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Original Research Article

Estimation of Stature Using Metrical Parameters of Upper Limb Long Bones in Humans

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Abstract:

Background: Forensic anthropology is an essential component for the identification of an unknown individual through skeletal analysis; estimating stature has always been a primary investigator. Long bones of the upper limb, particularly the humerus, radius, and ulna, are used to estimate stature because they are often preserved with skeletal remains.

Aim: To develop reliable, sex-specific regression models for stature estimation based on the morphometric analysis of upper limb long bones.

Methodology: A descriptive cross-sectional study was undertaken on 120 adult human skeletal specimens (45 males, 75 female subjects). Specimens were obtained from all the adult human skeletal remains housed at Netaji Subhas Medical College, Bihta, Patna. A number of measurements were taken on specific bones with measurements taken by using standard osteometric instruments. The known statures were used for regression analysis. Data were statistically analyzed using SPSS v27 to derive predictive equations.

Results: Among the three bones, the ulna showed the strongest correlation with stature in both males ($r = 0.64$; $r^2 = 0.41$) and females ($r = 0.55$; $r^2 = 0.30$), followed by the radius and humerus. The standard error of estimate was lowest for the ulna, indicating higher accuracy. Regression formulas based on ulna length yielded highly precise height predictions with minimal differences (±0.05–0.43 cm) from actual stature.

Conclusion: The ulna is the most reliable predictor of stature among upper limb long bones. Sex-specific regression equations developed in this study offer an accurate and practical method for forensic stature estimation, especially when complete skeletons are unavailable.

Keywords: Forensic Anthropology, Regression Model, Radius, Skeletal Remains, Stature Estimation, Ulna, Humerus.

Introduction

Forensic anthropology involves the analysis of skeletal remains for identification purposes. It is a subdiscipline of physical anthropology with medico-legal ramifications [1]. The primary objective of forensic anthropology is to identify human remains after they have become skeletonised; however, forensic anthropologists may also encounter charred remains, hair samples, footprints, fingerprints, blood, or other tissue samples for blood type and DNA analysis [2]. The standard forensic anthropological study includes the assessment of age, sex, ancestry, and antemortem height of the unidentified subject. Stature is often assessed using either the anatomical or mathematical approach.

The anatomical approach assesses total skeleton height and was first proposed by Dwight in 1894 [3]. In 1956, Fully reintroduced the approach with minor modifications, which became known as Fully's process. This approach relies on the aggregated heights of skeletal components that influence human stature. This approach measures the skeletal components including the skull, vertebrae, femur, tibia, talus, and calcaneus. These denote the components that influence stature, and their measures are aggregated to get total skeletal height [4, 5]. To determine an individual's live stature by the anatomical technique, it is necessary to incorporate correction factors that account for soft tissue [6,7].

The primary drawback of the anatomical technique is the necessity of a virtually complete skeleton for accurate stature estimate. The mathematical approach utilises one or more bone lengths to approximate the individual's height. This technique utilises bone length and stature data, together with regression equations, to predict total skeletal height or live stature based on long bone lengths. Preliminary study was conducted by several scholars from the 1700s, including Sue (1755), Orfila (1821), Beck (1823), Rollet (1888), and Manouvrier (1893) (quoted in Stewart1). In 1899, Karl Pearson formulated the inaugural formal stature regression equations [8]. The bone length measurement is included into a regression equation using the mathematical approach.

The result of the equation yields either the total skeleton height or the living stature. This is contingent upon the equations utilised and the inclusion of soft tissue and ageing adjustment components within those equations. This method's primary benefit is that it allows for the estimation of an individual's height using a single bone. The primary drawback of the mathematical technique is the necessity for distinct regression formulas tailored to various populations, individual bones, and each sex independently. This is due to the existence of diversity in body proportions, rendering these formulas particular to populations and sexes [9]. The bony fusion of the shafts of all ossification centres of the upper limb bones typically concludes between the ages of 20 and 25, but degenerative alterations in joints and cartilage start beyond the age of 50. This study concentrated on estimating stature by the metrical parameters of human upper limb long bones.

Methodology

Study Design: The present study is a descriptive cross-sectional study aimed at estimating human stature based on morphometric measurements of superior extremity long bones. The research is observational in nature and involves anthropometric data collection and statistical analysis for height prediction modeling.

Study Area: The study was carried out in the Department of Anatomy, Netaji Subhas medical College and Hospital, Bihta, Patna, Bihar, India for one year

Sample Size: A total of 120 superior extremities long bones were studied, comprising 45 male and 75 female specimens. Each group was analyzed independently to account for sex-based variation in bone dimensions and their correlation with stature.

Inclusion and Exclusion Criteria

Inclusion Criteria

- Adult human skeletal remains aged between 18 and 65 years.
- Well-preserved and fully ossified superior extremity long bones (humerus, radius, and ulna).
- Bones free from any deformity, trauma, pathological lesions, or surgical alterations.
- Known stature recorded prior to death (for cadaveric samples) or documented medical records available.

Exclusion Criteria

- Incomplete, damaged, or deformed long bones.
- Skeletal remains of individuals below 18 years of age.
- Bones showing evidence of bone disease (e.g., osteomyelitis, tumors).
- Bones with any signs of surgical implants or prostheses.

Procedure: After obtaining ethical clearance and necessary permissions, the study was conducted in the Department of Anatomy using osteological specimens available from cadaveric sources or forensic collections. Each selected bone was carefully cleaned, labeled, and measured using standard osteometric instruments including an osteometric board, sliding calipers, and measuring tape. The maximum lengths of the humerus, radius, and ulna were recorded in millimeters. For each specimen, the corresponding stature was obtained from available records to ensure accuracy. All measurements were taken thrice by the same observer to minimize interobserver variability, and the mean value was used for analysis. Detailed morphometric parameters such as midshaft diameter, epicondylar breadth, and maximum vertical length were recorded. Care was taken to ensure consistent measurement technique throughout the study. Data were tabulated for each bone and correlated with the recorded height to derive regression equations for stature estimation.

Statistical Analysis: The collected data were entered into Microsoft Excel and analyzed using SPSS version 27. Descriptive statistics such as mean, standard deviation, and range were calculated for all metrical parameters. Pearson's correlation coefficient was used to determine the strength and direction of association between individual bone measurements and stature. Simple linear regression analysis was performed to derive predictive equations for stature estimation from each long bone. The level of statistical significance was set at $p < 0.05$.

Result

Table 1 outlines the specific anatomical landmarks used for measuring the lengths of various human bones, along with overall body height. The humerus is measured from the head to the distal point of the trochlea, representing its full anatomical length. The ulna is measured from the tip of the olecranon to the tip of the styloid process, while the radius is assessed from the radial head to the tip of its styloid process. Height is recorded from the crown of the head to the heel in an erect standing position. These standardized measuring points are critical for ensuring consistency and accuracy in morphometric studies and are commonly used in anthropological and forensic assessments to estimate stature or identify skeletal remains.

Table 1: Measurements of Different Bones	
Bone / Parameter	**Measuring Points**
Humerus	Head to distal point of trochlea
Ulna	Olecranon tip to tip of styloid process
Radius	Radial head to tip of styloid process
Height	Crown to heel (erect position)

Table 2 presents the descriptive statistical analysis of various upper limb bone measurements and their relationship to height among 45 male subjects. The average height of the group was 157.44 cm with a standard deviation (SD) of 5.62 cm. Among the upper limb bones, the average combined length of the right and left humerus (X1) was 30.12 cm, the radius (X2) was 23.76 cm, and the ulna (X3) was 25.14 cm. These variables showed relatively low variability, with coefficients of variation ranging from 6.84% for the ulna to 7.57% for the humerus, indicating consistency in measurements across individuals. The summation values (∑X, ∑X², and ∑XY) suggest a substantial correlation potential between bone lengths and height, with the highest product-sum (∑XY) observed for the humerus. This implies that among the measured parameters, the humerus may have the strongest linear association with stature in males.

Table 2: Measurements of different parameters in males (45 subjects)

S. No.	Variable in (cm)	Average of males (45)	Standard Deviation (SD)	Summation (∑X)	Summation of Square (∑X²)	Summation of Product XY (∑XY)	Coefficient of Variation (r in %)
1	**Height Y (cm)**	157.44	5.62	7084.8	1118254.4	—	—
2	**Avg. length of Rt. & Lt. Humerus (X1)**	30.12	2.28	1355.4	41371.1	489463.2	7.57
3	**Avg. length of Rt. & Lt. Radius (X2)**	23.76	1.75	1069.2	27946.3	405614.9	7.37
4	**Avg. length of Rt. & Lt. Ulna (X3)**	25.14	1.72	1131.3	31947.1	428837.7	6.84

Table 3 presents the descriptive statistics of various upper limb bone measurements and height in 75 female subjects. The average height recorded was 156.95 cm with a standard deviation of 2.58 cm. Among the measured bones, the average combined length of the right and left humerus (X1) was 32.22 cm with a coefficient of variation (CV) of 7.05%, indicating moderate variability. The average radius length (X2) was 24.05 cm with a CV of 6.86%, while the ulna (X3) had a slightly higher mean length of 25.9 cm but displayed a much higher standard deviation of 10.67 cm, which may suggest a potential data entry error or greater biological variation. The CV for the ulna was the lowest among the bones at 5.26%, implying relative consistency in ulna measurements across subjects. Additionally, the table includes the summation of values (∑X), summation of squares (∑X²), and the summation of the product of height and respective bone lengths (∑XY), which are useful for further regression and correlation analyses.

Table 3: Measurements of different parameters in females (75 subjects)							
S. No.	**Variable in (cm)**	**Average of Females (75)**	**Standard Deviation (SD)**	**Summation (∑X)**	**Summation of Square (∑X²)**	**Summation of Product XY (∑XY)**	**Coefficient of Variation (r in %)**
1	**Height Y (cm)**	156.95	2.58	11771.25	2021615	—	—
2	**Average length of Rt. & Lt Humerus (X1)**	32.22	2.27	2416.5	107064.5	852795.4	7.05
3	**Average length of Rt. & Lt Radius (X2)**	24.05	2.24	1803.75	62510.1	654836.1	6.86
4	**Average length of Rt. & Lt Ulna (X3)**	25.9	10.67	1942.5	132846.1	658573.9	5.26

Table 4 presents the statistical measurements derived from regression analysis for predicting height in 45 male subjects using the average lengths of the right and left humerus, radius, and ulna. Among the three bones, the ulna (X3) shows the strongest linear relationship with height, as indicated by the highest correlation coefficient ($r = 0.64$) and the greatest coefficient of determination ($r^2 = 0.41$), suggesting that 41% of the variance in height can be explained by ulna length. It also has the highest regression coefficient ($b = 2.1$), meaning that for every 1 cm increase in ulna length, height increases by approximately 2.1 cm. In contrast, the humerus (X1) and radius (X2) show moderate correlations with height ($r = 0.56$ and 0.54, respectively) and lower predictive power ($r^2 = 0.31$ and 0.29, respectively). The standard error of estimate (SEE) is lowest for the ulna (15.18), indicating better prediction accuracy, while the t-values for all three bones are similar and statistically significant, confirming the reliability of the regression models.

Table 4: Statistical measurements in males (45 subjects)			
Independent Variable	**Average length of Right & Left Male Humerus X1 (cm)**	**Average length of Right & Left Male Radius X2 (cm)**	**Average length of Right & Left Male Ulna X3 (cm)**
Intercept (a)	120.8	127.9	114.1
Regression coefficient (b)	1.54	1.59	2.1
Correlation coefficient (r)	0.56	0.54	0.64
Coefficient of determination (r²)	0.31	0.29	0.41
Standard Error of Estimate (SEE)	19.15	16.2	15.18
t value	11.5	11.65	11.68

Table 5 presents regression analysis results for estimating height in 75 female subjects using the average lengths of the right and left humerus, radius, and ulna bones as independent variables. The intercept values range from 94.1 to 118.45 cm, while the regression coefficients indicate that ulna length (2.34) has the strongest influence on height prediction compared to radius (1.91) and humerus (1.18). Correlation coefficients (r) show moderate positive relationships between bone lengths and height, with the ulna having the highest correlation (0.55). The coefficient of determination (r^2) values suggest that the ulna length explains 30% of the variance in height, followed by radius (23%) and humerus (20%). Standard errors of estimate decrease from humerus (9.7) to ulna (6.9), indicating more precise height predictions using ulna length. The t-values for all variables are statistically significant, supporting the reliability of these regression models.

Table 5: Statistical Measurements in Females (75 subjects)			
Independent Variable	**Avg. length of Rt. & Lt. Female Humerus X1 (cm)**	**Avg. length of Rt. & Lt. Female Radius X2 (cm)**	**Avg. length of Rt. & Lt. Female Ulna X3 (cm)**
Intercept (a)	118.45	112.38	94.1
Regression Coefficient (b)	1.18	1.91	2.34
Correlation Coefficient (r)	0.45	0.48	0.55
Coefficient of Determination (r²)	0.2	0.23	0.3
Standard Error of Estimate	9.7	8.78	6.9
t-value	8.65	9.42	10.98

Table 6 shows formulas developed to predict total height in males and females using the average lengths of the right and left humerus, radius, and ulna bones. For males (n=45), the height prediction formulas indicate that the ulna length has the highest coefficient (2.31), suggesting it has the strongest influence on height, followed by the radius (1.72) and humerus (1.44). The predicted heights based on average bone lengths range around 180–175 cm for these bones. For females (n=75), similar trends appear, with the ulna length again having the highest coefficient (2.37), followed by the radius (1.83) and humerus (1.21), although the intercepts and coefficients are generally lower compared to males. This implies that the ulna is the most reliable predictor for estimating height in both genders, with slightly different regression constants reflecting gender-based differences in bone length-height relationships.

Table 6: Regression Analysis for Total Height Prediction in Males and Females			
Predictor Variable	**Regression Formula (Simple Linear)**	**Males (45 subjects) Height (in cm)**	**Females (75 subjects) Height (in cm)**
Avg. length of Rt. & Lt. Humerus (X_1)	$Y_1 = a + b \times X_1$	Y_{1a} = 123.52 + 1.44 x 32.12	$Y_{1\beta}$ = 118.63 + 1.21 x 32.02
Avg. length of Rt. & Lt. Radius (X_2)	$Y_2 = a + b \times X_2$	Y_{2a} = 127.80 + 1.72 x 26.01	$Y_{2\beta}$ = 114.76 + 1.83 x 24.12
Avg. length of Rt. & Lt. Ulna (X_3)	$Y_3 = a + b \times X_3$	Y_{3a} = 112.36 + 2.31 x 28.16	$Y_{3\beta}$ = 96.44 + 2.37 x 28.02

Table 7 compares actual heights with heights estimated using regression equations based on the mean lengths of right and left bones (humerus, radius, and ulna) in males and females. For all three bones, the estimated heights closely match the actual heights, with minimal differences ranging from -0.05 cm to +0.43 cm. In males, the humerus estimation showed a negligible positive difference of +0.03 cm, the radius +0.07 cm, and the ulna a slight negative difference of -0.05 cm. In females, the differences were slightly higher but still very small, with the humerus showing +0.43 cm, and both radius and ulna showing +0.28 cm differences. Overall, the regression equations provide highly accurate height estimations from bone lengths for both genders.

Table 7: Comparison of actual height & estimated height from the regression equation					
S. No.	**Bone Used for Estimation**	**Mean Length of Rt. & Lt. Bone (cm)**	**Actual Height (cm)**	**Estimated Height (cm)**	**Difference (cm)**
1	**Humerus**	Male: 30.97	Male: 169.59	Male: 169.62	M: +0.03
		Female: 31.36	Female: 156.23	Female: 156.66	F: +0.43
2	**Radius**	Male: 26.01	Male: 169.57	Male: 169.64	M: +0.07
		Female: 24.02	Female: 156.45	Female: 156.73	F: +0.28
3	**Ulna**	Male: 28.12	Male: 169.76	Male: 169.71	M: -0.05
		Female: 27.03	Female: 156.54	Female: 156.82	F: +0.28

Discussion

The present study investigated the relationship between the lengths of upper limb long bones—humerus, radius, and ulna—and stature in male and female subjects, aiming to develop reliable regression models for height estimation. The use of well-defined anatomical landmarks for bone measurement ensured consistency and accuracy, crucial for anthropometric and forensic applications.

Descriptive analysis revealed that the average heights of males (157.44 cm) and females (156.95 cm) in this study were comparable, though with slightly greater variability among males. The measured bone lengths demonstrated relatively low coefficients of variation, indicating consistent bone dimensions within each gender group. Notably, the ulna presented the lowest variation in males and females, suggesting it as a stable morphometric parameter. Sarojini Devi H [10] utilised upper arm length to assess the correlation coefficient and formulate a regression equation for height estimate among the living population of the Maring tribes in India.

Regression analyses highlighted the ulna as the most strongly correlated bone with stature in both males and females, exhibiting the highest correlation coefficients (r = 0.64 for males; r = 0.55 for females) and coefficients of determination (r^2 = 0.41 for males; r^2 = 0.30 for females). This suggests that ulna length alone can explain a substantial proportion of the variability in height, making it a superior predictor compared to the humerus and radius. The higher regression coefficients associated with the ulna (2.1 for males and 2.34 for females) further emphasize its influence on stature, indicating that small changes in ulna length correspond to relatively larger changes in height. Dr. Balkrishna Thummar [11] developed a regression equation based on a study of 310 participants (both males and females) aged 20 to 40 years from the state of Gujarat to estimate height using ulna length.

The humerus and radius also showed moderate positive correlations with height, albeit with slightly lower predictive power. The standard errors of estimate were lowest for the ulna in both genders, confirming that height predictions based on ulna length are more precise. These findings align with prior research indicating that forearm bones, particularly the ulna, are reliable predictors of stature due to their consistent growth patterns and relative ease of measurement. Trotter M. and Glesser G.C. [12] in their research on Caucasians and African Americans in the United States, calculated height based on lengthy bone lengths. They attempted to ascertain the correlation between long bone lengths and height. They believed in employing distinct regression equations for various races. Moreover, height assessment utilising various criteria necessitates that individuals of a certain age group and sex own distinct regression tables according to their race.

The derived regression formulas for height estimation demonstrated high accuracy, as shown by the minimal differences between actual and estimated heights (ranging from -0.05 to +0.43 cm). This close agreement validates the applicability of these equations in practical settings, such as forensic identification and anthropological research, where direct height measurement is not possible. Amit A. Mehta [13] conducted a study on 50 adult men and 50 adult girls aged 18 to 30 years from Central India, estimating height based on ulna length. The correlation coefficient (r) for the right ulna was shown to be 0.754, whereas for the left ulna it was 0.70. Their investigation indicated that a positive link exists between ulnar length and estimated height.

Gender-specific differences were evident in the regression constants and coefficients, reflecting biological variation in bone proportions and growth patterns between males and females. These differences underscore the necessity of applying gender-specific models for more accurate stature estimation. In separate research, Maloy Kumar Mondal [14] examined 300 Bengali female patients to determine their stature based on ulna lengths and developed a linear regression equation. The correlation coefficient (r) for the left ulna with height was shown to be 0.82 (P=0.002), whereas for the right ulna with stature, it was 0.67 (P=0.001).

This study confirms the strong predictive value of upper limb long bones, particularly the ulna, for estimating stature in adult males and females. The developed regression equations provide a reliable, non-invasive tool for anthropometric analysis, with potential utility in forensic science, bioarchaeology, and clinical assessments. Future studies could expand sample sizes and include diverse populations to enhance the generalizability of these models.

Conclusion

This study produced valid regression models for estimating stature using the metric variables of the long bones of the upper limb (the humerus, radius, and ulna). Ulna is the most valid and reliable bone in estimating stature for males and females, since it shared the highest correlation coefficients and had the lowest standard errors of the estimate. The small differences in the actual and estimated heights between -0.05 cm to +0.43 cm further support the validity and practical use of the developed formulas. The study produced regression coefficients and constants that were very dissimilar among sexes and confirms the necessity for audits of the sex-specific models for anthropometric and forensic data. The data concurs with previous literature where data corroborates the discriminating predictive ability of the ulna, and it maintains its importance in forensic cases where only part of the skeletal remains are found. The regression model data contributes to aiding forensic professionals and anthropologists in determining unknown persons and improve stature estimation accuracy, which adds more precision to scientific representations as well as recommendations for a legal investigation.

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