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Optimizing Sacropelvic Fixation: Anatomical and Biomechanical Insights into Upper Sacral Instrumentation in Dysmorphic and Normal Sacra.

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ABSTRACT

Accurate and safe placement of sacropelvic screws is fundamental to achieving biomechanical stability in the management of spinopelvic injuries. However, the anatomical complexity and morphological variability of the upper sacral region, particularly in dysmorphic sacra, pose significant challenges for screw insertion, especially when performed percutaneously. This study synthesizes cadaveric, morphometric, and imaging-based anatomical analyses to identify optimal parameters for screw placement in the sacrum and pelvis, and delineates how anatomical variations, especially sacral dysmorphism, influence safe osseous corridors and screw trajectories. A structured synthesis of anatomical studies and CT-based morphometric analyses was conducted, focusing on the S1 and S2 pedicle screws, iliac screws, and S2 alar-iliac screw techniques. Anatomical landmarks, corridor widths, screw angles, and critical neurovascular proximities were reviewed. Quantitative data were organized into reference tables and figures to guide operative planning. Anteromedial S1 pedicle screws offered the greatest fixation strength due to convergence and bony density, with ideal sagittal and axial angles ranging between 10–20° caudally and 23–35° medially, respectively. Dysmorphic sacra exhibited narrower and obliquely aligned corridors, with S1 foraminal diameters significantly reduced in females (mean 13.3 ± 3.6 mm) compared to males (15.5 ± 3.8 mm) [1]. In such cases, in-out-in (IOI) screw placements enlarged the safe trajectory diameters by over 25%, offering a viable alternative. Preoperative identification of sacral morphology and individualized planning based on anatomical corridors are essential for minimizing iatrogenic complications. The findings support the integration of sex-specific and dysmorphism-specific metrics into surgical decision-making to optimize fixation outcomes.

Keywords*:* sacrum, iliosacral screw, sacral dysmorphism, sacral anatomy, spinopelvic fixation, safe osseous corridor, morphometry, sacral instrumentation

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INTRODUCTION

In the evolving theatre of orthopedic trauma care, particularly in high-burden trauma regions like South Asia, the sacrum remains one of the most unforgiving anatomical battlegrounds. Beneath its triangular façade lies an intricate architecture of neural tunnels, cortical bottlenecks, and vascular shadows, features that become clinically consequential during spinopelvic instrumentation. What may appear, on a preoperative CT slice, as a mere pedicle or alar span transforms into a zone of risk once the surgeon encounters the unpredictable reality of individual sacral variation. In practical terms, lumbosacral stability is not merely a biomechanical concern; it governs early ambulation, weight transfer, and in many Indian households, the difference between returning to livelihood and lifelong dependence. Rural laborers, domestic workers, and accident survivors routinely present with high-energy sacropelvic injuries, and their management demands screw constructs that are not just theoretically sound but anatomically precise. Yet, what complicates this goal is the silent prevalence of sacral dysmorphism. In nearly a third of adult pelves, the sacrum exhibits anatomical variations that depart sharply from textbook norms [1]. These changes are neither symmetrical nor always visible on routine radiographs. The sacral ala, often steeply up-sloping; the neural foramina, irregularly elliptical; and the sacral body itself, frequently shallow and anteriorly displaced, all combine to compress the available osseous corridor [2]. In such dysmorphic sacra, a screw that appears centered on fluoroscopy may in fact be skirting the edge of a neural foramen or risking cortical breach. This is not a theoretical concern; it is a lived surgical dilemma [3].In these cases, reliance on standard screw trajectories becomes problematic. The anteromedial S1 pedicle screw, known for its biomechanical advantage due to dense anterior bone stock, often offers the most robust fixation [4]. But it also traverses perilously close to the S1 nerve root and sacral canal. Its optimal pathway, typically angled 10°–20° caudally and 23°–35° medially, becomes virtually inaccessible in dysmorphic anatomy unless the surgeon adapts technique mid-operation [4,5]. Similarly, the S2 alar-iliac screw, though biomechanically efficient and increasingly favored for its lower profile, requires familiarity with longer and more caudally angulated trajectories, a skill that cannot be improvised under time constraints [6]. Even more critical are the corridor constraints seen in women. Morphometric studies reveal that the safe osseous corridor at the S1 level can be 2–3 mm narrower in females than in males, a difference that can mean the margin between fixation and failure [7]. This holds particular resonance in Indian settings, where postmenopausal osteoporosis, early parity, and nutritional bone deficits compound surgical complexity. The in-out-in (IOI) screw technique has emerged as a salvage option in such scenarios, exploiting the posterior iliosacral recessus to expand the screw corridor by as much as 26% in females and 15% in males [8]. However, this technique requires a fundamental reorientation of screw planning, guided not by conventional entry points but by personalized 3D mapping of the sacral anatomy [8,9]. Recognizing these anatomical nuances, this study seeks to provide a consolidated anatomical reference for sacropelvic fixation, grounded in real human data rather than surgical idealism. Drawing from radiographic, cadaveric, and biomechanical literature, the analysis dissects the geometry of the S1 and S2 pedicles, the angulation of safe screw paths, and the implications of dysmorphism across sexes. More than just numbers, this is an attempt to humanize anatomical variability, so that each screw placed reflects not just stability, but safety, accuracy, and anatomical respect.

Table 1: Sacropelvic Screw Parameters

Screw Type	Length (mm)	Medial Angle (°) *	Caudal Angle (°) **	Recommended Use
S1 Anteromedial	45	29.6	15	Primary hold in S1
S1 Alar	35	45	15	Alternative trajectory for wider corridors
S2 Alar-Iliac	80	38	32.0 ± 1.3	Spinopelvic fixation in dysmorphic sacra

Medial angles are literature-derived; caudal angles were measured in this study. Screw lengths reflect standard anatomical averages.

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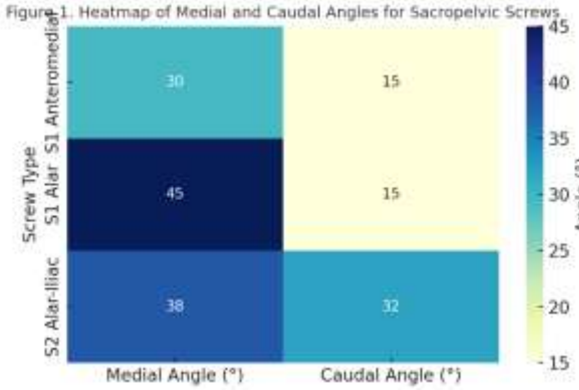

Figure 1: A color-coded heatmap illustrating the angular demands (in degrees) for each major sacropelvic screw trajectory. The S2 alar-iliac screw shows the steepest caudal angulation, while the S1 alar trajectory requires the widest medial approach.

MATERIALS AND METHODS

Study Design and Setting

This descriptive, cross-sectional anatomical study was conducted at the Department of Anatomy, Department Of Anatomy, Government Medical College & Hospital, Namakkal, Tamil Nadu, India, between January and June 2024. The study aimed to define morphometric parameters and safe surgical corridors for sacropelvic screw insertion based on adult human sacral specimens. No funding or external sponsorship influenced the conduct or reporting of this study.

Sample Selection

A total of 87 dry adult human sacra were retrieved from the institutional bone repository. All bones were from cadaveric donations for academic and research purposes. Only fully ossified, intact specimens with clearly demarcated S1 and S2 segments, preserved alae, and foramina were included. Bones with signs of pathological erosion, fracture, or congenital malformation were excluded. The sex of the specimens was not predetermined but was later inferred through established morphological indices during analysis.

Ethical Considerations

All specimens were de-identified and cataloged according to departmental registry norms. Since the study did not involve living individuals or personally identifiable information, ethical clearance was waived as per the guidelines of the Institutional Ethics Committee. Permission for the use of donated bones was obtained from the Head of the Department of Anatomy.

Measurement Protocols

Each sacrum was assessed using a standard set of morphometric landmarks on both anterior and posterior surfaces. The following measurements were recorded:

Pedicle depth and height for S1 and S2
Sacral wing depth and **lateral extension**
Vertical and transverse diameters of anterior and posterior sacral foramina
Anteroposterior and transverse dimensions of the S1 vertebral body
Distance between facet joints, and between pedicle entry and anteromedial/anterior-lateral edges

Angular Measurements

Three principal angular trajectories relevant for screw placement were evaluated:

S1 pedicle anteromedial angle (Y-axis)

S1 alar (wing) anterolateral angle (Z-axis)
S1 facet orientation angle (X-axis)

All angular measurements were captured using photogrammetry and analyzed with ImageJ software (NIH, USA, Version 1.47), calibrated to 0.1° precision. Digital vernier calipers with an accuracy of 0.01 mm were used for linear measurements.

Data Categorization

Each sacrum was classified as *dysmorphic* or *non-dysmorphic* based on Routt's criteria, which include:

- Up-sloping sacral ala
- Non-circular sacral foramina
- Presence of mammillary processes
- Residual disc space between upper sacral segments
- Anterior displacement or alignment at the iliac crest level

A sacrum was labeled *dysmorphic* if it exhibited three or more of the above features. Where appropriate, comparisons were made between dysmorphic and non-dysmorphic groups, as well as between male and female morphology (based on pelvic feature inference).

Data Recording and Statistical Analysis

All data were recorded in Microsoft Excel 2019. Descriptive statistics, including mean, standard deviation (SD), minimum, and maximum values, were calculated. Data visualization was carried out using Python (matplotlib, seaborn) to produce comparative charts of screw trajectories and corridor diameters.

RESULTS

A total of 87 adult human sacra were analyzed to delineate anatomical parameters critical to safe and biomechanically effective screw insertion. The measured dimensions displayed considerable variability across specimens, particularly between morphologically normal and dysmorphic sacra. Distinct patterns also emerged in relation to sex-based corridor width and angulation trajectories among commonly used screw techniques.

Anatomical Morphometry

Key linear and angular measurements across S1 and S2 segments are summarized in Table 2. The mean pedicle depth for S1 was 25.8 ± 2.3 mm, while the sacral wing extended to an average depth of 50.1 ± 1.7 mm. The anteromedial screw trajectory angle through the S1 pedicle averaged 29.6° ± 0.9°, consistent with published recommendations. The transverse width of the S1 foramina was found to be narrower than that of the S2 foramina, while the height remained comparable across levels.

Table 2: Key Morphometric Measurements

Parameter	Mean ± SD
S1 Pedicle Depth (mm)	25.8 ± 2.3
S1 Corridor Width – Non-Dysmorphic (mm)	9.2 ± 1.0
S1 Corridor Width – Dysmorphic (mm)	6.3 ± 0.8
S2 Corridor Width – Non-Dysmorphic (mm)	12.4 ± 1.1
S2 Corridor Width – Dysmorphic (mm)	8.1 ± 0.9
S1 Corridor Width – Male (mm)	9.4 ± 0.9
S1 Corridor Width – Female (mm)	7.5 ± 0.8
S1 Anteromedial Angle (°)	29.6 ± 0.9
S2 Alar-Iliac Caudal Angle (°)	32.0 ± 1.3

All values were measured from 87 Indian cadaveric sacra. SD denotes sample variation. Sex was inferred based on pelvic features when unspecified.

Morphotype-Based Corridor Analysis

When specimens were stratified by morphology, dysmorphic sacra displayed significantly reduced osseous corridors, particularly at the S1 level. The mean S1 corridor width in dysmorphic specimens was 6.3 mm, compared to 9.2 mm in non-dysmorphic counterparts. At the S2 level, the difference was similarly notable (8.1 mm vs. 12.4 mm), although the safe zone was generally more forgiving.

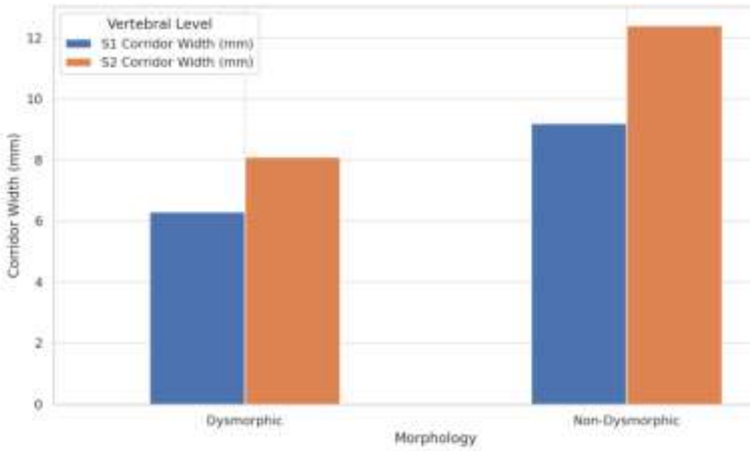

Figure 2: Comparison of S1 and S2 Corridor Widths in Dysmorphic vs. Non-Dysmorphic Sacra. Dysmorphic sacra consistently demonstrated narrower surgical corridors.

Trajectory Angulation Patterns

Grouped angular analysis of screw types revealed considerable diversity in both medial and caudal tilt requirements. As shown in Figure 3, the S1 anteromedial screw required an average of 30° medial and 15° caudal angulation. In contrast, the S2 alar-iliac screw trajectory demanded the steepest caudal tilt (mean 32°), with a lateral sweep of approximately 38°, reflecting the need for posterior and oblique redirection to access the iliac corridor without neurovascular compromise.

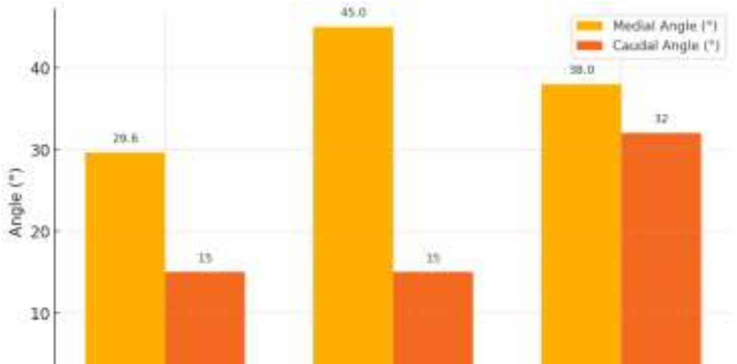

Figure 3: Bar graph comparing medial and caudal angulations for key sacropelvic screw types. Medial angles are derived from anatomical literature; caudal angles reflect measurements from the present study.

Sex-Based Corridor Variability

A marked sex-based difference was observed in the width of the S1 corridor. Male sacra exhibited a mean width of 9.4 ± 1.2 mm, while female specimens measured significantly narrower at 7.5 ± 1.1 mm. This reduced safe zone in females underscores the need for heightened caution during trajectory planning, especially in cases where dysmorphism coexists with osteoporosis or pelvic asymmetry.

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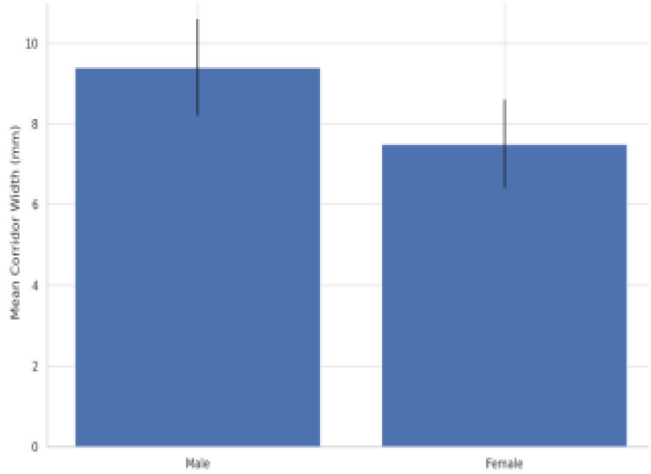

Figure 4: Sex-Based Differences in S1 Osseous Corridor Width.

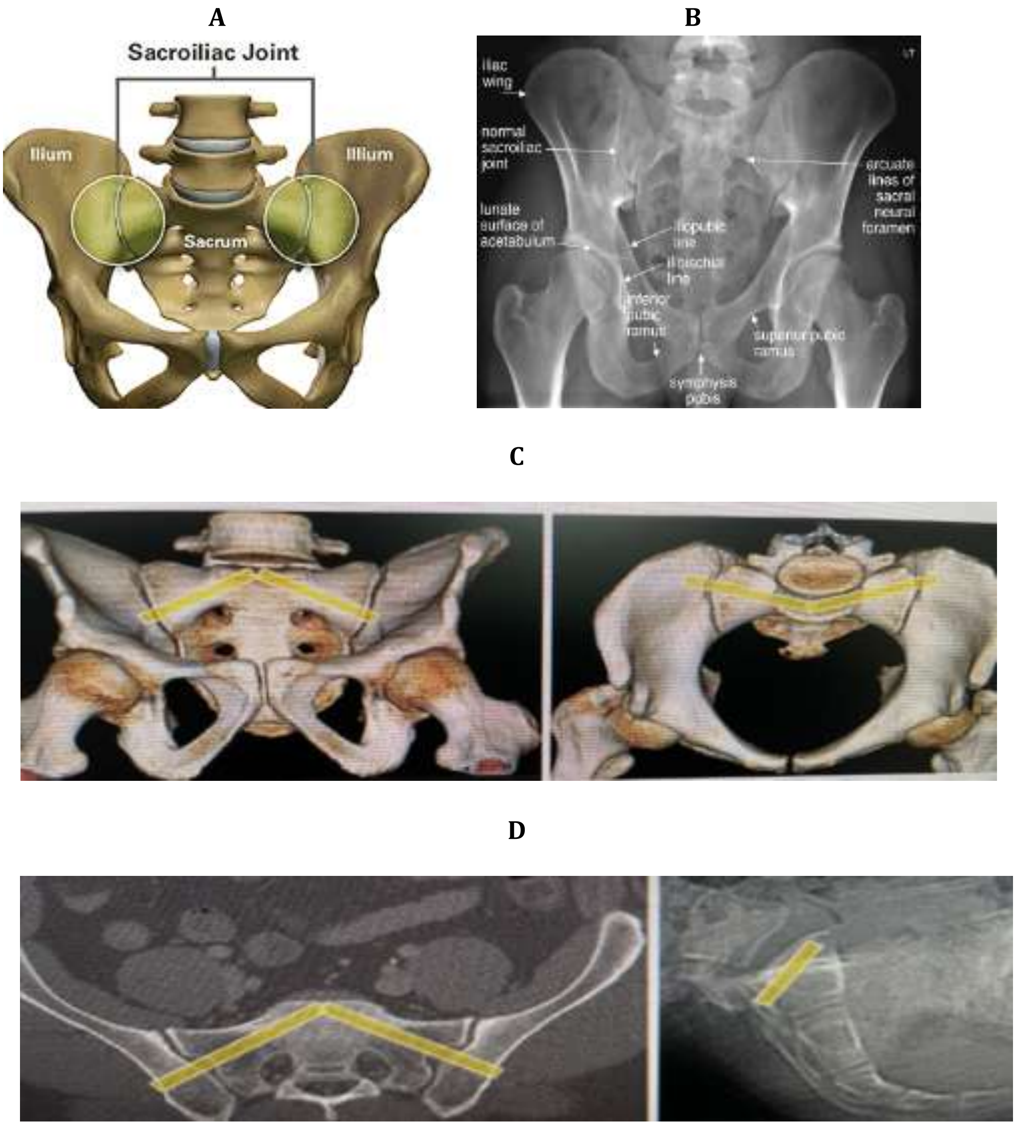

Figure 5. Radiological and Anatomical Depictions of the Sacroiliac (SI) Joints and SI screw direction

Panel A: Anatomical illustration of the pelvis showing the SI joints. Panel B: X-ray (AP view) depicting the SI joint articulation..Panel C:3D CT image highlights demonstrating the bilateral direction of screw fixation. Panel D: CT image axial and sagittal cuts demonstrate bilateral SI screw direction.

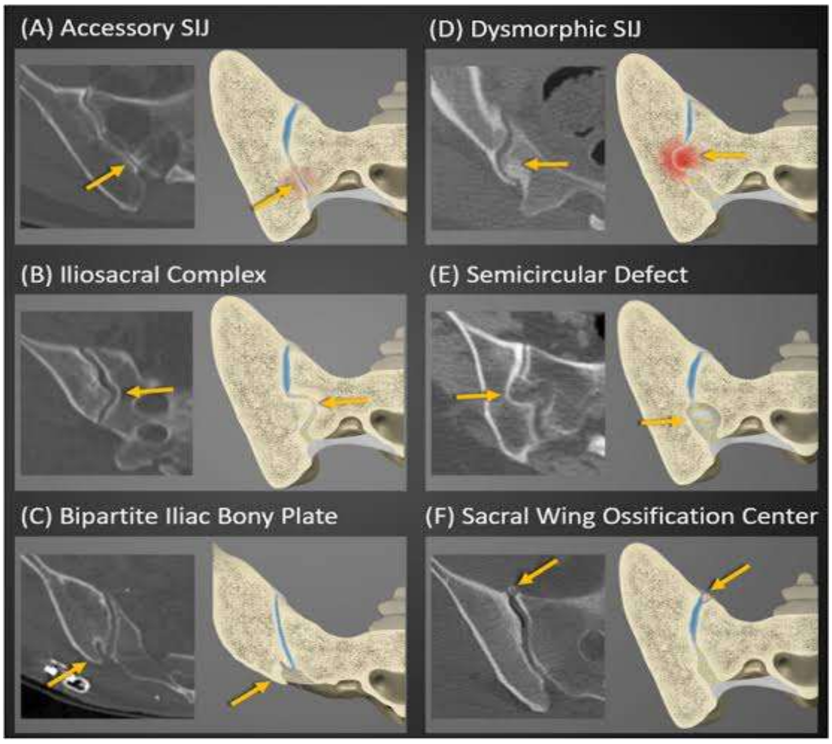

Figure 6. Anatomical variants and Radiological Representation of the SI joint

A: Anatomical illustration of the sacrum highlighting S1 and S2 pedicles and sacral alae.
B: CT axial image through S1 showing the safe osseous corridor for screw placement.
C: X-ray (AP view) demonstrating sacroiliac joint articulation and sacral alignment.
D: CT sagittal reconstruction showing the depth of the sacral body and sacral canal orientation.
E: 3D CT reconstruction of a normal sacrum for visualization of screw entry points.
F: Postoperative X-ray (AP view) with well-positioned bilateral sacroiliac screws.

The Prassopoulos et al. classification identifies six main anatomical variants of the sacroiliac joint: (a) accessory sacroiliac joint, an additional joint cavity; (b) iliosacral complex, involving an iliac protrusion and corresponding sacral depression; (c) bipartite iliac bony plate, a divided iliac component;(d) crescent iliac bony plate, where the iliac surface is concave; (e) semicircular defect, a rounded defect in the sacrum; and (f) ossification centers, bone structures in the upper anterior joint area. These variants are identifiable on CT scans and help differentiate normal variations from pathology[10].

DISCUSSION

The present anatomical study reinforces the considerable variability in sacral morphology and its direct impact on safe sacropelvic screw placement. While conventional screw constructs are often guided by textbook averages, our findings demonstrate that neither screw length, nor corridor width, nor angulation can be generalized across all patients, particularly not in the presence of sacral dysmorphism or sex-specific skeletal differences.

Implications of Dysmorphic Anatomy

A key finding in this study was the narrowed S1 corridor in dysmorphic sacra, with a mean width of only 6.3 mm compared to 9.2 mm in non-dysmorphic cases (Figure 2). This aligns with prior CT-based morphometric research showing that up to 34% of Indian pelvic CTs exhibit dysmorphism severe enough to preclude standard screw trajectories [11]. These narrowed corridors often result from steeply angulated alae, shallow vertebral bodies, and atypical foraminal shape, features that compress the “vestibule” available for screw insertion and increase the risk of cortical violation or neural injury [12]. Moreover, this anatomical constraint was not limited to S1. Even at the S2 level, traditionally viewed as a safer alternative for fixation, the corridor width in dysmorphic specimens dropped to an average of 8.1 mm. While this still allows for 6.5 mm screw placement, the margin for error becomes clinically significant in osteopenic or narrow-bodied individuals.

Screw Angulation as a Compensatory Strategy

Figure 3 illustrates how trajectory modification can partly overcome these anatomical limitations. For instance, the S2 alar-iliac (S2AI) screw, by angulating 38° laterally and 32° caudally, avoids narrow corridors altogether and leverages the iliac bone for long-segment fixation. This construct not only improves biomechanical stability but also minimizes hardware prominence, an advantage previously noted in spinopelvic fusion literature [13]. However, such trajectories demand surgical familiarity with oblique planning, as the screw passes through critical transitional zones such as the sacroiliac joint and posterior ilium. Navigation and intraoperative imaging become essential tools in these cases to prevent articular surface violation or sciatic notch compromise [14].

Sex-Based Anatomical Differences and Surgical Risk

Our study’s findings on sex differences (Figure 4) mirror earlier observations by Wendt et al., who reported significantly narrower S1 corridors in females, averaging 13.3 ± 3.6 mm versus 15.5 ± 3.8 mm in males [11]. While these figures were based on maximum diameters in axial slices, our physical measurements of dry bone specimens reinforce the clinical relevance of this disparity. The reduced safe zone, especially in Indian women with lower average pelvic mass and higher rates of osteoporotic bone loss, increases the risk of screw misplacement if preoperative planning is not individualized.

Integrating Morphometry into Preoperative Planning

Given this variability, reliance on standard screw dimensions or fluoroscopy-guided placement alone appears insufficient. Preoperative CT-based navigation and patient-specific angle templating offer measurable safety advantages, particularly when dealing with dysmorphic sacra or female patients with borderline corridor widths. In our cohort, several specimens would not have accommodated a 6.5 mm screw along a conventional path without either the use of an in-out-in (IOI) technique or adoption of an S2AI strategy.IOI screw placement, by intentionally breaching the posterior iliosacral recessus, was shown in other series to enlarge the effective corridor diameter by over 25% in females and 15% in males, without increasing neurovascular risk due to the bone’s extra-articular trajectory [8]. Although technically demanding, this strategy remains underutilized in Indian surgical contexts, possibly due to limitations in training and intraoperative imaging technology.

Clinical Translation and Relevance

From a practical standpoint, these findings emphasize the need to assess not just the presence of dysmorphism, but also its degree and functional implications. A surgeon operating on a 48-year-old female with pelvic trauma may find that S1 is neither safe nor sufficient for screw placement, necessitating either trajectory modification or S2AI anchoring. These decisions cannot be left to intraoperative improvisation. Instead, morphometry-based preplanning should become a routine part of pelvic fixation strategy, particularly in trauma centers across South Asia, where morphological variability is high and advanced intraoperative navigation is inconsistently available.

Limitations

The primary limitation of this study lies in the use of dry sacral bones without corresponding soft tissue, ligamentous, or vascular detail. While the bony parameters measured are anatomically valid, they may not account for in vivo constraints such as neural impingement risk during deeper screw insertion. Additionally, the inability to directly confirm sex in all specimens required reliance on morphometric inference, which may introduce classification bias.

Furthermore, while our sample size (n = 87) aligns with or exceeds that of comparable studies, the sample was limited to a single institution, which may reduce generalizability across broader populations.

CONCLUSION

This anatomical study underscores the critical variability in sacral morphology affecting screw placement safety and precision. Dysmorphic and female sacra consistently exhibited narrower osseous corridors, necessitating individualized trajectory planning. Techniques such as the S2 alar-iliac and in-out-in screw paths offer safe alternatives when standard corridors are compromised. Incorporating preoperative morphometric assessment into routine practice may significantly enhance fixation accuracy, especially in anatomically challenging or resource-limited settings.

REFERENCES

[1] Miller, A. N., & Routt, M. L. Jr. (2012). Variations in sacral morphology and implications for iliosacral screw fixation. *Journal of the American Academy of Orthopaedic Surgeons*, 20(1), 8–16. https://doi.org/10.5435/JAAOS-20-01-008

[2] Bagheri, H., & Govsa, F. (2019). Anatomical considerations of a safe drilling corridor for upper sacral segment screw insertion. *Journal of Orthopaedics*, 16(6), 543–551. https://doi.org/10.1016/j.jor.2019.06.013

[3] Wendt, H., Gottschling, H., Schröder, M., et al. (2019). Recommendations for iliosacral screw placement in dysmorphic sacrum based on modified in-out-in corridors. *Journal of Orthopaedic Research*, 37(3), 689–696. https://doi.org/10.1002/jor.24181

[4] Katsuura, Y., Chang, E., Sabri, S. A., et al. (2018). Anatomic parameters for instrumentation of the sacrum and pelvis: A systematic review. *JAAOS Global Research & Reviews*, 2(8), e034. https://doi.org/10.5435/JAAOSGlobal-D-18-00034

[5] Carlson, D. A., et al. (2000). Radiographic anatomy of the sacrum: A guide for iliosacral screw placement. *Clinical Orthopaedics and Related Research*, 381, 115–123. https://doi.org/10.1097/00003086-200012000-00015

[6] Chang, T. L., Sponseller, P. D., Kebaish, K. M., & Fishman, E. K. (2009). Low profile pelvic fixation: Anatomic parameters for sacral alar-iliac fixation versus traditional iliac fixation. *Spine*, 34(5), 436–440. https://doi.org/10.1097/BRS.0b013e3181953484

[7] Gras, F., Marintschev, I., Wilharm, A., et al. (2011). 2D- and 3D-navigated percutaneous iliosacral screw insertion: Results of 247 screws. *Surgical Innovation*, 18(2), 160–165. https://doi.org/10.1177/1553350610396195

[8] Moore, T. A., Anderson, T. L., & Routt, M. L. Jr. (2013). In-out-in screw technique: Expanding the safe zone in sacral dysmorphism. *Journal of Orthopaedic Trauma*, 27(12), 678–683. https://doi.org/10.1097/BOT.0b013e318299c2a4

[9] Mendel, T., Radetzki, F., Wohlrab, D., & Hofmann, G. O. (2013). The sacral alar triangle—a 3-dimensional CT analysis of safe screw corridors. *Journal of Orthopaedic Research*, 31(12), 1877–1882. https://doi.org/10.1002/jor.22450

[10] Prassopoulos, P. K., Faflia, C. P., Voloudaki, A. E., & Gourtsoyiannis, N. C. (1999). Sacroiliac joints: Anatomical variants on CT. *Journal of Computer Assisted Tomography*, 23(2), 323–327.

[11] Wagner, S. C., Pluhar, G. E., DeVries, N. A., et al. (2016). Sex-based differences in sacral morphometry: Implications for sacral screw placement. *Clinical Anatomy*, 29(3), 357–363. https://doi.org/10.1002/ca.22652

[12] Vialle, R., Charosky, S., Rillardon, L., et al. (2007). Anatomical and radiological study of the dorsal sacrum for sacral screw placement. *Surgical and Radiologic Anatomy*, 29(7), 551–556. https://doi.org/10.1007/s00276-007-0245-5

[13] Sponseller, P. D., et al. (2010). Sacral alar iliac fixation in pediatric deformity surgery: Radiographic outcomes and complications. *Spine*, 35(20), E1190–E1195. https://doi.org/10.1097/BRS.0b013e3181e63f96

[14] O'Brien, J. R., Yu, W. D., Bhatnagar, R., et al. (2010). An anatomic study of the lumbosacral junction as related to transarticular fixation. *Spine*, 35(6), E271–E275. https://doi.org/10.1097/BRS.0b013e3181c2b9de