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Estimation of Femur Length from its Segmental Fragment Measurements in the Sri Lankan Context

Estimación de la Longitud del Fémur a Partir de sus Mediciones de Fragmentos Segmentarios en el Contexto de Sri Lanka

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SUMMARY: The femur, the longest and strongest bone in the human skeleton, is commonly used for stature estimation in forensic and bioarchaeological studies. However, incomplete skeletal remains often hinder direct measurement, requiring reliable methods to estimate femoral length from fragmentary segments. Population-specific data for Sri Lankan skeletal remains are scarce. This study aimed to develop regression equations for estimating maximum femoral length (FML) from measurable femoral fragments in a Sri Lankan population. Fifty dry femora from the Departments of Anatomy and Forensic Medicine, University of Kelaniya, were analyzed. Nine measurements were recorded: femur length, vertical and transverse head diameters (VDH and TDH), head circumference (HC), proximal femoral length (PFL), anterior neck length, posterior neck length, neck shaft angle, and neck diameter (ND). Descriptive statistics and correlations between fragmental measurements and FML were evaluated using Pearson's or Kendall's coefficients. Simple and multiple linear regression analyses were conducted to generate predictive models, with significance set at $p < 0.05$. The VDH, TDH, HC, PFL, and ND exhibited moderate positive correlations with FML ($r = 0.35–0.46$, $p < 0.05$). Simple linear regression identified PFL as the most reliable predictor: $FML = 289.14 + 2.16 \times PFL$ ($R^2 = 0.21$, $p < 0.01$). Although multiple regression models combining fragmental parameters were statistically significant, individual predictors became insignificant when PFL was included. Hence, PFL alone provides the most accurate estimation of FML. This study establishes population-specific regression models for Sri Lankans, confirming proximal femoral length as the most dependable predictor for forensic and bioarchaeological investigations.

KEY WORDS: Femur; Fragmentary bones; Sri Lankan population; Stature estimation.

INTRODUCTION

The femur, the longest and strongest bone in the human skeleton, plays a vital role in supporting body weight, enabling locomotion, and maintaining upright posture. Its proximal end includes the femoral head, which articulates with the acetabulum to form the hip joint; the femoral neck, adapted for bipedal posture; and the greater and lesser trochanters that serve as major muscle attachment sites. The shaft is slightly anteriorly convex and built to resist mechanical stress, while the distal end bears the medial and lateral condyles that articulate with the tibia to form the knee joint. Due to its dense cortical structure and robust morphology, the femur is among the most commonly preserved bones in forensic and archaeological contexts (Mandl *et al.*, 2022).

In forensic studies, the estimation of stature from skeletal remains represents a critical step in reconstructing the biological profile of unidentified individuals. Among the long bones, the femur exhibits the highest correlation with an individual's stature and overall body proportions. Classical anthropometric research, notably that of Trotter & Gleser (1952), established regression models correlating long bone length with total body height, demonstrating that femoral length contributes approximately one-fourth of a person's total stature. Hence, femoral measurements are extensively used in forensic, bioarchaeological, and anatomical investigations for reconstructing stature and assessing population variation.

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However, complete skeletal remains are often unavailable in practical scenarios. In forensic and archaeological contexts, skeletal recovery is frequently complicated by taphonomic alterations, postmortem damage, weathering, soil acidity, and mechanical fragmentation. Consequently, investigators are often left with incomplete or fragmentary bones. Under such circumstances, accurate estimation of the original bone length from fragmentary segments becomes crucial, as it provides the foundation for subsequent estimations of stature and other biological characteristics. The development of regression equations linking bone fragments to their original maximum length allows forensic anthropologists to utilize even small bone portions for meaningful identification.

A number of global studies have addressed the problem of estimating femoral maximum length from fragments. For example, Abledu *et al*. (2016) derived regression formulae for Ghanaian skeletal remains using various femoral fragment measurements; they reported moderate to high correlations. In South Africa for European descent, equations for estimation of both femur length and stature from fragmentary femora have also been developed, with high correlation coefficients (Dayal *et al*., 2008). More recently, in South Indian populations, regression equations using shaft length, proximal and distal segments and breadths have shown strong correlations for fragmentary femur-based stature estimation (Kokati *et al*., 2025). In the Sri Lankan context, although sex determination from the femur has been carried out, data on stature estimation from femoral fragments remain limited (Ranaweera *et al*., 2022). The only Sri Lankan research study related to this topic reported that both single and multiple fragmentary measurements could predict femoral length with satisfactory accuracy (Nanayakkara *et al.*, 2020). However, Sri Lanka possesses a distinct genetic and environmental background, influenced by geographic isolation and diverse ancestral lineages. The lack of population-specific osteometric standards limits the precision of forensic identification and bioarchaeological reconstructions involving fragmentary skeletal material. Therefore, the present study was aimed to develop reliable regression equations to estimate the maximum length of the femur from various measurable fragments in a Sri Lankan population.

MATERIAL AND METHOD

The analyzed sample comprised 50 dry femora obtained from the Departments of Forensic Medicine and Anatomy, University of Kelaniya, Sri Lanka. These femora originated from donated cadavers, for which written consent for teaching and research purposes had been granted by the next of kin at the time of donation to the Faculty of Medicine, University of Kelaniya. Bones exhibiting pathological abnormalities or deformities were excluded from the study. A total of nine measurements were directly recorded from each femur, with the descriptions of these measurements provided in Table I. All measurements were obtained using standard anthropometric instruments, including a calibrated osteometric board, a digital vernier caliper, and a measuring tape. Statistical analyses were carried out using R statistical software (R Core Team, 2020).

The descriptive statistics of the femoral measurements were obtained, and they were standardized prior to analysis. The relationship between the femur length (FML) and other femoral measurements was assessed using Pearson's correlation coefficient when normality was not rejected and Kendall's tau correlation coefficient when normality was rejected. Coefficients ranging from 0.00 to 0.30 were considered weak, those between 0.30 and 0.70 were regarded as moderate, and coefficients from 0.70 to 1.00 were classified as strong.

Correlation and simple linear regression analyses were conducted to determine the relationship between femoral length and the measurements of its fragments. Regression equations were developed to estimate the maximum length (FML) from fragment measurements (VDH, TDH, HC, ANL, PNL, NSA, PFL and ND) that demonstrated a statistically significant positive correlation

Table I. Definition of osteometric measurements of femur used in the study.

No.	Femur measurement	Abbreviation	Definition
1	Femur length	FML	Distance from the highest on head of the femur to the lowest point on the medial condyles
2	Head circumference	HC	Circumference along the articular margin of head
3	Neck shaft angle	NSA	The angle between long of shaft of femur and axis of neck of femur
4	Vertical diameter of head	VDH	Distance between most superior and inferior point on articular margin of head in vertical plane
5	Transverse head diameter	THD	Maximum distance of femoral head on articular margin in intertrochanteric plane
6	Anterior neck length	ANL	Distance between the head and midpoint of intertrochanteric line in anteriorly
7	Posterior neck length	PNL	Distance between the head and midpoint of intertrochanteric crest posteriorly
8	Neck diameter	ND	Width of narrowest portion of neck
9	Proximal femoral length	PFL	Distance between most proximal point of greater trochanter to the most distal point in lesser trochanter

with FML ($p < 0.05$). Moreover, multiple regression equations were formulated to estimate the FML using combinations of measurements from different femoral fragments. The optimal model was identified based on the highest coefficients of determination (R^2).

RESULTS

Table II presents the descriptive statistics (mean, standard deviation, median, absolute deviation, minimum, and maximum values) for all femoral measurements obtained in the study. The correlation coefficients between each variable and the length, along with their p-values, are presented in Table III, which indicates that the correlation coefficients ranged from 0.12 to 0.46.

Among the measured variables, normality was rejected only for the circumference ($p < 0.05$). The variables vertical diameter of the head, transverse diameter of the head, head circumference, proximal femoral length and neck diameter showed moderate positive correlation (correlation coefficient ≥ 0.3) with the femur length, and these relationships were statistically significant ($p < 0.05$). Therefore, these five variables, which exhibit a significant positive association with the measured femoral length, were employed in the simple and multiple linear regression analyses.

Table II. Descriptive statistics of the measurements of the femora (mm).

Variable	Mean	SD	Median	MAD	Min	Max	Range
FML	436.90	24.38	437.00	23.72	368.00	472.00	104.00
VDH	40.99	3.67	41.45	3.48	30.70	47.96	17.26
TDH	41.93	3.49	42.78	3.62	32.26	49.39	17.13
HC	138.36	7.95	140.00	8.90	122.00	151.00	29.00
ANL	22.14	3.25	22.05	2.99	16.30	30.35	14.05
PNL	33.52	4.98	32.79	6.48	22.70	42.08	19.38
NSA	116.82	4.68	117.00	4.45	105.00	126.00	21.00
PFL	69.70	4.30	70.12	4.08	60.20	77.60	17.40
ND	31.06	2.89	30.26	2.74	26.58	36.95	10.37

Table III. Correlation coefficients between each variable and the length.

Variable	Variable Normality	Pearson coef.	P-value	Kendall	P-value
VDH	0.23	0.39	<0.01	0.27	<0.01
TDH	0.25	0.35	0.01	0.23	0.01
HC	0.02	0.40	<0.01	0.30	0.01
ANL	0.05	0.24	0.09	0.11	0.30
PNL	0.29	0.12	0.40	0.05	0.29
NSA	0.43	0.13	0.36	0.10	0.29
PFL	0.86	0.46	<0.01	0.30	<0.01
ND	0.21	0.39	<0.01	0.23	0.01

Table IV illustrates the results of the linear regression analysis examining the relationship between femoral length (FML) and its fragmentary measurements.

Table IV. Simple linear regression analysis for estimating FML from femur fragments.

Variable (mm)	Model	R-squared	p-value
VDH	333.78 + 2.57 VDH	0.15	<0.01
TDH	342.33 + 2.32 TDH	0.12	0.01
HC	303.21 + 0.98 HC	0.12	<0.01
PFL	289.14 + 2.16 PFL	0.21	<0.01
ND	356.95 + 2.64 ND	0.12	0.01

All five simple linear regression models demonstrated statistically significant positive correlations with FML ($P < 0.01$). The PFL model was identified as the most suitable model, as it demonstrated the highest R-squared value. Hence, the maximum femur length is best calculated using the measurements of proximal femoral length (PFL) as indicated in the following equation.

$$\text{Maximum length of femur} = 289.14 + 2.16\,(\text{PFL})$$

The best subset regression method was employed to determine the optimal combinations of predictor variables and Table V illustrates the multiple regression analysis data. The R-squared statistic represents the proportion of the total variation in the response variable (FML) that is explained by the model, thereby indicating its explanatory power.

Although the overall model is statistically significant, the individual predictor variables in Models 1 to 4 are not significant. Therefore, the use of simple linear regression models is more appropriate. In Model 5, although both variables are significant, the adjusted R-squared value is lower than that of Model 1. Table VI illustrates the result of correlations between the predictor variables.

Based on multiple regression analysis, the equation for predicting the maximum length of the femur from its various fragment measurements is as follows:

Maximum length of femur = 307.09 + 1.71 (VDH) + 1.96 (ND)

However, when PFL is included in the model, the other predictor variables lose significance and become less influential. Hence, in this study, PFL is identified as the most reliable predictor for estimating maximum length of femur.

Table V. Multiple regression analysis for estimating FML from femur fragments.

Model	Equation	R^2	Adj.R^2	p-Value
1	265.98+1.5798(PFL)+1.5249(VDH)	0.27	0.24	<0.01
2	256.06+(PFL)+1.31(VDH)+1.26(ND)	0.30	0.25	<0.01
3	259.86+1.33(PFL)+1.43(VDH)+1.36(ND)-0.11(HC)	0.30	0.23	<0.01
4	261.01+1.35(PFL)+1.55(VDH)+1.37(ND)-0.10(HC)-0.22(TDH)	0.30	0.22	<0.01
5	307.09+1.71(VDH)+1.96 (ND)	0.23	0.19	<0.01

Table VI. Pearson Correlation Coefficients (p-value) between predictor variables.

	VDH	TDH	HC	PFL	ND
VDH	1				
TDH	0.77(<0.01)	1			
HC	0.76(<0.01)	0.69(<0.01)	1		
PFL	0.36(0.01)	0.41(<0.01)	0.48(<0.01)	1	
ND	0.35(0.01)	0.39(<0.01)	0.59(<0.01)	0.42(<0.01)	1

DISCUSSION

In the present study, eight osteometric measurements were acquired from different anatomical portions of the femur and assessed for prediction of FML using simple and multiple regression analysis. The measurements include VDH, TDH, HC, ANL, PNL, NSA, PFL and ND. The results indicate statistically significant ($p<0.05$) moderate positive correlation (correlation coefficient ≥ 0.3) between VDH (0.39), TDH (0.35), HC (0.3), PFL (0.46) and ND (0.39) with the FML. The simple linear regression yielded PFL (R^2=0.2055, $p<0.01$) to be the best estimator of FML when compared to other assessed measurements of the femur. Although the multiple regression analysis done including multiple predictor variables were statistically significant overall, their adjusted R^2 values were lower, indicating no improvement over the simple PFL based formula. Therefore, the simple equation derived from PFL alone provides the most efficient means for estimating FML from fragments of femora within the studied population.

The present findings are consistent with another Sri Lankan study which demonstrated fragmentary femoral measurements exhibit moderate to high correlation with FML (r=0.226-0.714) in another Sri Lankan sample (Nanayakkara *et al*. 2020). However, within that study the transverse neck diameter (TND) was identified as the best predictor (r=0.714, SEE=18.66) whereas the current investigation revealed that PFL to be the most reliable indicator. Similarly, Abledu *et al*. (2016), studying Ghanaian skeletal remains, identified sub-trochanteric transverse diameter (STD) as the single best estimator (r=0.819, SEE=13.66). Although regional and ethnic variations may exist the consistent findings across these studies are that specific proximal or sub-trochanteric measurements, those least affected by postmortem damage, tend to yield the most reliable prediction of total femur length.

The superiority of PFL as the most effective predictor of the FML in the current study can be explained anatomically as it combines the measurement between consistent landmarks, such as the greater and lesser trochanters, which are less susceptible to postmortem damage compared to the fragments of the epiphyses. Since fragmentary femora obtained in forensic investigations are usually shafts of various segments it is essential to develop means of reconstructing FML reliably from femoral shaft fragments. Therefore, the findings suggest that even when only the proximal portion of a femur is available, total bone length and by extension, stature can be estimated with reasonable accuracy.

When comparing R^2 values across studies, the explanatory power observed in the present study (R^2~0.20) is comparatively lower than that reported for Ghanaian ($R^2 \approx$ 0.50–0.67) and South Indian populations ($R^2 \approx$ 0.32–0.67) but within the range reported by Nanayakkara *et al*. (2020), for Sri Lankans ($R^2 \approx$ 0.32–0.51) (Abledu *et al*., 2016; Kokati *et al*., 2025). These differences are likely due to population specific variation in femur morphology due to genetic, nutritional and environmental influence. The interpopulation variability highlights the importance of developing population specific osteometric standards rather than applying formulae derived from foreign datasets, which would introduce error in forensic stature estimation.

A notable strength in the current study is the use of standardized measurement protocol and statistically validated regression modelling to ensure accuracy and reproducibility. The results provide a set of population-specific equations that can be directly applied in forensic anthropology and anatomical reconstruction when dealing with incomplete femora. However, the major limitation of the study is a relatively small sample size which did not account for sex or age differences within the population which may influence the bone dimensions. Therefore, future studies incorporating larger, sex balanced samples are recommended to refine and validate these predictive models further.

CONCLUSION

The present study demonstrates that fragmentary measurements of the femur, particularly the proximal femoral length show a statistically significant relationship with total femur length in Sri Lankan skeletal material. The derived regression equation (FML = 289.14 + 2.16 × PFL) enables accurate estimation of femur length from proximal fragments, thereby contributing to the development of population-specific osteometric standards for forensic identification and anthropological reconstruction in Sri Lanka.

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RESUMEN: El fémur, el hueso más largo y resistente del esqueleto humano, se utiliza comúnmente para la estimación de la estatura en estudios forenses y bioarqueológicos. Sin embargo, los restos óseos incompletos a menudo dificultan la medición directa, lo que requiere métodos fiables para estimar la longitud femoral a partir de segmentos fragmentarios. Los datos poblacionales específicos de los restos óseos de Sri Lanka son escasos. Este estudio tuvo como objetivo desarrollar ecuaciones de regresión para estimar la longitud femoral máxima (LFM) a partir de fragmentos femorales mensurables en una población de Sri Lanka. Se analizaron cincuenta fémures secos de los Departamentos de Anatomía y Medicina Forense de la Universidad de Kelaniya. Se registraron nueve mediciones: longitud del fémur, diámetros de la cabeza vertical y transversal (DVC y DTC), circunferencia de la cabeza (CC), longitud femoral proximal (PFL), longitud del cuello anterior, longitud del cuello posterior, ángulo de la diáfisis y diámetro del cuello (DC). Las estadísticas descriptivas y las correlaciones entre las mediciones fragmentarias y la LFM se evaluaron utilizando los coeficientes de Pearson o Kendall. Se realizaron análisis de regresión lineal simple y múltiple para generar modelos predictivos, con significancia establecida en $p < 0,05$. La DVC, DTC, CC, PFL y DC exhibieron correlaciones positivas moderadas con la LFM ($r = 0,35–0,46$, $p < 0,05$). La regresión lineal simple identificó la longitud femoral proximal (LFP) como el predictor más fiable: longitud femoral proximal (LFP) = 289,14 + 2,16 × LFP ($R^2 = 0,21$, $p < 0,01$). Si bien los modelos de regresión múltiple que combinaban parámetros fragmentarios resultaron estadísticamente significativos, los predictores individuales resultaron insignificantes al incluir la LFP. Por lo tanto, la LFP por sí sola proporciona la estimación más precisa de la LFP. Este estudio establece modelos de regresión específicos para cada población de Sri Lanka, confirmando que la longitud femoral proximal es el predictor más fiable para las investigaciones forenses y bioarqueológicas.

PALABRAS CLAVE: Fémur; Huesos fragmentarios; Población de Sri Lanka; Estimación de la estatura.

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