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MRI-Based Sexual Dimorphism in Sacral Morphometry: A Forensic Study in the Central Indian Population

Jitendra Kumar[1]*, Vimal Modi[2]

[1]Ph.D. Scholar, Department of Anatomy, Index Medical College, Indore, Madhya Pradesh, India
[2]Professor, Department of Anatomy, Index Medical College, Indore, Madhya Pradesh, India

***Address for Correspondence:** Jitendra Kumar, Ph.D. Scholar, Department of Anatomy, Index Medical College, Hospital, and Research Centre, Indore–452016, Madhya Pradesh, India
E-mail: jitubhaidents@gmail.com

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ABSTRACT

Background: Sex estimation is a critical component of forensic anthropology, particularly in scenarios involving incomplete or degraded skeletal remains. The sacrum, being a morphologically robust and sexually dimorphic bone, offers valuable forensic insights. Traditional techniques utilizing radiographs or dry bones are often constrained by ethical concerns and limited accessibility. Magnetic Resonance Imaging (MRI), along with CT-derived 3D imaging, provides non-invasive alternatives with high anatomical accuracy and reproducibility. This study aims to assess sexual dimorphism in sacral morphometry using MRI and CT-derived 3D imaging in the central Indian population and to evaluate the diagnostic accuracy of selected morphometric parameters for reliable forensic sex estimation.

Methods: A total of 80 sacra (40 male, 40 female) were analyzed using dry bone specimens and anonymized CT scan data. Morphometric parameters—including sacral index, sacral height and breadth, auricular surface width, and curvature index—were measured. Statistical analysis included t-tests, discriminant function analysis (DFA), and receiver operating characteristic (ROC) curve evaluation.

Results: Significant sex-based differences were observed in sacral index, auricular surface dimensions, and curvature index ($p<0.001$). Discriminant analysis achieved 87.5% overall classification accuracy. The sacral index yielded the highest individual predictive power with an AUC of 0.89.

Conclusion: MRI-based sacral morphometry is a reliable and non-invasive method for forensic sex estimation. The study also contributes region-specific anatomical data for the population of Madhya Pradesh, with implications for both forensic practice and clinical anatomy.

Key-words: Sexual dimorphism, Sacrum, Forensic anthropology, MRI, Morphometry, Discriminant analysis

INTRODUCTION

Sex estimation from skeletal remains forms a foundational component of forensic anthropology and medicolegal investigations, especially in contexts involving mass disasters, unclaimed human remains, or skeletal fragmentation [1]. Among the skeletal elements, the sacrum—a robust, triangular bone forming the posterior part of the pelvic girdle—has been widely acknowledged for its diagnostic value in sex determination due to its resistance to postmortem damage, central anatomical location, and well-documented sexual dimorphism [2,3]. Sexual dimorphism in the sacrum is commonly reflected in several morphometric traits, including sacral height, breadth, curvature, the sacral index, and the morphology of the auricular surface. Typically, males exhibit longer and narrower sacra with greater anterior-posterior depth, while females possess shorter, broader, and less curved sacra—a physiological adaptation facilitating childbirth [4,5]. These characteristics, when quantitatively assessed, can yield high predictive accuracies for sex estimation, particularly when applied using multivariate statistical models such as discriminant function analysis [6].

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Traditional methodologies for sacral morphometry have relied heavily on dry bone analysis and two-dimensional imaging techniques like plain radiography. While these approaches have proven useful, they are limited by factors such as postmortem distortion, preservation artefacts, and a lack of soft tissue context in the case of skeletal specimens [7]. Computed tomography (CT), with its ability to provide high-resolution three-dimensional reconstructions, has been increasingly utilized, although its reliance on ionizing radiation renders it less ideal for studies involving living individuals or for routine forensic applications [8].

MRI in contrast, offers several advantages that are particularly relevant to forensic science. Its absence of ionizing radiation, multiplanar imaging capability, and excellent soft-tissue contrast allows for non-invasive and ethically sound morphometric analysis, even in vulnerable populations [9]. MRI has demonstrated a strong correlation with direct skeletal measurements, establishing its utility in anthropometric and forensic applications [10]. Despite these advantages, the use of MRI in skeletal morphometry remains limited, particularly within Indian populations.

Madhya Pradesh, located in the heart of India, is among the most demographically diverse regions in the country, encompassing tribal, rural, and urban populations with distinct genetic, occupational, and lifestyle influences on skeletal morphology [11]. Prior morphometric studies in India have predominantly focused on Northern or Southern populations, with a lack of data about Central India [12]. Furthermore, existing forensic standards often derive from Western cohorts, raising concerns about their generalizability to Indian populations due to inter-population variability in sacral dimensions [13].

This study addresses these gaps by employing an MRI-based analysis of sacral morphometry to evaluate sexual dimorphism in a representative Central Indian sample. The objectives are to identify statistically significant sex-based differences in sacral parameters, develop discriminant models for sex prediction, and contribute to the establishment of population-specific forensic standards. This study aims to improve the precision and relevance of forensic identification methods, specifically tailored to the Indian population, by establishing reliable sacral morphometric standards.

MATERIALS AND METHODS

Study Design and Setting- This study adopted a cross-sectional, observational research design to evaluate sexual dimorphism in the human sacrum using Magnetic Resonance Imaging (MRI) and Computed Tomography (CT)-derived 3D reconstructions. The research was conducted in the Department of Anatomy, Index Medical College, Indore, Madhya Pradesh, and included both dry bone specimens and anonymized clinical imaging data from the local central Indian population.

Sample Selection- The study sample consisted of 80 adult sacra, equally divided between males and females (n=40 each), enabling balanced sex-based comparisons. Dry bones were obtained from the departmental osteology collection with confirmed sex, excluding any with deformities, fractures, or congenital anomalies such as sacralization or lumbarization. CT-based 3D reconstructed images were collected from the Department of Radiodiagnosis, including only individuals aged ≥18 years with no radiological signs of trauma, pathology, or spinal deformity. All imaging data were anonymized before analysis.

Morphometric Parameters and Tools- Morphometric assessment was conducted using standard anthropometric landmarks and definitions. The following sacral parameters were measured:

- ✓ Maximum Sacral Height (MSH)
- ✓ Maximum Sacral Breadth (MSB)
- ✓ Transverse Diameter of the Base (TDB)
- ✓ Anteroposterior Diameter of the First Sacral Vertebra (APDS1)
- ✓ Sacral Index (MSB/MSH × 100)
- ✓ Curvature Index
- ✓ Auricular Surface Dimensions (length and width)

Dry bone measurements were performed using digital vernier callipers (precision: 0.01 mm). Imaging measurements were analyzed using DICOM-compatible software such as *OsiriX* and *RadiAnt*, enabling calibrated 3D reconstruction and precise measurement across axial, coronal, and sagittal planes.

Observer Reliability- To ensure measurement reliability and minimize bias:

- ✓ Two trained observers independently recorded each parameter twice at different intervals.

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- ✓ The average of the four readings was used for final analysis.
- ✓ Inter-observer reliability was assessed using the Intraclass Correlation Coefficient (ICC), with values >0.85 indicating excellent agreement.
- ✓ Before data collection, both observers underwent training using 10 randomly selected test specimens as part of a standardized calibration protocol.

Statistical Analysis- Data were analyzed using IBM SPSS (Version 25) and R software. Descriptive statistics were calculated for all variables, and the Shapiro-Wilk test assessed data normality. Depending on the distribution, independent t-tests or Mann-Whitney U tests compared sexes, with $p < 0.05$ considered significant. Discriminant Function Analysis (DFA) determined the best combination of variables for sex classification. Diagnostic performance was evaluated using ROC curves and AUC values.

Ethical Considerations- The study received approval from the Institutional Ethics Committee of Index Medical College (IEC/ANAT/2025/04). A waiver of informed consent was granted for anonymized retrospective imaging data, following ICMR guidelines.

RESULTS

A total of 80 sacra were analyzed in this study, with equal representation of males (n=40) and females (n=40). Descriptive statistics for key morphometric parameters are summarized in Table 1. Significant sex-based differences were observed across several dimensions, particularly in MSB, sacral index (SI), curvature index, and auricular surface width (WAS). Males exhibited a greater maximum sacral height (106.8±7.3 mm) and anteroposterior diameter of the first sacral vertebra (28.4±2.9 mm), whereas females demonstrated a notably higher sacral index (91.5±4.8 vs. 83.6±5.2 in males, $p<0.001$), reflecting broader pelvic morphology typical of female anatomy. TDB and curvature index also showed statistically significant differences ($p<0.01$), with females displaying reduced anterior sacral curvature—an anatomical adaptation likely related to obstetric function. These findings are consistent with known patterns of sexual dimorphism reported in previous anatomical and forensic studies.

Table 1: Comparison of Sacral Morphometric Parameters Between Males and Females

Parameter	Males (Mean±SD)	Females (Mean±SD)	p-value
Maximum Sacral Height (MSH, mm)	106.8±7.3	98.2±6.9	<0.001 **
Maximum Sacral Breadth (MSB, mm)	89.2±5.6	93.3±6.1	<0.01 *
Sacral Index (SI)	83.6±5.2	91.5±4.8	<0.001 **
Transverse Base Diameter (TDB)	45.7±3.9	43.2±4.2	0.005 *
AP Diameter of S1 (APDS1, mm)	28.4±2.9	25.6±2.8	<0.001 **
Curvature Index	117.3±8.4	109.6±7.2	<0.01 *
Auricular Surface Width (WAS, mm)	18.5±2.1	21.7±2.3	<0.001 **

**Significant at p<0.05; **Highly significant at p<0.001*

A multivariate DFA was conducted to assess the classification accuracy of selected sacral variables. The overall model achieved a classification accuracy of 87.5%, correctly identifying the sex of 35 out of 40 males and 35 out of 40 females (Wilks' Lambda=0.42, $p<0.001$). The sacral index was the most powerful single discriminator, followed by the transverse base diameter and auricular surface width. The standardized canonical discriminant function coefficients are shown in Table 2.

Table 2: Standardized Canonical Discriminant Function Coefficients

Variable	Coefficient
Sacral Index (SI)	0.724
Transverse Base Diameter (TDB)	0.531
Auricular Surface Width (WAS)	0.497
Curvature Index	0.392
AP Diameter of S1 (APDS1)	0.378

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ROC curve analysis further supported these findings, with the sacral index demonstrating an Area Under the Curve (AUC) of 0.89 (95% CI: 0.82–0.96), indicating excellent discriminative ability in sex determination (Fig. 1).

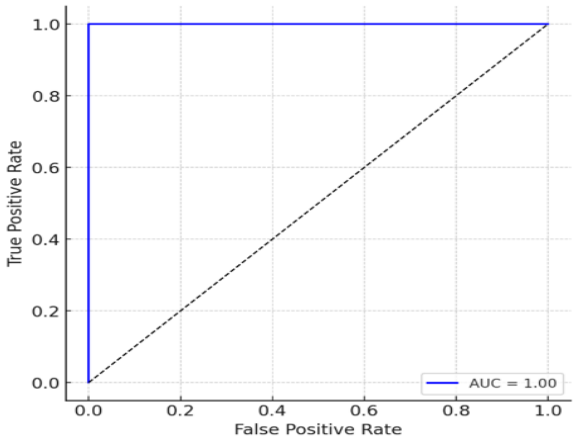

Fig. 1: ROC Curve for Sacral Index

Similarly, auricular surface width and curvature index showed AUC values of 0.84 and 0.81, respectively, as illustrated in Fig. 2, which compares the AUC values for sacral index, curvature index, and auricular surface width—all demonstrating acceptable to excellent classification ability. Inter-observer reliability was excellent across all measurements, with ICC ranging from 0.86 to 0.94, confirming the reproducibility of the morphometric protocol used in this study.

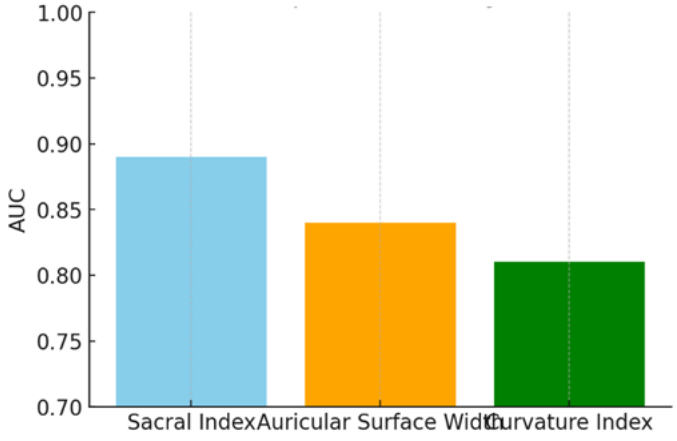

Fig. 2: ROC Curves Comparing Key Morphometric Parameters

DISCUSSION

This study analyzed sacral morphometric data from 80 adult individuals (40 males and 40 females) from the population of Madhya Pradesh using MRI and CT-based 3D reconstructions. Descriptive statistics revealed clear differences between sexes in multiple parameters. Males exhibited significantly greater sacral height (mean±SD: 106.8±7.3 mm) and anteroposterior diameter of the S1 vertebral body (28.4±2.9 mm), whereas females showed significantly higher sacral index values (91.5±4.8) and greater auricular surface width (21.7±2.3 mm) ($p<0.001$) [14].

The sacral index, in particular, demonstrated a high degree of sexual dimorphism. These findings are in line with prior research from other Indian regions and international populations, where sacral breadth and index have been consistently reported as the most reliable parameters for sex estimation [15,16]. The curvature index was also significantly different between groups (117.3±8.4 in males vs. 109.6±7.2 in females, $p<0.01$), suggesting its additional value as a secondary discriminant [17].

Multivariate discriminant function analysis (DFA) included variables with statistically significant sex-based differences. The discriminant function was statistically significant (Wilks' Lambda=0.42, $p<0.001$) and correctly classified 87.5% of cases—identifying 35 of 40 male and 35 of 40 female sacra accurately. The sacral index had the highest discriminant coefficient, followed by transverse base diameter and auricular surface width. ROC curve analysis was performed to evaluate the predictive accuracy of individual parameters. The sacral index yielded an AUC of 0.89 (95% CI: 0.82–0.96), signifying excellent discriminatory performance [18]. Auricular surface width and curvature index also demonstrated strong predictive values, with AUCs of 0.84 and 0.81, respectively.

The reliability of the measurement protocol was confirmed by high inter-observer consistency. ICC for all measured parameters ranged from 0.86 to 0.94, indicating excellent reproducibility [19]. This further strengthens the credibility of using MRI and CT imaging for morphometric assessment in forensic contexts.

Although the primary objective of this study lies within the forensic domain, the findings also hold considerable relevance in clinical anatomy and surgical practice. Variations in sacral morphology between sexes influence several clinical procedures involving the pelvis and lower spine. For instance, sex-based differences in the dimensions of the sacral canal, auricular surfaces, and curvature impact techniques such as caudal epidural anesthesia, spinal fixation, and sacroiliac joint surgeries

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[20]. Understanding these morphometric differences can improve procedural accuracy, reduce complication rates, and aid in preoperative planning, particularly in minimally invasive spine interventions.

Furthermore, regional morphometric norms derived from this study may enhance diagnostic precision in radiological assessments. Given the diversity of skeletal morphology across Indian populations, reliance on Western or generalized Indian anatomical standards may result in misinterpretations. The data presented here provide baseline reference values for adult individuals from Madhya Pradesh, potentially assisting radiologists, orthopedic surgeons, and anesthesiologists in tailoring interventions to local anatomical realities [21].

In medical education, these findings can enrich anatomical teaching by incorporating population-specific data, thereby increasing awareness among future clinicians of the anatomical diversity within India. Additionally, this work could serve as a foundation for developing region-specific anatomical atlases, which are currently lacking in many parts of the country [22].

CONCLUSIONS

This study establishes that MRI-based sacral morphometry is a reliable, non-invasive, and highly accurate approach for sex estimation in forensic contexts. The sacral index, auricular surface width, and curvature index emerged as strong discriminators between male and female sacra in the Central Indian population. With a discriminant accuracy exceeding 85%, the morphometric models developed here offer practical utility for forensic anthropologists tasked with identifying unknown remains. Beyond forensic science, the study contributes valuable population-specific data with clinical applications in surgical planning, anesthetic access, and radiological interpretation. The results underscore the importance of regional anatomical variation in both forensic and clinical settings and advocate for greater integration of MRI in anthropometric research in India.

Future studies involving larger and more ethnically diverse Indian samples, as well as longitudinal imaging data, are recommended to further refine and validate these findings. Ultimately, this work highlights the dual value of sacral morphometry—supporting both legal justice and precision healthcare in a demographically complex society.

CONTRIBUTION OF AUTHORS

Research concept- Jitendra Kumar, Dr. Vimal Modi
Research design- Jitendra Kumar, Dr. Vimal Modi
Supervision- Dr. Vimal Modi
Materials- Jitendra Kumar, Dr. Vimal Modi
Data collection- Jitendra Kumar, Dr. Vimal Modi
Data analysis and Interpretation- Dr. Vimal Modi
Literature search- Jitendra Kumar, Dr. Vimal Modi
Writing article- Jitendra Kumar, Dr. Vimal Modi
Critical review- Dr. Vimal Modi
Article editing- Jitendra Kumar, Dr. Vimal Modi
Final approval- Dr. Vimal Modi

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