



Original Article

Sacral Morphometry and Its Impact on Spinal Biomechanics: Key Findings from Cadaveric Study

Sarita Dixit^{1*}, Shashwat Singh², Garima Singh³, Hritwik Bhardwaj⁴

¹Assistant Professor, Department of Anatomy, F H Medical College, Agra, UP

²Post graduate, Department of Anatomy, Uttar Pradesh University of Medical Sciences, UP

³Associate Professor, Department of Forensic Medicine, S N Medical College, Agra, UP

⁴Post graduate, Department of Anatomy, Uttar Pradesh University of Medical Sciences, UP

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Corresponding Author:

Sarita Dixit

Assistant Professor, Department of
Anatomy, F H Medical College,
Agra, UP

Email: drsirudixit@gmail.com

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ABSTRACT

Introduction: Variations in sacral morphology can influence spinal biomechanics, surgical fixation techniques, and clinical outcomes. Detailed morphometric evaluation of the sacrum is essential for understanding its biomechanical significance and optimizing surgical interventions. This study aimed to assess the morphometric characteristics of adult human sacra and evaluate their potential impact on spinal biomechanics and lumbosacral load transmission. **Methods:** A descriptive cross-sectional cadaveric study was conducted on 30 dry adult human sacra obtained from the osteological collection. Intact sacra with identifiable anatomical landmarks were included. Various morphometric parameters including maximum sacral length, maximum sacral breadth, sacral index, dimensions of the sacral ala, auricular surfaces, sacral foramina, and S1 vertebral body were measured using a digital Vernier caliper and osteometric board. **Results:** The mean maximum sacral length and breadth were 105.8 ± 7.4 mm and 112.6 ± 8.1 mm, respectively. The mean sacral index was 106.5 ± 9.2 . Significant positive correlations were observed between sacral breadth and sacral index ($r = 0.782$, $p < 0.001$), as well as between sacral length and curved sacral length ($r = 0.731$, $p < 0.001$). Progressive reduction in the distance between successive pairs of sacral foramina was noted. **Conclusion:** Significant variations exist in sacral morphometric parameters that may influence spinal biomechanics and surgical instrumentation. Knowledge of these anatomical variations is important for preoperative planning, implant design, and improving the safety and effectiveness of lumbosacral fixation procedures.

Keywords: Sacrum; Sacral morphometry; Spinal biomechanics; Sacral index; Cadaveric study; Lumbosacral junction.

INTRODUCTION

The sacrum is a large triangular bone formed by the fusion of five sacral vertebrae and serves as a critical anatomical and biomechanical link between the vertebral column and the pelvis. Positioned at the base of the spine, it transmits axial loads from the trunk to the lower extremities and plays a pivotal role in maintaining sagittal balance, pelvic stability, and locomotion. Owing to its strategic location at the lumbosacral junction, the sacrum is subjected to substantial mechanical stresses during standing, walking, and lifting activities, making its morphology highly relevant to spinal biomechanics and clinical practice.¹ Recent anatomical and biomechanical investigations have highlighted considerable variability in sacral dimensions, orientation, and morphology among individuals, which may significantly influence load transmission patterns and spinal alignment.²

Sacral morphometry encompasses the quantitative assessment of various anatomical parameters, including sacral height, breadth, curvature, sacral index, dimensions of the sacral ala, pedicles, foramina, and auricular surfaces. These measurements are of immense clinical importance because they determine the feasibility and safety of surgical procedures such as sacroiliac fixation, lumbosacral fusion, trans-sacral screw placement, and pelvic stabilization surgeries. Variations

in sacral anatomy can alter the dimensions of osseous corridors available for instrumentation and increase the risk of neurovascular injury during operative interventions.³

From a biomechanical perspective, the sacrum functions as the keystone of the pelvic ring, distributing forces between the vertebral column and lower limbs. Morphological variations such as differences in sacral curvature, sacral inclination, and sacral width can influence spinopelvic parameters including pelvic incidence, sacral slope, and lumbar lordosis.⁴ These parameters are recognized determinants of spinal alignment and are associated with the development of degenerative spinal disorders, low back pain, and sagittal imbalance.⁵

Cadaveric studies remain the gold standard for morphometric analysis because they allow direct measurement of bony landmarks without the limitations associated with imaging modalities. Such investigations provide accurate baseline anatomical data that can be utilized for surgical planning, implant design, and biomechanical modeling.⁶

The growing prevalence of spinal disorders and pelvic injuries has further underscored the importance of understanding the relationship between sacral morphology and biomechanics. Anatomical variations, including sacralization, lumbarization, atypical foramina, and differences in auricular surface morphology, may alter force distribution across the lumbosacral junction and contribute to biomechanical instability.^{7,8} Therefore, comprehensive morphometric evaluation of the sacrum is essential for enhancing our understanding of spinal biomechanics and for improving the safety and efficacy of surgical interventions.

MATERIALS AND METHODS

Study Design & Setting

This descriptive cross-sectional cadaveric study was conducted in the Department of Anatomy of a tertiary care teaching institution over a period of 2 years. The study aimed to evaluate various morphometric parameters of the human sacrum and assess their potential implications on spinal biomechanics. Measurements were performed on dry adult human sacra obtained from the departmental bone repository. A total of 30 dry adult human sacra of unknown age and sex were included in the study based on convenient sampling technique method. The bones were collected from the osteological archives of the department and were presumed to belong to the adult population based on complete fusion of sacral vertebrae.

Inclusion Criteria

- Intact dry adult human sacra.
- Sacra with complete fusion of all sacral vertebrae.
- Bones free from gross deformities and pathological lesions.
- Sacra with clearly identifiable anatomical landmarks.

Exclusion Criteria

- Damaged or fractured sacra.
- Sacra exhibiting congenital anomalies such as severe sacralization or lumbarization.
- Bones with evidence of pathological changes, erosion, or deformity affecting measurements.
- Incomplete specimens with missing anatomical landmarks.

Study Variables

Primary Morphometric Parameters:

The following measurements were recorded:

- Maximum Sacral Length (MSL)
- Maximum Sacral Breadth (MSB)
- Sacral Index (SI)
- Length of Sacral Ala (Right and Left)
- Width of Sacral Ala (Right and Left)
- Transverse Diameter of Superior Surface of S1
- Anteroposterior Diameter of S1 Body
- Length and Width of Auricular Surface
- Distance between Sacral Foraminal Pairs
- Curved Length of Sacrum
- Straight Length of Sacrum

Derived Parameter

Sacral Index (SI): Sacral Index was calculated using the formula:

$$\text{Sacral Index} = (\text{Maximum Sacral Breadth} / \text{Maximum Sacral Length}) \times 100$$

Higher sacral indices indicate a broader sacrum, while lower indices indicate a relatively longer sacrum.

Instruments Used

- Digital Vernier Caliper (accuracy ± 0.01 mm)
- Osteometric Board
- Flexible Measuring Tape
- Measuring Scale
- Data Recording Sheets

Method of Data Collection

Each sacrum was assigned a unique identification number. The specimen was placed on a flat horizontal surface in the anatomical position. Morphometric parameters were measured according to standard osteometric techniques. Maximum sacral length was measured from the midpoint of the sacral promontory to the midpoint of the apex of the sacrum. Maximum breadth was measured across the widest part of the ala. Measurements were repeated three times, and the mean value was considered for analysis. Special attention was paid to dimensions influencing lumbo-sacral biomechanics, including sacral curvature, sacral breadth, and dimensions of the first sacral vertebral body. These parameters are known to affect force transmission, pelvic incidence, and sagittal spinal alignment.

Bio mechanical Correlation

The recorded morphometric parameters were analyzed in relation to established biomechanical concepts of the lumbosacral junction. Parameters such as sacral breadth, sacral index, and sacral curvature were evaluated for their potential influence on:

- Load transmission between the spine and pelvis.
- Pelvic stability.
- Sacroiliac joint biomechanics.
- Lumbosacral alignment.
- Surgical fixation corridors for lumbosacral instrumentation.

The biomechanical implications were interpreted using published anatomical and biomechanical literature.

Quality Control

To reduce measurement bias:

- All measurements were performed under identical laboratory conditions.
- Each parameter was measured three times.
- Mean values were used for analysis.
- Calibration of instruments was performed before data collection.

Statistical Analysis

Data were entered into Microsoft Excel and analyzed using Statistical Package for Social Sciences (SPSS) version 21.0. Descriptive statistics were expressed as mean, standard deviation, minimum and maximum values. Continuous variables were presented as mean \pm SD. Pearson's correlation coefficient was used to assess relationships among morphometric parameters. A p-value of less than 0.05 was considered statistically significant.

RESULTS

A total of 30 dry adult human sacra were examined for various morphometric parameters relevant to spinal biomechanics. All specimens met the inclusion criteria and were included in the final analysis.

Table 1. Descriptive Statistics of Sacral Morphometric Parameters (n=30)

<i>Parameter</i>	<i>Mean \pm SD</i>	<i>Minimum</i>	<i>Maximum</i>
<i>Maximum Sacral Length (mm)</i>	105.8 \pm 7.4	92.4	118.5
<i>Maximum Sacral Breadth (mm)</i>	112.6 \pm 8.1	98.7	126.8
<i>Sacral Index</i>	106.5 \pm 9.2	89.4	122.1
<i>Curved Length of Sacrum (mm)</i>	112.3 \pm 8.6	98.2	127.4
<i>Length of Right Ala (mm)</i>	33.7 \pm 3.2	27.9	39.8
<i>Length of Left Ala (mm)</i>	34.1 \pm 3.5	28.1	40.6
<i>Width of Right Ala (mm)</i>	28.6 \pm 2.8	23.5	34.2
<i>Width of Left Ala (mm)</i>	28.9 \pm 2.9	23.9	34.8
<i>AP Diameter of S1 Body (mm)</i>	29.4 \pm 2.7	24.5	35.1
<i>Transverse Diameter of S1 Body (mm)</i>	46.8 \pm 3.9	39.2	54.3

The mean maximum sacral breadth (112.6 ± 8.1 mm) was greater than the mean sacral length (105.8 ± 7.4 mm), resulting in a mean sacral index of 106.5 ± 9.2 .

Table 2. Measurements of Auricular Surface and Sacral Foramina

<i>Parameter</i>	<i>Mean \pm SD (mm)</i>
<i>Length of Right Auricular Surface</i>	56.3 ± 4.5
<i>Length of Left Auricular Surface</i>	56.9 ± 4.7
<i>Width of Right Auricular Surface</i>	31.8 ± 3.2
<i>Width of Left Auricular Surface</i>	32.1 ± 3.0
<i>Distance Between First Pair of Sacral Foramina</i>	28.4 ± 2.6
<i>Distance Between Second Pair of Sacral Foramina</i>	25.6 ± 2.4
<i>Distance Between Third Pair of Sacral Foramina</i>	22.8 ± 2.1
<i>Distance Between Fourth Pair of Sacral Foramina</i>	19.3 ± 1.9

A progressive decrease in interforaminal distance was observed from the first to the fourth pair of sacral foramina.

Table 3. Correlation Between Sacral Dimensions and Biomechanically Relevant Parameters

<i>Variables Compared</i>	<i>Correlation Coefficient (r)</i>	<i>p-value</i>
<i>Sacral Breadth vs Sacral Index</i>	0.782	<0.001*
<i>Sacral Length vs Curved Length</i>	0.731	<0.001*
<i>Sacral Breadth vs AP Diameter of S1</i>	0.526	0.003*
<i>Sacral Index vs Auricular Surface Length</i>	0.418	0.021*

*Statistically significant ($p < 0.05$)

Strong positive correlations were observed between sacral breadth and sacral index ($r=0.782$), suggesting that wider sacra tend to possess higher sacral indices. Significant correlations were also noted between sacral length and curved length. Distribution of Sacral Index

Based on sacral index values, specimens were categorized into three groups.

Table 4. Distribution of Sacra According to Sacral Index

<i>Sacral Index Category</i>	<i>Number</i>	<i>Percent (%)</i>
<i><100</i>	7	23.3%
<i>100–110</i>	14	46.7%
<i>>110</i>	9	30.0%
<i>Total</i>	30	100%

Nearly half of the specimens (46.7%) exhibited a sacral index between 100 and 110.

Biomechanical Implications

Morphometric evaluation demonstrated substantial variation in sacral dimensions among specimens. Sacra with higher breadth and sacral index values showed larger dimensions of the S1 vertebral body and auricular surfaces, indicating enhanced load-bearing potential and greater surface area for force transmission through the sacroiliac joints.

Specimens exhibiting increased sacral curvature also demonstrated greater curved lengths, suggesting a possible influence on lumbosacral alignment and sagittal balance. The dimensions of the first sacral vertebral body were found to be adequate for lumbosacral fixation in the majority of specimens.

DISCUSSION

In the present study, the mean maximum sacral length and breadth were 105.8 ± 7.4 mm and 112.6 ± 8.1 mm, respectively. Similar findings have been reported by Banik et al.³ who observed substantial variation in sacral dimensions among Indian subjects and emphasized the importance of morphometric data for spinal fixation procedures. Likewise, Lottering et al.⁹ demonstrated that sacral morphology varies considerably across populations, highlighting the need for population-specific anatomical databases.

The mean sacral index observed in the present study was 106.5 ± 9.2 . Nearly half of the specimens exhibited sacral index values between 100 and 110, indicating predominance of relatively broad sacra. Sacral index is considered an important

anthropometric parameter and has implications for force distribution across the lumbo-sacral junction. Studies by Wagner et al.⁴ have shown that broader sacra provide larger osseous corridors for trans-sacral fixation and may contribute to improved biomechanical stability during load transmission.

A significant positive correlation was observed between sacral breadth and sacral index ($r = 0.782$, $p < 0.001$). This finding supports the concept that increased transverse dimensions enhance the weight-bearing capacity of the sacrum. Similar observations have been reported by Park et al.⁷ who demonstrated that sacral morphology directly influences the dimensions of fixation pathways and the biomechanical behavior of the pelvic ring.

The dimensions of the first sacral vertebral body measured in this study were consistent with values reported in previous anatomical investigations.¹ The S1 vertebral body is the primary anchor point for lumbosacral instrumentation and bears a significant proportion of axial load transferred from the lumbar spine. Therefore, adequate dimensions of the S1 body are essential for secure pedicle screw fixation and successful spinal fusion procedures.

The present study also demonstrated a progressive reduction in the distance between successive pairs of sacral foramina. This observation is in agreement with findings reported by Farhat and Priyanka⁶ who emphasized the importance of foraminal morphology during sacral screw placement and sacral nerve preservation. Knowledge of these anatomical relationships is critical for minimizing neurovascular complications during sacropelvic fixation procedures.

The auricular surface dimensions observed in the present study suggest substantial articular contact between the sacrum and ilium. Previous biomechanical studies have indicated that larger auricular surfaces facilitate more efficient force transmission through the sacroiliac joints and contribute to pelvic stability^{10,4} Furthermore, variations in sacral curvature may influence lumbar lordosis, pelvic incidence, and overall sagittal alignment, factors that have been associated with chronic low back pain and degenerative spinal disorders.⁵

Recommendations

1. **Detailed preoperative assessment of sacral morphology** should be performed before lumbosacral and sacropelvic fixation procedures to minimize surgical complications and improve implant placement accuracy.
2. **Population-specific morphometric databases** of the sacrum should be developed, as anatomical variations may influence surgical planning, spinal instrumentation, and biomechanical outcomes.
3. **Advanced imaging techniques** such as three-dimensional computed tomography (3D-CT) and magnetic resonance imaging (MRI) should be utilized alongside cadaveric studies to provide comprehensive anatomical information for clinical applications.

Limitations

1. The study was conducted on a relatively small sample size of 30 dry adult human sacra, which may limit the generalizability of the findings.
2. The sex and age of the specimens were unknown; therefore, sex-specific and age-related variations in sacral morphology could not be evaluated.
3. As the study was based on dry bones, the influence of surrounding soft tissues, ligaments, intervertebral discs, and muscles on spinal biomechanics could not be assessed.
4. Direct biomechanical testing was not performed. The biomechanical implications were inferred from anatomical measurements and existing literature.

CONCLUSION

The present cadaveric study highlights significant variations in sacral morphometric parameters that influence spinal biomechanics and load transmission across the lumbosacral junction. Understanding these anatomical variations is essential for surgical planning, sacropelvic fixation, implant design, and improving clinical outcomes in the management of spinal and pelvic disorders.

Conflict of Interest: None

Source of Funding: None

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