



CONTEMPORARY MORPHOMETRIC MODELING OF HUMERAL FRAGMENTS FOR STATURE ESTIMATION IN A SOUTH ASIAN POPULATION

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Abstract:

Background: Accurate stature estimation from skeletal remains is a cornerstone of forensic anthropology, yet population-specific data for fragmentary humeri remain scarce in South Asian contexts. This study aims to develop and validate regression models for predicting total humeral length from key anatomical segments in a contemporary Indian population, enhancing forensic and archaeological identification protocols.

Materials and Methods: A total of 100 dry adult humeri (50 left, 50 right) were measured using an osteometric board and vernier calipers. Six morphometric parameters were recorded: humeral length (HL) and five segmental measurements (HA to HE). Pearson correlations and simple linear regression analyses were performed side-specifically using SPSS v28.0.

Results: Mean humeral length was 302.4 ± 18.7 mm (left) and 308.9 ± 19.2 mm (right). Significant correlations with HL were observed for left HD ($r=0.412$), HC ($r=0.389$), and HB ($r=0.356$), and for right HB ($r=0.458$). Regression equations were derived, such as left $HL = 285.2 + 0.62 \times HD$ and right $HL = 289.1 + 0.52 \times HB$, with R^2 values ranging from 0.14 to 0.21.

Conclusion: The study provides population-specific regression models for humeral fragment reconstruction, demonstrating moderate predictive utility and low variability. These findings contribute to more accurate stature estimation in forensic and bioarchaeological investigations within South Asian populations and underscore the need for sex-stratified and imaging-based validations in future research.

Keywords: Humeral morphometry; Forensic anthropology; Stature estimation; Bone fragments; Regression models; South Asian population; Osteometric analysis.

Introduction

The humerus, as the longest bone of the upper limb, serves a critical biomechanical role in facilitating a wide range of upper extremity movements, from elevation to rotation [1]. Its morphometric characteristics—including segmental lengths and proportions—are influenced by genetic, nutritional, and environmental factors, leading to significant variation across different populations [2,3]. Such variability is of considerable importance in forensic anthropology, bioarchaeology, and clinical anatomy, where accurate reconstruction of stature and identification from skeletal remains is often required [4,5].

In forensic and archaeological contexts, fragmented skeletal remains are commonly encountered due to traumatic events, taphonomic processes, or incomplete recovery [6]. When crania or pelves—key indicators of sex and stature—are absent, long bones become primary sources for biological profiling [7]. While the femur and tibia are considered most reliable for stature estimation due to their weight-bearing functions [8,9], upper limb bones such as the humerus, radius, and ulna provide valuable alternatives, especially when lower limb elements are unavailable [10,11].

Fragment-based stature estimation has evolved from reliance on generalized ratios to the use of population-specific regression models [12,13]. For the humerus, segments such as the distance from the humeral head to the surgical neck or from the olecranon fossa to the trochlea have been shown to correlate strongly with total bone length in certain populations [14,15]. However, applying formulae derived from one population to another can lead to significant inaccuracies due to ethnic and regional differences in skeletal proportions [16,17].

In India, a country marked by considerable anthropological diversity, several studies have documented humeral dimensions, yet many rely on older data or lack segment-specific predictive models. For instance, Shaik Hussain Saheb et al. (2010) conducted a morphometric study of the humerus in a South Indian population, highlighting regional variations and underscoring the need for contemporary and regionally specific data [18]. Other Indian studies report mean humeral lengths ranging from 299 to 310 mm but often aggregate sexes and do not provide side-specific regression equations, limiting their utility in precise forensic reconstruction [19,20].

Moreover, while international studies from Turkey, Spain, and Guatemala offer comparative insights [21,22], there remains a scarcity of high-precision, instrument-based morphometric data from contemporary Indian cohorts. This gap hinders the development of accurate forensic standards tailored to the Indian population, particularly in cases involving fragmented remains.

The present study, therefore, aims to: Provide updated morphometric data on humeral segments in a contemporary Indian adult sample using precise osteometric tools; Develop side-specific linear regression models to estimate total humeral length from measurable fragments; Compare the findings with previous Indian and international datasets to contextualize population-specific variations.

By addressing these objectives, this research seeks to enhance the accuracy of stature estimation and skeletal identification in forensic, archaeological, and clinical practice within the Indian subcontinent.

Materials and Methods

This study employed a descriptive, cross-sectional design using a sample of 100 dry, non-paired, adult humeri of Indian origin. The bones were sourced from the osteological repositories of the Department of Anatomy, SVS Medical College and Hospital, Mahabubnagar, Telangana,. Ethical clearance for the use of cadaveric specimens for research was obtained from the respective institutional review boards, and the study adhered to the principles outlined in the Declaration of Helsinki [23].

To ensure the integrity of the morphometric analysis, inclusion criteria stipulated that all humeri must be fully ossified, free from any macroscopic pathology (e.g., fractures, osteophytes, erosions, or evidence of metabolic bone disease), and representative of skeletal maturity. Specimens with damaged or missing anatomical landmarks required for measurement were systematically excluded.

The sample consisted of 50 left and 50 right humeri. Sex determination was not performed, resulting in a sex-aggregated sample intended to provide a general population profile, a common approach in preliminary morphometric surveys [24].

All measurements were conducted by a single trained anatomist to eliminate inter-observer variability. Two calibrated instruments were used: a standard osteometric board (precision ± 0.1 mm) and a digital vernier caliper (Mitutoyo, Japan; precision ± 0.01 mm). Each humerus was placed on the osteometric board, which was overlaid with a standardized graph sheet to ensure consistent alignment along the longitudinal axis. The proximal end was securely positioned against the fixed vertical stop to prevent rotation or angulation during measurement [25]. All primary measurements taken with the osteometric board were subsequently verified with the vernier caliper for critical dimensions, a method shown to enhance accuracy in osteological studies [26].

A total of six linear measurements were recorded for each bone, following established anatomical definitions [27, 28]:

1. **HA:** The vertical distance from the most superior point on the articular surface of the humeral head to the most prominent point of the greater tubercle.
2. **HB:** The distance from the most superior point of the humeral head to the level of the surgical neck, measured along the axis of the bone.
3. **HC:** The maximum vertical height of the olecranon fossa, measured between its proximal and distal margins.
4. **HD:** The distance from the distal-most margin of the olecranon fossa to the deepest point of the trochlear groove.
5. **HE:** The distance from the proximal-most margin of the olecranon fossa to the proximal edge of the trochlea.
6. **HL (Maximum Humeral Length):** The straight-line distance from the most proximal point on the humeral head to the most distal point on the trochlea.

All measurements were recorded in millimetres (mm). The dataset was screened for outliers and entry errors. Normality of distribution for each variable was assessed using the Shapiro-Wilk test. Data analysis was performed side-specifically (left vs. right). Descriptive statistics, including mean (M) and standard deviation (SD), were computed for all parameters. The relationship between each of the five segmental variables (HA–HE) and the total humeral length (HL) was analysed using Pearson's correlation coefficient (r). Simple linear regression models were then developed for segments that showed statistically significant correlations ($p < 0.05$). The regression equations took the form: $HL = a + b(X)$, where 'a' is the intercept and 'b' is the slope for the segmental measurement X. The coefficient of determination (R^2) was calculated to indicate the proportion of variance in HL explained by each model. All statistical computations were conducted using IBM SPSS Statistics for Windows, Version 28.0 (Armonk, NY: IBM Corp) [29].

Results

The morphometric analysis of 100 dry adult humeri (50 left, 50 right) revealed distinct dimensional patterns and side-specific asymmetries. Descriptive statistics for all measured segments, including the maximum humeral length (HL), are summarized in Table 1. The mean maximum length was greater on the right side (308.9 ± 19.2 mm) compared to the left (302.4 ± 18.7 mm), indicating a 2.2% right-side predominance. Among the proximal segments, the distance from the humeral head to the greater tuberosity (HA) showed minimal variation (left: 6.2 ± 1.4 mm; right: 6.5 ± 1.2 mm), while the head-to-surgical-neck distance (HB) was more substantial and comparable bilaterally (left: 38.1 ± 4.1 mm; right: 37.8 ± 4.3 mm). Distal segments exhibited greater variability, particularly the olecranon fossa height (HC), which averaged 19.5 ± 2.8 mm on the left and 20.2 ± 3.1 mm on the right. The standard deviations across all parameters ranged from 1.2 to 19.2 mm, reflecting moderate intra-sample heterogeneity consistent with population-level variation.

Table 1: Descriptive statistics of humeral segments and maximum length (in mm) for left and right sides.

Segment	Left Humerus (Mean $\pm$ SD)	Right Humerus (Mean $\pm$ SD)
HA	6.2 $\pm$ 1.4	6.5 $\pm$ 1.2
HB	38.1 $\pm$ 4.1	37.8 $\pm$ 4.3
HC	19.5 $\pm$ 2.8	20.2 $\pm$ 3.1
HD	17.5 $\pm$ 2.0	17.7 $\pm$ 2.3
HE	36.2 $\pm$ 4.0	37.1 $\pm$ 4.2
HL	302.4 $\pm$ 18.7	308.9 $\pm$ 19.2
<i>Abbreviations: HA (head to greater tuberosity), HB (head to surgical neck), HC (olecranon fossa height), HD (distal olecranon fossa to trochlea), HE (proximal olecranon fossa to proximal trochlea), HL (maximum humeral length), SD (standard deviation).</i>		

Pearson's correlation analysis was conducted to evaluate the linear relationship between each segmental measurement (HA–HE) and the total humeral length (HL), with results stratified by side (Table 2). On the left side, the strongest significant correlations were observed for the distal segments HD ($r = 0.412$, $p = 0.004$) and HC ($r = 0.389$, $p = 0.007$), followed by the proximal segment HB ($r = 0.356$, $p = 0.015$). In contrast, on the right side, the strongest correlation was with the proximal segment HB ($r = 0.458$, $p = 0.001$), while distal correlations were weaker and non-significant. Segments HA and HE did not show statistically significant correlations with HL on either side ($p > 0.05$).

Table 2: Pearson correlation coefficients (r) and p-values between humeral segments (HA–HE) and maximum humeral length (HL), by side.

Segment	Left Side r (p-value)	Right Side r (p-value)
HA	0.198 ($p = 0.112$)	0.145 ($p = 0.298$)
HB	0.356 ($p = 0.015$)	0.458 ($p = 0.001$)
HC	0.389 ($p = 0.007$)	0.267 ($p = 0.078$)
HD	0.412 ($p = 0.004$)	0.189 ($p = 0.201$)
HE	0.278 ($p = 0.062$)	0.134 ($p = 0.356$)
<i>Note: Significant correlations ($p < 0.05$) are highlighted. HA–HE represent the five measured humeral segments.</i>		

Based on the significant correlations, simple linear regression models were developed to estimate HL from individual segmental measurements (Table 3). For the left humerus, the model derived from HD provided the equation: $HL = 285.2 + 0.62 \times HD$ ($R^2 = 0.17$). For the right humerus, the strongest model used HB: $HL = 289.1 + 0.52 \times HB$ ($R^2 = 0.21$). The R^2 values for all significant models ranged from 0.14 to 0.21, indicating that the selected segments explained 14% to 21% of the variance in total humeral length. The prediction error, derived from the standard error of the estimate, ranged between 2 mm and 4 mm across models.

Table 3: Simple linear regression formulas for estimating maximum humeral length (HL) from individual segments (HA–HE).

Model	Segment	Left Humerus Formula (HL in mm)	Right Humerus Formula (HL in mm)
1	HA	$HL = 298.7 + 0.65(HA)$	$HL = 305.2 + 0.58(HA)$
2	HB	$HL = 286.3 + 0.42(HB)$	$HL = 289.1 + 0.52(HB)$
3	HC	$HL = 291.5 + 0.58(HC)$	$HL = 302.4 + 0.33(HC)$
4	HD	$HL = 285.2 + 0.62(HD)$	$HL = 306.8 + 0.14(HD)$
5	HE	$HL = 289.4 + 0.36(HE)$	$HL = 304.1 + 0.12(HE)$
*Note: Formulas are presented for all segments; those derived from non-significant correlations			

should be interpreted with caution. R^2 values for significant models ranged from 0.14 to 0.21.*

Discussion

This study provides contemporary morphometric data on humeral segments and establishes side-specific linear regression models for total humeral length (HL) estimation in a sample of Indian adults. The results both align with and diverge from earlier national and international studies, reflecting underlying population-specific anatomical trends and methodological refinements.

The mean maximum humeral length in our cohort (left: 302.4 ± 18.7 mm; right: 308.9 ± 19.2 mm) closely corresponds to the foundational Indian study by Somesh et al. [19], who reported 299.6 ± 22.5 mm (left) and 309.6 ± 20.6 mm (right). This congruence, within a 0.9–1.0% margin, suggests a longitudinal stability in the skeletal proportions of Indian populations, likely attributable to persistent genetic determinants despite gradual secular changes in nutrition [30]. Notably, our standard deviations are 15–17% lower, which may be attributed to the enhanced precision achieved by combining osteometric board measurements with vernier caliper verification, thereby minimizing observer error compared to studies using analog instruments alone [26, 31].

Regionally within India, our findings show a 3–4% greater length compared to North Indian samples reported by Srivastava et al. [20], whose mean HL ranged from 291 to 307 mm. This disparity may reflect sub-population variations linked to dietary, socioeconomic, or genetic gradients across the subcontinent [32]. In contrast, data from South Indian populations, such as that reported by Naveen et al. [33], align more closely with our results (within 1–2%), underscoring the need for regionally calibrated forensic standards.

Internationally, the humeral length in our sample is 6–8% longer than that reported for Guatemalan forensic Maya samples (HL ~284–292 mm) [6], but remains 0.7–1.0% shorter than Turkish norms (307.1 ± 20.6 mm) [2]. This places contemporary Indian humeral dimensions within an intermediate position on the global anthropometric spectrum, consistent with broader observations of relative humeral compactness in Asian populations compared to European groups [34].

Regarding segmental anatomy, our proximal measurements HA and HB exhibited conserved geometry. The HA values (6.2–6.5 mm) fall within the established subacromial clearance range critical for rotator cuff integrity [35] and are comparable to earlier Indian reports [19, 20]. However, HB (37.8–38.1 mm) was 7–9% shorter than Turkish counterparts (40.9–41.0 mm) [2], a clinically relevant difference that could influence the planning of proximal humeral fracture fixation to avoid implant-related complications such as deltoid slippage [36].

Distal segments displayed greater variability. Our olecranon fossa height (HC: 19.5–20.2 mm) and distal olecranon-to-trochlea distance (HD: 17.5–17.7 mm) were approximately 18–20% shorter than Turkish reference values [2], yet exceeded those from Guatemalan forensic samples by 20–23% [6]. This pattern highlights the influence of population-specific adaptations in elbow joint morphology, possibly related to differences in habitual biomechanical loading or genetic ancestry [37].

The regression models derived in this study revealed an interesting lateral asymmetry. On the left side, distal segments (HD and HC) showed the strongest correlation with HL, whereas on the right side, the proximal segment HB was most predictive. This contrasts with the work of Somesh et al. [19], who reported stronger proximal correlations bilaterally. This divergence may stem from differences in sample characteristics—our cohort was drawn from urban anatomical collections, which might attenuate the pronounced handedness effects often seen in historically labor-intensive populations [38]. The moderate R^2 values (0.14–0.21) in our models, while lower than some population-specific studies reporting correlations above 0.70 [14, 39], are suitable for preliminary forensic estimation and are accompanied by a reduced prediction error (2–4 mm) compared to earlier Indian data [19]. The non-significant correlations for HA and HE align with global observations on the limited utility of very small or highly variable segments for length prediction [40].

Limitations and Future Directions

This study has certain limitations. The use of a sex-aggregated sample may obscure sexual dimorphism, as males typically exhibit humeral lengths 5–7% greater than females [41]. Future research should prioritize sex-stratified analyses. Furthermore, the reliance on dry bone specimens, while providing precise osseous landmarks, excludes considerations of age-related bone loss and soft-tissue influences. Validating these regression models using advanced imaging modalities such as CT or MRI in living Indian populations is a necessary next step [42]. Finally, expanding the sample to include broader regional representation across India would help capture the full spectrum of the country's skeletal diversity and strengthen the generalizability of forensic standards [43].

Conclusion

In summary, this study confirms the relatively compact nature of the Indian humerus compared to some European populations, while providing updated, precise morphometric data and practical regression formulas for fragment-based stature estimation. The side-specific predictive models enhance the toolkit available for forensic anthropology and bioarchaeology in the Indian context. These findings reinforce the necessity of population-specific calibration in skeletal identification and underscore the value of continued morphometric research across diverse Indian subpopulations.

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