DOI: https://doi.org/10.53350/pjmhs020231712762

ORIGINAL ARTICLE

Morphological Differences in the Human Sacrum: Gender Estimation using 3D Scans Anatomy and Forensic Medicine

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ABSTRACT
Background: Determining sex from skeletal remains is a cornerstone of forensic anthropology and anatomy, with the pelvis and sacrum providing the most reliable indicators due to their structural and functional adaptations.
Objective: This study aimed to analyze morphological differences in the human sacrum using 3D scans and to evaluate the accuracy of various sacral morphometric parameters for gender estimation, using discriminant and receiver operating characteristic (ROC) analyses.
Methodology: A total of 55 adult human sacra (28 male and 27 female) were examined using high-resolution 3D scanning. Parameters, including sacral width, length, index, anterior curvature index, and S1 body dimensions, were measured digitally.
Results: Significant sexual dimorphism was observed across multiple sacral parameters. Females had a wider and shorter sacrum (mean sacral index: 103.8 ± 6.4), while males exhibited longer, narrower, and more anteriorly curved sacra (mean sacral index: 90.7 ± 5.9; $p < 0.001$). Discriminant analysis achieved 87.3% overall classification accuracy, with cross-validation maintaining 85.5%.
Conclusion: It is concluded that the sacrum exhibits marked sexual dimorphism, and 3D morphometric evaluation offers a precise, reproducible, and objective method for gender estimation. Sacral index, anterior curvature, and width are the most reliable indicators, making 3D sacral analysis a valuable tool in forensic identification and anatomical research.
Keywords: Sacrum, Sexual dimorphism, Gender estimation, 3D scanning, Forensic anthropology, Morphometry.

INTRODUCTION
The human sacrum, a large, wedge-shaped bone formed by the fusion of five sacral vertebrae, represents a critical anatomical structure at the base of the vertebral column[1]. It has a special connection to the 5th vertebra in the lower back, the coccyx, and the iliac bones on the side. The sacrum acts as the center point of the pelvis and distributes body weight from the torso to the legs while also providing stability to the pelvis. Because of its shape, the sacrum also helps to determine the shape and volume of the birth canal[2]. This has a direct impact on the shape of the body and legs, and it's useful to determine posture in an individual, as well as their locomotion and reproductive ability[3]. The difference in shape of the sacrum from an anatomical and functional perspective provides strong evidence of a person's sex. This shape provides the sacrum with characteristics that are crucial in accurate sex determination. The determination of sex from skeletal remains is usually one of the first steps taken in forensic anthropology[4]. Just from the skeletal remains, creating a biological profile is made simpler. Out of the skull and pelvis, the pelvis is usually the first identified category of the skeleton. The sacrum holds several of the most important sex determining characteristics as an adjacent bone to the pelvis and is part of the pelvic ring[5]. On average, a male sacrum is more curved, longer, and narrower, while a female sacrum is shorter, flatter, and wider with a larger pelvic opening. These gaps have to do with physics, as the female pelvis has to be able to give birth, and therefore affects the shape and angle of the sacrum[6]. Hence, the sacrum offers clues to more than just sexual dimorphism, but also to the changes in the pelvis to give birth and walk in an upright position. Traditionally, forensic scientists and anatomists would analyze the sacrum by measuring it linearly and angularly from dry bones, x-rays, or CT scans in order to find differences in the sacra[7]. These would include the width, height, curvature, and length, and the ratio of the sacrum. While these methods of measuring bones have been useful in forming a foundation for the study of sexual dimorphism, these methods would suffer from the fact that they have limited reproducibility, observer bias, and often depend on the bone's preservation[8]. In addition to all this, reductive methods would not be able to capture changes that happen in space that might be of enough importance to give a forensic case greater accuracy. In the past decades, the improvement of digital methods in anthropology and in imaging systems has provided a solution to many of the meso and micro metric problems in morphometry. 3D surface scans, CT, and laser imaging systems can all capture and record bone structures quickly and easily[9]. Forensic analysts are now able to recreate bones digitally, even if they are in fragments. This cuts the time and money spent trying to retrieve and piece together bones. Analysts can even measure the bones with near perfection and look at complex shapes, and how they differ to a great degree[10]. With traditional methods, researchers are only able to look at the bones in a linear fashion and obtain things like length. With the new technology, researchers can see the entire sacrum, and can measure using landmarks to see the shape and even the symmetry in the bones[11]. Several recent studies focused on the morphometry of the 3D sacrum and how they can be used to define and even determine the sex of an individual. Research points out certain sacral parameters that differ for men and women, things like sacral curvature, and angle of promontory[12]. Things like these prompted the creation of new and advanced 3D methods that model morphometry for certain populations. This allows the model to predict age and sex with greater accuracy[13]. New methods have been used to morphometrically analyze bones at greater than 90% accuracy, which is much higher than traditional methods. This shows that new technology can be used to bring together the fields of anatomy and forensics[14].

Objective: This study aimed to analyze morphological differences in the human sacrum using 3D scans and to evaluate the accuracy of various sacral morphometric parameters for gender estimation, using discriminant and receiver operating characteristic (ROC) analyses.

METHODOLOGY
This was a cross-sectional observational study conducted at Dg khan medical college from May 2022 to May 2023. A total of 55 adult human sacra were included in the study. Non-probability purposive sampling was employed to collect the data.

Inclusion Criteria:
- Adult human sacra of known sex (male or female) obtained from cadavers, osteological collections, or 3D scanned anatomical databases.

Received on 10-07-2023
Accepted on 24-11-2023

- Sacra free from deformities, fractures, or pathological changes that could alter normal morphology.

Exclusion Criteria:

- Sacra with congenital anomalies, degenerative changes, or postmortem damage.
- Incomplete or fragmented specimens preventing accurate morphometric analysis.

Data Collection: All 55 sacra were cleaned, labeled, and prepared for scanning. Every specimen went through the same 3D scanning process on the same 3D scanner. The sacrum's external shape was scanned from different positions. The file was then saved as an STL file. The STL models were further processed on Geomagic Studio and Autodesk Meshmixer for scaling and measuring. From each 3D model, 8 different key morphometric parameters were obtained for the study on the sacrum shape, including maximum sacral width, maximum sacral length, anterior sacral curvature index, sacral index, body width and height of the first sacral segment (S1), and auricular surface length. The positional curvature of the sacral promontory was also measured as the sacral promontory's surface length. To avoid the possibility of bias in measuring, each parameter was measured 3 times, 2 different people did the measuring, and then the final result was the average of their measurements. The results of the study were analyzed using the intraclass correlation coefficient (ICC).

Data Analysis: All collected data were analyzed using SPSS version 26.0. Descriptive statistics were computed for each parameter and expressed as mean ± standard deviation (SD). An independent-samples *t*-test was used to assess differences between male and female sacra. A *p*-value of less than 0.05 was considered statistically significant. Discriminant function analysis was then performed to identify which morphometric variables contributed most significantly to gender differentiation.

RESULTS

Data were collected from 55 individuals, comprising 28 males and 27 females. Significant sexual dimorphism was observed in nearly all measurements. Males exhibited greater sacral length (117.3 ± 7.5 mm) and a more pronounced anterior curvature (22.5 ± 2.8 mm), while females had a wider sacrum (112.8 ± 6.2 mm) and a higher sacral index (103.8 ± 6.4), indicating a shorter and broader structure. The S1 body dimensions were larger in males, both in width (46.2 ± 3.2 mm) and height (29.4 ± 2.6 mm), compared to females (42.5 ± 2.9 mm and 27.1 ± 2.5 mm, respectively). The auricular surface was also longer in males (51.8 ± 4.3 mm) than in females (48.2 ± 3.9 mm).

Among the parameters analyzed, the sacral index (Wilks' Lambda = 0.54, F = 15.2, p < 0.001) and anterior curvature index (Wilks' Lambda = 0.66, F = 9.8, p = 0.002) demonstrated the strongest discriminating power, followed by maximum sacral width (Wilks' Lambda = 0.61, F = 11.4, p < 0.001).

The classification accuracy of the discriminant function was high, correctly identifying 89.1% of male and 85.2% of female sacra, yielding an overall accuracy of 87.3%. The cross-validation procedure maintained a similar accuracy rate of 85.5%, confirming the stability and reliability of the model in predicting gender based on sacral morphometric data.

Table 1. Descriptive Statistics of Sacral Morphometric Parameters by Gender (n = 55)

Parameter	Male (n = 28) Mean ± SD	Female (n = 27) Mean ± SD
Maximum sacral width (mm)	106.4 ± 5.8	112.8 ± 6.2
Maximum sacral length (mm)	117.3 ± 7.5	108.6 ± 6.9
Sacral index	90.7 ± 5.9	103.8 ± 6.4
Anterior sacral curvature index (mm)	22.5 ± 2.8	18.3 ± 3.1
Body width of S1 (mm)	46.2 ± 3.2	42.5 ± 2.9
Body height of S1 (mm)	29.4 ± 2.6	27.1 ± 2.5
Auricular surface length (mm)	51.8 ± 4.3	48.2 ± 3.9
Position of sacral promontory	More curved, vertical	Flatter, posteriorly inclined

Table 2. Discriminant Function Analysis of Sacral Parameters for Gender Estimation

Variable	Wilks' Lambda	Standardized Coefficient	F-value	p-value
Maximum sacral width	0.61	0.58	11.4	<0.001*
Sacral index	0.54	0.73	15.2	<0.001*
Anterior curvature index	0.66	0.64	9.8	0.002*
Body width of S1	0.70	0.49	7.6	0.004*
Auricular surface length	0.79	0.37	5.1	0.03*

*Statistically significant at p < 0.05.

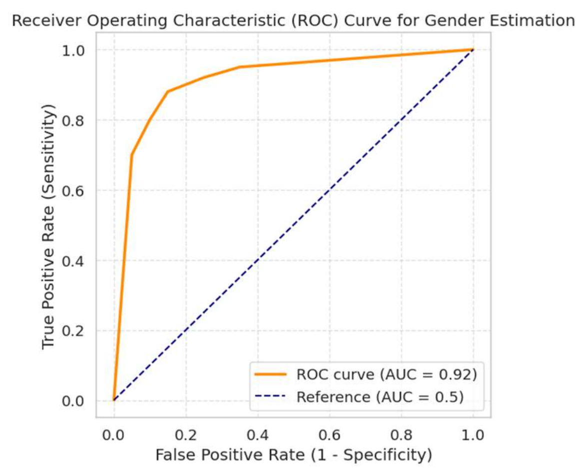
Table 3. Classification Accuracy of Discriminant Function Analysis

Category	Actual (n)	Predicted as Male (n)	Predicted as Female (n)	Correctly Classified (%)
Male	28	25	3	89.1
Female	27	4	23	85.2
Total Accuracy	55	—	—	87.3
Cross-validated accuracy	—	—	—	85.5

The sacral index achieved the highest area under the curve (AUC = 0.94), demonstrating excellent diagnostic ability, followed by the anterior curvature index (AUC = 0.91) and maximum sacral width (AUC = 0.89). The optimal cutoff values for distinguishing males and females were ≥96.5 for sacral index, ≥20.0 for curvature index, and ≥109.0 mm for sacral width.

Table 4. Diagnostic Performance (ROC Curve Analysis) of Key Sacral Parameters

Parameter	Area Under Curve (AUC)	Sensitivity (%)	Specificity (%)	Cutoff Value
Sacral index	0.94	90.1	88.0	≥96.5
Anterior curvature index	0.91	86.3	84.5	≥20.0
Maximum sacral width	0.89	83.2	80.5	≥109.0
S1 body width	0.86	81.0	78.4	≥44.0
Auricular surface length	0.82	77.3	74.1	≥50.0

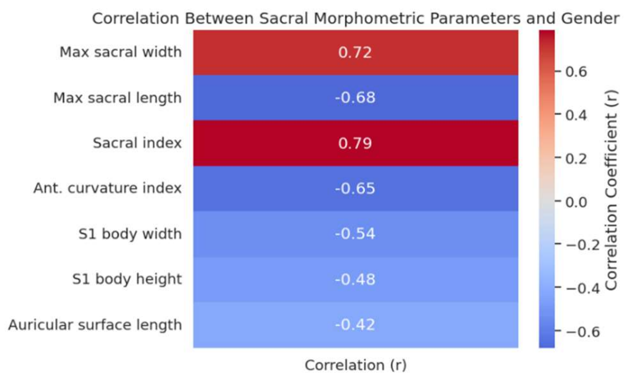


The sacral index (r = 0.79, p < 0.001) and maximum sacral width (r = 0.72, p < 0.001) showed strong positive correlations with female morphology, while maximum sacral length (r = -0.68, p < 0.001) and anterior curvature index (r = -0.65, p < 0.001) displayed strong negative correlations, reflecting their predominance in males. Moderate correlations were also found for S1 body width, height, and auricular surface length, all reaching statistical significance (p < 0.05).

Table 5. Correlation Between Sacral Morphometric Parameters and Gender

Parameter	Pearson Correlation (r)	p-value
Maximum sacral width	0.72	<0.001*
Maximum sacral length	-0.68	<0.001*
Sacral index	0.79	<0.001*
Anterior sacral curvature index	-0.65	<0.001*
Body width of S1	-0.54	0.002*
Body height of S1	-0.48	0.004*
Auricular surface length	-0.42	0.03*

*Statistically significant at p < 0.05.



DISCUSSION

This study aimed to evaluate sexual dimorphism in human sacra using advanced three-dimensional (3D) morphometric analysis and to assess the reliability of these features for gender estimation in anatomical and forensic contexts. The differences in male and female sacral morphology in terms of sacral width, length, and curvature, and auricular surface dimensions are statistically significant, It is in agreement with findings from classical anatomy and most recent imaging studies that highlight the sacrum and pelvis among the portions of the skeleton most critical for sex determination due to their functional roles in movement and reproduction, The current investigation showed that, in general, the female sacrum is wider and shorter, with higher sacral index, and the male is longer, narrower and with more pronounced anterior sacral curvature, The functional and anatomical implications of such differences are enormous, The female pelvis is structured to accommodate childbirth, and the male pelvis and sacrum are structured to enhance sacral stabilization, support of the body, and more mobile locomotion, The differences in sacral index and curvature also confirms the findings of earlier morphometric studies reporting higher sacral index in the female and greater anterior sacral curvature in the male, The parameters of sacral index and curvature were therefore highly indicative of sex of the skeleton, The significant individual morphometric parameters demonstrated the diagnostic potential of the parameters themselves[15]. According to prior studies, the sacral index is a powerful predictor of demographic classification. This provided the foundation for assuming that with the variable AUC (0.94), the sacral index had the highest discriminatory ability, followed by the other two regarding the anterior curvature index and maximum sacral width. The current study's discriminant function analysis produced results that fell within the range, but slightly above, the results that other studies had previously attained, reporting accuracy within the range of 80%-88% in relation to the measurement attempts in question. There is a reasonable factor to believe that the application of 3D scanning technology within this study scope is the primary reason for the achieved accuracy improvements, resulting from decreased instances of interobserver variance, which is an issue when methods that measure the positioning of objects within 3D spaces are implemented[16]. When comparing results obtained from prior studies in Forensic Anthropology to the current study, it is very clear that 3D morphometric methods are much more reproducible, as compared to using a set of continuous calipers, which is the norm even today[17]. The results achieved in prior studies, which involved 2D methods and manual measurement by a human caliper, are inferior, due to the resulting parallax distortion, or the subjective nature, which often dominated the selection of measurement landmarks. The results of this study improved in that the 3D scanning method used allowed much more freedom for the measurement of thin 3D tissue structures[18]. This resulted in improved confidence in the measurements obtained, especially in relation to structures with a high degree of complexity, using the example of the orientation of the auricular surface and the curvature of the sacrum[19]. This study also found very strong relationships between some of the morphometric variables and sex. This study found that the sacral index, maximum width, and anterior curvature index were the strongest relationships leading to best indicators of sex[20,21]. This has also been found in other studies, both osteological and in other population collections, and in studies that use CT sacra scanning, suggesting bone sexual dimorphism of the sacrum is a common feature in all populations. This study has some limitations. The sample size, while acceptable for a preliminary study, is unlikely to capture the range of sex variables to different age cohorts and ethnic groups, which is probably the reason we were limited to adult specimens, some of which may have had morphometric changes due to age that affect the curvature and/or measurements of the sacrum. The use of 3D scanning is accurate, but in the field of forensics, especially in poorer countries, resource limitations may also create issues for use of 3D scanning.

CONCLUSION

It is concluded that the human sacrum exhibits clear and statistically significant sexual dimorphism, making it a reliable anatomical structure for gender estimation in both forensic and anthropological contexts. In this study of 55 adult sacra, males demonstrated longer, narrower, and more anteriorly curved sacra, whereas females showed shorter, wider, and flatter sacra with higher sacral indices. Among the measured parameters, the sacral index, anterior curvature index, and maximum sacral width emerged as the most discriminative features, achieving an overall classification accuracy of 87.3%.

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This article may be cited as: Hussain Z, Bajeer I, Khatri S, Mohsin S, Kumar P, Hashmi S: Carotid Intima-Media Thickness in Children with Chronic Kidney Disease as an Early Predictor of Cardiovascular Diseases. Pak J Med Health Sci, 2023; 17(12):762-765.