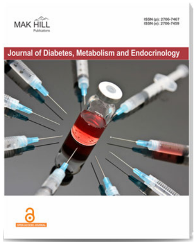

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Research Article

# Sexual Dimorphism and a Cross-Validated Logistic Regression Model for Sex Estimation from Lumbar Vertebral Morphometry in a Central Indian Population

**Tribhuvan Yadav[1] and Avantika S. Bamne[2*]**

[1]Department of Anatomy, Malwanchal University, Indore, Madhya Pradesh, India

[2]Department of Anatomy, Malwanchal University, Index City, NH-59A, Nemawar Road, Indore (M.P.) 452016, India

***Corresponding Author**
S. Bamne Avantika

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**Abstract: Purpose:** Lumbar vertebral morphometry has an established role in forensic sex estimation when the pelvis or skull are unavailable, but discriminant models are known to be population-specific. No sex-estimation model derived from lumbar vertebral morphometry has previously been reported for the Madhya Pradesh and Central Indian population. This study aimed to characterise sexual dimorphism across nine lumbar vertebral morphometric parameters and to develop a cross-validated logistic regression model for sex estimation in this population. **Methods:** Documented-sex dry adult lumbar vertebrae (61 males, 49 female; 110 total, 22 at each of L1-L5) from a departmental osteology collection were measured in triplicate for nine linear parameters. Sex differences were assessed using independent-samples t-tests with Levene's test and Cohen's d effect size. A binary logistic regression model was constructed using the parameters showing significant dimorphism, with performance evaluated by 10-fold stratified cross-validation and receiver operating characteristic (ROC) analysis. **Results:** Of nine parameters, only vertebral body height (male 29.14±1.49 mm vs. female 27.25±1.43 mm; $t = 6.77$, $p<.001$, $d = 1.29$) and transverse width (male 47.58±3.58 mm vs. female 46.02±3.83 mm; $t = 2.19$, $p = .031$, $d = 0.42$) differed significantly by sex; pedicle width, interpedicular distance, canal dimensions, and spinous process length did not (all $p>0.45$). A logistic regression model combining body height and transverse width classified sex with 83.6% cross-validated accuracy, 85.2% sensitivity, 81.6% specificity, and an area under the ROC curve of 0.904. **Conclusion:** Sexual dimorphism in the Central Indian adult lumbar vertebra is concentrated in the vertebral body rather than distributed across the vertebra as a whole, consistent with international forensic morphometric literature. The resulting logistic regression model provides the first population-specific tool for morphometric sex estimation from lumbar vertebral remains in this region.

**Keywords:** Sex Estimation, Lumbar Vertebrae, Sexual Dimorphism, Forensic Anthropology, Logistic Regression, Central India, Medico-Legal



## INTRODUCTION

Sex estimation from skeletal remains is a foundational task in forensic and biological anthropology, conventionally based on the pelvis or skull [1]. In forensic, archaeological, and mass-disaster contexts, however, these preferred elements are frequently absent, fragmented, or unavailable, and the lumbar vertebrae, by virtue of their robust, weight-bearing structure and relative resistance to post-mortem destruction, have received growing attention as an alternative skeletal element for sex estimation [2]. Bozdag and Karaman [2] applied three-dimensional computed-tomography-derived morphometry to the first lumbar vertebra in a Turkish population, achieving correct sex classification in approximately 70-74% of specimens, with vertebral body parameters providing the strongest individual discrimination. Azofra-Monge and Aleman Aguilera [3] demonstrated significant sexual dimorphism across all five lumbar vertebrae in a Spanish population and derived population-specific logistic regression equations, while Malatong *et al.* [4] compared caliper, image-analysis, and deep-learning approaches to lumbar vertebral sex estimation in a Thai population. Chinese contributions, exemplified by Hou *et al.* [5] on the twelfth thoracic vertebra, have similarly identified vertebral body and pedicle measurements as the strongest individual sex discriminators among a large panel of linear measurements tested.

A systematic review by Rohmani, Shafie, and Nor [6], screening nineteen studies of vertebral sex estimation, concluded that vertebral body measurements consistently rank among the strongest sex discriminators across the vertebral column, and explicitly emphasised that discriminant equations derived in one population perform poorly when applied to another without local recalibration. This population-specificity principle was placed on a formal empirical footing by Hora and Sladek [7], who demonstrated a statistically significant reduction in cross-population classification accuracy for vertebral sex-estimation models applied outside their population of origin.

Despite this substantial international literature, no population-specific morphometric model for sex estimation from lumbar vertebrae has previously been developed for the Madhya Pradesh or wider Central Indian population. The two existing Central Indian lumbar morphometric studies, Agichani *et al.* [8], who reported sex-associated differences in vertebral body height within specific age strata of an Indore-based sample, and Verma and Agrawal [9], who examined pedicle dimensions in a Bhopal-based sample without documenting sex, did not generate a usable discriminant model. Yadav *et al.* [10] reported significantly larger canal and vertebral body dimensions in men than women across most lumbar levels in a North Indian computed-tomography cohort, but did not develop a classification model. This study aimed to characterise sexual dimorphism across a comprehensive panel of lumbar vertebral morphometric parameters in a Central Indian population, and to develop and internally cross-validate a logistic regression model for sex estimation, following the analytical approach used in comparable international forensic morphometric literature [2,3].

## MATERIALS AND METHODS

### Study Design and Specimens

This cross-sectional osteometric study was conducted in the Department of Anatomy, Malwanchal University, Indore, using dry adult human lumbar vertebrae from the departmental osteology collection for which sex was documented in departmental accession records. Of 110 total specimens meeting inclusion criteria (22 at each of L1-L5), 61 were documented male and 49 documented females. The study used exclusively archived, unidentified skeletal material; no living participant was involved, and Institutional Ethics Committee approval was obtained.

Sample size was calculated for the estimation of a population mean with specified precision ($n = (Z1\text{-}\alpha/2)^2\sigma^2/d^2$, Z = 1.96, anticipated σ = 5.1 mm based on Ashish *et al.* [11], d = 1.0 mm), yielding a minimum of 100 specimens, inflated to 110 to allow for exclusions.

### Morphometric Measurements

Nine linear parameters were measured in triplicate using a digital Vernier caliper (accuracy ±0.02 mm): vertebral body height (mid), transverse width and antero-posterior length (superior border), pedicle width (right and left), interpedicular distance, vertebral canal antero-posterior and transverse diameter, and spinous process length, following the protocol of Ashish *et al.* [11] and Panjabi *et al.* [1].

### Statistical Analysis

Descriptive statistics were calculated for male and female specimens for each parameter. Sex differences were tested using independent-samples t-tests with Levene's test for equality of variances (Welch correction applied throughout for methodological consistency) and Cohen's d effect size (interpreted as small ≈0.2, medium ≈0.5, large ≈0.8). A binary logistic regression model for sex classification was constructed using the parameter(s) found to show statistically significant sexual dimorphism. Because in-sample accuracy over-estimates true generalisable performance, ten-fold stratified cross-validation was used: the model was repeatedly trained on nine folds and used to predict the held-out tenth, generating out-of-fold predicted probabilities from which overall accuracy, sensitivity, specificity, and the area under the receiver operating characteristic (ROC) curve were calculated. Analyses used Python (pandas, SciPy, statsmodels, scikit-learn); $p<0.05$ was considered significant.

## RESULTS

Of the nine morphometric parameters examined, two showed statistically significant sexual dimorphism (Table 1). Vertebral body height (mid) was significantly greater in males (29.14±1.49 mm) than females (27.25±1.43 mm; t = 6.77, $p<0.001$), with a large effect size (Cohen's d = 1.29). Vertebral body transverse width (superior) was also significantly greater in males (47.58±3.58 mm) than females (46.02±3.83 mm; t = 2.19, p = .031), with a small-to-moderate effect size (d = 0.42). No other parameter showed a significant sex difference: antero-posterior length (t = -0.75, p = .454, d = -0.14), right pedicle width (t = -0.24, p = .809, d = -0.05), left pedicle width (t = -0.14, p = .886, d = -0.03), interpedicular

Table 1: Sex-Wise Descriptive Statistics and Independent-Samples T-test for Each Morphometric Parameter

| Parameter | Male (n =61) | Female (n = 49) | t | p | d |
|---|---|---|---|---|---|
| Vertebral body height, mid (mm) | 29.14±1.49 | 27.25±1.43 | 6.77 | < .001 | 1.29 |
| Vertebral body transverse width, sup. (mm) | 47.58±3.58 | 46.02±3.83 | 2.19 | 0.031 | 0.42 |
| Vertebral body AP length, sup. (mm) | 32.76±1.51 | 32.97±1.47 | -0.75 | 0.454 | -0.14 |
| Pedicle width, right (mm) | 10.19±1.66 | 10.27±1.78 | -0.24 | 0.809 | -0.05 |
| Pedicle width, left (mm) | 10.19±1.74 | 10.23±1.79 | -0.14 | 0.886 | -0.03 |
| Interpedicular distance (mm) | 26.14±1.67 | 26.14±1.81 | -0.02 | 0.988 | -0.00 |
| Vertebral canal AP diameter (mm) | 18.85±1.43 | 18.96±1.65 | -0.38 | 0.702 | -0.07 |
| Vertebral canal transverse diameter (mm) | 30.93±1.48 | 30.98±1.62 | -0.19 | 0.851 | -0.04 |
| Spinous process length (mm) | 42.88±1.87 | 42.94±1.97 | -0.16 | 0.873 | -0.03 |

Table 2: Cross-Validated Classification Performance of the Logistic Regression Model

| Metric | Value |
|---|---|
| Overall accuracy (10-fold CV) | 83.6% |
| Sensitivity (male) | 85.2% |
| Specificity (female) | 81.6% |
| AUC | 0.904 |
| True positives (male) | 52 |
| True negatives (female) | 40 |
| False positives | 9 |
| False negatives | 9 |

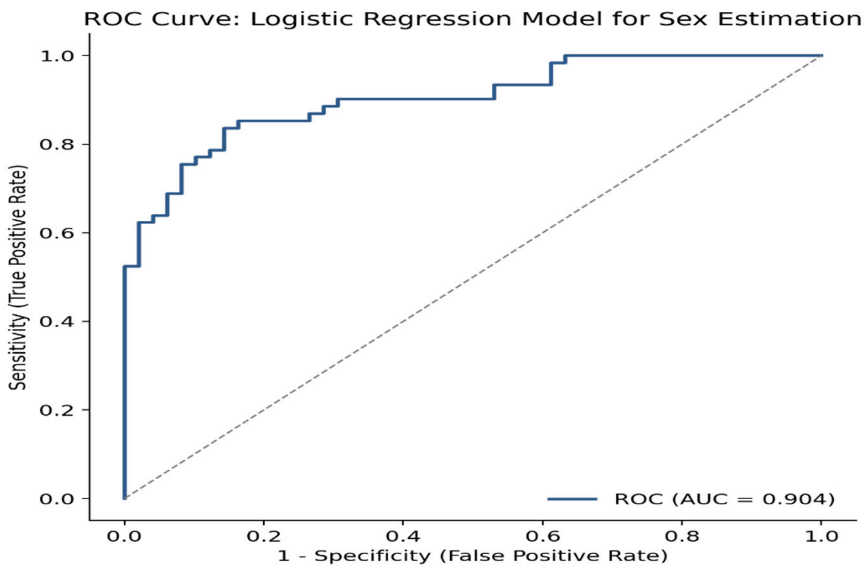


Figure 1: Receiver Operating Characteristic (ROC) Curve for the Logistic Regression Model Estimating Sex from Vertebral Body Height and Transverse Width

distance (t = -0.02, p = .988, d<0.01), canal antero-posterior diameter (t = -0.38, p = .702, d = -0.07), canal transverse diameter (t = -0.19, p = .851, d = -0.04), and spinous process length (t = -0.16, p = .873, d = -0.03). Levene's test did not indicate a significant violation of the equal-variance assumption for any parameter (all p>0.28).

The binary logistic regression model combining vertebral body height and transverse width was: logit(P[Male]) = -30.852+2.188 x [Body height, mid] - 0.654 x (Body transverse width, sup.)

Ten-fold cross-validation gave an overall classification accuracy of 83.6% (92 of 110 specimens correctly classified), with 85.2% sensitivity for male specimens and 81.6% specificity for female specimens (Table 2). The area under the ROC curve was 0.904, indicating excellent discriminatory performance (Figure 1). A univariate model using vertebral body height alone achieved 69.1% cross-validated accuracy (AUC = 0.802), confirming that transverse width contributed meaningful incremental discriminatory information despite its smaller individual effect size.

## DISCUSSION

This study demonstrates that sexual dimorphism in the adult lumbar vertebra in this Central Indian population is concentrated specifically in vertebral body dimensions, height most markedly, and transverse width to a lesser degree, while pedicle, interpedicular, canal, and posterior element dimensions show no significant sex difference. This body-predominant pattern of dimorphism is strongly consistent with the international literature: Bozdag and Karaman [2] similarly found vertebral body and end-plate parameters to be the strongest individual sex discriminators among the Turkish L1 parameters tested, and the systematic review of Rohmani *et al.* [6] concluded that vertebral body measurements consistently rank among the strongest discriminators across the vertebral column as a whole. Hou *et al.* [5], examining the Chinese twelfth thoracic vertebra, likewise found the highest discriminant accuracy among vertebral body and pedicle measurements, though with considerable variation across the thirty measurements tested, illustrating that statistical significance and practical discriminatory value are not synonymous, a distinction reflected in our own reporting of effect sizes alongside p-values.

Our finding that pedicle width showed no significant sex difference contrasts with Yadav *et al.* [10], who reported significantly larger canal and vertebral body dimensions in men across most levels in a North Indian in-vivo cohort. This discrepancy may reflect genuine regional variation in the pattern of sexual dimorphism between the Central Indian dry-bone population studied here and the North Indian in-vivo population, or may reflect that our sample, while adequately powered to detect the large effect size for body height, was comparatively less well powered to detect a smaller pedicle-specific sex effect of the magnitude observed for transverse width (d = 0.42).

Our cross-validated classification performance (83.6% accuracy, AUC = 0.904) compares favourably with the international literature: Bozdag and Karaman [2] reported 69.7-74% accuracy using various Turkish L1 parameter subsets, and the systematic review of Rohmani *et al.* [6] reported a wide range of accuracies across nineteen studies, with vertebral-body-based models generally toward the higher end. A specific feature of our fitted model warrants comment: the coefficient for transverse width became negative when entered jointly with body height, in apparent contradiction to its positive univariate association with male sex. This reflects the strong correlation between the two predictors (r = .836) and represents a statistical suppression effect, a well-recognised phenomenon in multivariate regression, rather than an error; the two-parameter model nonetheless achieved meaningfully superior accuracy (83.6% vs. 69.1% for body height alone), confirming that transverse width carries genuine incremental information despite its counter-intuitive partial coefficient sign.

Consistent with the population-specificity principle formally demonstrated by Hora and Sladek [7] and emphasised throughout the systematic review of Rohmani *et al.* [6], the present model should be regarded as applicable specifically to skeletal remains recovered within, or believed to originate from, the Madhya Pradesh and Central Indian population from which our specimens were drawn, rather than assumed to generalise to other Indian regional populations without independent validation, notwithstanding broad pan-Indian similarities in overall vertebral morphometry [11].

Limitations include the absence of external validation on an independent Central Indian sample, and the absence of documented donor age precluding assessment of age-related change in the dimorphism pattern. The model should be regarded as a preliminary, internally validated tool pending external validation, and should be used alongside, rather than as a replacement for, other available skeletal or contextual evidence in medico-legal casework.

## CONCLUSION

Sexual dimorphism in the adult lumbar vertebra in this Central Indian population is confined principally to vertebral body height and, to a lesser extent, transverse width, rather than distributed across the vertebra as a whole, a pattern consistent with international forensic morphometric literature. A logistic regression model combining these two parameters classified sex with 83.6% cross-validated accuracy and an AUC of 0.904, providing the first population-specific tool for morphometric sex estimation from lumbar vertebral remains recovered within Madhya Pradesh and the wider Central Indian region, pending external validation.

## DECLARATIONS

- **Funding:** This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors
- **Conflicts of Interest:** The authors declare no conflicts of interest
- **Ethical Approval:** This study used archived, unidentified osteological specimens with documented sex from departmental accession records, no living participants were involved. Institutional Ethics Committee approval was obtained prior to commencement
- **Informed Consent:** Not applicable (archived osteological specimens only)
- **Data Availability:** The datasets generated and analysed during the current study are available from the corresponding author on reasonable request
- **Author Contributions: TY:** data collection, formal analysis, writing – original draft. ASB: conceptualisation, supervision, writing – review and editing

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