e-ISSN: 0975-9506, p-ISSN: 2961-6093

Available online on www.ijpqa.com

International Journal of Pharmaceutical Quality Assurance 2026; 17(9); 143-149

Original Research Article

Sexual Dimorphism of the Dry Human Humerus: A Morphometric Study for Sex Estimation

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Received: 12-08-2026 / Revised: 26-08-2026 / Accepted: 11-09-2026

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Conflict of interest: Nil

Abstract:

Background: Sex estimation is an important component of forensic identification, particularly when only isolated or incomplete skeletal remains are available. The humerus is a robust long bone that exhibits measurable sexual dimorphism and can therefore provide useful information for sex estimation.

Aim: To assess sexual dimorphism of the dry human humerus and evaluate selected morphometric parameters for sex estimation.

Methodology: A cross-sectional observational morphometric study was conducted in Darbhanga Medical College and Hospital, Laheriasarai, Darbhanga, Bihar, India, over 3 months. A total of 55 dry adult human humeri of known sex were examined. Maximum humeral length, vertical head diameter, maximum and minimum midshaft diameters, midshaft circumference, and epicondylar breadth were measured using standard osteometric techniques. Data was analyzed using descriptive statistics and independent *t*-test.

Results: Male humeri showed significantly higher mean values for all parameters than females ($P < 0.001$). Maximum humeral length was 312.84 ± 12.46 mm in males and 284.63 ± 11.72 mm in females, while epicondylar breadth was 61.24 ± 3.18 mm and 52.46 ± 2.94 mm, respectively.

Conclusion: The humerus demonstrated marked sexual dimorphism and its morphometric parameters may assist forensic sex estimation.

Keywords: Humerus; Sexual dimorphism; Morphometry; Sex estimation; Forensic anthropology; Osteometry.

DOI: 10.25258/ijpqa.17.9.21

Introduction

Sex estimation is one of the most crucial elements of forensic anthropology and is one of the first steps in the biological profile of unidentified skeletal remains. Identification can be difficult in the medicolegal or forensic context, particularly due to the body being dismembered, burnt, decomposed or skeletonized. Under such conditions, skeletal features are important for sex, age, stature and population affinity estimation. The most important areas for sex determination are the pelvis and the cranium, but these are not always completely recovered or well preserved. Thus, the evaluation of the postcranial skeletal elements, especially long bones, plays an important role in the process of forensic identification [1]. Sexual dimorphism is manifested in differences in size, proportions and morphology of the bones between sexes. These differences are progressive, and are influenced by genetic, hormonal, nutritional and biomechanical factors.

The humerus is a very useful long bone, being both strong and less subject to post-mortem decay and having a number of measurable characteristics which show sexual differences. Therefore, when other skeletal elements are missing or unable to be used, morphometric analysis of the humerus can provide useful information. The studies revealed that the dimensions of humerus like maximum length, head diameter, epicondylar breadth, shaft dimensions, circumference of humerus had marked difference between male and female [2]. In a comparative study of Chinese, Japanese and Thai skeletal populations, humerus was systematically proven to be important in sex estimation by İşcan et al. [3]. They measured six parameters, namely maximum length, vertical head diameter, minimum midshaft diameter, maximum midshaft diameter, midshaft circumference and epicondylar breadth.

The six dimensions were significantly higher in males than in females, $P < 0.001$. Their discriminant function analysis also showed that by using different combinations of the humeral measurements, sex could be successfully classified, and in Chinese, Japanese and Thai samples, the overall classification accuracy was 86.8%, 92.4% and 97.1%, respectively. A significant point of the results of İşcan et al. was the significance of the influence of population variation in skeletal sex estimation. The Chinese, Japanese and Thai samples were broadly related and Asian populations but differences in size and distribution of sexual dimorphism were observed. Cross-population validation showed that formulae that worked well for one population resulted in much poorer accuracy when applied to another population. This means that the size of the skeleton and the extent of sexual dimorphism vary from population to population and any standards based on one geographical and/or ethnic group should not be transferred to another population.

This will therefore be critical for the development of regional reference standards to promote the reliability of forensic sex estimation [4]. The diagnostic value of the single humeral parameters was also shown in various populations: the vertical head diameter and epicondylar breadth were consistently used in the discriminant analyses, but the maximum humeral length was only selected in the Chinese population. They also observed that the breadth and circumferential measurements were better discriminators than length measurements. In an Indian study, multiple humeral measurements were found to be useful for sex estimation by Reddy and Doshi [5] and they found transverse diameter of humeral head as an important single humeral measurement. They noted that in general multiple variables used together yield a better classification than single variables. Other Indian groups have confirmed the value of the humeral morphometry. Pendro et al. [6] studied 200 dry humeri in a central Indian population and found that there were significant differences between the males and females.

Taking the measurements together, the accuracy of classification exceeded 82%, and transverse diameter and head circumference proved to be the measurements with greatest discriminatory power. In a similar fashion, Ahmed et al. [7] did an osteometric analysis on 176 adult humeri samples from Maharashtra and showed that multivariate humeral measurements are useful for sexing. The study confirmed the forensic importance of humerus as a post cranial skeletal element in identifying sex in Indian population. Later Nadaf et al. [8] performed a morphometric analysis on 82 dry adult humeri of Indian origin and examined the humeral length, vertical diameter of the head, epicondylar breadth and maximum and minimum midshaft diameter of the humerus. They found that the vertical diameter of the humeral head was the most useful parameter for discrimination, followed by epicondylar breadth and maximum length, and that a combination of parameters was superior to any single parameter.

The discriminatory contribution of each humeral measurement may vary between populations, which further underscores the need for population-specific investigations, as these findings are relevant. In addition to the traditional osteometric analyses, morphological and geometric morphometric analyses have shown sexual dimorphism in the humerus. The differences in the olecranon fossa, medial epicondyle, trochlea symmetry and trochlea constriction between the sexes have been reported in studies of the distal humerus and both quantitative and qualitative features can be involved in sex estimation [9]. Another study has examined the use of geometric morphometric methods to determine sex in humeri and found that humeri size alone is not as accurate at sexing as when shape data is also used with size [10].

However, traditional morphometric measurements are still useful for routine forensic and anatomical analyses as they are relatively simple, inexpensive, repeatable, and can be used with dry skeletal remains. Considering the population related variations in skeletal dimensions and sexual dimorphism reported, it is necessary to have population specific study of the humerus in Indian population. Hence, the present study concentrates on the sexual dimorphism of the dry humerus of human skeleton from population of Laheriasarai, Darbhanga, Bihar, India through morphometric parameters and tries to evaluate differences in the humerus between male and female specimen.

The purpose of the study is to find out the humeral dimensions that show sex dimorphism and to assess their sexual dimorphic value. The results can give osteometric information for the region which may help in identification, anthropological estimation and study of isolated or incomplete skeletons related to the population of Bihar.

Methodology

Study Design: The present study was conducted as a cross-sectional observational morphometric study to assess sexual dimorphism of the dry human humerus and to evaluate the usefulness of selected morphometric parameters for sex estimation.

Study Area: The study was conducted in Darbhanga Medical College and Hospital, Laheriasarai, Darbhanga, Bihar, India, where available dry human humerus specimens were examined for morphometric assessment.

Study Duration: The study was carried out over a period of 3 months.

Sample Size: A total of 55 dry human humerus specimens (N = 55) were included in the present study for morphometric evaluation and assessment of sexual dimorphism.

Sample Population: The study population comprised adult dry human humerus specimens of known sex available in the study setting. Both male and female specimens were included to compare their morphometric characteristics and determine the parameters showing significant sexual dimorphism.

Data Collection: Data were collected by direct examination and morphometric measurement of the selected dry human humerus specimens. The measurements recorded included maximum humeral length, vertical diameter of the humeral head, maximum midshaft diameter, minimum midshaft diameter, midshaft circumference, and epicondylar breadth. These parameters were selected based on their established usefulness in humeral sex estimation studies.

Inclusion Criteria

- Adult dry human humerus specimens were included.
- Specimens with known sex were included.
- Specimens with adequate preservation were included.
- Specimens with clearly identifiable anatomical landmarks were included.
- Specimens sufficiently complete for obtaining the required morphometric measurements were included.
- Specimens suitable for standard osteometric measurement were included.

Exclusion Criteria

- Cadavers with severe damage to the gluteal region were excluded.
- Specimens with extensive surgical alteration of the gluteal or pelvic region were excluded.
- Specimens with severe decomposition or inadequate preservation were excluded.
- Specimens in which the sciatic nerve or piriformis muscle could not be clearly identified were excluded.
- Specimens with pathological or traumatic alterations affecting the structures under investigation were excluded

Procedure: The selected humerus specimens were examined and identified before measurement. Morphometric measurements were obtained using standard osteometric instruments, including an osteometric board, sliding caliper, and measuring tape, following established osteometric procedures. Maximum humeral length, vertical diameter of the humeral head, maximum and minimum midshaft diameters, midshaft circumference, and epicondylar breadth were measured and recorded in millimeters (mm).

Statistical Analysis: The data collected was entered into Microsoft Excel and analyzed using IBM SPSS Statistics. Descriptive statistics including mean and standard deviation were calculated for each morphometric parameter according to sex. Differences between male and female measurements were assessed using an independent-samples t-test, with $P < 0.05$ considered statistically significant. Discriminant function analysis was used, where appropriate, to evaluate the discriminatory ability of individual and combined humeral measurements for sex estimation, following previously established methodology".

Result

Table 1 presents the distribution of the 55 dry human humerus specimens according to sex. Out of the total 55 specimens, 30 (54.5%) were male and 25 (45.5%) were female. Thus, male specimens constituted a slightly higher proportion of the study population than female specimens.

Table 1: Distribution of Dry Human Humerus Specimens According to Sex

Sex	Number of specimens	Percentage (%)
Male	30	54.5
Female	25	45.5
Total	**55**	**100**

Table 2 shows the comparison of maximum humeral length and vertical diameter of the humeral head between male and female specimens. The mean maximum humeral length was higher in males (312.84 ± 12.46 mm) than in females (284.63 ± 11.72 mm). Similarly, the mean vertical diameter of the humeral head was greater in males (45.18 ± 2.71 mm) compared with females (39.82 ± 2.36 mm). Both differences were statistically highly significant ($P < 0.001$), indicating significant sexual dimorphism in these parameters.

Table 2: Comparison of Maximum Humeral Length and Vertical Head Diameter Between Male and Female Humeri				
Morphometric parameter (mm)	**Male (n=30), Mean ± SD**	**Female (n=25), Mean ± SD**	**t-value**	**P-value**
Maximum humeral length	312.84 ± 12.46	284.63 ± 11.72	8.66	<0.001
Vertical diameter of humeral head	45.18 ± 2.71	39.82 ± 2.36	7.57	<0.001

Table 3 compares the maximum midshaft diameter, minimum midshaft diameter, and midshaft circumference between male and female humeri. All three parameters showed higher mean values in males than females. Maximum midshaft diameter was 22.41 ± 1.82 mm in males compared with 19.58 ± 1.63 mm in females, while minimum midshaft diameter was 17.36 ± 1.54 mm and 14.92 ± 1.37 mm, respectively. Midshaft circumference was also greater in males (65.18 ± 4.21 mm) than females (57.24 ± 3.86 mm). All differences were statistically highly significant (P < 0.001), demonstrating marked sexual dimorphism in humeral shaft dimensions.

Table 3. Comparison of Midshaft Measurements Between Male and Female Humeri				
Morphometric parameter (mm)	**Male (n=30), Mean ± SD**	**Female (n=25), Mean ± SD**	**t-value**	**P-value**
Maximum midshaft diameter	22.41 ± 1.82	19.58 ± 1.63	5.99	<0.001
Minimum midshaft diameter	17.36 ± 1.54	14.92 ± 1.37	6.03	<0.001
Midshaft circumference	65.18 ± 4.21	57.24 ± 3.86	7.21	<0.001

Table 4 presents the comparison of epicondylar breadth between male and female humeri. The mean epicondylar breadth was considerably greater in males (61.24 ± 3.18 mm) than in females (52.46 ± 2.94 mm). The observed difference was statistically highly significant (P < 0.001), suggesting that epicondylar breadth is an important morphometric parameter for differentiating male and female humeri in the present study population.

Table 4: Comparison of Epicondylar Breadth Between Male and Female Humeri				
Morphometric parameter (mm)	**Male (n=30), Mean ± SD**	**Female (n=25), Mean ± SD**	**t-value**	**P-value**
Epicondylar breadth	61.24 ± 3.18	52.46 ± 2.94	10.34	<0.001

Table 5 provides an overall comparison of all six morphometric parameters evaluated in the study. Male humeri demonstrated consistently higher mean values than female humeri for maximum humeral length, vertical head diameter, maximum midshaft diameter, minimum midshaft diameter, midshaft circumference, and epicondylar breadth. All six parameters showed statistically highly significant differences (P < 0.001). The greatest mean difference was observed for maximum humeral length (28.21 mm), followed by epicondylar breadth (8.78 mm) and midshaft circumference (7.94 mm). Overall, the findings indicate pronounced sexual dimorphism of the dry human humerus and support the potential usefulness of these morphometric parameters for sex estimation.

Table 5: Overall Comparison of Morphometric Parameters and Their Statistical Significance for Sex Estimation					
Morphometric parameter	**Male Mean ± SD (mm)**	**Female Mean ± SD (mm)**	**Mean difference (mm)**	**P-value**	**Sexual dimorphism**
Maximum humeral length	312.84 ± 12.46	284.63 ± 11.72	28.21	<0.001	Significant
Vertical head diameter	45.18 ± 2.71	39.82 ± 2.36	5.36	<0.001	Significant
Maximum midshaft diameter	22.41 ± 1.82	19.58 ± 1.63	2.83	<0.001	Significant
Minimum midshaft diameter	17.36 ± 1.54	14.92 ± 1.37	2.44	<0.001	Significant
Midshaft circumference	65.18 ± 4.21	57.24 ± 3.86	7.94	<0.001	Significant
Epicondylar breadth	61.24 ± 3.18	52.46 ± 2.94	8.78	<0.001	Significant

Discussion

The present study showed a distinct sexual dimorphism in all six morphometric parameters studied in 55 dry human humeri. Male specimens showed consistently greater mean values than females for maximum humeral length (312.84 ± 12.46 vs. 284.63 ± 11.72 mm), vertical diameter of the humeral head (45.18 ± 2.71 vs. 39.82 ± 2.36 mm), maximum midshaft diameter (22.41 ± 1.82 vs. 19.58 ± 1.63 mm), minimum midshaft diameter (17.36 ± 1.54 vs. 14.92 ± 1.37 mm), midshaft circumference (65.18 ± 4.21 vs. 57.24 ± 3.86 mm) and epicondylar breadth (61.24 ± 3.18 vs. 52.46 ± 2.94 mm), with all differences being statistically highly significant ($P < 0.001$). The results corroborate the overall impression that there is significant sexual dimorphism in the humerus and that it may be of some assistance for sex determination in the absence of more diagnostically useful skeletal parts. The same was found by Frutos (2005) in a forensic sample of 118 complete humeri (68 males and 50 females) from Guatemala".

The study was conducted to assess maximum length, maximum head diameter, midshaft circumference, maximum and minimum midshaft diameter, and epicondylar breadth which are similar to the variables measured in the present study. The highest classification accuracy reported by Frutos with their maximum midshaft diameter to maximum head diameter was 76.8% and 95.5%, respectively, and the stepwise discriminant function achieved an overall accuracy of 98.2% [11]. In the present study, the differences were also significant for both the proximal and shaft measurements, but because of the much smaller number of specimens (55) comparisons of classification accuracy are not possible. However, the uniformity of the larger values among males reinforces the indication of sexual dimorphism of the humerus.

The sex specific nature of epicondylar breadth of the humerus is also confirmed by Albanese et al. (2005), who specifically investigated the epicondylar breadth of the humerus and created a methodology for sexing based on a larger sample set. They concluded that the allocation accuracy was around 83–96% for sample sizes of more than 40 individuals and a sex ratio of less than 1.5:1 from their experiments using measurements from the distal humerus of the Coimbra Collection [12]. In the current study, the epicondylar breadth was 52.46 ± 2.94 mm in females and 61.24 ± 3.18 mm in males with a difference of 8.78 mm ($P < 0.001$). As such the strong difference seen in the present sample is in line with earlier evidence that the distal humeral breadth may be a very effective sex discriminator. The study of Hamzehtofigh et al. (2019) on 61 dry adult humeri from central Iran, 35 of which were male and 26 females, also showed variation of the population. They reported a mean humeral length of 320.07 ± 1.14 mm in males and 280.99 ± 1.05 mm in females, while epicondylar width averaged 58.37 ± 3.46 mm in males and 54.51 ± 3.77 mm in females [13]. The male humeral length in the present study was slightly lower (312.84 ± 12.46 mm) but the female value was slightly higher (284.63 ± 11.72 mm) when compared to the other studies. The epicondylar breadth in the present males (61.24 ± 3.18 mm) was greater than the epicondylar breadth of Iranian males (59.74 mm) but was slightly less than that of the females (52.46 ± 2.94 mm). These differences despite the similar general trend of male predominance highlight the differences in absolute size of the humerus between the populations and the need for locally derived reference data for forensic use. These findings from Robinson and Bidmos (2009) also make a point of the necessity for the equations used for sex estimation to be validated across populations. Their investigation verified the reliability of discriminant function equations which were developed from South African populations, and they found that equations developed from one skeletal sample may not perform the same when applied to another sample [14]. This is significant for the current study from Dmch, Laheriasarai, Darbhanga, Bihar in which marked differences were found in all six parameters and could be a regional variation in body size and skeletal proportions. Thus, the following measurements are population specific and should not be used as standards.

The same has been observed in the present study and is corroborated by evidence from the geometric morphometric work. Maass P et al. (2018) analyzed 1046 adult South African humeri and discovered that there were significant differences in mean centroid size between the male and female humeri, and that humerus form was sexually dimorphic. Their study found classification accuracy over 76% for combined sex-ancestry groups and showed that humeral morphology can provide information about biological traits even in a population that has significant internal diversity [15]. The present study employed traditional linear osteometric methodology but the increase in size noted in males is similar to that noted by them. López-Lázaro et al. (2020) analyzed 72 adult humeri using a different methodology: geometric morphometry. The classification accuracies of shape variables were relatively low, ranging from 54.95–77.92% for males and 56.87–71.78% for females. Combination of shape variables with centroid size increased the accuracy from 81.86–94.92% for males to 84.08–94.88% for females [16]. The present findings are consistent with the results of those studies that indicate humeral size is an important aspect of sexual dimorphism. The present study shows that the significant differences in maximum length, head diameter and shaft dimensions suggest that conventional metric variables can be used to successfully reveal sex-related differences, but that multiple parameters may be more effective at classification.

The distal humerus has also been demonstrated to have a significant discriminative value. Ammer et al. (2019) examined 151 humeri by shape analysis of the trochlear constriction and olecranon fossa. The olecranon fossa had a significantly higher classification accuracy of 94.0% [17] while trochlear constriction yielded 63.6%. This is in accordance with the current results, which indicated that epicondylar breadth, as a measure of the distal humeral morphology, may give sex-related information. The difference in methodology suggests that different aspects of sexual dimorphism might be represented by the dimensional and the shape-based variables. Additional evidence is provided by a study of 483 humeri from an identified skeletal collection from Brazil by Soriano et al. (2021) with 208 males and 193 females. Their data gave the best results with the accuracy of 93.8-97.5% in humeral sex determination using transverse and vertical head diameters and epicondylar width, and the transverse diameter of the right humeral head was the most dimorphic measurement [18].

Although the present study does not use formal classification as the primary outcome, the highly significant differences in vertical head diameter (45.18 ± 2.71 mm in males vs. 39.82 ± 2.36 mm in females) also indicate strong proximal humeral sexual dimorphism. Results from the present study are generally in agreement with the earlier morphometric and geometric studies which have shown that the humerus of the male is, in general, larger and stouter than that of the female. The differences between the maximum humeral length (28.21 mm), epicondylar breadth (8.78 mm) and midshaft circumference (7.94 mm) are particularly large, suggesting that both size and breadth-related characteristics are contributing to sexual dimorphism. Comparisons with other populations, including the Iranian, Guatemalan, South African and Brazilian, show that these differences are geographically variable. So the marked sex dimorphism found in the present sample of Laheriasarai, Darbhanga, Bihar population was found to be of forensic value and the necessity of establishing population specific standards for accurate sex identification has been highlighted.

Conclusion

Finally, the present study showed that there was a significant sexual dimorphism in dry human humerus studied from 55 specimens from Laheriasarai, Darbhanga, Bihar, India. For each of the parameters measured, the mean values of the male humeri were always significantly higher than those of the female humeri ($P < 0.001$ in all cases). The greatest number of significant differences between males and females was observed between maximum humeral length, epicondylar breadth and midshaft circumference, suggesting that these parameters may be useful for sex differentiation. In conclusion the results indicate that morphometric examination of the humerus can be useful for sex determination and that it may be more useful in forensic circumstances where skeletal remains are isolated, incomplete and/or unidentified. The study also points to the need for population-specific morphometric data, since the magnitude of sexual dimorphism can change among different populations geographically. Hence the present results are of value for the regional osteometric data with regard to the population of Darbhanga, Bihar and it highlights the possibilities of using humeral morphometry as an auxiliary tool in forensics anthropological investigation.

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