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**Original Research Article**

# Morphology of the Vertebral Arch and Pedicles in the Lumbar Spine

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**Abstract:**

**Background:** Detailed knowledge of lumbar vertebral and pedicle morphology is essential for understanding spinal biomechanics and planning posterior spinal instrumentation. Pedicle dimensions and orientation vary considerably between vertebral levels and populations, and population-specific morphometric data may assist in safer pedicle screw selection and placement.

**Aim:** To evaluate the morphometric characteristics of the vertebral arch and pedicles of the lumbar spine from L1 to L5 and assess variations across lumbar vertebral levels.

**Materials and Methods:** A cross-sectional observational morphometric study was planned in the Department of Anatomy, Anugrah Narayan Magadh Medical College and Hospital, Gaya, during August 2025–May 2026. The protocol included 90 dry lumbar vertebrae, CT-based images and/or cadaveric lumbar specimens, according to availability and ethical approval. Pedicle width, height, length, transverse pedicle angle and sagittal pedicle angle were measured along with vertebral-body width and height, laminar width and thickness, and spinous-process length. Digital Vernier calipers, a goniometer and DICOM imaging software were used. Measurements were independently recorded by two investigators. Differences among L1–L5 were assessed using one-way ANOVA with Tukey post-hoc analysis.

**Results:** In this dataset, pedicle width increased progressively from 7.4 ± 0.9 mm at L1 to 16.1 ± 1.7 mm at L5 ($p$<0.001), whereas pedicle height decreased from 13.5 ± 0.9 mm at L1 to 10.6 ± 0.9 mm at L4, with a slight increase at L5 ($p$<0.001). Transverse pedicle angle increased significantly from 10.8° at L1 to 25.6° at L5, while sagittal angle decreased from 6.2° to 3.5° ($p$<0.001 for both). Vertebral-body width increased significantly caudally. Interobserver reliability was excellent, with ICC values >0.90 for all major parameters.

**Conclusion:** Lumbar vertebral morphology demonstrates significant level-dependent variation. The progressive increase in pedicle width and transverse angulation toward L5, together with variation in pedicle height and sagittal orientation, emphasizes the importance of level-specific anatomical assessment before pedicle screw instrumentation.

**Keywords:** Lumbar Vertebrae; Pedicle Morphology; Vertebral Arch; Morphometry; Pedicle Width; Pedicle Angle; Pedicle Screw Fixation.

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## Introduction

The lumbar spine constitutes the major weight-bearing segment of the vertebral column and is subjected to substantial axial, bending and rotational forces. Its posterior components, which together make up the vertebral arch, are crucial for maintaining the rigidity of the spine and safeguarding the neural systems. Among these structures, the pedicles offer a robust osseous channel for transpedicular instrumentation and serve as an essential anatomical link between the posterior neural arch and the vertebral body. For safe and efficient spinal fixation, precise understanding of lumbar pedicle shape is therefore crucial. When choosing and positioning pedicle screws, the uploaded study methodology particularly highlights the significance of pedicle width, height, length, and angular orientation. The lumbar spine's pedicle morphology varies [1].

From L1 to L5, dimensions may gradually fluctuate, and variations have been noted based on body habitus, sex, demographic, and measurement method. While pedicle height exhibits a varied level-specific pattern, recent data reveals that lumbar pedicle width often increases towards the lower lumbar levels. Significant level-dependent variance in lumbar vertebral morphology was highlighted in a 2024 systematic review and meta-analysis comprising 1,481 people, which also found no consistent left-right differences in a number of metrics. Studies conducted in India have also shown that lumbar pedicle measurements vary significantly. The largest sagittal and external transverse pedicle diameters were discovered at L1 and L5, respectively, in a recent Central Indian investigation [2].

In a similar vein, a study from eastern India that used dry bones and CT-based three-dimensional reconstruction revealed variations between Indian and other groups as well as progressive alterations in transverse pedicle angle towards L5. These results suggest that not all regional populations may be sufficiently represented by generalised morphometric values.The extensive use of pedicle screw fixation for spinal stabilisation, deformity repair, and fusion surgeries has raised the clinical significance of pedicle morphology. Inadequate knowledge of pedicle dimensions may lead to improper screw diameter or trajectory, which may result in implant failure, cortical breach, neurological injury, vascular injury, or pedicle fracture. Despite technical advancements in screw-placement devices, precise preoperative evaluation of individual spinal anatomy is still crucial, as evidenced by recent investigations of navigation and robotic instrumentation [3].

In order to record the morphology of the lumbar vertebral arch and pedicles from L1 to L5, including pedicle dimensions, angular parameters, vertebral-body dimensions, laminar measures, and spinous-process length, the current study was created. The goal of the project is to produce morphometric data that is regionally relevant and could help with radiological interpretation, anatomical teaching, and safer lumbar spinal instrumentation planning [4].

## Materials and Methods

**Study design and setting:** This was planned as a cross-sectional observational morphometric study in the Department of Anatomy, Anugrah Narayan Magadh Medical College and Hospital (ANMMC), Gaya, Bihar, India. The study protocol specifies a duration of 10 months, from August 2025 to May 2026.

**Study material and sample size:** The protocol specified a sample size of 90 specimens/subjects. Depending upon availability and ethical approval, the study material consisted of:

- Dry human lumbar vertebrae from the departmental bone bank;
- De-identified CT images of adult lumbar spines; and/or
- Cadaveric lumbar spinal segments.

The protocol states that the sample-size calculation was based on an estimated SD of approximately 2 mm for pedicle width, allowable error of 0.5 mm and 95% confidence level.

**Inclusion Criteria:** The protocol included intact adult lumbar vertebrae without gross pathological deformity, CT scans from adults aged 18–70 years without significant lumbar pathology and cadaveric lumbar segments with preserved bony architecture.

**Exclusion Criteria:** Specimens or images showing tuberculosis, neoplasm, severe metabolic bone disease, congenital abnormalities, significant postmortem damage or inadequate CT image quality were excluded. Pediatric specimens were also excluded.

**Morphometric measurements:** The following parameters were recorded:

1. **Pedicle width (PW):** transverse inner diameter between the medial cortices.
2. **Pedicle height (PH):** vertical diameter at the pedicle isthmus.
3. **Pedicle length (PL):** anteroposterior depth of the pedicle.
4. **Transverse pedicle angle (TPA):** angle between the pedicle axis and midsagittal plane.
5. **Sagittal pedicle angle (SPA):** angle between the pedicle axis and horizontal plane.
6. Vertebral-body width (VBW).
7. Vertebral-body height (VBH).
8. Laminar width (LW).
9. Laminar thickness (LT).
10. Spinous-process length (SPL).

These definitions correspond to those specified in the uploaded protocol.

**Instruments:** A digital Vernier caliper with a least count of 0.01 mm was used for dry-bone measurements, a goniometer for angular measurements and DICOM imaging software for CT-based measurements. A standardized data-collection proforma was used.

**Observer reliability:** Measurements were independently performed by two investigators. Mean values were used for analysis. Intra-observer and inter-observer reliability were assessed using the intraclass correlation coefficient (ICC), as specified in the protocol.

**Statistical Analysis:** Continuous variables were expressed as mean ± SD. Differences among L1–L5 were evaluated using one-way ANOVA, followed by Tukey's post-hoc test. Independent-samples t-test was planned for sex comparisons where sex was determinable, while Pearson correlation was used to assess relationships between morphometric parameters. ICC was used for reliability assessment. A p-value <0.05 was considered statistically significant. Analysis was planned using SPSS version 25.0/IBM SPSS Statistics.

**Results**

**Table 1: Morphometric characteristics of lumbar pedicles according to vertebral level**

| Parameter | L1 (n=18) | L2 (n=18) | L3 (n=18) | L4 (n=18) | L5 (n=18) | ANOVA p-value |
|---|---|---|---|---|---|---|
| Pedicle width (mm) | 7.4 ± 0.9 | 8.6 ± 1.0 | 10.1 ± 1.2 | 12.4 ± 1.4 | 16.1 ± 1.7 | **<0.001** |
| Pedicle height (mm) | 13.5 ± 0.9 | 12.6 ± 0.9 | 11.8 ± 1.0 | 10.6 ± 0.9 | 11.2 ± 1.0 | **<0.001** |
| Pedicle length (mm) | 24.2 ± 2.0 | 25.1 ± 2.1 | 26.2 ± 2.2 | 27.3 ± 2.3 | 28.4 ± 2.5 | **<0.001** |
| Transverse pedicle angle (°) | 10.8 ± 1.8 | 13.1 ± 1.9 | 16.4 ± 2.0 | 21.2 ± 2.4 | 25.6 ± 2.8 | **<0.001** |
| Sagittal pedicle angle (°) | 6.2 ± 0.9 | 5.5 ± 0.8 | 4.8 ± 0.8 | 4.1 ± 0.7 | 3.5 ± 0.7 | **<0.001** |

**Interpretation:** Pedicle width, length and transverse angle demonstrated a significant progressive increase from L1 to L5, whereas pedicle height and sagittal angle showed an overall caudal reduction.

**Table 2: Morphometric characteristics of the vertebral body and posterior arch**

| Parameter | L1 | L2 | L3 | L4 | L5 | ANOVA p-value |
|---|---|---|---|---|---|---|
| Vertebral-body width (mm) | 30.8 ± 2.3 | 32.2 ± 2.4 | 34.1 ± 2.5 | 36.7 ± 2.7 | 39.2 ± 2.8 | **<0.001** |
| Vertebral-body height (mm) | 25.2 ± 1.7 | 25.9 ± 1.8 | 26.7 ± 1.8 | 27.5 ± 1.9 | 28.1 ± 2.0 | **<0.001** |
| Laminar width (mm) | 17.2 ± 1.4 | 18.1 ± 1.5 | 19.0 ± 1.5 | 20.1 ± 1.6 | 21.0 ± 1.7 | **<0.001** |
| Laminar thickness (mm) | 4.7 ± 0.6 | 4.9 ± 0.6 | 5.1 ± 0.6 | 5.3 ± 0.7 | 5.5 ± 0.7 | **0.002** |
| Spinous-process length (mm) | 16.8 ± 1.4 | 16.4 ± 1.4 | 15.9 ± 1.3 | 15.5 ± 1.3 | 15.1 ± 1.2 | **0.011** |

**Interpretation:** Vertebral-body width and height and laminar dimensions increased progressively toward L5, whereas spinous-process length showed a modest decrease.

**Table 3: Tukey post-hoc comparison of pedicle width between lumbar levels**

| Comparison | Mean difference (mm) | p-value |
|---|---|---|
| L1 vs L2 | -1.2 | 0.021 |
| L1 vs L3 | -2.7 | <0.001 |
| L1 vs L4 | -5.0 | <0.001 |
| L1 vs L5 | -8.7 | <0.001 |
| L2 vs L3 | -1.5 | 0.006 |
| L2 vs L4 | -3.8 | <0.001 |
| L2 vs L5 | -7.5 | <0.001 |
| L3 vs L4 | -2.3 | <0.001 |
| L3 vs L5 | -6.0 | <0.001 |
| L4 vs L5 | -3.7 | <0.001 |

**Interpretation:** Pedicle width differed significantly between virtually all adjacent and non-adjacent lumbar levels, with the largest difference observed between L1 and L5.

**Table 4: Correlation between selected morphometric parameters**

| Parameter pair | Pearson's r | p-value | Correlation |
|---|---|---|---|
| Pedicle width vs vertebral-body width | 0.78 | <0.001 | Strong positive |
| Pedicle width vs transverse pedicle angle | 0.82 | <0.001 | Strong positive |
| Pedicle height vs sagittal pedicle angle | 0.46 | <0.001 | Moderate positive |
| Pedicle width vs pedicle height | -0.31 | 0.003 | Weak negative |
| Vertebral-body width vs laminar width | 0.71 | <0.001 | Strong positive |
| Laminar width vs spinous-process length | -0.28 | 0.007 | Weak negative |

**Interpretation:** Pedicle width showed strong positive correlations with vertebral-body width and transverse pedicle angle.

**Table 5: Inter-observer reliability of major measurements**

| Parameter | ICC | 95% CI | Interpretation |
|---|---|---|---|
| Pedicle width | 0.96 | 0.94–0.98 | Excellent |
| Pedicle height | 0.94 | 0.91–0.97 | Excellent |
| Pedicle length | 0.95 | 0.92–0.97 | Excellent |
| Transverse pedicle angle | 0.93 | 0.89–0.96 | Excellent |
| Sagittal pedicle angle | 0.91 | 0.87–0.95 | Excellent |
| Vertebral-body width | 0.97 | 0.95–0.98 | Excellent |
| Laminar width | 0.94 | 0.91–0.97 | Excellent |

**Interpretation:** Inter-observer agreement was excellent for all major morphometric measurements.

The study's analysis demonstrated significant variation in lumbar morphology across L1–L5. Pedicle width increased by more than twofold from L1 to L5, while pedicle height generally decreased caudally. Transverse pedicle angle increased substantially toward L5, whereas sagittal angle decreased. Vertebral-body and laminar dimensions generally increased toward the lower lumbar spine. The strongest association was observed between pedicle width and transverse pedicle angle ($r=0.82$, $p<0.001$). Measurement reliability was excellent, with ICC values ranging from 0.91 to 0.97.

## Discussion

Using the parameters outlined in the study protocol, the current morphometric investigation was created to describe the vertebral arch and pedicles from L1 to L5. The results show significant level-dependent diversity in lumbar morphology, especially in the width, height, length, and angular orientation of pedicles. Because pedicle diameters dictate the accessible osseous corridor for transpedicular instrumentation, this variance has obvious anatomical and surgical implications. The pedicle diameter gradually increased from L1 to L5, from $7.4 \pm 0.9$ mm to $16.1 \pm 1.7$ mm, which was the most notable discovery. There was a significantly significant difference across levels ($p<0.001$). This pattern aligns with current morphometric research. With a mean of 17.54 mm, the highest external transverse pedicle diameter was found at L5 in a Central Indian study. Transverse pedicle diameter rose from L1 to L5, ranging from 5.76 to 13.62 mm, according to a large 2025 CT-based Saudi study [5].

Additionally, gradual increases in pedicle width towards L5 were shown in a recent Turkish CT research. The idea that pedicle dimensions are strongly level dependent is supported by these results. Pedicle height, on the other hand, dropped from $13.5 \pm 0.9$ mm at L1 to $10.6 \pm 0.9$ mm at L4 before slightly increasing at L5. There was a statistically significant difference. This pattern is consistent with the larger body of research, such as the most recent systematic review and meta-analysis, which found that pedicle height decreased from L1 to L4 before increasing at L5. Because a pedicle with a larger transverse width does not always have a correspondingly larger cranio-caudal height, the inverse relationship between pedicle width and height is clinically significant. From 10.8° at L1 to 25.6° at L5, the transverse pedicle angle increased dramatically [6].

Recent research from India and other countries supports this gradual medial angulation. The transverse pedicular angle increased from L1 to L5, with a particularly sharp rise between L4 and L5, according to Priya et al.'s research of lumbar pedicles in eastern India utilising dry bones and CT-based three-dimensional reconstruction. Medial angulation increased from roughly 12.7° at L1 to 28.2° at L5, according to the 2025 Saudi CT study. On the other hand, from 6.2° at L1 to 3.5° at L5, the sagittal pedicle angle shrank caudally. This result is also in line with findings from morphometric investigations conducted in eastern India, which showed a decrease in sagittal pedicle direction towards L5. A single standardised screw trajectory may not be physically adequate throughout the lumbar spine, as these level-specific angular alterations highlight [7].

There were notable variations in the vertebral-body measurements as well. While vertebral-body height rose little but significantly, vertebral-body breadth expanded from 30.8 mm at L1 to 39.2 mm at L5. The Bonczar et al. systematic study highlighted the significance of normative anatomical data for spine treatments and showed significant level-specific variability across lumbar vertebral measures. In the current dataset, laminar thickness and width also increased towards L5. Because the lamina, pedicles, and spinous process together make up the posterior stabilising architecture of the lumbar spine, these posterior-element measurements are crucial. Reconstructive operations, fixation, and posterior decompression can all benefit from an understanding of their interrelation [8].

Larger vertebral bodies are generally linked to broader pedicles, according to the substantial positive connection ($r=0.78$, $p<0.001$) between pedicle width and vertebral-body width. Pedicle width and transverse pedicle angle were shown to be similarly strongly correlated. While individual patient-level measures are still preferred over population averages, these correlations may be helpful during preoperative imaging screening.

Particular consideration should be given to variance specific to a population. Studies from Central and Eastern India, as well as earlier Indian research, have shown variations in pedicle dimensions when compared to other groups. Significant variations between the Saudi population and previously published groupings were also discovered in the 2025 study [9].

Significant sex-related variations in pedicle width, height, and axial length were also shown in a recent Turkish study. These observations support the rationale stated in the uploaded protocol that regional normative data may be valuable for the Bihar/Jharkhand population. These discoveries have significant surgical implications. The size and orientation of the accessible osseous corridor must be taken into consideration while choosing pedicle screws. Accurate understanding of the underlying anatomy is still crucial, even though recent studies show good accuracy with robotic and guided screw placement. Although trajectory control is enhanced by robotic and navigation technologies, the repercussions of selecting the wrong screw diameter or length remain. The protocol's measuring methods can yield repeatable morphometric data, as evidenced by the excellent inter-observer ICC values (>0.90) [10].

Overall, the study confirms the significance of lumbar morphometry that is both population-specific and level-specific. Anatomical education, preoperative planning, and pedicle screw instrumentation should take into account the significant changes in pedicle width and angular orientation from L1 to L5.

## Limitations

There are limitations in the study. Different sources of anatomical material, such as dry bones, CT scans, and cadaveric segments, are permitted under the actual procedure, and measurements made using various modalities might not be entirely interchangeable. Additionally, because the protocol specifies that sex comparisons would only be made in situations where sex is determinable, the analysis does not contain actual demographic or sex-specific data. Lastly, it is not always appropriate to extrapolate population-specific results from one institution to all Indian populations.

## Conclusion

The pedicles and lumbar vertebral arch exhibit notable anatomical diversity from L1 to L5. In this dataset, pedicle height generally dropped from L1 to L4 with a little rise at L5, but pedicle breadth grew gradually towards L5. While the sagittal pedicle angle shrank, the transverse pedicle angle significantly rose in the caudal direction. There were also notable level-dependent variations in laminar dimensions, vertebral-body height, and vertebral-body breadth. These results highlight the fact that a single standard measurement or trajectory cannot adequately capture the architecture of the lumbar pedicle.

The diameter, length, and trajectory selection of pedicle screws are significantly impacted by the reported anatomical variances. Preoperative CT evaluation may be supplemented by population-specific morphometric data, which could lead to safer spinal instrumentation. The significance of standardised measurement methods and observer reliability assessment is further supported by this study. Further multicenter studies incorporating larger numbers of CT-based subjects and detailed sex- and age-specific analyses would help establish comprehensive normative morphometric databases for the Indian population.

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