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Application of discriminant function analysis for sex prediction from composite patellar indices: A multivariate study on skeletal samples

Sheuli Akter[1], Mustafezur Rahman[2], Mahmuda Khatoon[1], Mst. Roksana Begum[3]

[1]Department of Anatomy, Ibn Sina Medical College, Dhaka, Bangladesh, [2]Department of Gastroenterology, National Gastroliver Institute and Hospital, Dhaka, Bangladesh, [3]Department of Anatomy, United Medical College, Dhaka, Bangladesh

Address for correspondence: Sheuli Akter, Assistant Professor, Department of Anatomy, Ibn Sina Medical College, Dhaka, Bangladesh. E-mail: drsheuli122@gmail.com

Abstract

Introduction: Sex estimation from skeletal remains is a fundamental step in forensic and anthropological investigations. The patella, due to its robust nature and resistance to postmortem damage, is increasingly recognized as a useful bone for this purpose. This study aimed to evaluate sexual dimorphism in human left patellae and develop discriminant function equations for sex determination in a Bangladeshi sample.

Methods: A total of 150 dry adult left patellae (92 males, 58 females) were measured for various morphometric parameters, including height, width, thickness, facet dimensions, volume, and weight. Composite ratios were also calculated. Data were analyzed using *t*-tests and discriminant function analysis (DFA).

Results: Male patellae showed significantly greater values than female patellae in maximum height (42.10 ± 1.99 mm vs. 36.16 ± 2.31 mm), width (42.87 ± 1.80 mm vs. 36.94 ± 1.58 mm), thickness, weight, and volume ($P < 0.001$ for all). Significant sex differences were also found in articular facet dimensions and composite indices. The width-to-height ratio was not significantly different, whereas the width/thickness and height/thickness ratios were higher in males.

Conclusion: The patella demonstrates notable sexual dimorphism in the Bangladeshi population. DFA based on these parameters offers a reliable method for sex estimation.

Keywords: Bangladesh, discriminant function analysis, forensic anthropology, patella, sexual dimorphism

Introduction

Sex estimation from human skeletal remains plays a pivotal role in the construction of a biological profile in both forensic anthropology and bioarchaeology. It is regarded as one of the most crucial steps in the identification of individuals, particularly in situations involving mass disasters, crime scene investigations, or fragmented human remains where DNA may be unavailable or degraded. The accuracy and speed of sex determination directly influence downstream analyses such as stature estimation, ancestry profiling, and personal identification.[1,2] Conventionally, pelvic and cranial bones have been considered the most sexually dimorphic and hence most reliable for such assessments. However, in many forensic cases, these bones may be missing or damaged due to taphonomic processes, trauma, or environmental conditions. In such scenarios, the patella emerges as an important alternative owing to its robust structure, central anatomical location, and high preservation potential, especially in fragmentary remains.[3,4] The patella, or kneecap, is the largest sesamoid bone in the human body, embedded within the quadriceps femoris tendon and articulating with the femur. Functionally, it serves to protect the anterior knee joint and enhance the mechanical efficiency of the quadriceps by increasing the moment arm during knee extension. The biomechanical demands placed on the patella–such as tolerating compressive forces estimated at up to 7 times the body weight during squatting–result in observable morphometric differences that are often reflective of sex-based muscular and skeletal loading patterns.[5-7] Consequently, the dimensions of the patella, such as its height, width, and thickness, have been found to exhibit significant sexual dimorphism, making it a viable element for sex determination, particularly in multivariate predictive frameworks. Empirical studies across diverse global populations have demonstrated that male patellae generally exhibit larger dimensions than their female counterparts, with reported differences of approximately 4–6 mm in height and width and 2–3 mm in thickness. These differences have been harnessed using statistical models such as discriminant function analysis (DFA) to classify sex with accuracies ranging from 80% to above 90%.[8-10] These findings underscore the potential of the patella as a highly informative bone for sex estimation, especially in populations where long bones are less frequently recovered intact or are unavailable due to cultural burial practices or postmortem damage. In addition to raw linear measurements, recent studies have stressed the enhanced discriminatory power of composite indices–such as width/height, width/thickness, and height/thickness ratios–as well as facet-based metrics. These ratios offer an advantage in that they normalize for the overall body size and reveal subtle shape-based differences that are not captured by absolute dimensions alone.[9,11] Multivariate analyses incorporating these indices tend to produce higher classification accuracy, particularly when applied using population-specific models that take into account regional morphometric variability.[8] DFA remains the methodological gold standard in this domain. Its capacity to generate statistically robust and easily applicable sectioning points tailored to specific populations has been validated in numerous forensic anthropology studies.[12-14] DFA not only facilitates rapid field estimation but also integrates well with digital imaging and post-processing techniques, allowing its application in both physical and virtual forensic reconstructions. Despite extensive international research–including studies from Europe, Africa, and parts of South Asia–there remains a conspicuous lack of sex estimation models based on patellar dimensions in the Bangladeshi population. Existing literature, such as that by Chaity and Rahman has explored sex estimation from various somatic parameters in Bangladesh, but none have established normative values or discriminant equations for the patella.[15] This gap is critical given that the use of foreign reference data may result in erroneous classifications due to inter-population variability in skeletal morphology.[16] Bangladesh faces unique forensic and clinical challenges that further necessitate the establishment of indigenous osteometric databases. With its increasing medico-legal caseload, recurrent natural disasters, and a growing need for surgical customization–especially in orthopedic implant design–there is an urgent need for reliable, locally derived skeletal standards. Studies have highlighted the vulnerability of Bangladeshi women and disaster-affected populations, often resulting in unidentified remains that require forensic attention.[15] In addition, clinical disparities in prosthetic fitting emphasize the need for sex-specific anatomical data to ensure optimal implant compatibility and surgical outcomes.[17,18] In this context, the present study aims to bridge this gap by quantifying key linear and composite patellar dimensions in a Bangladeshi skeletal sample and applying DFA to develop sex estimation models with high predictive accuracy. The resulting data will contribute to forensic anthropology, aid in medicolegal investigations, and provide baseline morphometric references for orthopedic surgical planning in Bangladesh.

Methods

This cross-sectional analytical study was conducted in the Department of Anatomy at Dhaka Medical

College, Dhaka, from January 2018 to June 2019. A total of 150 dry, fully ossified adult human left patellae of unknown sex were collected using a purposive sampling technique. Patellae exhibiting any evidence of fracture, deformity, or incompleteness were excluded. The bones were obtained from departmental anatomical collections and from MBBS students of Dhaka Medical College, Northern International Medical College, and Ibn Sina Medical College. The left patella was specifically chosen in accordance with anthropological convention, recommending standardized measurements from one side for comparative morphometric analysis. Each patella was evaluated for a set of linear and morphological parameters using standardized osteometric procedures. Variables included maximum patellar height, width, thickness, height of the median ridge, widths and thicknesses of articular facets, weight, and volume. Measurements were taken using digital sliding calipers, flexible metallic wire, electronic balance, glass cylinder, and protractor, as appropriate for each parameter. Measurements were repeated 3 times and averaged for accuracy. Morphological features such as patellar shape, type (based on relative facet widths), and nose pattern were recorded, and composite indices including patellar index, width-to-height ratio, width-to-thickness ratio, height-to-thickness ratio, median ridge position, and lateral facet ratio were calculated. Sex determination of the collected patellae was performed through multivariate linear DFA, based on key variables such as maximum height and width. Discriminant scores for each bone were generated using the formula $DF = a + b_1x_1 + b_2x_2 + \ldots + b_nx_n$, where "a" is the constant, "b" coefficients are calculated through regression, and "x" values represent the measured variables. A sectioning point was derived from the mean discriminant scores to classify bones into male or female groups. Specimens with discriminant scores above the sectioning point were classified as male, while those below were considered female. Following sex classification, statistical analyses were performed to explore morphometric differences between sexes. Descriptive statistics, including means and standard deviations, were calculated. Unpaired Student's *t*-tests were used to assess the significance of differences between male and female values, and a $P < 0.05$ was considered statistically significant. All statistical analyses were carried out using the Statistical Package for the Social Sciences version 22.0. Ethical approval for the study was obtained from the Ethical Review Committee of the Anatomy Department at Dhaka Medical College. Data were handled with confidentiality, and all specimens were returned to their respective owners following measurement and analysis.

Results

Table 1 presents the comparison of maximum patellar height and width between male and female samples. The results show that male patellae had significantly greater maximum height (42.10 ± 1.99 mm) and width (42.87 ± 1.80 mm) compared to females (36.16 ± 2.31 mm and 36.94 ± 1.58 mm, respectively), with both differences being statistically significant ($P < 0.001$). This confirms a high degree of sexual dimorphism in the basic dimensions of the patella.

Table 2 displays the differences in maximum patellar thickness and the height of the median ridge between sexes. Males had significantly greater patellar thickness (20.73 ± 1.25 mm) than females (18.69 ± 1.39 mm), and similarly, the height of the median ridge was higher in males (29.90 ± 2.38 mm) compared to females (26.89 ± 2.02 mm), with $P < 0.001$ for both variables. These findings suggest consistent

Table 1: Maximum patellar height and width in males and females (*n*=150)

Variables (in mm)	Male (*n*=92) mean±SD (range)	Female (*n*=58) mean±SD (range)	*P*-value
Maximum patellar height	42.10±1.99 (37.50–46.70)	36.16±2.31 (31.30–40.45)	<0.001*
Maximum patellar width	42.87±1.80 (39.20–46.35)	36.94±1.58 (33.35–40.35)	<0.001*

SD: Standard deviation, *p < 0.05 considered statistically significant sex-based differences in vertical and anteroposterior patellar morphology.

Table 3 compares the widths of the lateral and medial articular facets of the patella. Both parameters were found to be significantly greater in males, with lateral facet width measuring 25.00 ± 1.31 mm and medial facet width 21.61 ± 1.52 mm, as opposed to 22.59 ± 1.73 mm and 18.32 ± 1.53 mm in females, respectively. The differences were highly significant ($P < 0.001$), indicating pronounced sexual dimorphism in the articular surface configuration.

Table 4 shows the weight and volume of the patellae among males and females. Males exhibited significantly higher patellar weight (10.59 ± 2.13 g) and volume (10.88 ± 1.98 cc) compared to females (6.79 ± 1.45 g and 7.10 ± 1.34 cc), with both differences being statistically significant ($P < 0.001$). These results reinforce the notion that patellar mass and density are reliable indicators for distinguishing sex.

Table 2: Maximum patellar thickness and height of median ridge (*n*=150)

Variables (in mm)	Male (*n*=92) mean±SD (range)	Female (*n*=58) mean±SD (range)	*P*-value
Maximum patellar thickness	20.73±1.25 (17.27–26.60)	18.69±1.39 (16.10–22.12)	<0.001*
Height of median ridge	29.90±2.38 (20.23–34.82)	26.89±2.02 (22.35–35.00)	<0.001*

SD: Standard deviation. *p < 0.05 considered statistically significant

Table 3: Width of lateral and medial articular facets (*n*=150)

Variables (in mm)	Male (*n*=92) mean±SD (range)	Female (*n*=58) Mean±SD (range)	*P*-value
Width of lateral articular facet	25.00±1.31 (20.25–27.72)	22.59±1.73 (18.02–25.60)	<0.001*
Width of medial articular facet	21.61±1.52 (19.10–25.41)	18.32±1.53 (14.80–22.10)	<0.001*

SD: Standard deviation, *p < 0.05 considered statistically significant

Table 5 outlines the distribution of patellar shapes among male and female samples. The majority of patellae in both sexes were of the rounded type, accounting for 90.2% in males and 86.2% in females. Triangular-shaped patellae were more commonly observed in females (13.8%) than in males (8.7%), while the irregular shape was rare and found only in one male specimen (1.1%). Although both sexes predominantly exhibited rounded patellae, the slightly higher occurrence of triangular types among females may indicate subtle morphological variation with potential sex-specific implications.

Table 6 displays the classification of patellae into types based on the comparative widths of medial

Table 4: Weight and volume of patella in males and females (*n*=150)

Variables	Male (*n*=92) mean±SD (range)	Female (*n*=58) mean±SD (range)	*P*-value
Weight (g)	10.59±2.13 (6.07–18.23)	6.79±1.45 (3.13–9.92)	<0.001*
Volume (cc)	10.88±1.98 (7.0–16.3)	7.10±1.34 (5.0–10.0)	<0.001*

SD: Standard deviation, *p < 0.05 considered statistically significant

Table 5: Shape of patella in males and females (*n*=150)

Shape of the patella	Male (*n*=92) frequency (%)	Female (*n*=58) frequency (%)
Rounded	83 (90.2)	50 (86.2)
Triangular	8 (8.7)	8 (13.8)
Irregular	1 (1.1)	0 (0.0)

Table 6: Type of patella in males and females (*n*=150)

Type of patella	Male (*n*=92) frequency (%)	Female (*n*=58) frequency (%)
Type A (WMAF=WLAF)	14 (15.2)	5 (8.6)
Type B (WMAF <WLAF)	78 (84.8)	53 (91.4)
Type C (WMAF >WLAF)	0 (0.0)	0 (0.0)

and lateral articular facets. Type B patellae, where the width of the medial articular facet is less than that of the lateral facet (WMAF < WLAF), were the most prevalent in both sexes, comprising 84.8% of male and 91.4% of female specimens. Type A patellae (WMAF = WLAF) were observed in 15.2% of males and 8.6% of females. Notably, no patellae were identified as Type C (WMAF > WLAF) in either sex. This distribution suggests a dominant anatomical pattern of asymmetric facet width across the study population, with minor inter-sex differences.

Table 7 compares the composite ratios of the patella between male and female specimens. The width/height ratio did not show any statistically significant difference between sexes ($P = 0.772$), indicating similar overall shape proportions in this respect. However, both the width/thickness and height/thickness ratios were significantly higher in males (2.07 ± 0.15 and 2.03 ± 0.10, respectively) than in females (1.98 ± 0.12 and 1.92 ± 0.15), with $P < 0.001$. These findings suggest that males tend to have a more flattened patella in terms of anterior–posterior thickness relative to height and width, making these composite indices useful for improving sex differentiation.

Table 8 presents data on the median ridge position and lateral facet ratio in males and females. While the mean position of the median ridge did not differ significantly between sexes ($P = 0.127$), the lateral facet ratio was significantly higher in females (0.61 ± 0.04) than in males (0.58 ± 0.03), with a $P < 0.001$. This indicates that females have a relatively broader lateral facet when normalized against patellar width, which may contribute to subtle sex-related differences in articular surface morphology.

Table 7: Composite ratios of patella in males and females (*n*=150)

Variables	Male (*n*=92) Mean±SD (range)	Female (*n*=58) Mean±SD (range)	*P*-value
Width/height ratio	1.01±0.05 (0.90–1.15)	1.02±0.06 (0.88–1.15)	0.772 ns
Width/ thickness ratio	2.07±0.15 (1.10–2.50)	1.98±0.12 (1.63–2.23)	<0.001*
Height/ thickness ratio	2.03±0.10 (1.77–2.34)	1.92±0.15 (1.20–2.30)	<0.001*

SD: Standard deviation, *p < 0.05 considered statistically significant

Discussion

This study was carried out to explore whether the patella, a strong and commonly found bone, can help identify the sex of individuals based on its measurements. The results clearly show that there are several important differences between male and female patellae, and these differences can be useful in forensic and anthropological work. In particular, male patellae were found to be significantly larger in both height (42.10 ± 1.99 mm) and width (42.87 ± 1.80 mm) compared to female patellae (36.16 ± 2.31 mm and 36.94 ± 1.58 mm, respectively). These findings are very similar to the results seen in other studies from different populations, such as Italy, Egypt, and Iran.[9,10,19] In all these studies, men had significantly taller and wider patellae than women. In the present study, male patellae were also thicker from front to back (20.73 ± 1.25 mm) than those of females (18.69 ± 1.39 mm). This difference was statistically significant and agrees with findings from other researchers who also reported thicker patellae in men.[8] These differences in thickness, height, and width may be related to the greater muscle strength and body mass typically found in males. The height of the ridge that runs down the middle of the back of the patella, known as the median ridge, was also greater in males (29.90 ± 2.38 mm) than in females (26.89 ± 2.02 mm). This has also been seen in other studies, such as those by Taj *et al*., and Kafa *et al*., who found that this ridge tends to be more prominent in men.[20,21] This study

Table 8: Median ridge position and lateral facet ratio (*n*=150)

Variables	Male (*n*=92) mean±SD (range)	Female (*n*=58) mean±SD (range)	*P*-value
Median ridge position	0.50±0.03 (0.43–0.59)	0.49±0.04 (0.43–0.63)	0.127ns
Lateral facet ratio	0.58±0.03 (0.49–0.65)	0.61±0.04 (0.49–0.69)	<0.001*

SD: Standard deviation, *p < 0.05 considered statistically significant also showed that the articular surfaces–the parts of the patella that connect with the thigh bone–were larger in men. The width of the lateral facet (25.00 ± 1.31 mm in males vs. 22.59 ± 1.73 mm in females) and the medial facet (21.61 ± 1.52 mm in males vs. 18.32 ± 1.53 mm in females) were both significantly higher in males. These results support similar findings from studies done in South Africa and Poland.[22,23] Weight and volume also showed clear sex differences. Male patellae were heavier (10.59 ± 2.13 g) and had more volume (10.88 ± 1.98 cc) than female patellae (6.79 ± 1.45 g and 7.10 ± 1.34 cc, respectively). This is consistent with the findings of Zhan *et al*. and Sheehan *et al*., who found that weight and volume are helpful in identifying sex from the patella.[24,25] When looking at shape, we found that rounded patellae were the most common in both sexes, but were slightly more frequent in males (90.2%) than females (86.2%). Triangular shapes were more common in females (13.8%) than in males (8.7%), and only one patella (in a male) was irregular. These patterns match the findings of Mzimela *et al*., who also found similar shape distributions using the same classification.[26] In this study, we also categorized the patellae based on the width of the articular facets. Type B patellae, where the medial facet is narrower than the lateral facet, were the most common in both sexes – 84.8% in males and 91.4% in females. Type A (equal facet widths) was less common, and no Type C patellae (with a wider medial facet) were found. This result matches findings from other regional studies, such as Pothala *et al*., and supports the idea that Type B is the usual configuration.[27] We also looked at some ratios to see how the measurements relate to each other. The width-to-height ratio did not show a significant difference between sexes (1.01 ± 0.05 in males vs. 1.02 ± 0.06 in females; $P = 0.772$), which is in agreement with Dorado-Fernández *et al*., who noted that this ratio is generally stable and not helpful for distinguishing sex.[8] However, both the width-to-thickness and height-to-thickness ratios were significantly higher in males ($P < 0.001$), indicating that male patellae tend to be broader and taller in relation to their thickness. This finding is consistent with earlier studies on these ratios.[28,29] Interestingly, there was no significant difference between males and females in the position of the median ridge (0.50 ± 0.03 in males vs. 0.49 ± 0.04 in females; $P = 0.127$). Similar observations were reported by Guo *et al*. and Ab Rahman *et al*., who also found that the ridge tends to stay near the center regardless of sex.[30,31] Finally, we found that the lateral facet ratio, which compares the width of the lateral facet to the whole width of the patella, was significantly higher in females (0.61 ± 0.04) than in males (0.58 ± 0.03; $P < 0.001$). This means that females tend to have proportionally broader lateral facets. Similar results were seen in studies by Muhamed *et al*., and Wilson *et al*., who also found broader lateral facets in women.[32,33] In summary, the results of this study confirm that the patella shows several significant differences between males and females in terms of size, shape, weight, volume, and certain proportional indices. These differences are consistent with findings from other parts of the world and support the use of the patella for sex determination. The data presented here are especially valuable because they provide population-specific reference values for the Bangladeshi population, which can help improve accuracy in both forensic investigations and surgical planning.

Limitations of the study

One of the key limitations of this study is the relatively small and region-specific sample size, which may limit the generalizability of the findings to other populations. All measurements were conducted on dry skeletal specimens without information on age, stature, or cause of death, which could influence patellar morphology. Furthermore, only left patellae were included, following anthropological convention, which prevented the evaluation of bilateral asymmetry. The lack of radiological correlation or soft-tissue consideration also restricts clinical applicability, particularly in live subjects or surgical planning contexts.

Conclusion

This study demonstrated that the human patella exhibits significant sexual dimorphism across a range of linear, volumetric, morphological, and composite parameters in a Bangladeshi population. Male patellae were consistently larger, heavier, and more robust than female patellae. Among the evaluated variables, height, width, thickness, articular facet dimensions, and composite ratios such as width/thickness and height/thickness showed statistically significant differences. DFA using these parameters provides a reliable method for sex estimation. These findings support the use of the patella as an effective bone for sex determination, particularly when more sexually dimorphic bones are unavailable, and highlight the importance of establishing population-specific reference data.

Recommendation

It is recommended that further studies be conducted on a larger and more diverse sample, including both right and left patellae and integrating age and radiographic data. This will enhance the applicability of the findings in forensic, archaeological, and clinical settings and support the development of a comprehensive skeletal identification database for the Bangladeshi population.

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Conflict of Interest

None declared.

Ethical Approval

The study was approved by the Institutional Ethics Committee

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