

ORIGINAL ARTICLE

Craniofacial and Mandibular Morphometrics for Sex Determination in an Indian Population: A Radiographic Discriminant Function Analysis

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ABSTRACT

Introduction: Sex determination based on skeletal features plays a crucial role in forensic identification. There is sparse data on the metric cranial and mandibular criteria for Indians. This study aimed to establish population-specific standards for sex determination in the crania and mandibles of adults using logistic regression analysis.

Materials and methods: The sample consisted of 300 participants (150 males, 150 females; age range: 18-30 yrs) of Indian origin. Fifteen standard cranial and 10 mandibular measurements were recorded on radiographic images and processed using a computer-aided drafting program (Adobe Photoshop 7 CS3 extended). To ascertain the usefulness of these parameters in sex prediction, a logistic regression analysis was performed.

Results: All cranial parameters, except the upper facial height (G-ANS) and orbital measurements, showed sexual dimorphism. All mandibular parameters, except the mandibular angle, showed sexual dimorphism. The cranial measurements had a sex assessment accuracy of 86%, and the mandibular measurements had an accuracy of 82.7%. The combination of these parameters significantly improved the accuracy to 89.7%.

Conclusion: This study on crania and mandibles of the Indian population clearly indicates that they have satisfactory potential for sex determination in adult Indians in forensic contexts. The width measurements, that is, bizygomatic breadth for the crania and bigonial breadth for the mandibles, were the most discriminatory.

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KEYWORDS

- Sex assessment • Cranial Anthropometry • Mandibular Anthropometry
- Indians

INTRODUCTION

Sex determination is a fundamental aspect of forensic anthropology and osteology, and plays a critical role in human identification. Sexual dimorphism in skeletal morphology arises from a combination of genetic, environmental, and biomechanical factors. While genetic factors, including sex chromosomes and racial heritage, establish the baseline skeletal structure, phenotypic expression is modulated by extrinsic variables such as nutrition, physical activity, and lifestyle.¹ In forensic contexts, where dismemberment or mutilation may obscure victim identity, accurate sex estimation becomes particularly challenging. Although intact skeletal remains allow for nearly 100% accuracy in sex determination,² fragmented remains, common in mass disasters, necessitate reliance on individual bones with pronounced sexual dimorphism.³

The skull, second only to the pelvis in terms of diagnostic reliability, exhibits significant sex-related variations. Williams and Rogers (2006) achieved 96% accuracy using cranial and mandibular traits, with a subset of six features (mastoid process, supraorbital ridge, skull size and architecture, zygomatic extension, nasal aperture, and mandibular gonial angle) yielding 94% precision.⁴ Population-specific differences further influence these metrics, as demonstrated by Steyn and Iscan (2008) in South African populations, where cranial dimensions provide 86% accuracy, while mandibular bigonial breadth is the most dimorphic parameter.⁵

When an intact skull is unavailable, the mandible serves as a viable alternative due to its robust structure and high sexual dimorphism.⁴ As the largest and most durable facial bone, it resists postmortem degradation better than many skeletal elements. Mandibular dimorphism manifests in size and shape, influenced by differential growth patterns, masticatory forces, and hormonal effects on bone remodeling.⁶ The mandibular ramus, in particular, exhibits distinct sex-based variations in developmental timing and biomechanical adaptation.⁷

Traditional sex estimation methods include morphological (non-metric) and metric

analyses, with geometric morphometrics and discriminant function analysis enhancing objectivity and reproducibility.⁸ While molecular techniques (e.g., DNA analysis) offer high precision, metric approaches remain advantageous in fragmentary remains because of reduced inter-observer variability.⁹ Despite these advancements, population-specific standards for cranial and mandibular sex estimation remain understudied in Indian populations. This study aimed to evaluate the craniofacial and mandibular parameters to derive discriminant functions for accurate sex determination in forensic and anthropological applications.

MATERIALS AND METHODS

Study Design

This cross-sectional study aimed to evaluate the craniofacial and mandibular morphometric parameters for sex determination in an Indian population. This study was conducted at a dental institution with a diverse population of students of different ethnic origins. Standardized lateral and poster anterior cephalograms were obtained and linear measurements were recorded following established anthropological protocols. The study was approved by the institutional ethics committee. The study adhered to ethical guidelines and the data were anonymized to maintain confidentiality.

Sample Size Estimation

The sample size was calculated using G*Power software (v3.1.9.7) based on a prior study by Poongodi *et al.* assessing sexual dimorphism in mandibular dimensions.¹⁰ Assuming an effect size of 0.3, power of 80%, and significance level of 0.05, a minimum of 150 males and 150 females (total N=300) was required to ensure robust discriminant function analysis.

Inclusion and Exclusion Criteria

Inclusion criteria:

- Adults (18–30 years) of Indian origin with no craniofacial deformities.
- Availability of high-quality lateral and poster anterior cephalograms.

- No history of orthognathic surgery or orthodontic treatment, fractures, or congenital anomalies affecting cranial/mandibular morphology.

Exclusion criteria:

- Poor radiographic clarity or missing landmarks.
- Pathological conditions (e.g., osteoporosis, tumors) altering bone dimensions.
- Individuals with significant dental attrition or edentulism affecting mandibular morphology.

Radiographic images were processed using a computer-aided drafting program (Adobe Photoshop 7 CS3 extended). Cranial and mandibular measurements were recorded in centimeters once the standard was set using the reference pin on the radiographs. Fifteen cranial and ten mandibular measurements (Table 1) were recorded using Martin and Seller's anthropometric guidelines¹¹. Landmarks were identified using standardized protocols and measurements were recorded twice for reliability (Figure 1A, 1B).

Table 1: Cranial and mandibular parameters

Radiograph	Cranial		Radiograph	Mandibular	
<i>Lateral cephalogram</i>	Glabella – Menton	G-M	<i>Lateral cephalogram</i>	Max. ramus width	MaRB
	Glabella – Anterior Nasal Spine	G-ANS		Min. ramus width	MiRB
	Basion – Nasion	B-N		Condylar height	CnH
	Basion – Anterior Nasal Spine	B-ANS		Coronoid height	CrH
	Frontal sinus height	FSH		Height of chin	Ch Ht
<i>Posterior anterior radiograph</i>	Left orbital breadth	Lt OB	<i>Posterior anterior radiograph</i>	Mandibular body length	BL
	Left orbital height	Lt OH		Mandibular body height	BH
	Right orbital breadth	Rt OB		Mandibular angle	MA
	Right orbital height	Rt OH		Bi condylar width	BiCoW
	Bi euric breadth	BEB		Bi gonial width	BiGoW
	Min frontal width	MiFB			
	Max. frontal width	MaFB			
	Nasal height	NH			
	Nasal width	NB			
	Bi zygomatic width	BiZB			

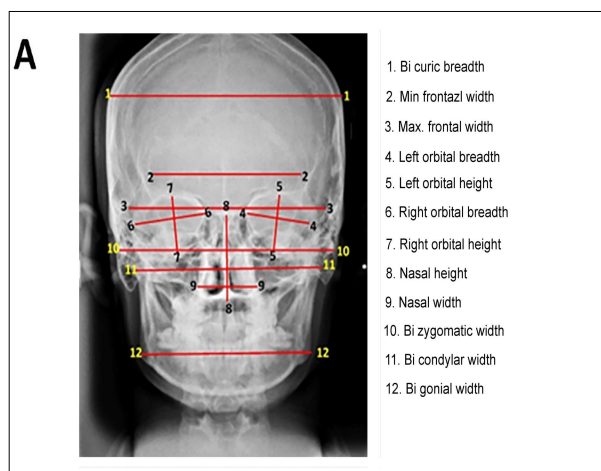


Figure 1A: Posterior-anterior radiograph showing the various cranial and mandibular parameters

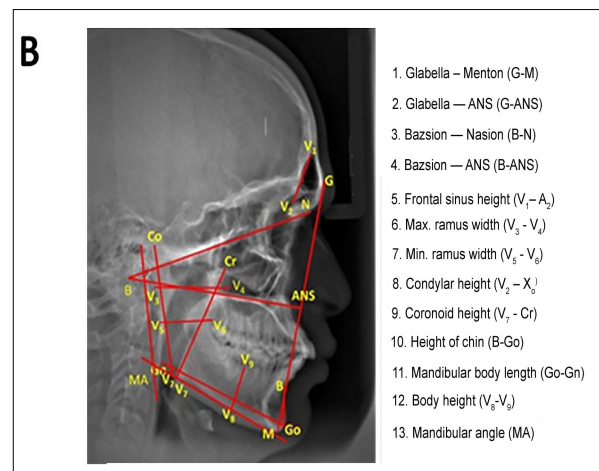


Figure 1B: Lateral Cephalogram showing the various cranial and mandibular parameters

Reliability of Measurements

Intra and inter-observer reliabilities were assessed using intraclass correlation coefficients (ICC). A trained anthropologist repeated 20% of the measurements after a two-week interval. ICC values >0.90 indicated excellent reproducibility. Calibration sessions minimized landmark identification errors and digital tools reduced manual measurement bias.

Statistical Analysis

The data were analysed using SPSS v23.0. Descriptive statistics (mean $\pm$ SD) were calculated for each parameter. Sexual dimorphism was evaluated using an independent t-test and Mann-Whitney U test (normality assessed via Shapiro-Wilk test). Discriminant function analysis (DFA) identified the most dimorphic variables, and cross-validation classified sex with accuracy rates. Multivariate regression adjusted for population-specific variations. Statistical significance was set at $P < 0.05$. Sexual dimorphism ratios were calculated to assess general patterns of dimorphism. Student's

t-test was used to establish whether significant differences existed ($p \leq 0.05$) between the mean measurements of men and women.

RESULTS

Table 2 shows significant sexual dimorphism in cranial parameters, with males exhibiting larger mean values for most measurements. Highly significant differences ($p < 0.001$) were observed in the glabella-menton length (G-M), basion-nasion (B-N), basion-ANS (B-ANS), frontal sinus height (FSH), bi-eyron breadth (BEB), maximum/minimum frontal breadth (MaFB / MiFB), nasal height (NH), nasal breadth (NB), and bi-zygomatic breadth (BiZB). Notably, BiZB exhibited the greatest dimorphism ($t=14.282$). The orbital dimensions (Lt/ Rt OB/OH) demonstrated no significant differences ($p > 0.05$), suggesting a limited discriminatory value. These findings confirm that specific cranial metrics, particularly facial breadth and neurocranial dimensions, are reliable sex discriminators in this population, supporting their use in forensic anthropological analyses.

Table 2: Comparison of cranial parameters (in cm) between male and females with unpaired t-test

Radiograph	Parameters	Female		Male		t-value	P-value
		Mean	Std. Dev.	Mean	Std. Dev.		
<i>Lateral Cephalogram</i>	G-M	12.44	5.22	12.99	4.85	7.440	0.000*
	G-ANS	6.5	7.07	6.59	6.07	1.912	0.057
	B-N	10.28	5.83	10.89	5.87	8.305	0.000*
	B-ANS	9.44	5.82	10	5.8	8.454	0.000*
	FSH	2.51	24.7	2.91	23.71	5.219	0.000*
<i>Posterior anterior radiograph</i>	BEB	13.87	4.25	14.17	4.16	4.373	0.000*
	MiFB	9.54	3.98	9.71	4.22	3.520	0.000*
	MaFB	11.55	4.67	11.92	4.44	5.907	0.000*
	Lt OB	3.76	6.11	3.79	5.54	1.027	0.350
	Lt OH	3.19	9.72	3.22	8.69	0.917	0.360
	Rt OB	3.69	6.23	3.74	6.95	1.817	0.070
	Rt OH	3.18	10.69	3.19	9.09	0.226	0.821
	NH	4.65	7.52	4.89	6.34	6.466	0.000*
	NB	3.13	8.31	3.34	8.38	6.540	0.000*
	BiZB	12.06	4.39	12.92	3.56	14.282	0.000*

* $p < 0.05$: significant; data are presented as the mean and standard deviation (SD).

The analysis of mandibular parameters (Table 3) revealed significant sexual dimorphism ($p < 0.001$) across most measurements, with males consistently exhibiting larger

dimensions. Key discriminators included the maximum and minimum ramus breadth (MaRB, MiRB), condylar and coronoid heights (CnH, CrH), chin height, body length

(BL), body height (BH), and bi-condylar and bi-gonial widths (BiCoW, BiGoW). Notably, mandibular angle (MA) showed no significant difference ($p=0.056$), suggesting a limited value for sex determination. The greatest dimorphism was observed in BiCoW

($t=-11.225$), highlighting its forensic utility. These findings demonstrate that mandibular metrics, particularly ramus dimensions and bicondylar breadth, are reliable sex discriminators in skeletal analysis.

Table 3: Comparison of mandibular parameters (in cm) between male and females with unpaired t-test

Radiograph	Parameters	Female		Male		t-value	P-value
		Mean	SD	Mean	SD		
<i>Lateral Cephalogram</i>	MaRB	3.28	7.32	3.48	7.47	-6.965	0.000*
	MiRB	2.77	7.58	2.92	7.87	-6.060	0.000*
	CnH	6.31	7.60	6.85	6.71	-9.984	0.000*
	CrH	5.89	8.66	6.36	6.92	-8.534	0.000*
	Chin Hgt	1.85	10.27	2.04	9.31	-8.569	0.000*
	BL	7.44	6.72	7.80	6.66	-6.110	0.000*
	BH	2.13	10.33	2.3	10.82	-6.788	0.000*
	MA	123.1	3.97	122	3.94	1.917	0.056
<i>Posterior anterior radiograph</i>	BiCoW	10.73	4.47	11.38	4.57	-11.225	0.000*
	BiGoW	8.94	6.49	9.61	6.14	-9.877	0.000*

* $p<0.0$: significant; data are presented as the mean and standard deviation (SD)

Step-wise discriminant function analysis (Table 4) identified key parameters for sex determination, with cranial and mandibular measurements showing strong discriminatory power. Among cranial parameters, bizygomatic breadth (BiZB) emerged as the most significant predictor ($F=103.52$), followed by basion-nasion length (B-N), nasal breadth (NB), frontal sinus height (FSH), and minimum frontal breadth (MiFB). Among the

mandibular traits, bi-condylar width (BiCoW) demonstrated the highest predictive value ($F=125.99$), followed by chin height (Chin Hgt), bi-gonial width (BiGoW), maximum ramus breadth (MaRB), and coronoid height (CrH) also contributing significantly. The standardized coefficients revealed that BiZB and BiCoW had the strongest influence in distinguishing the sexes, highlighting their forensic utility.

Table 4: Step-wise discriminant function analysis sectioning points in original cranial and mandibular parameters

Parameters		Standardized coefficient	Structure coefficient	F-value
<i>Cranial</i>	BiZB	-0.8384	-0.8749	103.5204*
	B-N	-0.3392	-0.4916	16.6561*
	NB	-0.2136	-0.3871	6.4186*
	FSH	-0.2085	-0.3089	6.2871*
	MiFB	0.2274	-0.2083	6.1228*
<i>Mandibular</i>	BiCoW	0.4363	0.6887	125.9920*
	Chin Hgt	0.3693	0.5257	91.1263*
	BiGoW	0.4134	0.6060	72.2259*
	MaRB	0.2933	0.5236	62.5242*
	CrH	0.2371	0.4273	52.4203*

*Significant predictors

The discriminant functions demonstrated high accuracy in sex classification, with cranial parameters achieving an overall accuracy of 83.67% (82.67% for males and 84.67% for females). Mandibular measurements showed a slightly lower performance (81.00% overall, 83.33% male, 78.67% female accuracy). Notably, combining both cranial and mandibular parameters significantly

improved the classification to 88.00% accuracy (89.33% male, 86.67% female), indicating their complementary value in sex determination (Table 5). These results validate the effectiveness of stepwise discriminant analysis in forensic applications, with the combined model showing promise for reliable sex estimation in unidentified skeletal remains.

Table 5: Sex classification accuracy of the stepwise discriminant functions by using logistic regression analysis

Parameters	Male		Female		Total	
	n	%	n	%	n	%
Cranial	124/150	82.67%	127/150	84.67%	251/300	83.67%
Mandibular	125/150	83.33%	118/150	78.67%	243/300	81.00%
Combined	134/150	89.33%	130/150	86.67%	264/300	88.00%

DISCUSSION

Sex determination constitutes a fundamental pillar in establishing biological profiles of unidentified human remains, with craniometric analysis serving as a particularly valuable tool when pelvic bones, the gold standard for sex assessment, are unavailable.⁴ Our study systematically evaluated the efficacy of lateral cephalograms and posteroanterior radiographs in sex determination, confirming their utility in revealing architectural details and multiple comparative landmarks that facilitate accurate analysis.¹² While the skull remains the second most reliable skeletal element for sex estimation after the pelvis, its reliability significantly increases post-puberty when sexual dimorphism becomes fully expressed.⁵ This developmental trajectory underscores the importance of considering sex-related changes when interpreting craniofacial metrics.

The imperative for population-specific standards emerges clearly from our findings, aligning with the well-established principle that osteometric relationships vary significantly across ethnic groups.¹³ These variations stem from complex interactions between genetic factors (such as population-specific allele frequencies affecting bone growth) and environmental influences including nutritional patterns, climatic adaptations, and biomechanical loading from culturally-specific mastication habits.¹⁴ The high intra- and inter-observer reliability scores (ICC>0.90) in our measurement protocol validate the reproducibility of our approach,

a critical consideration given the documented challenges in craniometric analysis.¹⁵

Our results identified bizygomatic breadth as the most sexually dimorphic cranial parameter, with males exhibiting an approximately 7.1% greater width than females ($p<0.001$). This finding corroborates multiple studies,^{5,16} while contradicting findings in indigenous South Africans.¹⁷ The observed dimorphism likely reflects biomechanical adaptations to greater masticatory forces in males, mediated through both hormonal influences on bone growth and functional adaptation to dietary patterns.¹⁸ The developmental trajectory of zygomatic morphology warrants particular attention - male skulls demonstrate extended lateral growth of the zygomatic arch combined with posterior displacement of the malar bone, creating characteristically broader and more robust facial architecture.¹² This sexual dimorphism proves so pronounced that even traditional morphological assessments (without metric analysis) can reliably detect differences in clinical settings.⁴

The mandibular analysis yielded equally compelling results, with bigonial breadth emerging as the most dimorphic parameter (8.3% greater in males, $p<0.001$). This aligns with the observations in previous studies, confirming the mandible's status as the most sexually dimorphic cranial bone.^{5,17} The biomechanical basis for this dimorphism appears rooted in differential masticatory forces males typically exhibit greater muscle mass in the temporalis and masseter muscles,

resulting in more pronounced gonial flaring and overall mandibular robusticity.¹⁴ Our findings contradict some literature regarding mandibular angle dimorphism,¹⁹ instead supporting the contention that angular measurements show limited sexual dimorphism in certain populations.²⁰ This discrepancy highlights the critical importance of population-specific standards, as our Indian cohort demonstrated different patterns than those reported in European or African populations.

Stepwise discriminant analysis proved particularly effective, reducing our initial 25 parameters to 10 highly discriminatory variables while maintaining classification accuracy. This methodological refinement addresses a common critique of osteometric studies - the potential for overfitting with excessive variables.¹⁷ Our final model achieved 88% accuracy when combining cranial and mandibular parameters, surpassing the reported 84.1% accuracy¹⁶ and slightly below 93% when long bone tibia was used.²¹ This variance likely reflects both methodological differences and population-specific morphological characteristics. Notably, our cranial-only (83.67% accuracy) and mandibular-only models (81% accuracy) both outperformed many population-specific standards,^{3,22} suggesting particularly pronounced sexual dimorphism in our Indian cohort.

Several unexpected findings merit further discussion. The inverse dimorphism observed in minimum frontal breadth (MiFB) challenges conventional assumptions about male robusticity and may reflect unique population-specific growth patterns or measurement methodologies. Similarly, the limited dimorphism in orbital dimensions contradicts some literature,²³ while supporting more recent geometric morphometric studies.¹⁴ These discrepancies underscore the complex interplay between genetic determinants and functional adaptation in cranial development.

The practical application of our findings is substantial. In forensic contexts, our discriminant functions can assist

1. Identification from fragmentary remains (particularly valuable in mass disasters)
2. Validation of archaeological sex determinations
3. Reconstruction of biological profiles in criminal investigations

The population-specific nature of our standards makes them particularly valuable for Indian forensic casework, where previous reliance on European or African standards may have introduced errors. Our radiographic approach offers additional advantages in clinical forensic medicine, allowing analysis even when maceration is impossible or desirable.

Methodologically, our study advances the field by:

1. Demonstrating the efficacy of combined cranial and mandibular analysis
2. Establishing rigorous reliability standards for radiographic osteometry
3. Providing validated population-specific discriminant functions

However, the limitations of this study must be acknowledged. Our institutional-based sampling may underrepresent rural populations and certain caste groups, which potentially limits the generalizability of our findings. The 18-30 age range excludes important developmental and senescent changes that warrant further investigation. Future research should consider the following:

1. Expansion to subpopulation groups within India
2. Incorporation of 3D imaging modalities
3. Application of machine learning algorithms to improve predictive accuracy
4. Investigation of age-related changes in sexual dimorphism patterns

CONCLUSION

Our study established robust, population-specific standards for sex determination using cranial and mandibular metrics in an Indian population. The demonstrated accuracy rates, particularly with the combined parameters, provide forensic practitioners with reliable tools for human identification. Methodological rigor and statistical validation advance anthropological practice while highlighting the critical importance of population-specific osteometric databases. These findings significantly contribute to the growing literature on forensic anthropology applications in South Asia and provide a foundation for future research on population variation in human sexual dimorphism.

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