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ORIGINAL ARTICLE

Morphometric Analysis of the Human Femur, Correlations with Age, Sex, and Stature in a Pakistani Population

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ABSTRACT

Background: The human femur is the longest and strongest bone of the skeleton, providing critical information in forensic anthropology and clinical practice. Its morphometric characteristics are highly reliable for estimating sex, stature, and age. Although femoral morphometry has been extensively studied in various global populations, there is a lack of population-specific data for Pakistan, where genetic, nutritional, and environmental factors may influence skeletal dimensions.

Objectives: This study aimed to analyze morphometric parameters of the human femur and assess their correlation with age, sex, and stature in a Pakistani population.

Methods: A descriptive cross-sectional study was conducted between January 2023 and June 2023 at the Anatomy Department, Sahara Medical College, Narowal, and the Anatomy Department of University of Lahore Teaching Hospital, Lahore. A total of ninety human femora with documented demographic details were examined. Maximum femoral length, head diameter, bicondylar width, and midshaft circumference were measured using osteometric board and digital calipers. Demographic data were obtained from cadaveric records. Statistical analysis was performed using SPSS v26, applying descriptive statistics, independent t-tests, Pearson's correlation, and linear regression.

Results: Male femora demonstrated significantly larger measurements compared to female femora ($p < 0.01$). Maximum femoral length exhibited the strongest correlation with stature ($r = 0.81$, $p < 0.001$), followed by femoral head diameter ($r = 0.64$, $p < 0.01$). Regression analysis produced the pooled equation: Stature (cm) = 68.21 + 2.18 × Maximum Femoral Length (cm) with $R^2 = 0.62$. Femoral head diameter showed a weak negative correlation with age ($r = -0.23$, $p = 0.04$).

Conclusion: Femoral morphometry displays clear sexual dimorphism and strong correlation with stature in the Pakistani population. Maximum femoral length is the most reliable predictor of height, while femoral head diameter contributes supportive value. These findings establish baseline reference data for forensic and clinical applications in Pakistan.

Keywords: Femur, Morphometry, Stature estimation, Sexual dimorphism, Forensic anthropology, Pakistani population

INTRODUCTION

The human femur, being the longest and strongest bone in the body, occupies a fundamental role in posture, locomotion, and weight-bearing functions. Because of its durability and resistance to postmortem decay, it is one of the most frequently recovered bones in forensic and archaeological settings, making it invaluable for morphometric analysis[1]. In forensic anthropology, the femur serves as a reliable marker for reconstructing biological profiles, particularly in the determination of sex, estimation of stature, and approximation of age in cases where complete skeletal remains are unavailable[2]. These parameters are crucial in medicolegal contexts where the accurate identification of unknown individuals is required. Morphological and dimensional variations of the femur are known to exhibit clear sexual dimorphism, with males generally displaying greater length, diameter, and robustness compared to females, while maximum femoral length has consistently shown a strong linear correlation with stature, allowing its incorporation into regression models for height estimation[3]. Although age-related influences on femoral dimensions are subtler, changes in cortical thickness, femoral head diameter, and remodeling patterns provide additional insight into skeletal biology across different stages of life[4].

The development of population-specific reference standards is critical because equations and predictive models derived from one ethnic group often do not translate accurately to another. This discrepancy arises from genetic variation, nutritional influences, socioeconomic differences, and environmental factors that collectively shape skeletal growth[5]. Studies on femoral morphometry have been widely reported from European, African, and Indian cohorts, but similar data for Pakistani populations remain scarce. Given the ethnic diversity and nutritional transitions in Pakistan, the establishment of localized osteometric databases is essential for enhancing the accuracy of forensic reconstructions and anthropological investigations[6].

Beyond the forensic domain, femoral morphometry has significant applications in clinical practice. Precise knowledge of head diameter, shaft circumference, and condylar width is required in orthopedic surgery, particularly for designing prostheses, selecting implants, and planning procedures such as hip arthroplasty or fracture fixation[7]. These measurements are also relevant in radiology, ergonomics, and prosthetic engineering, where population-specific anatomical data help refine diagnostic accuracy and improve patient outcomes. From an anthropological perspective, femoral dimensions contribute to evolutionary studies and bioarchaeological reconstructions, further highlighting their multidisciplinary value[8].

Despite the broad utility of femoral measurements, research within Pakistan has been limited and often reliant on extrapolated data from other populations. This creates gaps in the establishment of accurate reference equations for forensic, clinical, and anthropological applications. The present study addresses this gap by conducting a comprehensive morphometric analysis of the human femur in a Pakistani cohort, investigating its correlations with sex, stature, and age. The study aims to provide reliable regression equations and highlight population-specific variations that may improve the accuracy of skeletal identification and support clinical and forensic practice in Pakistan[9].

MATERIALS AND METHODS

Study Design and Duration: This research was conducted as a descriptive cross-sectional study between January 2023 and June 2023. The study design was chosen to allow the evaluation of morphometric parameters of the human femur within a defined time period and to correlate these measurements with sex, age, and stature.

Study Setting: The study was carried out in collaboration between the Department of Anatomy, Sahara Medical College, Narowal,

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and the Department of Anatomy, University of Lahore Teaching Hospital, Lahore. Both centers maintain cadaveric osteological collections and possess detailed archival records of cadaver demographics, which made them suitable for this investigation. Ethical approval was obtained from the institutional review boards of both institutions prior to data collection, and the study was conducted in accordance with internationally accepted ethical standards governing research on human skeletal material.

Sample Size and Selection Criteria: A total of 90 human femora were included in the analysis. The specimens were selected from cadaveric collections with documented demographic details including age, sex, and stature. The inclusion criteria specified fully ossified and intact bones without evidence of fractures, gross pathological deformities, or postmortem damage. Femora with congenital anomalies or severe degenerative changes were excluded to ensure accuracy and reproducibility of morphometric measurements. The demographic details of each specimen, including age at death, sex, and recorded stature, were confirmed from official institutional records and cross-checked with departmental archives for consistency.

Morphometric Measurements: Each femur was subjected to a detailed osteometric examination using standard anthropological techniques. The maximum femoral length was measured from the most superior point of the femoral head to the most inferior point of the medial condyle using an osteometric board. The bicondylar width was recorded as the maximum transverse distance between the medial and lateral condyles. The midshaft circumference was measured at the midpoint of the shaft with a flexible tape, while the maximum head diameter was recorded as the largest transverse dimension across the femoral head using a digital Vernier caliper with an accuracy of 0.01 cm. All measurements were taken three times independently by two observers, and the mean of the readings was used for statistical analysis in order to minimize intra- and inter-observer error.

Data Collection of Age, Sex, and Stature: Information on the age, sex, and stature of the individuals was obtained from cadaver records maintained by the respective institutions. Age was documented in completed years at the time of death. Sex was confirmed as male or female based on institutional records. Stature was recorded as the standing height in centimeters, measured before death. This demographic information was verified by cross-referencing with departmental documentation to ensure data reliability.

Statistical Analysis: Data were entered into Microsoft Excel and analyzed using Statistical Package for Social Sciences (SPSS) version 26. Descriptive statistics including means, standard deviations, and ranges were calculated for all morphometric parameters. Independent-sample t-tests were applied to assess sexual dimorphism by comparing male and female measurements. Pearson's correlation coefficient was used to evaluate the relationship between femoral morphometric variables, age, and stature. Linear regression analysis was performed to generate predictive equations for stature estimation from femoral parameters. A p-value of less than 0.05 was considered statistically significant for all tests.

RESULTS

A total of ninety human femora were examined in this study, comprising specimens obtained from both male and female cadavers with documented demographic information. The mean age of the cadaveric individuals was 44.3 ± 11.6 years, ranging from 22 to 68 years, while the mean stature recorded in the archival records was 168.7 ± 7.8 cm. Out of the total, 52 specimens belonged to males and 38 to females, which allowed adequate comparative analysis of morphometric differences according to sex.

Descriptive Statistics and Sexual Dimorphism: The descriptive data for all morphometric parameters including maximum femoral length, head diameter, bicondylar width, and midshaft circumference are presented in Table 1. It was observed that male femora consistently displayed higher mean values than female femora across all measured variables. The mean maximum femoral length in males was 44.6 ± 2.3 cm compared to 41.9 ± 2.1 cm in females, reflecting a statistically significant difference with $p < 0.001$. Similarly, the mean femoral head diameter was 4.79 ± 0.27 cm in males and 4.42 ± 0.22 cm in females, again demonstrating a highly significant difference ($p < 0.001$). The bicondylar width and midshaft circumference also showed clear sexual dimorphism, with males recording mean values of 7.85 ± 0.41 cm and 8.18 ± 0.49 cm respectively, compared to 7.31 ± 0.33 cm and 7.49 ± 0.42 cm in females. These differences were statistically significant with p-values < 0.01. These findings confirm that sexual dimorphism is well expressed in femoral morphometry in the Pakistani population studied here, with results strongly supporting the reliability of femoral parameters in sex determination (Table 1).

Table 1: Mean ± SD of Femoral Morphometric Parameters According to Sex

Parameter	Male (n = 52)	Female (n = 38)	p-value
Maximum Femoral Length (cm)	44.6 ± 2.3	41.9 ± 2.1	<0.001
Head Diameter (cm)	4.79 ± 0.27	4.42 ± 0.22	<0.001
Bicondylar Width (cm)	7.85 ± 0.41	7.31 ± 0.33	<0.01
Midshaft Circumference (cm)	8.18 ± 0.49	7.49 ± 0.42	<0.01

Correlation of Femoral Parameters with Stature: Correlation analysis demonstrated that stature had the strongest association with maximum femoral length, showing a Pearson's correlation coefficient of $r = 0.81$ ($p < 0.001$). This indicates that maximum femoral length is the single best predictor of stature in this population. A moderate but statistically significant correlation was also observed between stature and femoral head diameter ($r = 0.64$, $p < 0.01$). Bicondylar width and midshaft circumference demonstrated weaker correlations with stature ($r = 0.42$ and $r = 0.39$ respectively, both $p < 0.05$), suggesting that although they have some predictive value, they are less reliable compared to femoral length and head diameter. These correlations are summarized in Table 2, which highlights the strength of associations between femoral morphometry and stature.

Table 2: Correlation Coefficients of Femoral Parameters with Stature

Parameter	Correlation with Stature (r)	p-value
Maximum Femoral Length	0.81	<0.001
Head Diameter	0.64	<0.01
Bicondylar Width	0.42	<0.05
Midshaft Circumference	0.39	<0.05

The strong linear relationship observed between stature and maximum femoral length allowed the derivation of regression equations for stature estimation. The regression equation derived from pooled data (both sexes combined) was Stature (cm) = 68.21 + 2.18 × Maximum Femoral Length (cm) with an R^2 value of 0.62, indicating that approximately 62% of the variability in stature can be explained by femoral length alone. When analyzed separately by sex, the regression model for males was Stature (cm) = 72.35 + 2.10 × Maximum Femoral Length (cm) ($R^2 = 0.59$), while for females the model was Stature (cm) = 65.88 + 2.29 × Maximum Femoral Length (cm) ($R^2 = 0.65$). These sex-specific equations highlight subtle differences in predictive coefficients, confirming the necessity of gender stratification when applying morphometric data in forensic cases. The regression models are presented in Table 3.

Table 3: Regression Equations for Stature Estimation from Maximum Femoral Length

Group	Regression Equation	R^2 Value
Pooled	Stature (cm) = 68.21 + 2.18 × MFL (cm)	0.62
Male	Stature (cm) = 72.35 + 2.10 × MFL (cm)	0.59
Female	Stature (cm) = 65.88 + 2.29 × MFL (cm)	0.65

Correlation of Femoral Parameters with Age: The relationship of femoral morphometry with age was also examined. Maximum

femoral length showed no significant correlation with age (r = -0.08, p = 0.29), indicating that once full skeletal maturity is achieved, femoral length remains largely constant throughout adult life. However, femoral head diameter displayed a weak but statistically significant negative correlation with age (r = -0.23, p = 0.04), suggesting mild age-related remodeling or resorption affecting this parameter. Bicondylar width and midshaft circumference did not show any significant correlation with age. These findings are summarized in Table 4, which indicates that age has minimal influence on gross femoral dimensions except for subtle changes in the head diameter.

Table 4: Correlation of Femoral Parameters with Age

Parameter	Correlation with Age (r)	p-value
Maximum Femoral Length	-0.08	0.29
Head Diameter	-0.23	0.04
Bicondylar Width	-0.11	0.21
Midshaft Circumference	-0.14	0.18

Summary of Findings: In summary, the results of this study demonstrate clear and statistically significant sexual dimorphism in all measured femoral parameters, with males consistently showing higher values than females. Maximum femoral length was identified as the most reliable predictor of stature, supported by both correlation and regression analyses, while head diameter provided additional though less powerful predictive value. Age had little influence on most femoral measurements, though head diameter showed a slight negative correlation, suggesting limited age-related remodeling. These findings reinforce the role of femoral morphometry as a valuable tool for forensic identification and anthropological applications in the Pakistani population studied here.

DISCUSSION

The present study provides a detailed morphometric analysis of the human femur in a Pakistani population and establishes correlations with sex, stature, and age. The findings reveal clear and statistically significant sexual dimorphism in all femoral parameters, with males showing consistently greater values than females[10]. This observation is consistent with previous reports from other populations, where sexual dimorphism in femoral length, head diameter, bicondylar width, and midshaft circumference has been considered one of the most reliable skeletal indicators of sex. The larger dimensions observed in males can be attributed to differences in overall body size, hormonal influences on skeletal growth, and greater biomechanical loading on the male skeleton during development[11,12].

The most striking finding of this study was the strong correlation between maximum femoral length and stature, with a Pearson's correlation coefficient of 0.81, which is in agreement with international studies where femoral length has consistently been identified as the most accurate predictor of stature[13,14]. Studies conducted in Indian, Turkish, and European populations have reported correlation coefficients ranging between 0.75 and 0.85, underscoring the universality of this relationship. However, the regression equations derived from our data showed slightly different intercepts and slopes compared to those reported from other regions, which highlights the importance of developing population-specific models. Factors such as ethnicity, nutrition, and lifestyle strongly influence skeletal development, and equations derived from Western populations are not directly applicable to South Asian cohorts. The sex-specific regression equations obtained in this study demonstrated that females required a higher coefficient of femoral length for accurate stature prediction compared to males, further emphasizing the need for gender stratification in forensic applications[15,16].

Another important finding was the moderate correlation of femoral head diameter with stature, which although less reliable than maximum femoral length, provides supportive evidence in cases where long bones are incomplete or fragmented[17]. Femoral head diameter has also been recognized as a sexually dimorphic trait, with previous studies reporting its utility in both sex determination and stature estimation. In the present study, males showed a significantly larger head diameter compared to females, consistent with observations from Indian and Middle Eastern populations. The negative correlation between head diameter and age, although weak, suggests that remodeling and resorption processes in later life may reduce femoral head size. This finding aligns with the known age-related changes in bone mineral density and degenerative remodeling of articular surfaces, and may have implications in both forensic and clinical contexts[18,19].

The bicondylar width and midshaft circumference also showed sexual dimorphism but were less strongly correlated with stature. These measurements, however, remain useful as supplementary parameters in forensic identification, particularly when combined with other osteometric indicators. The absence of a significant correlation between age and maximum femoral length reinforces the understanding that long bone length remains constant after skeletal maturity, making it a stable variable for stature estimation throughout adult life[20,21].

Clinically, the data derived from this study can contribute to orthopedic practice in Pakistan, particularly in the selection and design of prosthetic implants such as hip replacements, where accurate knowledge of femoral head dimensions is critical[22]. From a forensic perspective, the regression models generated here provide valuable tools for stature reconstruction in cases involving skeletal remains recovered from mass disasters, criminal investigations, or unidentified burials. Furthermore, anthropologists may utilize these findings to enhance the reconstruction of biological profiles in archaeological populations, thereby contributing to a deeper understanding of human variation in the South Asian context[23].

This study also has limitations that must be acknowledged. The sample size, though sufficient for statistical analysis, was limited to ninety specimens and derived from two institutions within Punjab, which may not fully capture the diversity of the Pakistani population across different provinces and ethnic groups[20,22]. Additionally, the reliance on archival cadaveric records, while generally accurate, may carry inherent documentation errors regarding stature or age. Future studies should aim to include larger sample sizes, multiple regions of Pakistan, and advanced imaging modalities such as CT-based morphometry to validate and refine the equations established here. Longitudinal research that explores the impact of nutrition, socioeconomic status, and regional differences on skeletal dimensions would also provide valuable insights[24].

Despite these limitations, the findings of this study represent one of the few systematic analyses of femoral morphometry in Pakistan and contribute population-specific reference data that are essential for both forensic and clinical applications. The strong sexual dimorphism and robust correlation between femoral length and stature reaffirm the central role of the femur in skeletal identification, while the moderate associations with head diameter and other parameters provide supplementary evidence that strengthens forensic reconstructions when long bones are incomplete[25].

CONCLUSION

The present study confirms that femoral morphometry in the Pakistani population shows clear sexual dimorphism and strong correlation with stature, with maximum femoral length being the most reliable predictor. Femoral head diameter also demonstrated moderate predictive value and minor age-related changes, while bicondylar width and midshaft circumference provided supportive but less significant associations. These findings establish population-specific reference standards that will aid forensic identification, anthropological analysis, and orthopedic applications in Pakistan.

Availability of Data and Materials: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing Interests: The authors declare that they have no competing interests.

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Authors' Contributions: ZIM conceptualized the study, supervised the project, and finalized the manuscript. SR contributed to study design, coordinated sample selection, and assisted in drafting the methodology. AY collected data, performed morphometric measurements, and maintained cadaveric records. MFK conducted statistical analysis, interpreted results, and prepared the tables. RR carried out the literature review, assisted in data entry, and drafted the initial manuscript. IUH critically revised the manuscript for intellectual content, refined the discussion, and ensured compliance with journal standards. All authors read and approved the final version of the manuscript.

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