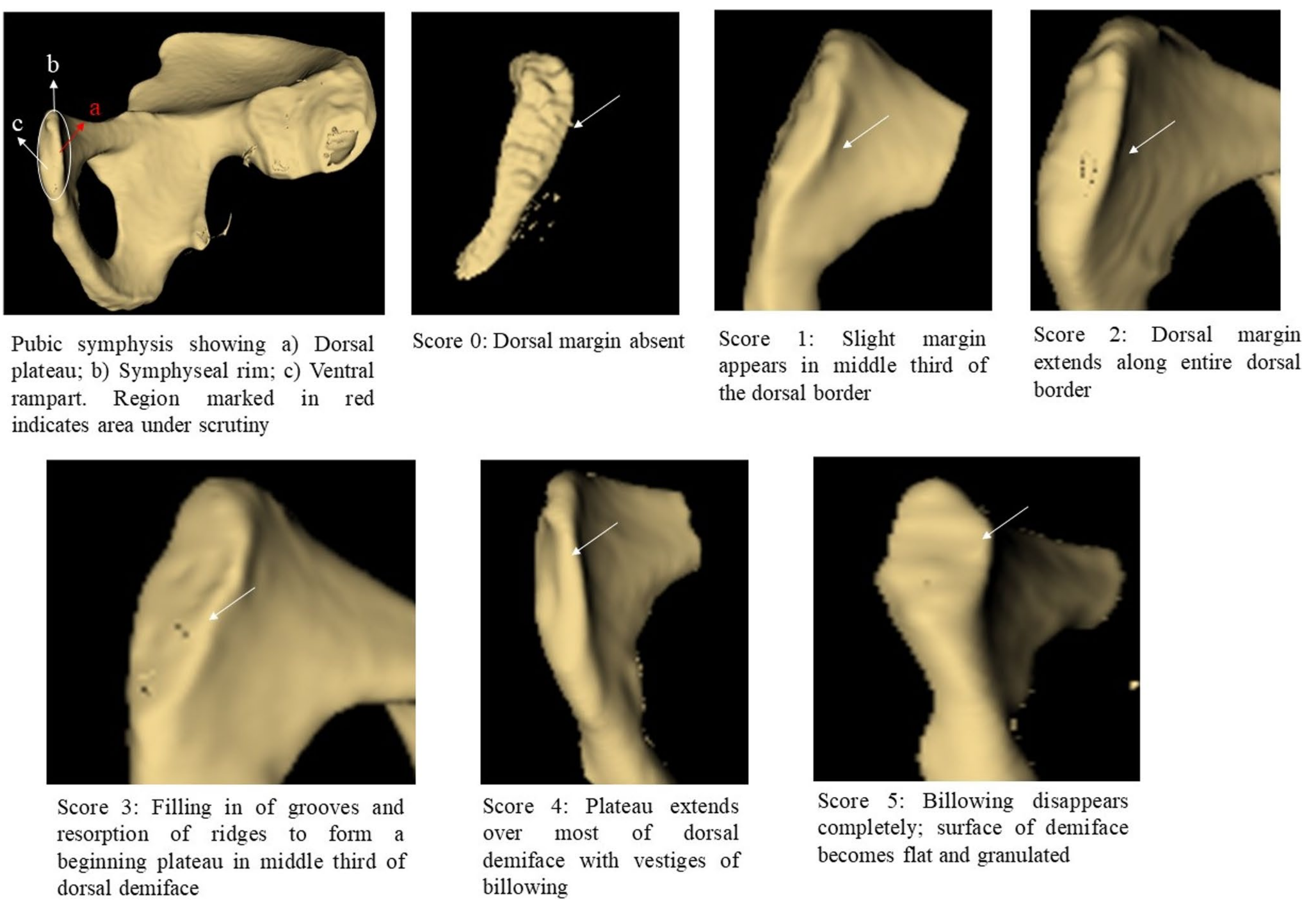

Fig. 1 3D CT representations of different gradations for the dorsal plateau

ois.edu/lylek/; Getz 2020; Nikita et al. 2018; Nikita and Nikitas 2019). $p < 0.05$ was considered significant for all statistical evaluations.

Inter- and intra-observer error was assessed using Cohen's weighted κ. Inter-observer error was computed based on the scoring of 40 pubic bones by two independent investigators. In order to compute the intra-observer

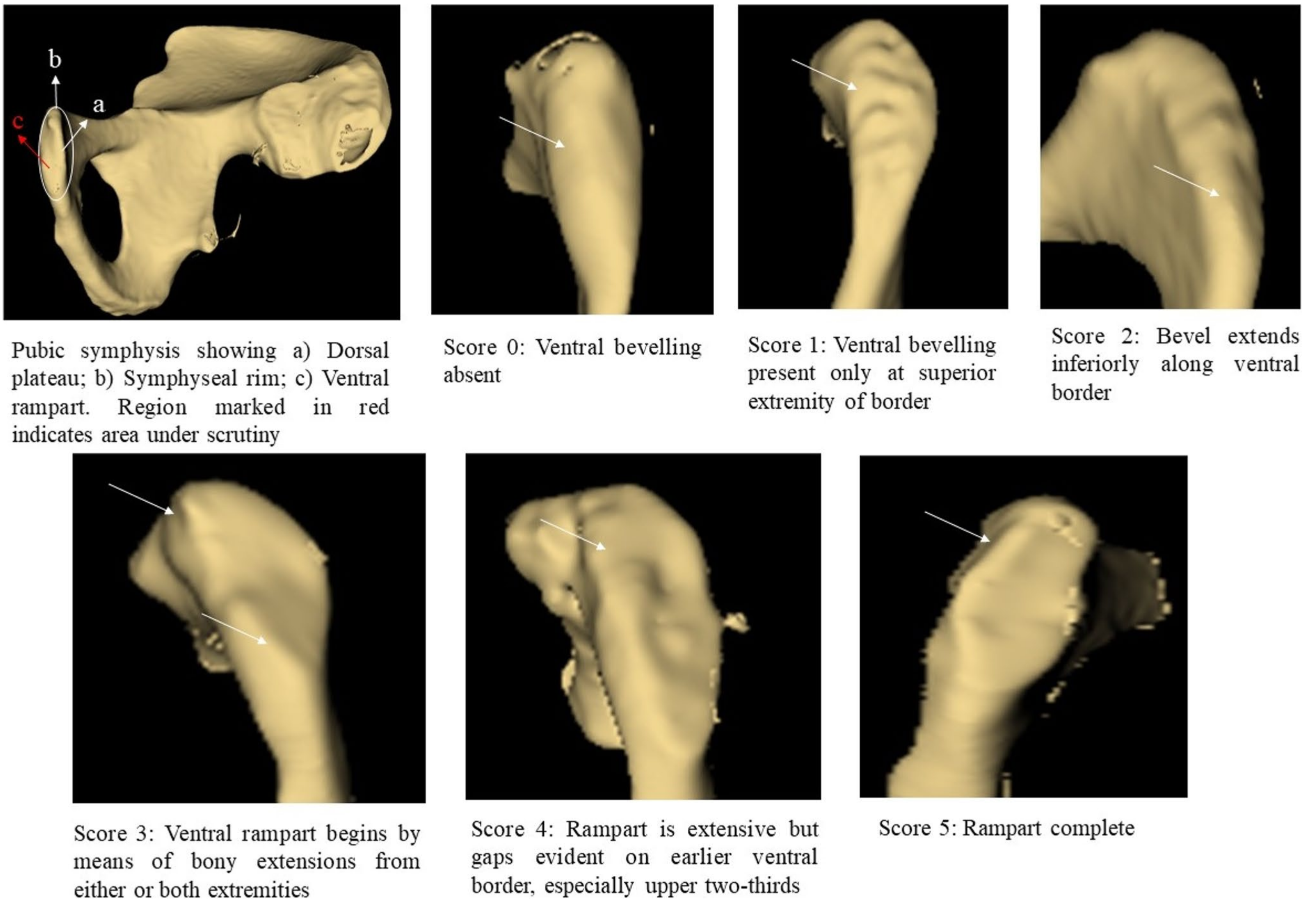

Fig. 2 3D CT representations of different gradations for the ventral rampart

error, the same 40 samples were re-evaluated by the lead investigator (VW) after a duration of 2 weeks from the time of initial examination. Obtained κ values were interpreted using the system described by McHugh (2012) as $\kappa < 0.20$: no agreement, $\kappa = 0.21$–0.39: minimal agreement, $\kappa = 0.40$–0.59: weak agreement, $\kappa = 0.60$–0.79: moderate agreement, $\kappa = 0.80$–0.90: strong agreement, and $\kappa > 0.91$: almost perfect agreement.

Bilateral differences in the scoring of individual components were evaluated using the Wilcoxon test, while sex differences associated with the same were analysed using the Mann–Whitney *U* test. The correlation between morphological changes transpiring within the pubic symphysis, and the documented age of participants was established using Spearman's rho. Correlation coefficients were established for each individual component, as well as for the cumulative score, with age. Each of these statistical analyses were undertaken using the study set of 380 individuals.

In keeping with the first objective of this study, overall accuracy percentages, inaccuracy and bias values, and those associated with each individual component were established for males of this study set (N = 190). An individual was classified as accurately aged when their documented age fell within the age ranges reported by McKern and Stewart in their original study (McKern and Stewart 1957). Subsequently, accuracy percentages were estimated using the formula

$$\%Accuracy = (Number\ of\ individuals\ aged\ correctly / Total\ number\ of\ participants) * 100$$

Inaccuracy, an absolute estimate of the error associated with the method, was estimated following the prescribed formula

$$\Sigma(|Estimated\ mean\ point\ age - Chronological\ age|)/n$$

whereas bias, an estimate of the extent of under-aging/over-aging associated with the method, was garnered using the mathematical equation

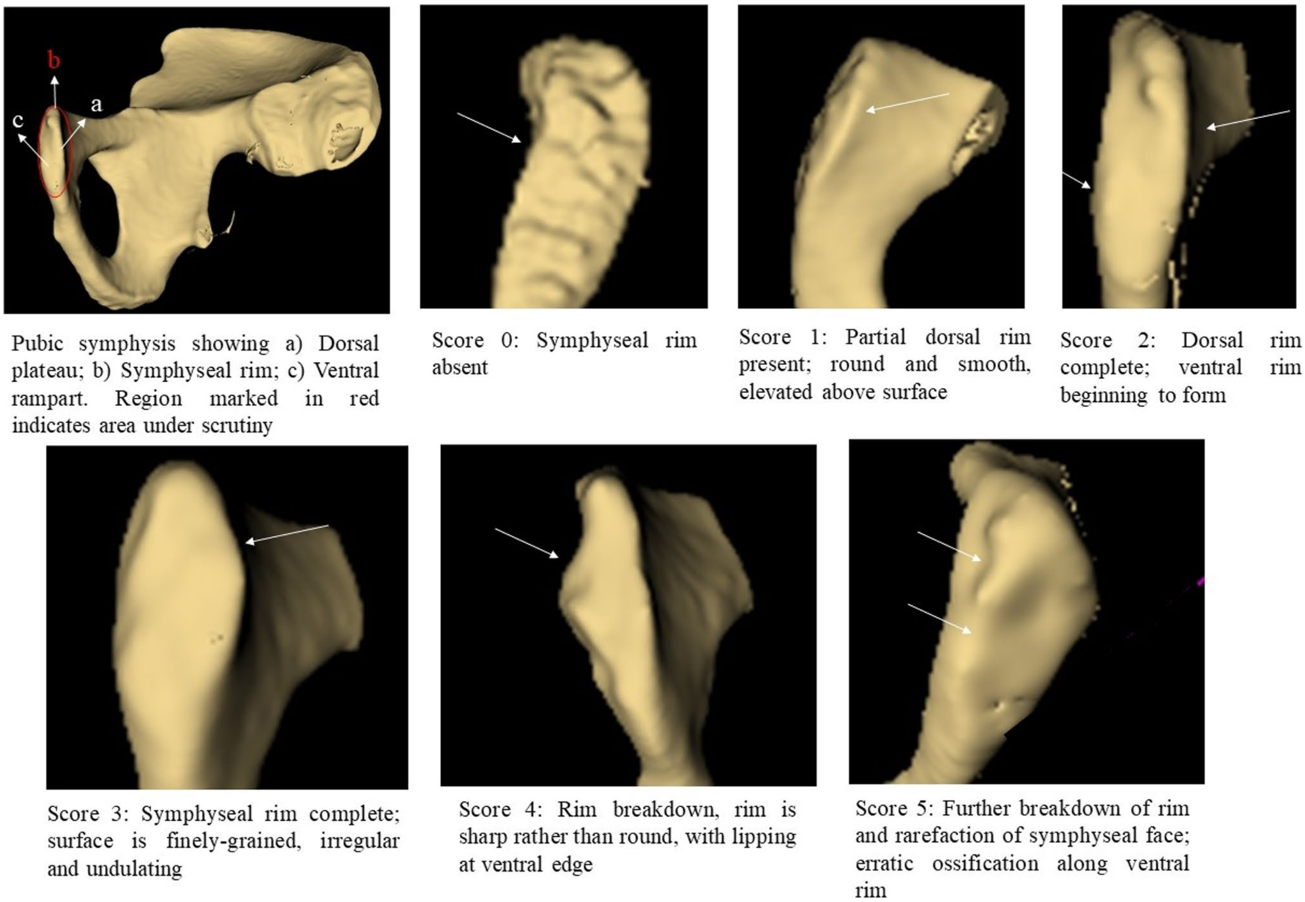

Fig. 3 3D CT representations of different gradations for the symphyseal rim

$$\Sigma(\textit{Estimated mean point age} - \textit{Chronological age})/n$$

Estimated mean point age values required for computations of inaccuracy and bias denote mean values reported by McKern–Stewart (1957).

As the descriptives of mean age and age range required to compute aforementioned accuracy and error were reported by McKern–Stewart exclusively for males, these values were not utilized herein to establish accuracy, inaccuracy, and bias for female participants. However, the applicability of McKern–Stewart's components in aging males and females was assessed using Bayesian parameters, with the aim of furnishing more realistic age profiles while circumventing age mimicry. Thus, highest posterior density (HPD) and highest posterior density region (HPDR) values were computed for males and females using probability density functions, i.e., Bayesian analysis, in keeping with the second objective of this study. HPD approximates the age-at-death/estimated age, and HPDR approximates the 95% confidence intervals of the HPD. In order to carry out such an analysis, the study set of 380 participants was divided arbitrarily into a larger training group comprising of 280 individuals (140 males, 140 females), and a smaller test group of 100 individuals (50 males, 50 females). Pubic symphyseal data obtained from the larger training group ($N = 280$) was utilized to compute HPD, and HPDR associated with individual components through probability density functions described within Bayes theorem, as follows:

$$P(A/MS) = P(MS/A) * f(A) / \int_{\text{shift}}^{\infty} P(MS/x) * f(x)dx$$

where f(A) is the probability density function of age, or the prior probability.

P(MS/A) indicates the likelihood ratio, i.e., the probability of observing different age-related changes as a function of chronological age.

P(A/MS) denotes the posterior probability for age estimation.

∫ P(MS/x) * f(x)dx is the constant of proportionality, with shift denoting the minimum age in the informative prior A = age; MS = Scores assigned to different components of the McKern–Stewart method

Table 2 Age and sex distribution of the study population ($N = 380$)

Age range (years)	Males (%)	Females (%)	Combined population (%)
10–19	09 (04.73)	09 (04.73)	18 (04.73)
20–29	38 (20.00)	19 (10.00)	57 (15.00)
30–39	28 (14.73)	20 (10.52)	48 (12.63)
40–49	30 (15.78)	42 (22.10)	72 (18.94)
50–59	27 (14.21)	45 (23.68)	72 (18.94)
60–69	32 (16.84)	36 (18.94)	68 (17.89)
≥70	26 (13.68)	19 (10.00)	45 (11.84)

f(x) depicts the demographic profile of the informative prior. Demographic profile of the informative prior (see sample collection) was estimated herein using the Gompertz model (Nikita and Nikitas 2019).

Accuracy percentages, inaccuracy, and bias values were computed for each individual component using the HPD and HPDR values garnered with Bayesian analysis. In order to do so, the test group ($N = 100$) comprising of an equal number of male and female participants was utilized. Accuracy percentages were estimated by tallying the proportion of individuals whose documented ages fell within the computed HPDR values. Inaccuracy and bias values were established using the differences between HPD and the chronological age of individuals.

Lastly, in accordance with the third objective, weighted summary age models were derived with the aim of garnering more reliable estimates of age, as follows:

$$[(WC1 * MDP) + (WC2 * MVR) + (WC3 * MSR)] / (WC1 + WC2 + WC3)$$

where WC1, WC2, and WC3 denote weighted coefficients for the dorsal plateau, ventral rampart, and symphyseal rim. These weighted coefficients were computed using principal component analysis, and denote the correlation of each component with the first principal component (Miranker 2016; Warrier et al. 2022b; Lovejoy et al. 1985; Bedford et al. 1993). MDP, MVR, and MSR represent the HPD values for the dorsal plateau, ventral rampart, and symphyseal rim, respectively.

Derived summary age models were further applied to the test group ($N = 100$), and inaccuracy and bias values associated with the same were established for either sex.

Results

The total study sample of 380 participants comprised of an equal number of males and females, with a mean age ± SD of 45.92 ± 18.303 years and 48.69 ± 16.123 years, respectively. Age and sex distribution of this study sample

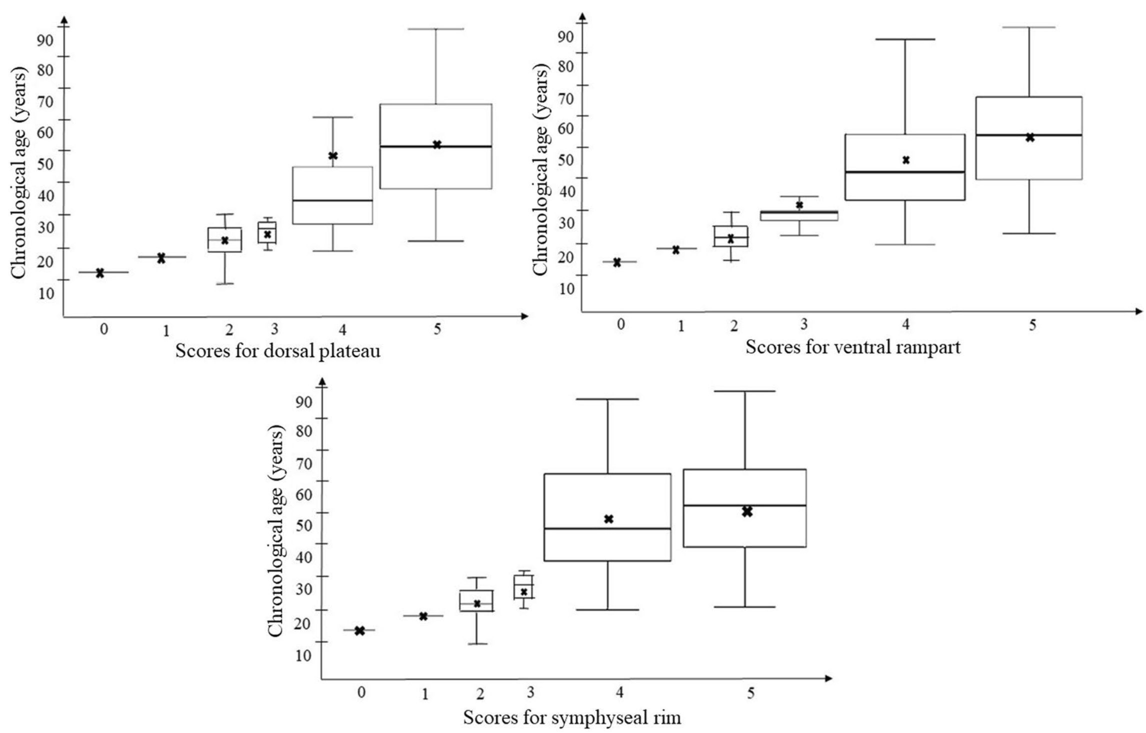

Fig. 4 Box and whisker plots representing the age distribution pertaining to different components (males)

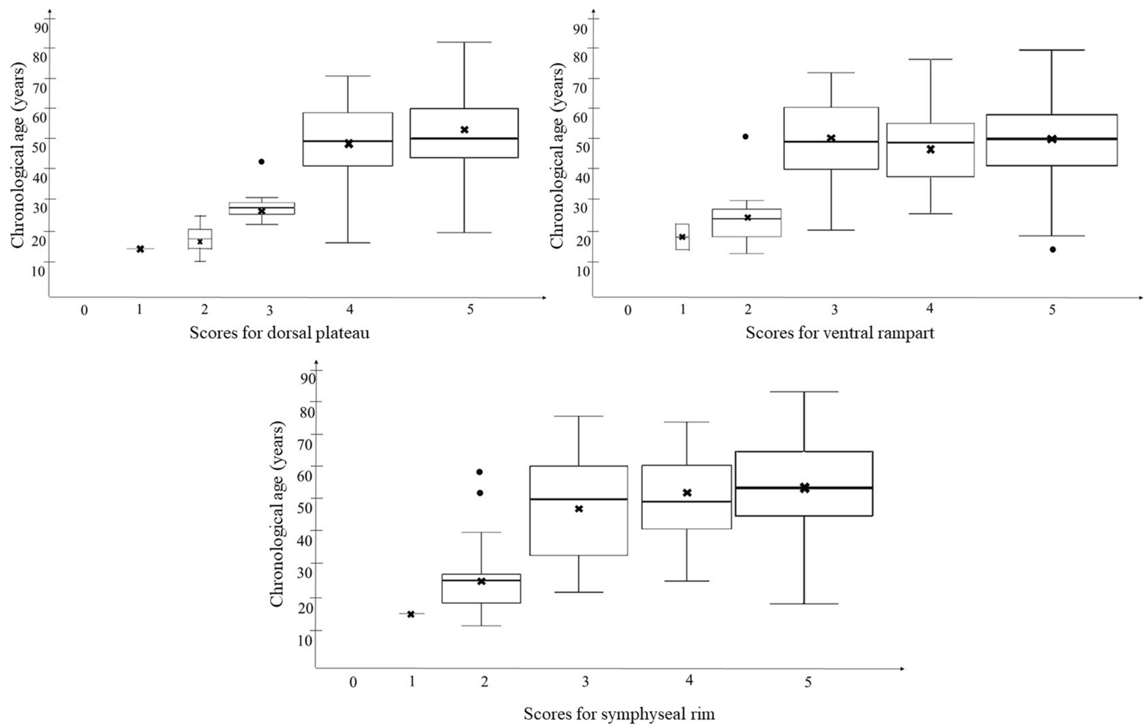

Fig. 5 Box and whisker plots representing the age distribution pertaining to different components (females)

is shown in Table 2. Box and whisker plots representing the age distribution pertaining to scores 0–5 of individual components are shown in Fig. 4 (males) and Fig. 5 (females). Within the study sample, no female participant displayed morphological features characteristic of score 0 for each of the three components.

Cohen's weighted κ values for inter-observer error (dorsal plateau = 0.824, ventral rampart = 0.790, symphyseal rim = 0.740) and intra-observer error (dorsal plateau = 0.900, ventral rampart = 0.810, symphyseal rim = 0.780) illustrate a moderate to strong agreement in the scoring of different components using CT images, with the scoring of dorsal plateau changes exhibiting greater repeatability in comparison.

No statistically significant sex differences were observed with the scoring of all three components (dorsal plateau: $p = 0.819$, Z-score = −0.228; ventral rampart: $p = 0.877$, Z-score = −0.154; symphyseal rim: $p = 0.060$, Z-score = −1.880). No statistically significant bilateral differences ($p > 0.05$) were observed with the scoring of individual components (dorsal plateau: $p = 0.405$, Z-score = −0.832; ventral rampart: $p = 0.236$, Z-score = −1.185; symphyseal rim: $p = 0.097$, Z-score = −1.661). Owing to the lack of significant bilateral differences, further statistical analysis was undertaken with the left pubic bone.

An overall statistically significant correlation of 0.513 and 0.313 was obtained between morphological features pertaining to different cumulative scores, and documented age, in males and females, respectively. Amongst the three components, ventral rampart displayed the strongest correlation with age in both males (0.561) and females (0.333). In males, the dorsal plateau and symphyseal rim garnered correlation values of 0.495 and 0.463, respectively. In females, the corresponding correlations obtained were 0.283 and 0.302, respectively. Males displayed a relatively stronger correlation in comparison to females. An additional partial correlation analysis between all three components while controlling for age yielded statistically significant residual correlations between the components, in both sexes. With males, the correlation between individual components ranged from 0.754 to 0.851, whereas in females, this partial correlation ranged from 0.481 to 0.613.

Table 3 Accuracy, inaccuracy, and bias associated with the McKern–Stewart method ($N = 190$)

Component	Males		
	Accuracy (%)	Bias (years)	Inaccuracy (years)
Dorsal plateau	64.70	−16.63	18.17
Ventral rampart	72.10	−18.15	19.19
Symphyseal rim	77.90	−08.68	14.28
Cumulative score	68.90	−12.03	15.12

Table 4 Highest posterior density and highest posterior density region computed with the training group ($N = 280$)

Component	Score	Males		Females	
		HPD	HPDR	HPD	HPDR
Dorsal plateau	0	10.00	10.00–30.62	-	-
	1	10.00	10.00–38.55	15.00	15.00–59.32
	2	14.79	10.00–58.53	47.78	15.00–65.35
	3	27.06	10.00–60.73	52.46	12.91–67.25
	4	44.42	16.04–70.63	58.03	27.01–74.02
	5	57.64	28.77–78.55	61.78	37.29–75.97
Ventral rampart	0	10.00	10.00–45.75	-	-
	1	10.63	10.00–53.39	15.00	15.00–55.75
	2	19.21	10.00–60.40	43.35	15.00–64.38
	3	33.23	10.00–64.25	54.12	22.39–71.45
	4	47.10	15.76–72.06	57.20	28.69–73.42
	5	57.58	27.52–78.64	61.52	37.13–75.78
Symphyseal rim	0	10.00	10.00–37.47	-	-
	1	10.00	10.00–45.73	15.00	15.00–59.45
	2	15.43	10.00–59.42	52.47	13.04–67.15
	3	33.23	10.00–64.25	55.58	22.56–72.27
	4	47.10	15.76–72.06	58.70	29.52–74.40
	5	57.58	27.52–78.64	61.98	37.99–76.04

HPD, highest posterior density; *HPDR*, highest posterior density region (95% CI of HPD); *CI*, confidence interval

Using the age ranges reported by McKern–Stewart, an overall accuracy percentage of 68.90% was obtained in males. The corresponding values for overall inaccuracy and bias, computed using mean ages given by McKern–Stewart for cumulative scores 0–15, were 15.12 years and −12.03 years. Highest and lowest accuracy percentages were obtained with the symphyseal rim and the dorsal plateau, respectively. Highest inaccuracy and bias values were obtained with the ventral rampart, whereas lowest error computations were furnished with the symphyseal rim (Table 3).

Hazard parameters, computed with the informative prior, for males include a3 (baseline mortality) = 0.003944482, b3 (senescent component) = 0.06188876, and shift (minimum age in the informative prior) = 10 years. With females, the corresponding hazard parameters were 0.001052896, 0.1, and 15 years, respectively. HPD and HPDR pertaining to each individual component are shown in Table 4. Higher HPD values were observed in females for all three components.

Accuracy, inaccuracy, and bias obtained with Bayesian analysis in males and females is shown in Table 5. Highest accuracy percentages of 92.00% were obtained with the ventral rampart, in males, whereas the dorsal plateau and symphyseal rim garnered highest accuracy percentages of 82.00% in females. Lowest error computations were observed with the symphyseal rim in males, and the ventral rampart in females. Males, in comparison to females, furnished higher accuracy percentages, and lower inaccuracy and bias values for all three components. Using Bayesian analysis, a tendency of under-aging was observed with the dorsal plateau and symphyseal rim in males. With females, over-aging was obtained throughout (Table 5).

Bartlett's test ($p < 0.001$) and Kaiser–Meyer–Olkin test (KMO measure = 0.716) indicated a satisfactory correlation between the three components, permitting a principal component analysis of data (Kaiser 1970; Dziuban and Shirkey 1974). Summary age models yielded inaccuracy and bias values of 11.51 years and −0.40 years, respectively, in males. The corresponding error computations obtained with females were 17.92 years and 13.04 years, respectively (Table 6).

Discussion

The pubic symphysis constitutes a robust and relatively immobile region within the human pelvis. This limited mobility, coupled with its gradual display of developmental and degenerative changes, renders the pubic symphysis an ideal marker for human age estimation (Lungmus 2009). With the aim of exploiting these advantages for human identification, Todd, in 1920, derived the first pubic symphyseal age estimation method by grouping transpiring morphological changes into ten distinct phases (Todd 1920). In order to overcome limitations encountered within Todd's method, McKern–Stewart, in 1957, subsequently devised their three-component age estimation method using skeletal remains of young American males (McKern and Stewart 1957). Their approach, a modification of Todd's ten-phase method,

Table 5 Accuracy, inaccuracy, and bias obtained with Bayesian analysis ($N = 100$)

Component	Males			Females		
	Accuracy (%)	Bias (years)	Inaccuracy (years)	Accuracy (%)	Bias (years)	Inaccuracy (years)
Dorsal plateau	90.00	−01.67	12.56	82.00	13.41	17.87
Ventral rampart	92.00	01.12	11.57	80.00	12.03	17.43
Symphyseal rim	90.00	−00.37	11.17	82.00	13.68	18.47

grouped observed morphological changes into what they considered to be three independently developing components. They believed that such a component-based approach would not only confer objectivity to the evaluation process but also encompass the individual variability overlooked within Todd's method (McKern and Stewart 1957; Lungmus 2009). A systematic review and meta-analysis of data procured from several studies employing the McKern–Stewart method indicated that the method demonstrates uniformity for aging the human pubic symphysis of different population affinities (Warrier et al. 2022a). However, this review could not empirically comment on the overall accuracy and precision associated with the method, as observational studies incorporated within the review had not reported the same.

The present study endeavoured to ascertain the applicability of the McKern–Stewart method, through computations of accuracy and precision by employing an equally represented male and female study group. While no statistically significant sex differences were observed with the scoring of individual components, a negligible to low positive correlation (Mukaka 2012; Hinkle et al. 2003) with age was obtained in females. Males, on the other hand, furnished a moderate positive correlation (Mukaka 2012; Hinkle et al. 2003) with age. Our findings pertaining to sexual symmetry are in contrast to those reported by Sharma et al. (2008). However, female participants within this singular investigation were significantly under-represented in comparison to males. Our study attempted to overcome this methodological limitation by incorporating an equal number of male and female participants. Similar investigations employing homogenously represented population groups are currently wanting in order to validate our findings pertaining to sexual symmetry. Within the present investigation, no statistically significant bilateral differences were observed during the scoring of individual components. Our findings pertaining to bilateral symmetry corroborate those of previous studies (Sharma et al. 2008; Kumar et al. 2009; Gorchiya et al. 2020). Hence, either pubic symphysis can be utilized for age estimation with equal vigour, and by extension, human identification.

Regarding the primary objective of this study, i.e., establishing the accuracy and precision of the McKern–Stewart method in Indian males, overall low accuracy percentages of 68.90% were obtained. Lungmus (2009) reported higher accuracy percentages of 77.80% with males of the Bass collection, in comparison to the present study. Amongst the three components, symphyseal rim yielded highest accuracy percentages and dorsal plateau the lowest. Overall inaccuracy and bias values obtained with males herein are comparable to those reported by Lungmus (2009). Highest and lowest inaccuracy and bias values were obtained with the ventral rampart and the symphyseal rim, respectively, in males. Our findings pertaining to the differential accuracy

Table 6 Summary age models derived in the present study and associated error rates

Sex	Summary age model	Bias (years)	Inaccuracy (years)
Males	[(0.953 × MDP) + (0.935 × MVR) + (0.958 × MSR)] / (0.953 + 0.935 + 0.958)	−00.40	11.51
Females	[(0.823 × MDP) + (0.874 × MVR) + (0.890 × MSR)] / (0.823 + 0.874 + 0.890)	13.04	17.92

MDP, mean age (HPD value) for dorsal plateau; *MVR*, mean age (HPD value) for ventral rampart; *MSR*, mean age (HPD value) for symphyseal rim

percentages, inaccuracy, and bias values obtained across the three components could not be corroborated due to a lack of similar data. An overall tendency of under-aging was observed on applying the McKern–Stewart method to Indian males. This could be attributed to the age structure of the original study population which comprised largely of younger males. Low accuracy percentages and high error rates garnered within the present investigation indicates that the McKern–Stewart method, in its primal form, lacks both accuracy and precision, a vital requisite within forensic, bioarchaeological, repatriation, and humanitarian contexts. Moreover, applying mean ages and age ranges reported by McKern–Stewart within their original study to different population groups can result in age mimicry (Vossoughi et al. 2022), thus garnering imprecise estimates of age and dampening the applicability of the method.

In order to overcome these issues of age mimicry and furnish more accurate estimates of age, a Bayesian analysis of McKern–Stewart's components was undertaken, in keeping with the second objective of this study. Since the applicability of the McKern–Stewart method in its primal form was not evaluated for females, as the original study reports descriptives for male remains alone, applicability of these three components in aging males and females of an Indian population was subsequently evaluated through Bayesian inference. Such a Bayesian analysis using McKern–Stewart's components is presently lacking.

Obtained Bayesian HPD values suggest that pubic symphyseal changes described by McKern and Stewart transpire at a much later age in females, with scores 2–5 for all three components garnering mean ages ≥40 years. Contrary to this, with males, a gradual progression from development to degeneration was observed with increasing age. These findings indicate that age-related changes transpiring within female pubic bones cannot be efficiently elucidated using McKern–Stewart's components. Higher inaccuracy and bias values obtained with females corroborate the limited applicability of McKern–Stewart's components in aging this sex. Hence, an in-depth understanding of the anatomical construct of different age markers, as well as the various intrinsic and extrinsic factors influencing the aging process, is warranted prior to devising and applying age estimation methods for human identification.

High accuracy percentages were obtained on applying HPDR values garnered with Bayesian analysis to males and females of the test group. Higher accuracy associated with a Bayesian approach, as opposed to the simple descriptive analysis of data/non-Bayesian approach, can be ascribed to the age brackets garnered with the former. Broader, closed age brackets were computed using Bayesian analysis, as opposed to the optimistically narrow age intervals described by McKern–Stewart for scores 0–4, and the open-ended age cohorts described by them for score 5, of each component. The increment in accuracy percentages obtained with individual components can be attributed to these realistic yet broad age brackets garnered with Bayesian analysis. These broad confidence intervals, in turn, illustrate the wide variability associated with changes transpiring within each component. Since McKern and Stewart scrutinized and described pubic symphyseal changes presenting within young pubic bones alone, they were unable to accommodate for features specific to older individuals. Thus, all individuals presenting with a score 5, i.e., a flat and granulated dorsal demi-face, and/or, a completed rampart, and/or, a broken rim with rarefaction of the symphyseal face, were coalesced into a single broad age category, inclusive of both young and old individuals. Incorporating a scored evaluation of additional features described by Hartnett (2010) might help further differentiate between younger and older individuals, garnering narrower age brackets.

Accuracy and precision values computed within the present investigation demonstrate the superior performance of Bayesian analysis, over the conventionally employed descriptive statistics for age estimation. Furthermore, the significant under-aging observed initially on applying the McKern–Stewart method to males was also redressed through Bayesian analysis. However, an effective application of Bayesian inference warrants the careful selection of an informative prior, with best results garnered when the informative prior and the target population exhibit similar demographic characteristics. In forensic, bioarchaeological, and repatriation contexts, the target sample constitutes the unknown, and thus pertinent information regarding the demographic profile of the target is, more often than not, lacking. Previous investigations have demonstrated that even when the informative prior and target sample originate from different population groups, the overall accuracy obtained with Bayesian analysis remains higher than those obtained with a descriptive reporting of data (Godde and Hens 2012). Alternatively, a uniform prior may also be employed for age estimation (Godde and Hens 2012).

Previously undertaken investigations with the McKern–Stewart method utilized cumulative score-based approaches for age estimation (Sinha and Gupta 1995; Sharma et al. 2008; Kumar et al. 2009; Kumar 2011; Singh et al. 2013; Prasad et al. 2015; Selvamurugan et al. 2019; Javvadi et al. 2016; Kumaran et al. 2019; Janardhan et al. 2016; Pal and Tamankar 1983). However, such an approach presents with the issue of assigning equal weight to all contributing components. Similar investigations with the acetabulum have empirically demonstrated that individual features contribute differentially towards the final estimate of age (Warrier et al. 2022b, c). The differing accuracy percentages, inaccuracy, and bias values obtained herein using both descriptive analysis and Bayesian statistics substantiate the same. The statistically sound approach for multivariate age estimation using all three components involves incorporating the partial correlation between all three components (Boldsen et al. 2002). Failure to do so reinforces the assumption of conditional independence, resulting in age ranges that are too narrow, and hence, imprecise (Sgheiza 2022). Partial correlations obtained herein between the three components invalidate this assumption of conditional independence. Nevertheless, the computational syntax required in order to carry out such a multivariate analysis (Boldsen et al. 2002; Hirk et al. 2020; Genz et al. 2021) was found to be quite complicated. As an alternative, a simplified multivariate approach has been suggested within this study-weighted summary age models.

Within these models, the generated intercorrelation matrix is subjected to principal component analysis, and the correlation of individual components with the first principal component is taken as the weight of each component (Lovejoy et al. 1985). The resulting weights were subsequently utilized to generate weighted summary age models, in keeping with the tertiary and final objective of this study. Summary age models derived using McKern and Stewart's components garnered lower error rates in comparison to Bayesian error computations for the dorsal plateau and the ventral rampart, in males. The symphyseal rim, however, furnished even lower inaccuracy and bias values in comparison to summary age models, illustrating its efficiency as an independent age marker in males. With females, summary age models garnered lower error rates in comparison to the symphyseal rim, alone. An overall tendency to over-age females and under-age males was demonstrated through summary age models.

Although the present study indicated no statistically significant sex differences with McKern–Stewart's components, weaker correlations, lower accuracy percentages and higher inaccuracy, and bias values were obtained with females. Furthermore, the three components described by McKern and Stewart fail to appropriately accommodate for age-related changes transpiring within the female pubic bone. While Bayesian analysis and summary age models did garner increased accuracy and precision with males of the study group, overall error computations associated with the method remain still quite high. Moreover, Bayesian age brackets, while realistically account for individual variability, are too broad to be of practical utility for human identification. Thus, McKern–Stewart's age estimation method exhibits limited applicability for males and females of an Indian population. Alternative pubic symphyseal age estimation methods such as those devised by Suchey–Brooks (1990), Gilbert–McKern (1973), Berg (2008), and Hartnett (2010) should be investigated for an Indian population.

Computed tomographic investigations are slowly taking precedence over gross macroscopic examination due to the numerous advantages that they offer. CT scans remain resistant to superimposition induced artefacts and magnification errors, problems commonly encountered with alternate visualization techniques of conventional radiography (Ekizoglu et al. 2016; Lottering et al. 2017; Carew et al. 2019). Previously undertaken CT-based investigation with the McKern–Stewart method indicates a satisfactory reproduction of morphological changes on CT scans (Gorchiya et al. 2020). CT-images obtained within the present study corroborate these findings. Low inter- and intra-observer errors associated with the scoring of individual components, too, validate the potential of CT for age estimation. Computed tomographic examinations can further be extrapolated to incorporate various sub-surface features for age estimation (Villa et al. 2013). Trabecular bone criteria, scrutinized within previous investigations, have illustrated satisfactory results as an age marker (Acśadi and Nemeskéri 1970). Incorporating these additional features might help further enhance the significance of CT for human age estimation. Despite these multifarious advantages, the use of computed tomography for age estimation is not recommended in living individuals. Alternatively, clinically obtained CT data can be relied on as a corroborative evidence for age estimation in repatriation and humanitarian contexts. Furthermore, post-mortem CT evaluations can be undertaken in the deceased to enable a non-invasive evaluation of age-related changes within forensic and bioarchaeological contexts.

The present study incorporated CT scans of individuals undergoing routine examinations following the advice of their treating physicians, and thus, a large, homogenous representation of participants within the informative prior and study group could not be ensured. A quasi-novel observation within this study was that age-related pubic symphyseal changes can be appreciated in males and females as young as 10 years old.

Conclusion

The McKern–Stewart method for pubic symphyseal age estimation simplifies the evaluation of age-related changes through its component-based approach. No statistically significant bilateral differences were observed with the scoring of the pubic bone, indicating that either pubic symphysis can be utilized for human age estimation with equal vigour. While no statistically significant sex differences were observed with McKern–Stewart's components, a weaker correlation, lower accuracy percentages, and higher error rates were observed in females. Thus, an in-depth understanding of the anatomical construct of different age markers, as well as various intrinsic and extrinsic factors influencing the aging process in both sexes, is warranted prior to utilizing different age estimation methods. Inaccuracy and bias values computed with descriptive analysis, Bayesian inference, and principal component analysis demonstrate the limited applicability of the McKern–Stewart method for human age estimation within forensic, bioarchaeological, repatriation, and humanitarian contexts. Alternate methods should be explored to enable accurate and precise human identification.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by VW, RS, and TK. The first draft of the manuscript was written by VW and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Approval was obtained from the Institutional Ethics Committee (Letter no. AIIMS/IEC/2019-20/1007) prior to commencement of the study. Compliance with ethical standards was ensured at each step of the present study.

Informed consent All participants were informed about parameters of the study and CT images of consenting individuals were collected.

Conflict of interest The authors declare no competing interests.

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