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MORPHOMETRIC ANALYSIS OF CLAVICULAR MIDSHAFT DIAMETERS AND CURVATURE RADII: IMPLICATIONS FOR FORENSIC IDENTIFICATION AND ORTHOPAEDIC RECONSTRUCTION

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ABSTRACT

Background: The clavicle's cross-sectional morphology and curvatures exhibit significant sexual dimorphism and bilateral asymmetry, rendering it a valuable tool for forensic sex estimation and stature reconstruction. Despite its clinical relevance in fracture fixation, population-specific data for South Indian cohorts remain limited, hindering precise implant design and medico-legal applications. This study quantified midshaft anteroposterior and mediolateral diameters alongside medial and lateral curvature radii to establish normative values and assess dimorphic patterns.

Materials and Methods: A cohort of 250 dry adult clavicles (140 male, 110 female; 125 right, 125 left) from Tamil Nadu osteological collections was analysed. Measurements were obtained using vernier callipers (0.1 mm accuracy) for diameters at the midshaft and a flexible curvature gauge (0.5 mm resolution) for radii. Data were stratified by sex and side, with descriptive statistics (means ± SD, ranges) computed. Independent t-tests evaluated intergroup differences ($p < 0.05$ significant), and discriminant function analysis assessed sex classification accuracy.

Results: Males exhibited significantly larger diameters than females: anteroposterior (8.45 ± 1.12 mm vs. 7.23 ± 0.98 mm, $p < 0.001$) and mediolateral (10.67 ± 1.45 mm vs. 9.12 ± 1.23 mm, $p < 0.001$). Medial curvature radii were tighter on the right (85.2 ± 12.3 mm in males) than left (92.1 ± 14.5 mm, $p = 0.02$), with females showing greater lateral radius asymmetry ($p = 0.04$). Combined diameters yielded 82% accuracy in sex prediction (85% sensitivity for males, 78% for females). No significant correlations existed between diameters and radii ($r < 0.12$, $p > 0.2$).

Conclusion: These findings delineate sex- and side-specific clavicular morphometrics in a South Indian population, enhancing forensic profiling efficacy and informing contoured orthopaedic implants to reduce fixation failures. The data underscore ethnic variability, advocating for localized norms in anthropology and surgery. Future research integrating 3D morphometry could refine these metrics for broader applicability.

Keywords: Clavicle, Midshaft Diameters, Curvature Radius, Sexual Dimorphism, Forensic Anthropology, Orthopaedic Fixation.

INTRODUCTION

The clavicle, a slender double-curved bone that serves as the sole osseous connection between the upper limb and the trunk, plays a pivotal role in the biomechanics of the shoulder girdle, transmitting forces from the arm to the axial skeleton while permitting a wide range of scapulothoracic motion.[1] Its distinctive S-shaped morphology arises from a medial convexity and lateral concavity, with cross-sectional profiles transitioning from a flattened ovoid configuration at the acromial end to a more rounded form near the sternal articulation; these features not only enhance structural efficiency under torsional loads but also reflect adaptations to locomotor demands in Homo sapiens.[2] Midshaft diameters, in particular, provide robust indicators of skeletal robusticity and sexual dimorphism, as males typically exhibit greater mediolateral and anteroposterior dimensions due to higher mechanical loading from muscle attachments and body size disparities.[3]

In forensic anthropology, the clavicle's relative durability against taphonomic processes—such as fragmentation or erosion—positions it as a superior element for biological profiling, enabling sex estimation with accuracies of 75–85% and stature reconstruction via regression equations that incorporate length and diameter metrics.[4,5] These applications are especially pertinent in mass disasters or archaeological contexts, where upper limb bones like the humerus may be underrepresented, yet clavicular data can yield reliable demographic insights.[4] Clinically, midshaft clavicle fractures constitute 2.6–5% of all adult skeletal injuries, predominantly resulting from high-energy trauma such as falls or vehicular accidents, and often necessitate surgical intervention via plating or intramedullary nailing.[6] However, the efficacy of these procedures is compromised by the bone's inherent curvatures, which demand intraoperative contouring of fixation devices; mismatches in plate geometry can precipitate malunion rates of up to 18% or hardware failure due to stress concentrations at the midshaft.[7]

Population-specific morphometric variations further complicate these challenges. Global anthropometric surveys indicate ethnic gradients in clavicular dimensions: for instance, European cohorts display midshaft mediolateral diameters averaging 10–12 mm, whereas Asian populations exhibit narrower profiles (8–10 mm), attributable to differences in genetic heritage, nutrition, and occupational ergonomics.[8,9] In India, inter-regional disparities are pronounced; studies from northern populations report male midshaft anteroposterior diameters of 9.5 ± 1.2 mm,[10] yet comparable data from southern cohorts, such as Tamil Nadu, are conspicuously absent, limiting the generalizability of forensic models and the customization of orthopaedic implants for local demographics.[11] Bilateral asymmetries in curvature radii—often more pronounced on the dominant side due to handedness-related biomechanical biases—add another layer of complexity, with right-handed individuals showing subtly tighter medial radii on the right clavicle.[12]

This investigation addresses these gaps by quantifying midshaft anteroposterior and mediolateral diameters, as well as medial and lateral curvature radii, in a cohort of dry adult clavicles from Tamil Nadu. We hypothesize significant sexual dimorphism in diameters and subtle side-specific differences in curvatures, informed by evolutionary principles of upper limb functionality. By establishing normative values for this understudied population, the study seeks to enhance the precision of forensic identification algorithms, optimize pre-contoured fixation devices to mitigate surgical complications, and contribute to bioarchaeological understandings of modern human skeletal variation.

MATERIALS AND METHODS

This cross-sectional observational study was conducted on a cohort of dry, macerated adult human clavicles sourced from osteological teaching collections at Departments of Anatomy, GMC, Ongole, Kadapa, Andhra Pradesh, Wanaparthy, Telangana and BMC&RI, Bangalore, Karnataka.[13] The study adhered to ethical guidelines for research on archival human remains, with institutional approvals obtained from the respective anatomy departments, ensuring no additional ethical clearance was required given the non-identifiable, historical nature of the specimens.[14] Data collection occurred between January and June 2024, focusing on morphometric parameters without any interventions or follow-up, in line with STROBE recommendations for reporting observational studies.[15]

A total of 250 complete, intact adult clavicles were included after systematic screening from available collections exceeding 500 specimens per institution. Eligibility criteria encompassed morphological integrity, with exclusions applied for any evidence of fractures, pathological deformities (e.g., osteophytes or erosions), congenital anomalies, postmortem artifacts (e.g., rodent damage), or incomplete ossification suggestive of sub-adult status.[16] Specimens were stratified by biological sex (140 male, 110 female) and laterality (125 right, 125 left) to ensure balanced representation, reflecting the natural distribution in the collections. Sex determination followed standard forensic anthropological protocols, integrating multiple indicators from associated skeletal elements of the same donor, including pelvic features (e.g., greater sciatic notch angle and subpubic angle) and cranial traits (e.g., mastoid process robusticity and supraorbital margin development), achieving over 95% concordance across assessments by two independent observers.[17,18] Age estimation, where documented, confirmed all specimens as adults (≥20 years) based on epiphyseal fusion at the sternal and acromial ends,[19] though precise ages were unavailable for the majority due to the archival context.(Figure 1)

The primary outcome variables were midshaft anteroposterior and mediolateral diameters, along with medial and lateral curvature radii, selected for their established utility in forensic dimorphism and orthopaedic templating.[20] Total clavicular length was measured secondarily along the superior border for normalization and contextualization. All measurements were performed non-invasively using standardized manual instrumentation to minimize observer variability. Anteroposterior diameter was quantified at the midshaft (precisely 50% of total length from the sternal facet) perpendicular to the longitudinal axis, while mediolateral diameter was captured orthogonally at the same locus, employing digital vernier calipers (Mitutoyo Corporation, Japan; resolution 0.1 mm) to compress any residual soft-tissue adhesions gently.[21] Curvature radii were assessed geometrically using a flexible acrylic curvature gauge (custom-fabricated template with 0.5 mm gradations): the medial radius encompassed the arc of the sternal two-thirds of the bone, and the lateral radius spanned from midshaft to acromial end, with the gauge aligned superiorly for reproducibility.[22] To address potential measurement bias, each parameter was recorded three times by a single trained observer (RK) under consistent ambient lighting and magnification (2x loupe), with the arithmetic mean used for analysis; intra-observer reliability was validated via intraclass correlation coefficients (ICC > 0.95 for all metrics), mitigating errors from bone orientation or instrument placement.[23]

Sample size was determined a priori based on power calculations for detecting moderate sex differences (effect size d = 0.6) in midshaft diameters, assuming $\alpha = 0.05$ and power = 0.80, yielding a minimum of 100 per sex group; the final cohort of 250 exceeded this to accommodate subgroup analyses by side and enhance generalizability within the South Indian population.[24] No formal blinding was feasible due to the descriptive nature of the study, but sequential randomization of specimens prevented selection bias. Data were entered into a secure Excel spreadsheet (Microsoft Corporation, version 16.0) and analysed using GraphPad Prism software (version 9.0, GraphPad Software, San Diego, CA, USA).[25] Normality of distributions was confirmed via Kolmogorov-Smirnov tests (all $p > 0.05$), justifying parametric approaches. Descriptive statistics included means ± standard deviations (SD), medians, ranges, and frequencies, stratified by sex and side. Between-group comparisons employed independent Student's t-tests for continuous variables, with Cohen's d for effect sizes; paired t-tests assessed side differences within sexes. Discriminant function analysis was applied to combined diameters for sex classification accuracy, incorporating Wilks' lambda for model fit.[26] Statistical significance was set at $p < 0.05$ (two-tailed), with no adjustments for multiple comparisons given the exploratory design. No missing data occurred, as incomplete measurements were re-assessed immediately.

Figure 1. Materials used for study

RESULTS

The morphometric analysis of 250 adult clavicles revealed pronounced sexual dimorphism in midshaft diameters, with males consistently exhibiting greater anteroposterior and mediolateral dimensions compared to females, reflecting underlying differences in skeletal robusticity and body size. Bilateral asymmetries were minimal for diameters but more evident in curvature radii, particularly for medial curvatures in males and lateral curvatures in females. These patterns align with biomechanical adaptations to upper limb dominance and load distribution, as evidenced by the statistically significant inter-sex differences ($p < 0.001$) and select side-specific variations ($p < 0.05$). Descriptive statistics, including means, standard deviations (SD), ranges, and sample sizes (n), are stratified by sex and side in the following tables. No outliers were identified via boxplot inspections, and all data distributions were approximately normal, supporting the use of parametric tests.

Midshaft diameters underscored the dimorphic gradient, with overall anteroposterior values averaging 7.89 ± 1.15 mm and mediolateral values 9.98 ± 1.42 mm across the cohort. Males demonstrated dimensions approximately 14–17% larger than females, a disparity that held across both sides without significant laterality effects ($p > 0.05$ for right-left comparisons). This uniformity suggests symmetrical developmental influences on cross-sectional growth, though female variability (higher SDs) hints at greater heterogeneity potentially linked to reproductive or nutritional factors. Table 1 presents these metrics in detail, highlighting the robust sex effect sizes (Cohen's d > 0.8) that render midshaft diameters reliable discriminators in forensic contexts.

Table 1: Midshaft Diameters by Sex and Side

Parameter	Side	Mean (mm)	SD (mm)	Range (mm)	n
Anteroposterior Diameter					
Males	Right	8.42	1.15	6.0–10.8	70
	Left	8.48	1.10	6.5–11.2	70
	Overall	8.45	1.12	6.2–11.0	140
Females	Right	7.20	1.00	5.0–9.3	55
	Left	7.26	0.96	5.2–9.7	55
	Overall	7.23	0.98	5.1–9.5	110

Note: Sex differences significant (independent t-test, $p < 0.001$; Cohen's d = 1.12 for anteroposterior, d = 1.05 for mediolateral). No significant side differences ($p > 0.05$).

Curvature radii further illuminated functional asymmetries, with medial radii averaging 88.6 ± 13.4 mm and lateral radii 76.2 ± 11.8 mm overall. Males displayed steeper curvatures (smaller radii), indicative of enhanced torsional resistance, while females exhibited more pronounced bilateral dispersion, particularly in lateral radii ($p = 0.04$ for side difference). The tighter right medial radius in males ($p = 0.02$) supports handedness-related remodeling, where dominant-side bones adapt to repetitive overhead activities by accentuating inner bends. These findings, summarized in Table 2, emphasize the need for side-specific templating in implant design, as deviations exceeding 10 mm from norms could influence surgical trajectories.

Table 2: Curvature Radii by Sex and Side

Parameter	Side	Mean (mm)	SD (mm)	Range (mm)	n
Medial Radius					
Males	Right	85.2	12.3	62–110	70
	Left	92.1	14.5	68–128	70
	Overall	88.7	13.7	62–128	140
Females	Right	90.4	13.1	65–115	55
	Left	88.7	12.8	64–112	55
	Overall	89.6	13	64–115	110
Lateral Radius					
Males	Right	74.5	10.9	52–96	70
	Left	78.3	12.2	55–102	70
	Overall	76.4	11.6	52–102	140
Females	Right	76.8	11.5	54–98	55
	Left	80.1	13	58–106	55
	Overall	78.4	12.3	54–106	110

Note: Male right-left medial difference significant (paired t-test, $p = 0.02$; d = 0.50). Female lateral side difference significant ($p = 0.04$; d = 0.28). Overall sex differences marginal ($p = 0.08$).

To evaluate the forensic applicability of these metrics, discriminant function analysis was performed using combined anteroposterior and mediolateral diameters, yielding a classification accuracy of 82% for sex determination (Wilks' lambda = 0.72, $p < 0.001$). Sensitivity was higher for males (85%) than females (78%), consistent with the greater male variability and overlap in smaller dimensions. Curvature radii contributed modestly when included in stepwise models (incremental accuracy +4%), suggesting diameters as primary predictors. Table 3 outlines the discriminant function coefficients and classification matrix, illustrating the model's cross-validated performance, which outperforms length-based alternatives (76% accuracy in prior studies) and supports midshaft measurements for fragmented remains.

Table 3: Discriminant Function Analysis for Sex Classification Using Midshaft Diameters

Metric	Standardized Coefficient	Unstandardized Coefficient (B)	F-to-Enter	Classification Accuracy (%)
Anteroposterior Diameter	0.62	1.45	28.4	-
Mediolateral Diameter	0.58	1.32	25.7	-
Classification Matrix				
Predicted Sex	Actual Male (%)	Actual Female (%)		Overall
Male	85 (119/140)	22 (24/110)		82
Female	15 (21/140)	78 (86/110)		

Note: Function equation: $Z = -12.3 + 1.45(AP) + 1.32(ML)$. Cross-validated via leave-one-out method. Threshold $Z = 0$ for classification.

Exploratory correlations between parameters revealed weak associations, with no significant links between diameters and radii (Pearson's r ranging from -0.08 to 0.11, all $p > 0.20$), implying independent ontogenetic controls—diameters influenced by appositional growth and curvatures by endochondral remodeling. Similarly, total length (measured secondarily: males 148.2 ± 9.8 mm, females 136.5 ± 8.7 mm; $p < 0.001$) correlated modestly with diameters ($r = 0.42–0.51$, $p < 0.01$) but not with radii ($r < 0.15$), reinforcing the value of cross-sectional metrics for isolated bone analysis. These results collectively establish a normative dataset for South Indian clavicles, highlighting dimorphic and asymmetric features with direct translational potential.

DISCUSSION

The findings from this morphometric analysis of 250 South Indian adult clavicles affirm the clavicle's utility as a sexually dimorphic marker, with midshaft anteroposterior and mediolateral diameters exhibiting robust inter-sex differences (14–17% larger in males), consistent with patterns of greater male skeletal robusticity driven by androgen-mediated periosteal apposition and higher mechanical loading during growth.[26,27] These dimensions—averaging 8.45 ± 1.12 mm anteroposterior and 10.67 ± 1.45 mm mediolateral in males—align closely with North Indian cadaveric data reporting 9.5 ± 1.2 mm anteroposterior values,[10] yet fall within the narrower spectrum observed in Asian cohorts (7–9 mm anteroposterior) compared to broader Caucasian profiles (9–11 mm),[8,28] underscoring ethnic influences possibly modulated by genetic (e.g., COL1A1 polymorphisms) and environmental factors such as stature variations (South Indian males averaging 165–170 cm).[29] The absence of significant side differences in diameters supports symmetrical cross-sectional development, as posited by Wolff's law for balanced load distribution across the shoulder girdle,[2] though elevated female SDs (±0.98–1.23 mm) suggest greater intrasex variability, potentially attributable to estrogen fluctuations during reproductive phases that attenuate bone accrual.[30]
Curvature radii provided nuanced insights into bilateral asymmetry, with males displaying tighter right medial radii (85.2 ± 12.3 mm vs. 92.1 ± 14.5 mm left; $p = 0.02$), a pattern evoking handedness biases where dominant-side bones undergo adaptive remodeling to optimize torque during unilateral activities like throwing or tool use.[12,31] This rightward medial accentuation echoes 3D analyses of European clavicles, which documented 5–8 mm smaller dominant-side radii linked to upper limb laterality rates exceeding 90% in modern populations.[22] In females, the more pronounced left lateral radius (80.1 ± 13.0 mm vs. 76.8 ± 11.5 mm right; $p = 0.04$) may reflect compensatory flaring for pelvic alignment during gestation or bipedal gait stabilization, aligning with sexual selection theories for enhanced maternal skeletal plasticity.[15,32] Overall, the marginal sex effect on radii ($p = 0.08$) contrasts with stronger dimorphism in diameters, implying curvatures are more environmentally tuned, as evidenced by the lack of correlations with length ($r < 0.15$), which supports independent endochondral versus appositional growth trajectories.[19,33]
Forensically, the 82% sex classification accuracy from combined diameters surpasses traditional length-based models (70–76%) and rivals multivariate approaches incorporating pelvic metrics,[4,34] with higher male sensitivity (85%) mirroring the bone's greater male size variance that buffers against misclassification in fragmented remains—a common taphonomic challenge in tropical climates like South India's.(35) Integrating these midshaft norms into discriminant equations ($Z = -12.3 + 1.45[AP] + 1.32[ML]$) could elevate biological profiling precision in medico-legal investigations, particularly for unidentified decedents in high-trauma regions, where clavicles persist in 60–70% of cases.[3,36] The modest contribution of radii (+4% accuracy) highlights diameters as primary discriminators, yet their inclusion in advanced algorithms could refine individualization, especially for stature estimation, where midshaft data boost regression R^2 by 10–15% over length alone.[5,37]
Clinically, these population-specific metrics hold promise for orthopedic innovation, as narrower South Indian diameters necessitate downsized intramedullary nails (8–10 mm caliber) to avert iatrogenic fractures, while asymmetric radii inform pre-contoured locking plates that reduce intraoperative bending—associated with 12–18% failure rates in mismatched fixations.[7,38] For midshaft fractures, comprising 80% of clavicular injuries, superiorly aligned plates contoured to 85–90 mm medial radii could enhance union rates by 20–25%, mitigating complications like nonunion (5–10%) in resource-limited settings.[6,39] The observed ethnic gracility further advocates for region-tailored implant libraries, potentially decreasing revision surgeries in diverse demographics.[40]
Limitations of this study include its reliance on dry bone collections, which may underestimate in vivo soft-tissue overlays on curvatures, and the regional sampling from Tamil Nadu, limiting extrapolation to pan-Indian or global populations despite broad ethnic representation.[41] Manual measurements, while reliable (ICC > 0.95), lack the sub-millimeter resolution of CT-based morphometry, though vernier calipers ensured accessibility for resource-constrained research.[21] Future investigations should validate these norms via 3D laser scanning of live cohorts to quantify dynamic asymmetries under load, incorporate genetic markers for dimorphism heritability, and extend to pediatric samples for longitudinal growth modeling.[42,43] Ultimately, this dataset bridges forensic anthropology and clinical orthopedics, furnishing actionable insights to

optimize skeletal profiling and fracture management in South Indian contexts, where clavicular injuries burden 1–2% of trauma admissions annually.[44]

CONCLUSION

This study establishes normative morphometric profiles for clavicular midshaft diameters and curvature radii in a South Indian cohort, revealing significant sexual dimorphism (14–17% larger male dimensions) and subtle bilateral asymmetries (e.g., tighter right medial radii in males), with combined diameters achieving 82% accuracy in forensic sex estimation. These findings enhance biological profiling in medico-legal contexts and inform tailored orthopedic implants to optimize fracture fixation outcomes, mitigating complications in diverse populations.

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