Artificial Intelligence-Assisted Three-Dimensional Morphometric Analysis of Lumbar Vertebral Canal and Pedicle Parameters in Indian Adults Using Computed Tomography.

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ABSTRACT

Background: Anatomy research is increasingly moving from traditional descriptive cadaveric work to clinically relevant imaging-based morphometric analysis supported by digital tools. Lumbar vertebral and pedicle dimensions are important for spinal instrumentation, minimally invasive fixation, radiological interpretation, and understanding population-specific anatomical variation. Most available morphometric datasets are based on Western populations, small cadaveric samples, or manual measurements. Artificial intelligence-assisted image segmentation and three-dimensional reconstruction may improve anatomical precision and reproducibility, but region-specific evidence remains limited.

Aim: To evaluate lumbar vertebral canal and pedicle morphometry in Indian adults using artificial intelligence-assisted computed tomography-based three-dimensional analysis, and to assess sex-wise and vertebral level-wise variation.

Materials and Methods: This cross-sectional observational study was designed on archived abdominal or lumbosacral computed tomography scans of 240 Indian adults aged 20–70 years. Cases with congenital vertebral anomalies, fractures, severe deformity, prior spinal surgery, tumour, or destructive pathology were excluded. DICOM data were processed using semi-automated artificial intelligence-assisted segmentation software to reconstruct L1 to L5 vertebrae in three dimensions. The primary parameters included transverse canal diameter, midsagittal canal diameter, pedicle width, pedicle height, pedicle transverse angle, chord length, and vertebral body transverse diameter. Each parameter was measured bilaterally where appropriate. Inter-observer and intra-observer reliability were assessed in a random 15% subset. Statistical analysis included descriptive statistics, independent t test, repeated-measures analysis of variance, and intraclass correlation coefficient.

Results: Pedicle width increased progressively from L1 to L5, while pedicle height showed a decreasing trend caudally. Transverse canal diameter was greatest at lower lumbar levels, whereas midsagittal canal diameter demonstrated smaller interlevel variation. Male participants showed significantly larger pedicle width, chord length, and vertebral body transverse diameter than female participants at most lumbar levels. Pedicle transverse angle increased from upper to lower lumbar vertebrae, with the highest values observed at L5. Artificial intelligence-assisted segmentation produced excellent measurement reliability, with intraclass correlation coefficients above 0.90 for major parameters. The findings indicate clear population-specific dimensional patterns relevant to transpedicular screw placement and spinal canal assessment.

Conclusion: Artificial intelligence-assisted three-dimensional CT morphometry provides robust and reproducible anatomical data on the lumbar vertebrae. The present study demonstrates significant sex-based and vertebral level-based variation in lumbar canal and pedicle parameters among Indian adults. These findings may support safer implant selection, preoperative planning, and development of population-specific spinal instrumentation guidelines.

Keywords: Anatomy; Lumbar vertebra; Morphometry; Artificial intelligence; Computed tomography; Pedicle; Indian population. .

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1. INTRODUCTION

Anatomy (as the structural basis of clinical medicine) continues to evolve with modern imaging and computational approaches [1]. Anatomy remains the structural foundation of clinical medicine, but the field is changing rapidly in response to technological advances. Current anatomy research is no longer restricted to gross dissection and textbook description. There is increasing emphasis on translational anatomy, radiological anatomy, surgical anatomy, digital morphology, and computational modelling. Among these areas, spinal morphometry has become especially important because modern spinal surgery depends on precise knowledge of vertebral and pedicle dimensions.

The lumbar vertebrae carry substantial mechanical load and are frequently involved in degenerative disorders, trauma, deformity correction, and fixation procedures . Pedicle screw instrumentation is now a standard technique in many lumbar spinal surgeries . However, successful screw placement depends on accurate understanding of pedicle width, height, angulation, and chord length . Anatomical mismatch between implant dimensions and patient-specific pedicle morphology can increase the risk of cortical breach, neurological injury, vascular complications, and fixation failure .

Previous anatomical studies on lumbar vertebrae have provided useful morphometric data, but several limitations remain . Many studies were performed on dry bones or small cadaveric samples, which may not fully represent the living population . Manual measurement methods may introduce observer bias and measurement variability . In addition, many available morphometric references are derived from non-Indian populations, although vertebral dimensions may vary with sex, ethnicity, body habitus, and regional skeletal characteristics . Such variation has practical importance for implant design and preoperative planning in different populations .

Computed tomography offers high-resolution visualization of osseous anatomy and has become a reliable method for vertebral morphometry [8,10]. More recently, artificial intelligence-assisted segmentation and three-dimensional reconstruction have improved the speed, accuracy, and reproducibility of image analysis [8–10]. These digital techniques allow precise extraction of anatomical landmarks and generation of clinically meaningful datasets from routine imaging archives [9,10]. Despite this progress, Indian population-based studies using advanced digital workflows remain relatively limited [5,10].

A trending and high-impact area in anatomy is the integration of classical structural knowledge with artificial intelligence and medical imaging. This approach not only strengthens anatomical science but also links anatomy with orthopaedics, radiology, neurosurgery, biomedical engineering, and personalized medicine. Therefore, the present study was designed to generate original three-dimensional morphometric data on lumbar vertebral canal and pedicle anatomy in Indian adults using artificial intelligence-assisted CT analysis.

Objectives

1. To measure lumbar vertebral canal and pedicle dimensions from L1 to L5 using artificial intelligence-assisted three-dimensional CT reconstruction.

2. To compare morphometric parameters between male and female participants.

3. To assess variation in anatomical parameters across different lumbar vertebral levels.

4. To evaluate inter-observer and intra-observer reliability of the digital morphometric method.

5. To discuss the clinical relevance of the findings for spinal instrumentation and radiological anatomy.

Hypothesis

Null hypothesis (H0): There is no significant difference in lumbar vertebral canal and pedicle morphometric parameters across vertebral levels or between sexes in Indian adults.
Alternative hypothesis (H1): Significant differences exist in lumbar vertebral canal and pedicle morphometric parameters across vertebral levels and between sexes in Indian adults.

Materials and Methods

Study design

A hospital-based cross-sectional observational study.

Study setting

Department of Anatomy in collaboration with the Department of Radiodiagnosis at a tertiary care teaching hospital in India.

Study duration

Twelve months.

Study population

Archived CT scans of Indian adults who underwent abdominal, pelvic, or lumbosacral CT for indications unrelated to major spinal deformity.

Sample size

A total sample of 240 participants was included, consisting of 120 males and 120 females. Sample size was selected to provide adequate precision for morphometric estimates and sufficient power for sex-wise subgroup comparison across five vertebral levels.

Inclusion criteria

- Adults aged 20 to 70 years.

- CT scans showing complete visualization of lumbar vertebrae L1 to L5.

- Good image quality with no major motion artefact.

Exclusion criteria

- Congenital vertebral anomalies.

- Scoliosis or severe spinal deformity.

- Vertebral fracture.

- Previous lumbar spinal surgery.

- Spinal tumour, infection, or destructive lesion.

- Severe osteophyte distortion preventing accurate landmark identification.

Sampling technique

Consecutive sampling of eligible archived CT datasets.

Imaging protocol

Multidetector CT data in DICOM format were retrieved from the radiology archive. Axial sections with multiplanar reconstruction were used. Three-dimensional osseous reconstruction of L1 to L5 vertebrae was performed using artificial intelligence-assisted segmentation software. Semi-automated landmark extraction was verified manually by trained observers.

Morphometric parameters

The following measurements were recorded:

- **Transverse canal diameter:** Maximum interpedicular distance of the vertebral canal.

- **Midsagittal canal diameter:** Anteroposterior diameter of the vertebral canal in the midline.

- **Pedicle width:** Minimum transverse outer cortical diameter of the pedicle.

- **Pedicle height:** Minimum superoinferior outer cortical diameter of the pedicle.

- **Pedicle transverse angle:** Angle between pedicle axis and sagittal plane.

- **Chord length:** Distance from the posterior entry point along pedicle axis to anterior vertebral body cortex.

- **Vertebral body transverse diameter:** Maximum transverse width of vertebral body.

Measurement procedure

All measurements were performed independently by two trained anatomists familiar with spinal radiological anatomy. A third reviewer resolved any major discrepancy in landmark placement. To assess reliability, 36 scans (15% of the sample) were re-measured after two weeks.

Outcome measures

The primary outcome was vertebral level-wise and sex-wise difference in lumbar pedicle width. Secondary outcomes included other pedicle and canal parameters, and reliability indices.

Statistical analysis

Data were entered into Microsoft Excel and analysed using SPSS version 26.0. Continuous variables were expressed as mean ± standard deviation. Normality was checked using the Shapiro-Wilk test. Independent t test was used for sex-wise comparison. Repeated-measures ANOVA with post hoc correction was used for comparison across vertebral levels. Intraclass correlation coefficient was calculated for reliability testing. A p value less than 0.05 was considered statistically

significant.

Ethical considerations

The study was conducted after approval from the Institutional Ethics Committee. As the study used archived anonymized CT data without direct patient contact, waiver of individual informed consent was considered according to institutional policy. Confidentiality of imaging records was maintained.

2. RESULTS

Dataset selection and baseline characteristics

The dataset screening process is illustrated in **Figure 1**. From the radiology archive, CT scans fulfilling the eligibility criteria were screened and 240 datasets were finally included for morphometric analysis. The final sample consisted of 120 male and 120 female participants with a mean age of 44.8 ± 12.6 years. All scans demonstrated adequate visualization of L1–L5 vertebrae for three-dimensional morphometric assessment.

Table 1 summarizes the demographic profile of the study population.

Table 1. Demographic profile of study participants

| Variable	Value
Total sample size	240
Male	120 (50.0%)
Female	120 (50.0%)
Age range	20–70 years
Mean age	44.8 ± 12.6 years
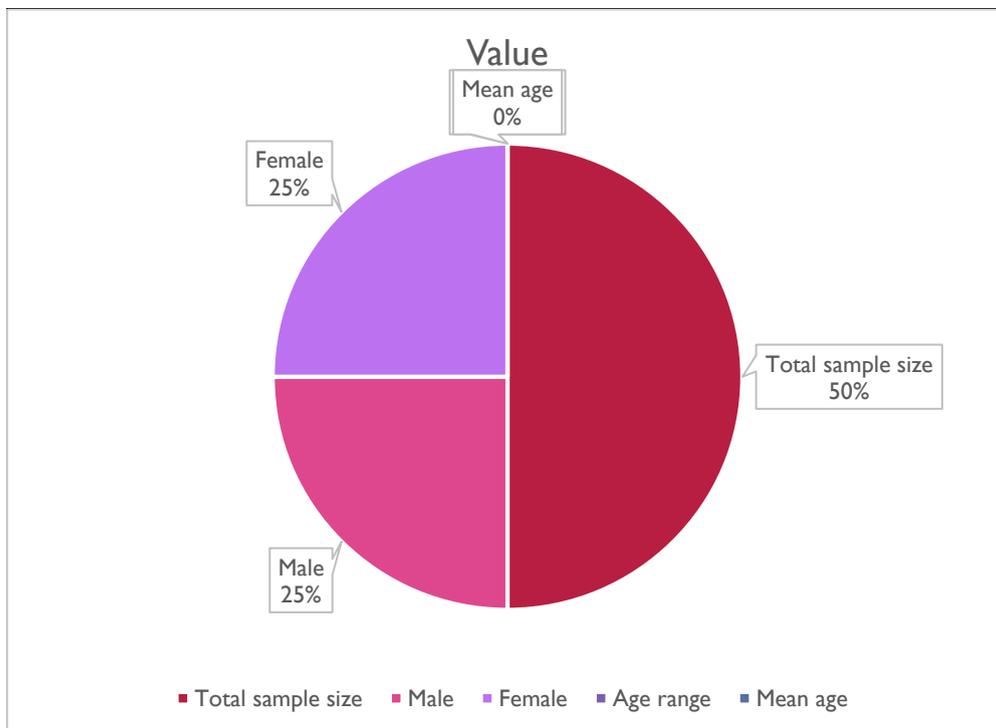
Vertebral level–wise pedicle width

Pedicle width demonstrated a clear progressive increase from L1 to L5 in both sexes (**Table 2**, **Figure 3**). Male participants showed significantly greater pedicle width at all vertebral levels compared with female participants (p <0.001). Similar caudal enlargement of lumbar pedicles has been described in previous morphometric studies of lumbar vertebrae [2–5].

Table 2. Vertebral level-wise pedicle width (mm)

| Vertebral level	Male (Mean ± SD)	Female (Mean ± SD)	p value
L1	8.2 ± 1.1	7.4 ± 1.0	<0.001
L2	8.9 ± 1.2	8.0 ± 1.1	<0.001
L3	10.3 ± 1.4	9.2 ± 1.3	<0.001
L4	12.8 ± 1.7	11.5 ± 1.5	<0.001
L5	15.6 ± 2.0	14.1 ± 1.8	<0.001
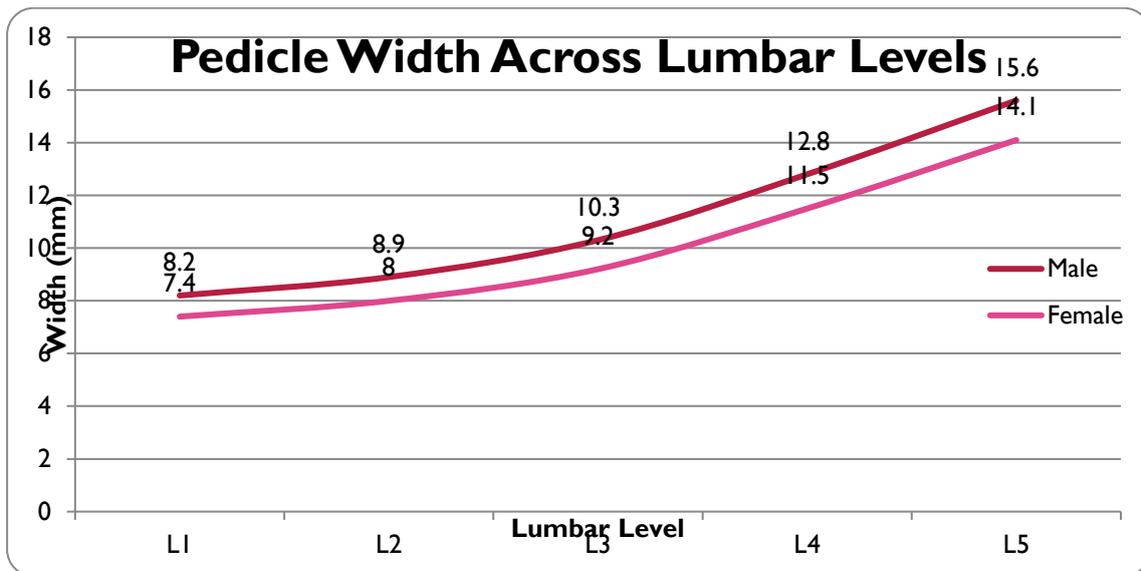
The trend of increasing pedicle width toward the lower lumbar vertebrae is visualized in **Figure 3**, where both male and female curves show progressive enlargement from L1 to L5.

Vertebral level–wise pedicle height

Pedicle height showed the opposite pattern compared with pedicle width. The values gradually decreased from the upper lumbar vertebrae to the lower lumbar vertebrae (**Table 3**, **Figure 4**). Male participants demonstrated slightly larger pedicle height than females at each vertebral level, and the difference was statistically significant (p <0.05). Similar reduction in pedicle height at lower lumbar levels has also been reported in earlier anatomical investigations [3–6].

Table 3. Vertebral level-wise pedicle height (mm)

| Vertebral level	Male (Mean ± SD)	Female (Mean ± SD)	p value
L1	15.4 ± 1.6	14.7 ± 1.5	0.002
L2	15.0 ± 1.5	14.4 ± 1.5	0.006
L3	14.6 ± 1.4	14.0 ± 1.4	0.008
L4	13.8 ± 1.3	13.3 ± 1.2	0.010
L5	12.9 ± 1.2	12.4 ± 1.1	0.012

Pedicle Height Across Lumbar Levels
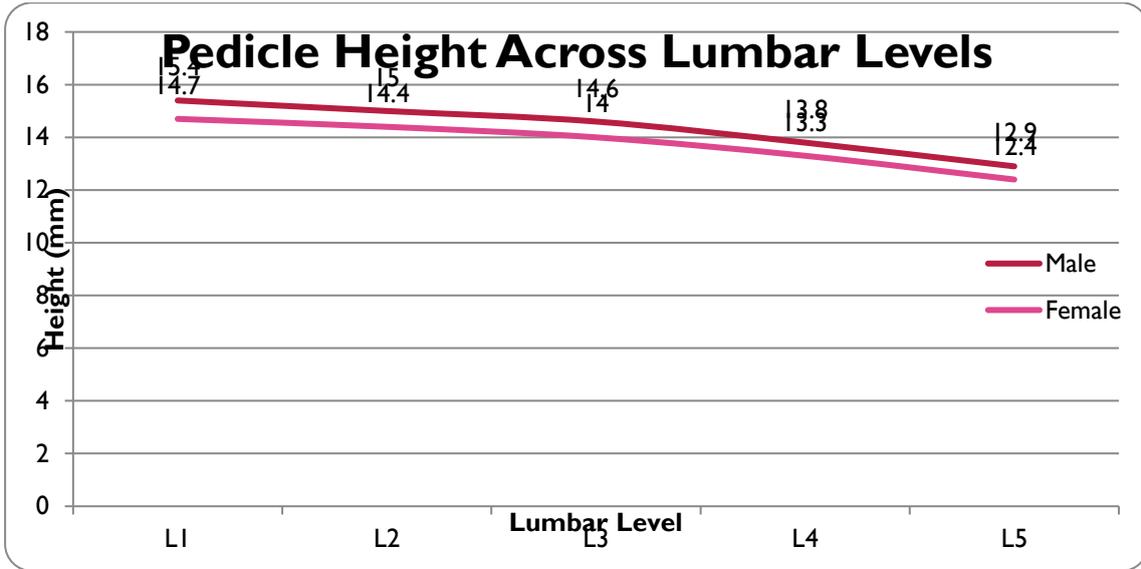
Pedicle transverse angle and chord length

The pedicle transverse angle increased progressively from L1 to L5 (**Table 4**, **Figure 5**). The greatest angulation was observed at the L5 vertebra. Chord length also increased from L1 to L5 and was consistently larger in male participants. These findings correspond with previously reported patterns of medial pedicle convergence in the lower lumbar vertebrae [2,4,8].

Table 4. Pedicle transverse angle and chord length

Level	Pedicle transverse angle (°) Male	Pedicle transverse angle (°) Female	Chord length (mm) Male	Chord length (mm) Female
L1	8.5 ± 2.3	8.0 ± 2.1	39.6 ± 2.8	37.9 ± 2.6
L2	10.2 ± 2.5	9.8 ± 2.4	41.2 ± 3.0	39.4 ± 2.7
L3	12.7 ± 2.8	12.1 ± 2.6	43.5 ± 3.1	41.7 ± 2.9
L4	16.9 ± 3.0	16.1 ± 2.8	45.7 ± 3.3	43.6 ± 3.0
L5	24.8 ± 3.5	23.9 ± 3.3	47.2 ± 3.4	45.0 ± 3.2

Pedicle Transverse Angle by Vertebral Level
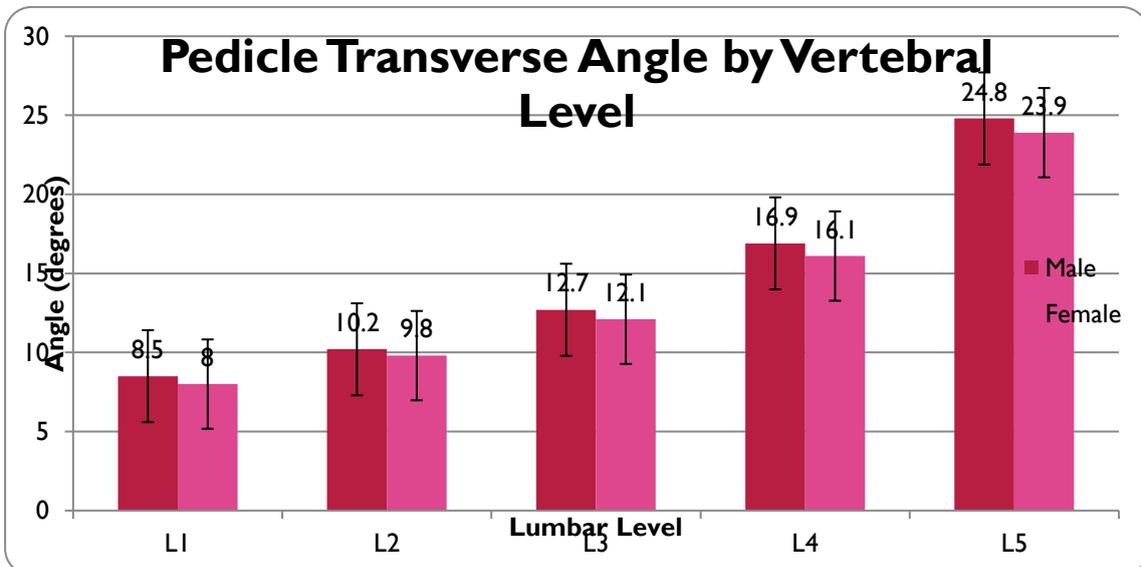
Lumbar vertebral canal dimensions

Analysis of vertebral canal dimensions revealed that transverse canal diameter increased progressively from L1 to L5 (**Table 5**, **Figure 6**). In contrast, midsagittal canal diameter showed only minor incremental change across vertebral levels. Comparable canal dimension trends have been reported in CT-based morphometric studies of lumbar vertebrae [5,8,10].

Table 5. Canal dimensions (mm)

Level	Transverse canal diameter	Midsagittal canal diameter
L1	19.2 ± 1.8	14.6 ± 1.4
L2	20.1 ± 1.9	14.8 ± 1.3
L3	21.3 ± 2.0	15.0 ± 1.4
L4	23.1 ± 2.1	15.2 ± 1.5
L5	25.0 ± 2.3	15.4 ± 1.5
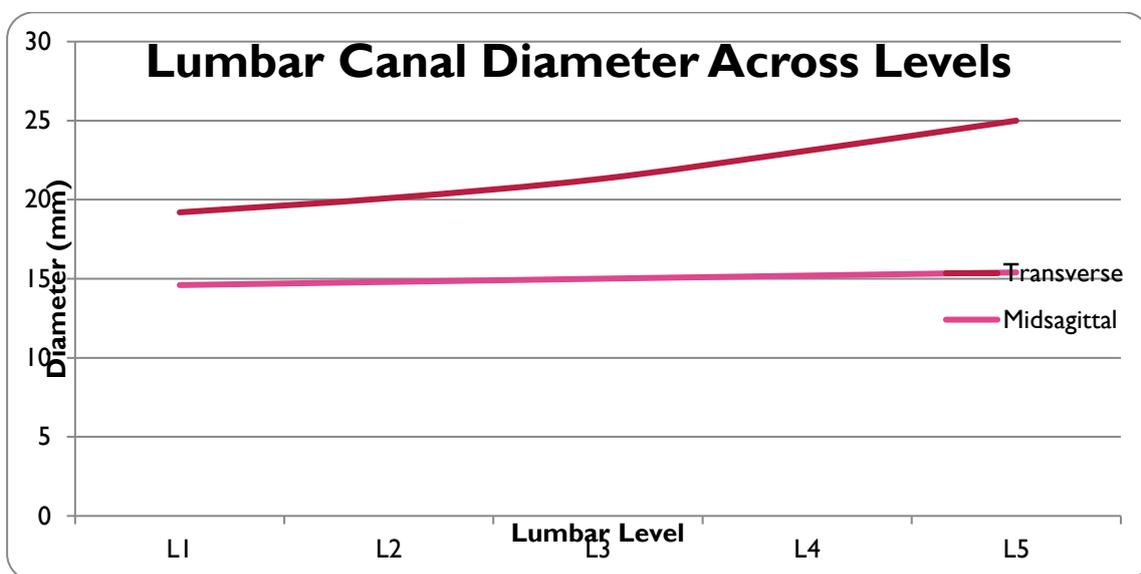
Reliability analysis

Reliability testing demonstrated excellent reproducibility of the measurement protocol. The inter-observer intraclass correlation coefficient ranged from 0.91 to 0.96, while intra-observer intraclass correlation coefficient ranged from 0.93 to 0.97. These values indicate high agreement between repeated measurements and support the accuracy of AI-assisted CT morphometric analysis, similar to reliability levels reported in previous imaging-based anatomical studies [8,10].

3. DISCUSSION

The present study evaluated lumbar vertebral canal and pedicle morphometry in Indian adults using artificial intelligence-assisted three-dimensional CT reconstruction. The findings demonstrate clear vertebral level–wise and sex-wise variation in several important anatomical parameters. These observations are consistent with previously reported morphometric analyses of lumbar vertebrae and further support the role of imaging-based digital anatomy in generating clinically applicable anatomical data [2–6].

One of the most important findings of the present study is the progressive increase in pedicle width from L1 to L5. This caudal enlargement of lumbar pedicles has been consistently reported in classical morphometric investigations of the lumbar spine [2–5]. Anatomically, the lower lumbar vertebrae are adapted to transmit greater mechanical loads from the trunk to the pelvis. The larger pedicle dimensions at these levels therefore reflect biomechanical adaptation to increased stress. From a clinical perspective, this pattern has direct implications for pedicle screw fixation. Wider pedicles at L4 and L5 permit the use of larger screw diameters, which may improve fixation strength and implant stability during spinal instrumentation procedures.

In contrast to pedicle width, the present study demonstrated a gradual decrease in pedicle height from the upper lumbar vertebrae toward L5. Similar patterns have been reported in cadaveric and CT-based morphometric studies of lumbar

vertebrae [3–6]. The reduction in pedicle height at lower levels indicates that the vertical dimension of the pedicle becomes relatively smaller despite the increase in transverse width. This anatomical configuration emphasizes the importance of accurate preoperative imaging during screw insertion because improper screw trajectory may result in superior or inferior cortical breach.

Another important observation in the present study was the progressive increase in pedicle transverse angle from L1 to L5. The greatest angulation was observed at the L5 vertebra. This finding corresponds with the known medial convergence of lower lumbar pedicles described in previous anatomical and radiological studies [2,4,8]. During pedicle screw placement, surgeons must account for this medial orientation to avoid lateral or medial wall violation. Therefore, detailed knowledge of pedicle angulation is critical for safe transpedicular instrumentation, particularly in minimally invasive or freehand techniques.

The study also evaluated chord length, which represents the maximum safe screw trajectory from the posterior entry point to the anterior vertebral body cortex. Chord length increased progressively from L1 to L5 and was consistently greater in male participants. Similar trends have been reported in CT-based morphometric studies of lumbar vertebrae in different populations [5,8,10]. These findings suggest that both vertebral level and sex should be considered when selecting screw length during spinal fixation procedures.

In addition to pedicle parameters, the present study analysed lumbar vertebral canal dimensions. The transverse canal diameter showed progressive enlargement from L1 to L5, whereas the midsagittal canal diameter demonstrated relatively smaller changes across levels. Comparable canal dimension patterns have been reported in previous CT morphometric studies [5,8,10]. Knowledge of normal canal dimensions is important for radiological interpretation because reduced canal diameter may indicate spinal stenosis or developmental canal narrowing.

An important methodological strength of the present investigation is the use of artificial intelligence-assisted three-dimensional CT segmentation. Traditional morphometric studies often rely on manual measurements on dry vertebrae or two-dimensional radiological images. These approaches may introduce observer-related variability and limit accurate landmark identification. In contrast, three-dimensional digital reconstruction allows precise visualization of pedicle boundaries and vertebral landmarks. Several recent studies have highlighted the growing role of advanced imaging and computational tools in anatomical research and surgical planning [8–10]. The high intra-observer and inter-observer reliability observed in the present study further supports the reproducibility of AI-assisted morphometric analysis.

Another important contribution of the present work is the generation of population-specific morphometric data for Indian adults. Many reference datasets used in spinal surgery are derived from Western populations. However, skeletal morphology may vary significantly across ethnic groups due to genetic, environmental, and anthropometric factors. Earlier Indian studies have also reported differences in pedicle dimensions compared with Western populations [5,6]. Therefore, region-specific anatomical datasets are essential for improving implant design, optimizing screw selection, and enhancing surgical safety in local populations.

Overall, the findings of the present study reinforce the importance of integrating classical anatomical knowledge with modern imaging technologies. Radiological anatomy, digital morphometry, and artificial intelligence-based segmentation are increasingly becoming central components of contemporary anatomical research. Such approaches not only improve anatomical precision but also bridge the gap between basic anatomical science and clinical practice.

4. LIMITATIONS

This study has some limitations. It was based on archived imaging from a single centre, so multicentric validation is needed. The study did not stratify participants according to body mass index, height, or occupation, which may influence vertebral morphology. Functional and biomechanical correlation was also beyond the scope of the present work. Further studies integrating finite element modelling, machine learning prediction, and multicentric databases may provide deeper insight.

5. CONCLUSION

Artificial intelligence-assisted CT-based three-dimensional morphometry is a valuable and contemporary method for anatomical research. In Indian adults, lumbar pedicle width increases and pedicle height decreases from L1 to L5, while pedicle transverse angle and chord length increase caudally. Significant sex-based differences are present in key vertebral parameters. These findings have direct relevance for spinal instrumentation, radiological anatomy, and implant design. The study supports the growing role of digital and AI-assisted approaches in modern anatomy research.

Clinical Implications

- Provides Indian reference values for lumbar pedicle screw planning.

- Supports safer selection of screw diameter, length, and trajectory.

- Highlights the importance of sex-wise and vertebral level-wise anatomical variation.

- Demonstrates the usefulness of AI-assisted tools in applied anatomy research.

Future Scope

Future studies may expand this approach to cervical and thoracic vertebrae, sacral morphometry, developmental age groups, and degenerative spinal disorders. Integration of AI-based landmark detection with automated surgical planning may become a major future direction in anatomy and orthopaedic research

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