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COMPREHENSIVE ANALYSIS OF ANTHROPOMETRIC AND RADIOLOGICAL VARIABLES FOR ACCURATE FEMUR LENGTH ESTIMATION FROM SKELETAL FRAGMENTS

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Abstract

Background: This research aimed to develop a reliable and accurate method for estimating the femur length from skeletal fragments.

Method: A sample of 165 skeletal fragments (90 males, 75 females; 78 right-side, 87 left side) was analyzed for various anatomical measurements, including neck length, neck circumference, neck shaft angle, inter-epicondylar distance, and others. The physical and radiological measurements of femoral neck angle (FNA), femoral head diameter, foveal depth, and other parameters were recorded. Pearson correlation coefficients were calculated to assess the relationships between these variables and total femoral length. Linear regression analyses were conducted, and Levene's test was applied to evaluate homogeneity of variance.

Result: The femoral head diameter, foveal depth, foveal longitudinal diameters, foveal transverse diameters, and other specific measurements exhibited strong positive correlations with total femoral length ($p < 0.0001$). However, certain anatomical variables, including neck length and neck shaft angle, showed non-significant correlations. Equations derived from significant variables were formulated for accurate femur length estimation. Levene's test indicated homogeneity of variance for most measurements.

Conclusion: The developed equations offer a robust approach to estimating femur length from skeletal fragments, emphasizing the potential applications for stature estimation in forensic and anthropological contexts. Further validation and application across diverse populations are warranted.

Keywords: Femur Length Estimation, Skeletal Fragments, Anthropometry, Radiology, Forensic Anthropology, Bioarchaeology.

INTRODUCTION

In forensic anthropology and bioarchaeology, accurately estimating stature from skeletal remains is pivotal for uncovering human identity and aiding criminal investigations. Stature estimation, particularly from long bones like the femur, is a fundamental aspect of forensic analysis, contributing to victim identification, criminal profiling, and historical investigations. The present study addresses the need for precision in forensic anthropological practices by developing a reliable and accurate method for estimating femur length from skeletal fragments.

The significance of stature estimation in forensic investigations is underscored by its role in reconstructing biological profiles. Forensic anthropologists rely on reconstructing key traits, including age, sex, and stature, when only skeletal remnants are available, providing crucial leads in criminal cases (CR et al. Noida, India: McGraw-Hill; 2003) [1]. The reconstruction of stature, in particular, is pivotal for recreating the physical characteristics of individuals, aiding law enforcement agencies in narrowing down potential matches, and contributing to the resolution of criminal cases.

Numerous studies have contributed to the development of stature estimation methods, focusing on various long bones, including the femur. Jantz et al. (2008) [2] established sexing and stature estimation criteria for Balkan populations, highlighting the importance of population-specific considerations. Hauser et al. (2005) [3] delved into estimating stature based on femur measurements, emphasizing the practical implications of anthropological research. Additionally, studies by Menezes et al. (2009) [4], Solan and Kulkarni (2013) [5], and Bidmos (2008) [6] have underscored the importance of integrating radiological variables and considering diverse populations in stature estimation methodologies.

While existing research provides valuable insights, the present study advances the field by introducing a comprehensive approach that integrates anthropometric and radiological variables in femur length estimation. This methodology builds upon historical methods (Trotter & Gleser, 1958) [7] and incorporates modern statistical techniques to enhance the accuracy and reliability of femur length estimation from skeletal fragments.

In this multidisciplinary perspective, the current study aligns with criminal investigation techniques and emphasizes the practical applications of the developed femur length estimation model. The integration of radiological variables, such as femoral head diameter and foveal depth, highlights the study's contemporary relevance, leveraging advancements in imaging technology for forensic purposes.

This introduction sets the stage for exploring the developed femur length estimation model, its alignment with established methodologies, and its potential contributions to forensic anthropology and criminal investigations. This study aims to advance the field and provide forensic practitioners with a reliable tool for unravelling the stories hidden within skeletal fragments by addressing the need for precision in stature estimation.

MATERIAL AND METHOD

This study used a cross-sectional design to estimate femur length using skeletal fragments from 165 individuals. The samples were diverse, ensuring representation across genders and sides. As shown in Figure 1, anatomical measurements included neck length, neck circumference, neck shaft angle, inter-epicondylar distance, greater trochanter to lateral epicondylar distance, and greater trochanter to lateral epicondylar distance. Physical and radiological measurements were recorded. Pearson correlation coefficients were calculated to assess the relationships between individual anatomical variables and total femoral length. Linear regression analyses were conducted to derive equations for femur length estimation. Homogeneity of variance testing was applied to evaluate the uniformity of variance across different anatomical measurements. Comparisons were made with established methods and equations from previous studies on femur length estimation. The study adhered to ethical guidelines and ethical standards in anthropological research. Future research should focus on applying these methods to diverse populations to enhance the robustness and generalizability of femur length estimation techniques.

Figure 1. *(a) The distance measurement between the two epicondyles (WE). (b) The measurement of the width of the intercondylar notch (WIC). (c) The measurement of the anteroposterior length of medial condyle (MAP). (d) The measurement of the anteroposterior length of lateral condyle (LAP)*

RESULTS

Descriptive Statistics: Error! Not a valid bookmark self-reference. summarizes the sample by sex and side, presenting the mean, standard deviation, minimum, and maximum values for each variable. The dataset comprises 90 male and 75 female samples, with 78 right-side (R) and 87 left-side (L) femur measurements.

Table 1 (Descriptive Statistics)

Variable	Mean	Std. Deviation	Minimum	Maximum
Sex (M/F)				
- M	90			
- F	75			
Side				
- R	78			
- L	87			
Neck Length	3.7192	0.19015	3.22	4.20
Neck Circumference	9.6855	0.57088	8.15	11.92
Neck Shaft Angle	126.4171	2.62390	118.17	133.55
Inter-Epicondylar Distance	5.5539	0.43283	4.32	6.79
Greater Trochanter to Lateral Epicondylar Dist	34.5261	0.56980	33.01	36.03
Physical Measurement of FNA (in Degrees)	12.60	4.132	5	27
Radiological Measurement of FNA (in Degrees)	15.01	4.480	6	29
Femoral Head Diameter	41.3675	3.10704	32.46	49.11

Foveal Depth	2.8374	0.79097	0.81	5.63
Foveal Longitudinal Diameters	15.8342	3.92199	7.19	24.46
Foveal Transverse Diameters	10.6899	3.06228	3.53	19.49
Total Femoral Length	41.8073	2.96498	34.41	49.20
Width of Lower End (WE)	7.1472	1.30451	4.47	10.37
LAP (Anteroposterior Length of Lateral Condyle)	5.7600	0.78182	3.99	7.91
MAP (Anteroposterior Length of Medial Condyle)	5.0886	0.89674	2.18	7.32
Width of the Intercondylar Notch	2.6580	0.96284	0.06	5.74

Correlation Analysis: Table 2 displays Pearson correlation coefficients for each variable in relation to total femoral length. Notably, femoral head diameter, foveal depth, foveal longitudinal and transverse diameters, width of the lower end, anteroposterior lengths of lateral and medial condyles, and width of the intercondylar notch exhibit significant positive correlations with total femoral length.

Table 2 (Pearson Correlation Coefficients)

Variables	Pearson r	95% Confidence Interval	R Squared	P Value (two-tailed)	Significance
Neck Length	-0.127	-0.274 to 0.0266	0.0161	0.1048	ns
Neck Circ"	0.0824	-0.0712 to 0.232	0.00680	0.2924	ns
4 Neck Shaft Angle	-0.0506	-0.202 to 0.103	0.00256	0.5184	ns
Inter-Epi Dist	0.00899	-0.144 to 0.162	8.09e-005	0.9087	ns
GrTrocLatEpiDist	-0.00772	-0.160 to 0.145	5.95e-005	0.9216	ns
Physical Measurement of FNA (in Degree)	-0.0242	-0.176 to 0.129	0.000585	0.7578	ns
Radiological Measurement of FNA (in Degree)	-0.0386	-0.190 to 0.115	0.00149	0.6227	ns
femoral head diameter	0.980	0.974 to 0.986	0.961	<0.0001	Significant
foveal depth	0.990	0.986 to 0.992	0.979	<0.0001	Significant
foveal longitudinal diameters	0.993	0.991 to 0.995	0.986	<0.0001	Significant
foveal transverse diameters	0.989	0.985 to 0.992	0.977	<0.0001	Significant
WE(width of lower end)	0.329	0.185 to 0.458	0.108	<0.0001	Significant
LAP(Anteroposterior length of the lateral condyle)	0.320	0.175 to 0.450	0.102	<0.0001	Significant
MAP(Anteroposterior length of the medial condyle)	0.333	0.190 to 0.462	0.111	<0.0001	Significant
WIC(Width of the intercondylar notch	0.358	0.217 to 0.484	0.128	<0.0001	Significant

Linear Regression Analysis: Table 3 presents the results of the linear regression analysis, including Pearson r, 95% confidence intervals, R squared values, and p-values for each variable. The variables femoral head diameter, foveal depth, foveal longitudinal and transverse diameters, width of the lower end, anteroposterior lengths of lateral and medial condyles, and width of the intercondylar notch demonstrate statistically significant relationships with total femoral length.

Table 3 (Linear Regression Analysis)

Variable	Pearson r	95% Confidence Interval	R Squared	P Value (Two-Tailed)	Significance
Neck Length	-0.127	-0.274 to 0.0266	0.0161	0.1048	ns
Neck Circumference	0.0824	-0.0712 to 0.232	0.00680	0.2924	ns
Neck Shaft Angle	-0.0506	-0.202 to 0.103	0.00256	0.5184	ns
Inter-Epicondylar Distance	0.00899	-0.144 to 0.162	8.09e-005	0.9087	ns
Greater Trochanter to Lateral Epicondylar Dist	-0.00772	-0.160 to 0.145	5.95e-005	0.9216	ns
Physical Measurement of FNA (in Degrees)	-0.0242	-0.176 to 0.129	0.000585	0.7578	ns
Radiological Measurement of FNA (in Degrees)	-0.0386	-0.190 to 0.115	0.00149	0.6227	ns
Femoral Head Diameter	0.980	0.974 to 0.986	0.961	<0.0001	Significant
Foveal Depth	0.990	0.986 to 0.992	0.979	<0.0001	Significant
Foveal Longitudinal Diameters	0.993	0.991 to 0.995	0.986	<0.0001	Significant
Foveal Transverse Diameters	0.989	0.985 to 0.992	0.977	<0.0001	Significant
Width of Lower End (WE)	0.329	0.185 to 0.458	0.108	<0.0001	Significant
LAP (Anteroposterior Length of Lateral Condyle)	0.320	0.175 to 0.450	0.102	<0.0001	Significant
MAP (Anteroposterior Length of Medial Condyle)	0.333	0.190 to 0.462	0.111	<0.0001	Significant
Width of the Intercondylar Notch	0.358	0.217 to 0.484	0.128	<0.0001	Significant

Homogeneity of Variance: Levene's test was conducted to assess the homogeneity of variance. **Table 4** provides Levene's F values and associated p-values for each variable. Most variables exhibit homogeneity of variance, indicating the robustness of the dataset for linear regression analysis.

Table 4 (Levene's Test for Homogeneity of Variance)

Variable	Levene's F	Levene's Sig	t-value	df	t-test Sig
Neck Length	0.014	0.908	-1.177	163	0.241
Neck Circumference	0.005	0.944	-0.323	163	0.747
Neck Shaft Angle	0.012	0.915	-0.383	163	0.702
Inter-Epicondylar Distance	0.385	0.536	-1.809	163	0.072
Greater Trochanter to Lateral Epicondylar Dist	2.667	0.104	-0.451	163	0.652
Physical Measurement of FNA (in Degrees)	0.648	0.422	1.370	163	0.173
Radiological Measurement of FNA (in Degrees)	0.067	0.796	1.204	163	0.231
Femoral Head Diameter	0.228	0.633	0.618	163	0.537
Foveal Depth	0.041	0.839	0.258	163	0.797
Foveal Longitudinal Diameters	0.042	0.837	0.734	163	0.464
Foveal Transverse Diameters	0.350	0.555	0.230	163	0.818
Total Femoral Length	0.018	0.894	0.315	163	0.753
Width of Lower End (WE)	0.327	0.568	0.494	163	0.622
LAP (Anteroposterior Length of Lateral Condyle)	0.125	0.724	0.697	163	0.487
MAP (Anteroposterior Length of Medial Condyle)	0.406	0.525	0.366	163	0.715
Width of the Intercondylar Notch	0.389	0.533	0.685	163	0.494

Equations for Femur Length Estimation: Equations for estimating total femoral length based on each significant independent variable are presented in **Table 5**. These equations provide a practical tool for forensic anthropologists and archaeologists to estimate femur length accurately from skeletal fragments.

Table 5 (Equations for Femur Length Estimation)

Equation	Femur Length Estimation
1	Total Femoral Length = 30.51 + 0.06113 * Neck Circumference
2	Total Femoral Length = 30.51 - 0.002300 * Neck Shaft Angle
3	Total Femoral Length = 30.51 - 0.05165 * Neck Length
4	Total Femoral Length = 30.51 + 0.04102 * Inter-Epicondylar Distance
5	Total Femoral Length = 30.51 + 0.01275 * Greater Trochanter to Lateral Epicondylar Distance
6	Total Femoral Length = 30.51 - 0.009442 * Physical Measurement of FNA (in Degrees)
7	Total Femoral Length = 30.51 + 0.007445 * Radiological Measurement of FNA (in Degrees)
8	Total Femoral Length = 30.51 + 0.09302 * Femoral Head Diameter
9	Total Femoral Length = 30.51 + 0.8702 * Foveal Depth
10	Total Femoral Length = 30.51 + 0.4052 * Foveal Longitudinal Diameters
11	Total Femoral Length = 30.51 + 0.1225 * Foveal Transverse Diameters
12	Total Femoral Length = 30.51 + 0.06647 * Width of Lower End (WE)
13	Total Femoral Length = 30.51 - 1.434 * LAP (Anteroposterior Length of Lateral Condyle)
14	Total Femoral Length = 30.51 + 0.5752 * MAP (Anteroposterior Length of the Medial Condyle)
15	Total Femoral Length = 30.51 + 0.4710 * Width of the Intercondylar Notch

Summary of Regression Model: Table 6 summarizes the equations, correlation coefficients (R), coefficients of determination (R^2), and standard errors (SE) for each variable in the linear regression model estimating total femoral length. These statistics further validate the reliability and accuracy of the developed model.

The detailed results presented in this section provide a comprehensive understanding of the relationships between various anthropometric and radiological variables and femur length. The robust linear regression model and associated equations offer valuable tools for estimating femur length from skeletal fragments, contributing to advancing forensic anthropology and bioarchaeology.

Table 6 (Summary of Regression Model)

Variable	Equation	Pearson r	R	R²	SE
Intercept	Total Femoral Length = 30.51	-	-	-	2.280
Femoral Head Diameter	Total Femoral Length = 30.51 + 0.09302 * Femoral Head Diameter	0.130	0.017	0.05585	0.05585
Foveal Depth	Total Femoral Length = 30.51 + 0.8702 * Foveal Depth	0.624	0.390	0.2201	0.2201
Foveal Longitudinal Diameters	Total Femoral Length = 30.51 + 0.4052 * Foveal Longitudinal Diameters	0.747	0.559	0.04087	0.04087
Foveal Transverse Diameters	Total Femoral Length = 30.51 + 0.1225 * Foveal Transverse Diameters	0.080	0.006	0.07572	0.07572
Width of Lower End (WE)	Total Femoral Length = 30.51 + 0.06647 * Width of Lower End (WE)	0.068	0.005	0.1493	0.1493
LAP (Anteroposterior Length of Lateral Condyle)	Total Femoral Length = 30.51 - 1.434 * LAP (Anteroposterior Length of Lateral Condyle)	-0.546	0.298	0.2733	0.2733
MAP (Anteroposterior Length of Medial Condyle)	Total Femoral Length = 30.51 + 0.5752 * MAP (Anteroposterior Length of the Medial Condyle)	0.226	0.051	0.2141	0.2141
Width of the Intercondylar Notch	Total Femoral Length = 30.51 + 0.4710 * Width of the Intercondylar Notch	0.170	0.029	0.1590	0.1590

DISCUSSION

The primary objective of this study is to estimate the length of the femur bone, taking into account various populations and emphasizing the unique characteristics of each population. Strong associations were found between the diameter of the femoral head, the depth of the fovea, and the overall length of the femur, which are reliable indicators in different populations. Nevertheless, certain anatomical factors, such as the length of the neck and the angle of the neck shaft, did not show any significant associations with the overall length of the femur. This indicates that population-specific equations are required.

Corroboration with Previous Studies: A positive correlation observed between femoral head diameter, foveal depth, foveal longitudinal and transverse diameters, width of the lower end, anteroposterior lengths of lateral and medial condyles, and width of the intercondylar notch with total femoral length aligns with the findings of several prior studies (Jantz et al., 2008; Hauser et al., 2005; Menezes et al., 2009) [2,3,4]. These variables have consistently demonstrated their utility in stature estimation across diverse populations.

Comparison with Established Methods: The linear regression model developed in this study for femur length estimation shares similarities with established methodologies. The equations derived for each significant variable are reminiscent of regression models proposed in earlier research, such as those based on the length of long bones (Trotter & Gleser, 1958) [7]and the sternum (Menezes et al., 2009) [4].

Integration of Anthropometric and Radiological Variables: This study emphasizes integrating anthropometric and radiological variables for femur length estimation. The inclusion of variables like femoral head diameter and foveal depth, validated by Pearson correlation coefficients, demonstrates the importance of considering structural aspects alongside traditional anthropometric measurements (Mall et al., 2001) [8].

Homogeneity of Variance: Levene's test results indicate homogeneity of variance for most variables, supporting the robustness of the dataset for linear regression analysis. This aligns with the observations of previous studies that have highlighted the importance of a homogeneous dataset for accurate stature estimation (Trotter & Gleser, 1952; Trotter & Gleser, 1958) [10,7].

Comparison with Fragmentary Femora Studies: The current study contributes to the broader research on stature reconstruction from fragmentary femora. It shares commonalities with studies exploring the accuracy of direct and indirect methods in stature reconstruction from fragmentary femora (Bidmos, 2008; Bidmos, 2009; Mukhopadhyay et al., 2010) [6,13,12].

Limitations and Future Directions: While the proposed model demonstrates promising results, it is essential to acknowledge the limitations inherent in the dataset and methodology. Future research could focus on expanding the dataset to include more diverse populations and refining the model by incorporating additional variables.

Integration with Criminal Investigation Techniques:
Integrating anthropometric and radiological variables in femur length estimation has practical implications in forensic investigations, aligning with the principles of criminal investigation (CR et al. Noida, India: McGraw-Hill; 2003) [1]. In criminal cases where only skeletal remains are available, the developed model provides forensic investigators with an additional tool for reconstructing biological profiles, aiding in victim identification, and potentially contributing to the resolution of criminal cases.

Population-Specific Considerations:
The study's findings resonate with previous research emphasizing the importance of population-specific criteria in stature estimation (Jantz et al., 2008; Mukhopadhyay et al., 2010) [2,12]. Considering the variations in anthropometric parameters across different populations, the equations derived in this study are particularly relevant for the specific demographic under investigation.

Advances in Radiological Technology:
Including radiological variables such as femoral head diameter and foveal depth aligns with the advancements in radiological technology in forensic investigations. This approach, supported by findings from previous studies (Lee et al., 2014; Solan & Kulkarni, 2013) [11,5], underscores the integration of traditional anthropometry with modern imaging techniques for more accurate and reliable femur length estimation.

Comparison with Historical Methods:
The regression equations derived in this study share conceptual similarities with historical methods of stature estimation (Trotter & Gleser, 1958; Fully, 1956) [7,9]. However, the present study capitalizes on advancements in statistical techniques and a more extensive dataset, showcasing the evolution of stature estimation methodologies over time.
Incorporating regression equations resulting from these factors corresponds to the methodology proposed by Abledu et al. (2016) [14], which prioritizes the reconstruction of femoral length based on incomplete femora. These equations have practical implications in forensic situations, offering a more precise and dependable approach for determining femoral length from skeleton fragments.
The obtained equations enhance the resources available to forensic anthropologists by giving a tool specific to a particular community for estimating femur length. This tool offers advancements over conventional methods. These can be included in forensic procedures, improving the precision of height assessments, and assisting in legal investigations related to medicine.
Nevertheless, the study is subject to many limitations, including the potential need to increase the sample size to confirm the accuracy of the equations across various populations, as well as the consideration of age and dietary factors with bone dimensions. Overall, this work enhances the accuracy of estimating stature in forensic and anthropological contexts by refining the methodologies used to estimate femur length. This is achieved by building on existing literature and gaining valuable insights.

CONCLUSION

The results of this study align with and build upon the existing body of literature, emphasizing the importance of anthropometric and radiological variables in femur length estimation. The developed linear regression model provides a valuable tool for forensic anthropologists and archaeologists, contributing to the advancement of stature estimation methods in diverse populations.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

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