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Quantitative analysis of the innominate bone for sex estimation utilising the Phenice method

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Abstract

Background The Phenice method is a reliable qualitative analysis of the pubis and ischium region of the innominate bone to assess an individual's sex. Geometric morphometric provides methods of quantitative analysis of the region for identification purposes, which may be affected by environmental changes. This study analysed the Phenice method by utilising 3D (3 dimensional) CT (computed tomography) scans by geometric morphometrics for sex estimation. The CT scans of 231 adult individuals (148 males and 83 females) of the Malaysian population were landmarked by IDAV Landmark software and analysed by MorphoJ and SPSS.

Results The first four principal components (PCs) accounted for 41.9% of the total changes when utilising the Phenice method. Widening in pubic symphysis in a U shape with a general widening of the border of the true pelvis, which is typically seen in females, accounted for 21.8% of the eigenvalues.

Conclusions It was possible to quantify the changes seen in the ventral arc, subpubic concavity and the medial aspect of the ischio-pubic ramus for sex estimation utilising the Phenice method, and most of the changes were seen in PC1 at the pubic region, which accounted for 21.8%.

Keywords Geometric morphometric, Anthropology, Sexual dimorphism, Phenice method, Innominate, Forensic

Background

Within the scope of forensic anthropology, a precise sex classification of an individual may assist the law enforcement investigations. Accurate sex determination has led to a plethora of approaches, which have been created with the goal of extracting the most dimorphic characteristics of the human skeleton. Historically, the adult pelvic area has long been used to estimate sex (Iscan and Steyn 2013). The innominate bone consists of three bones, i.e. the ilium, ischium and pubis, which are found ossified at birth (Scheuer et al. 2000). The innominate bone is the most sexually dimorphic skeletal part in modern humans, with the accuracy approaching and exceeding 90% when the bone is employed alone for sex estimation (Stewart 1979; MacLaughlin and Bruce 1990; Rogers and Saunders 1994; Bruzek 2002; Ubelaker, Science and 2002, 2002; Bytheway and Ross 2010; Spradley and Jantz 2011). This sex-specific selection force resulted in a variety of morphological distinctions, which have been reliably employed for sex assessment, both qualitatively and quantitatively.

Females have bigger pubic bodies, longer and thinner pubic rami and greater degree of subpubic concavities than males (Letterman 1941; Phenice 1969; Stewart 1979; Krogman and Işcan 1986; MacLaughlin and Bruce 1990; Walker 2005). Numerous researches examining pubic

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bone shape are qualitative in nature and/or rely on visual assessments (Phenice 1969). As the obturator foramen is surrounded by sexually dimorphic pubis and ischium, they too can be utilised for sexing in individuals. Krogman and Işcan (1986) found that the male obturator foramen was larger and more ovoid in shape, while the female foramen was smaller and more triangular in shape. Rogers and Saunders (1994) identified similar sex differences in the shape of the obturator foramen and concluded that this feature was the second-best pelvic trait to employ for sex evaluation, after the ventral arc.

Numerous researches have been conducted on pelvic bone, either qualitatively or quantitatively. Qualitative approaches were used in some methods to examine shape and size variations (Phenice 1969; Bruzek 2002), whereas quantitative approaches were used in others (Gonzalez et al. 2009; Bytheway and Ross 2010; Klales et al. 2012). While qualitative methods are straightforward to employ, they are subjective and have numerous complications, especially when the pelvic bone does not exhibit sexual dimorphism or is fractured. These problems can be resolved by analysing the pelvis using geometric morphometric approaches (Wilson et al. 2008; Wilson et al. 2011; Franklin et al. 2012; Estévez et al. 2017; Estévez et al., 2018; Cox 2021; Baca et al. 2022).

Geometric morphometrics is a well-established and widely used technique for the analysis of individual variation patterns in the fields of physical and forensic anthropology. The data contain information about the spatial relationship between landmarks, which enables creation of evocative diagrams of morphological transformations or differences, as well as rapid visualisation of shapes and spatial localization of shape variations (Webster and Sheets 2010). This tool is extremely beneficial, since it does not only give a detailed and accurate description but also plays a critical role in visualisation, interpretation and communication of the results (Richtsmeier et al. 2002). The purpose of this study was to use geometric morphometric techniques to quantify the sexual dimorphism of the ventral arc, subpubic concavity and the medial aspect of the ischio-pubic ramus ischium of the innominate bone specifically adopting the Phenice method (Phenice 1969) on the Malays in the Malaysian population.

Methods

Sample collection and digitisation

A total of 231 CT (computed tomography) scans of 148 males and 83 females, aged between 18 and 94 years old, were obtained retrospectively from the picture archiving and communication systems (PACS) database of patients undergoing treatment at the hospital. DICOM files of normal pelvis without deformity or disease were selected for the study. The study was conducted at the Universiti Sains Malaysia, Kubang Kerian, Kelantan. The pelvis CT scans were collected from the Radiology Department, Hospital Universiti Sains Malaysia. Ethical approval prior to this research has been obtained with the assigned protocol code (protocol code no: USM/JEPeM/18050241).

The data included pelvic girdle scan images with a slice thickness of 1 mm captured by a CT scanner (Toshiba 160 slices). To ensure data confidentiality, the CT scan images were labelled with the patient's identification number and saved as DICOM files. Fracture, disease disorders and degenerative bone diseases such as osteophytes that may alter the morphology of the pelvic girdle were excluded from this research. Selected pelvic DICOM files were segmented and clean with InVesalius (CTI, 2001).

On an innominate bone, 17 single-point geometric morphometric landmarks were placed utilising the IDAV Landmark editor 3.6 (Hamann et al., 2005). The landmarks were placed on the left and right innominate bone. Figure 1 shows the location of the 17 landmarks (L0–S16). Description of the landmarks is shown in Table 1. Landmarks from IDAV landmark software were compiled in Morphologika format in Notepad++(Ho 2011) before analysing in MorphoJ (Klingenberg 2011). Reliability test was conducted by relandmarking 120 samples after a month of the initial landmarking procedure. To measure the relationship between intergroup and intragroup variations, the intraclass correlation coefficient (ICC) was calculated. If there was no difference in intragroup measurements, or if the intragroup variance was equal to zero, the correlation index is approximately equal to 1 (Menéndez 2017).

Statistical analysis

The error analysis was analysed by repeat digitisation (landmarking) of 149 specimens after a month of the initial specimen digitisation by the same researcher. Centroid size of both digitisation sessions was analysed with intraclass correlation coefficient (ICC) (Koo and Li 2016) in SPSS.

In MorphoJ, Procrustes fit by orthogonal projection, and covariate matrix was first conducted (Klingenberg 2011). This was followed by principal component analysis (PCA), discriminant function analysis (DFA) and Procrustes ANOVA (analysis of variance) on the dataset with various demographic data.

PCA was utilised to determine shape variation between individuals. PCA was performed to simplify the configurations of landmarks and to replace Procrustes coordinates with principal components (PCs) (Zelditch et al. 2004). The eigenvalues of all PCs and the first four PCs are shown in Fig. 2. The first four PC plots for sex are also

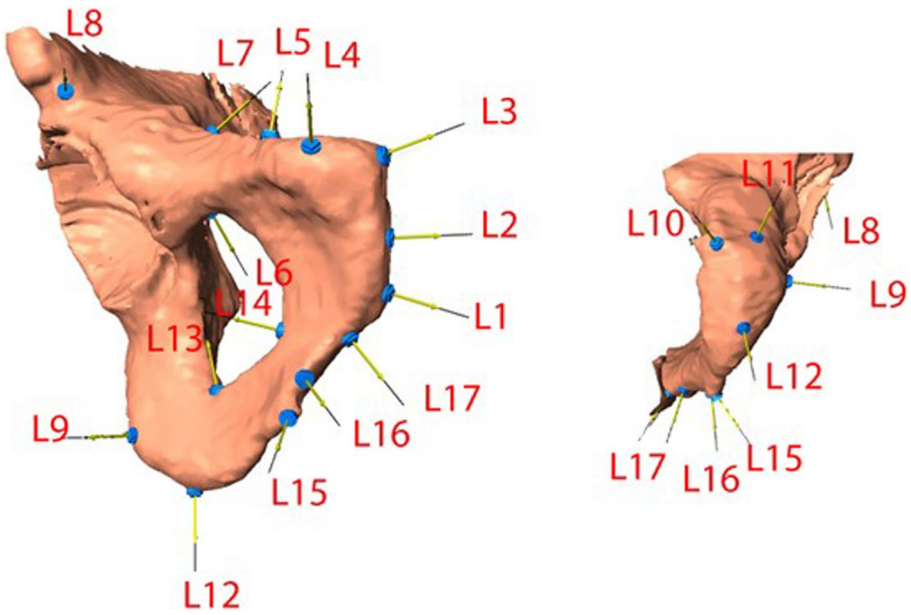

Fig. 1 The anterior view (left) and the inferior view (right) of the digitised landmarks on part of the innominate bone representing the Phenice method

Table 1 Landmark points definition

Landmarks	Landmarks definition
L1	Most inferior point on the inferior edge of the medial aspect of the pubic symphysis
L2	Medial aspect of the symphyseal surface of pubis
L3	Most superior point on the superior edge of the medial aspect of the pubic symphysis
L4	Most superior point of the pubic tubercle
L5	Most medial pectineal line of the superior ramus
L6	Most superior point of obturator foramen
L7	Most lateral pectineal line of the superior ramus
L8	Obturator crest point on the superior pubic ramus
L9	Ectoischion point of ischium
L10	Endoischion point of ischium
L11	Farthest point of the ischial curve from the centre of the obturator foramen
L12	Most inferior point of ischium
L13	Most posterior point of the obturator foramen
L14	Most anterior point of the obturator foramen
L15	Most anterior edge point of the ischiopubic ramus
L16	Most edge point of subpubic concavity contour
L17	Superior point of subpubic concavity angle

included (Figs. 3 and 4). The first four PCs were used to generate graphic coordinates, and principal component (PC) scores were plotted against the PC axes to visualise the position of each sample in shape space. Landmark editor was used to visualised the changes seen in PCs 1 to 4 (Fig. 3). Detailed PC changes on the pubic crest, pubis, ischium and obturator foramen as indicated in the Phenice method (Phenice 1969) are shown in Tables 3 and 4.

Procrustes ANOVA was used to analyse the effect of sex on the centroid size and shape variation as described previously (Klingenberg and McIntyre 1998) following Goodall's *F*-test (Goodall 1991). The percentage sum of squares (%SS) of the resulting Procrustes ANOVA was calculated following the methodology described previously by Viscosi and Cardini (2011). DFA cross-validation with 1000 permutations was also conducted on the shape

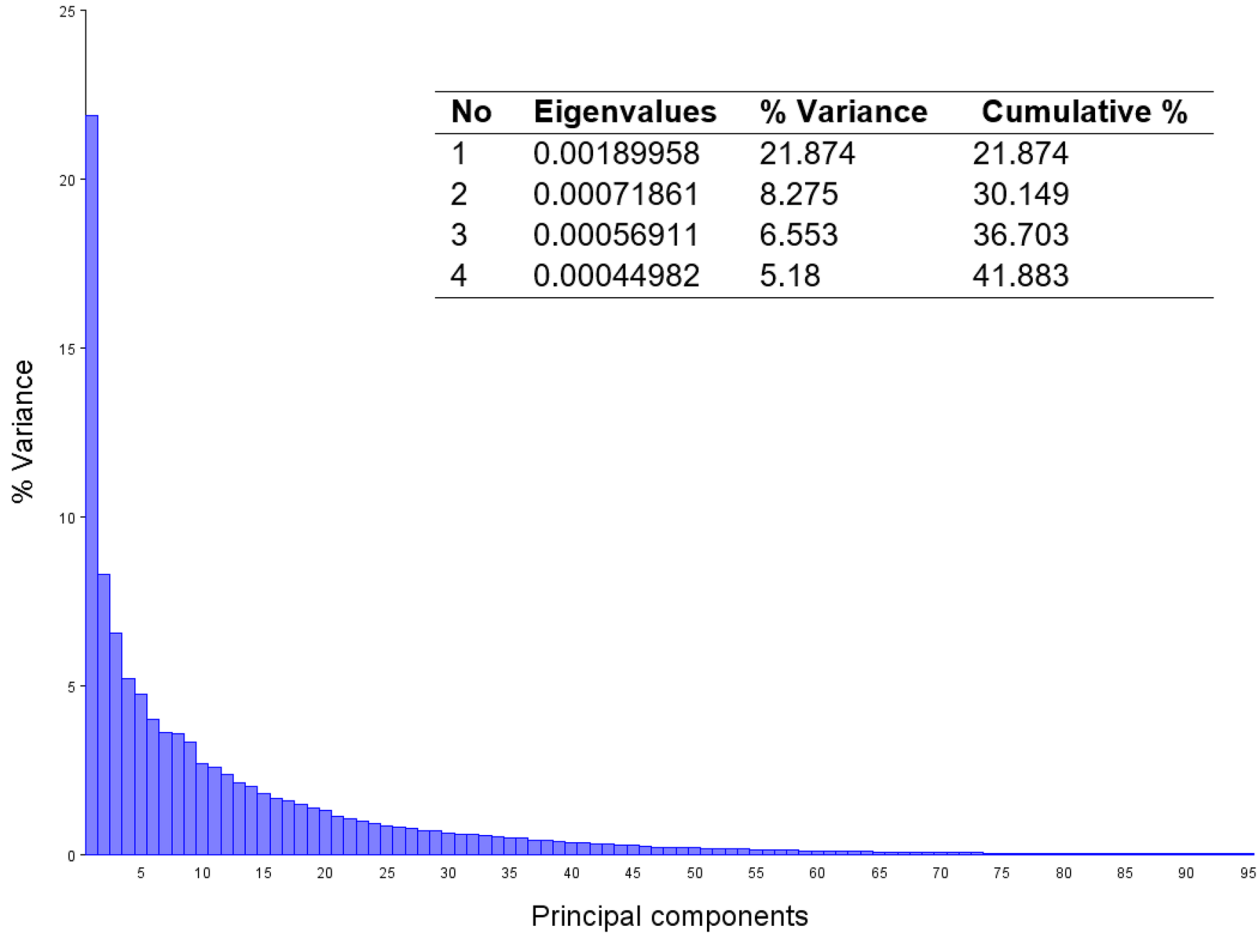

Fig. 2 Eigenvalues with the results of the first four principal components, which explained 42% of changes

coordinates to see if the landmarked selected yielded good sex estimation.

Procrustes distances were calculated between males and females with respect to shape variations. The effect of sex on centroid size and shape variation was evaluated using a hierarchical ANOVA, namely Procrustes ANOVA. The ANOVA method, which was initially applied to linear measurements, was extended to shape data [45].

Results

The ICC test for the centroid is shown in Table 2. The ICC score was 0.70, which was above the average correlation between the measurements. The average measurements were 0.82 which indicated acceptable reliability.

Results for the PCA analysis are shown in Figs. 2 to 4. Figure. 2 shows the total number of eigenvalues with the first four PCs shown in the inserted table. The first four PCs account for almost 42% of the changes seen in the region associated with the Phenice method. When comparing PC1 and PC2 scatterplots (Fig. 3), it showed good separation between males and females. PC1 accounted for almost 22% of the eigenvalues. On the positive value of PC1, there was a general widening of the pubic bone. Widening was seen in the pubic symphysis region. The pubic symphysis was U shaped with a general widening of the border of the true pelvis, which is typically seen in females. For the negative results of the PC1 plot, there was a narrowing of the pubic bone at the pubic symphysis region. Pubic symphysis was more V shaped, and the true border of the pelvis rim was smaller. This trait is generally seen in males. PC2 accounted for 8.3% of the eigenvalues. For the positive results of the PC2, the pubic tubercle on the pubic bone was seen jutting anteriorly, especially on the superior aspect of the pubic bone. The ventral arc was not pointed, and the ischiopubic ramus was thick, which is generally seen in males. The PC1-negative results showed that the pubic tubercle on the pubic bone was seen projecting superiorly, and there was a defined border at the ventral arc on the pubic bone. The ischiopubic ramus was slender, which is typically seen in the female pelvis.

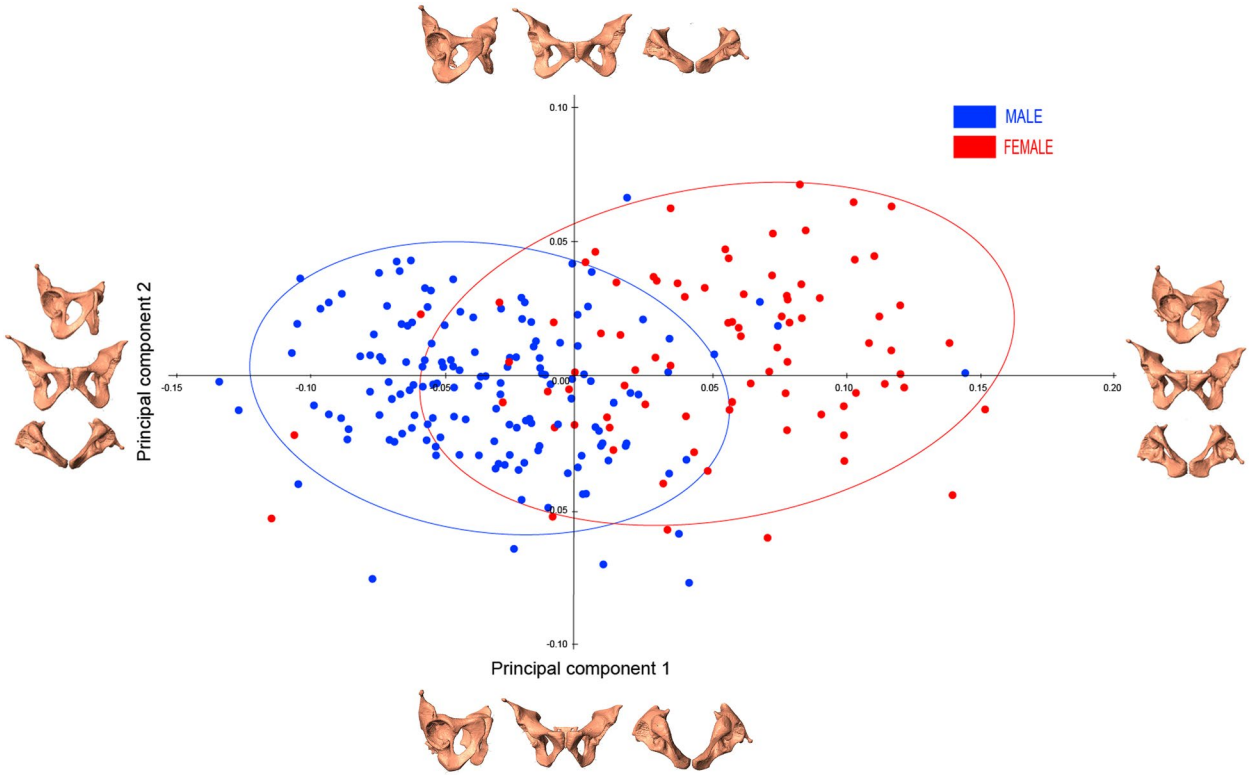

Fig. 3 The principal component plots for PC1 and PC2 with the 90% confidence ellipses for sex classification

For the PC3 and PC4 scatterplots (Fig. 4), it showed a good separation between males and females. PC3 accounted for 6.6% of the eigenvalues. For the positive scale of PC3, most of the changes were seen in the upper and lower borders of the innominate bone. The pubis became shorter at the superior aspect with a widening of the inlet of the pelvic girdle. Overall, the pubic bone and ischium were flattened, and the pelvic girdle became wider in shape. The lower border of the ischium retracted inwards in all directions, and the ischial tuberosity maintained its location inferiorly. This morphology is typically seen in females. For the PC3-negative scatterplot, changes were seen in the ischium bone or ischial tuberosity. The ischial tuberosity was pointed more inferiorly when the pelvic girdle was in the upright position. Changes in the ischium also meant that the lower border of the innominate was more V shaped, and the ramus was thicker. The rim of the true pelvis was seen to become higher due to the longitudinal increase in size of the pubic bone. This will affect the innominate overall size to appear taller than wider. The morphology is predominantly seen in males. PC4 only accounted for 5.2% of the total eigenvalues. For the PC4-positive scatterplot, results showed thinning of the superior aspect of the pubic bone and change in the inferior aspects of the innominate bone. The inferior aspect of the ischium bone projected inwards and to a more V shaped, a feature commonly seen in males. While for the negative PC4 scatterplot, there was an increase in the obturator foramen size in the superior and anterior regions. There was increased bone deposition on the superior part of the acetabulum between the pubis and ilium bone projecting anteriorly.

The Procrustes ANOVA (Table 3) of the centroid size and shape results were generated in MorphoJ. The *F*-value for shape was greater than the value for size, which indicated that for adults, the shape of the pelvic ventral arc, subpubic concavity and the medial aspect of the ischiopubic ramus were different between males and females. The landmarks at this region of the innominate bone can only differentiate about 21.73% of the shape and 7.38% of the size when adopting the Phenice method.

The DFA results (Table 4 and Fig. 5) for sex for the 231 specimens were carried out with and without cross-validated scores. The cross-validated scores were subjected to 1000 permutations. The results showed high separation among predicted group members with cross-validated scores for males and females of 95.27% and 91.57%, respectively, for the 231 specimens.

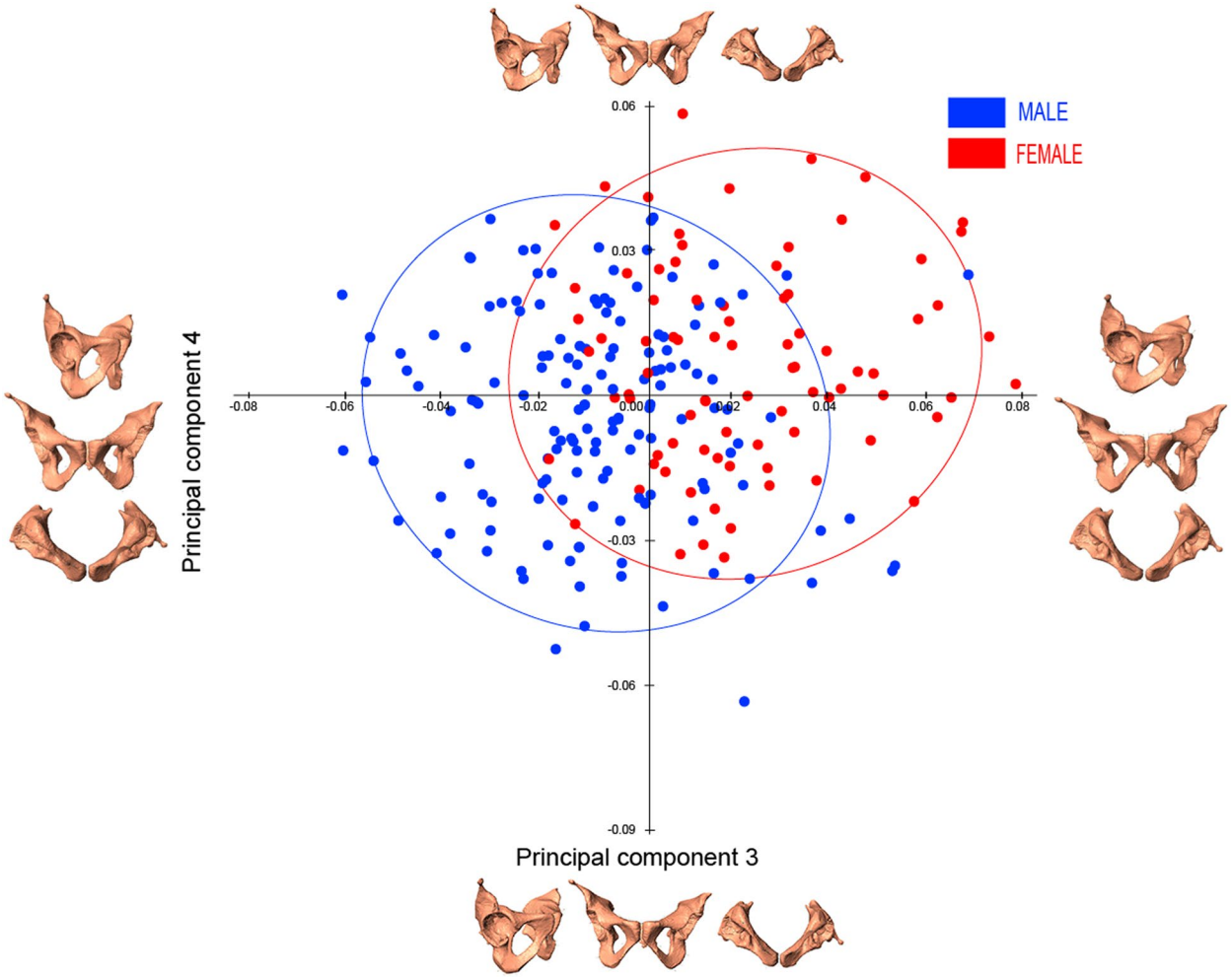

Fig. 4 The principal component plots for PC3 and PC4 with the 90% confidence ellipses for sex classification

Table 2 Intraclass correlation coefficient

	Intraclass correlation	95% confidence Interval	
		Lower bound	Upper bound
Single measures	0.70	0.61	0.77
Average measures	0.82	0.76	0.87

Discussion

The Phenice method (Phenice 1969) is a qualitative technic of assessing the innominate bone for sex, which is based on the ventral arc, sub-pubic concavity and the medial aspect of the ischiopubic ramus. The method is conducted by placing the bone at specific angles for the qualitative assessment. With the aid of geometric morphometrics, classification of the ventral arc, subpubic concavity and the medial aspect of the ischio-pubic ramus of the innominate bone by sex yield good results as indicated by PC1 to PC4 scatterplots (Figs. 3 and 4) and the DFA results (Table 4 and Fig. 5). Comparing the DFA results in Table 4 with the results obtained by Phenice (1969), the original results were higher for sex estimation compared to the cross-validated results. Phenice (1969) obtained around 95% accuracy when sexing the innominate bone. Population classification was excluded from this research study as it does not affect the morphology of the innominate. The original research by Phenice (1969) also showed little difference when compared between the two population groups; hence, the need to compare the analysis of different populations will not yield meaningful results.

Analysing the results of the Procrustes ANOVA showed that sex difference was only 22%. The reason for the low value here was postulated to result from the partial landmarking of the innominate bone itself limited to the region utilised for Phenice method and not the entire bone. It was predicted that the results will be

Table 3 Procrustes ANOVA of centroid size and shape

Effect	%SS	S	MS	df	*F*	*p*
Centroid siz						
Sex	7.38	4967.13	4967.13	1.00	18.24	< 0.0001
Individual	92.62	62,364.92	272.34	229.00		
Total	100	67,332.06				
Shape						
Sex	21.73	0.60	0.01	95.00	63.59	< 0.001
Individual	78.27	2.17	0.00	21,755.00		
	100	2.77				

Table 4 Discrimination function analysis of males and females with the corrected predicted groups highlighted

		Sex	Predicted group membership		Total
			Male	Female	
Original	Count	Male	145	3	148
		Female	2	81	83
	%	Male	97.98	2.02	100
		Female	2.41	97.59	100
Cross-validated	Count	Male	141	7	148
		Female	7	76	83
	%	Male	95.27	4.73	100
		Female	8.43	91.57	100

higher as indicated by SHM Ali ("Anatomical Society Summer Meeting Glasgow 2021: Cutting Edge Anatomy," 2022) when the whole os coxae was landmarked. It was expected that the Procrustes ANOVA size variation was low, i.e. 7.4%, as the samples were adults and had achieved size maturity by 18 years old.

What is interesting about this research is the ability to explain more of the changes in the innominate bone compared to just relying on fixed angles as in the Phenice method. Analysis of the PCs of a 3D bone allows reporting of the data, which cannot be achieved when the bone is held in fixed positions (Phenice 1969). The eigenvalues showed which PC has the most effect on the morphology of the ventral arc, subpubic concavity and the medial aspects of the ischio-pubic ramus of the innominate

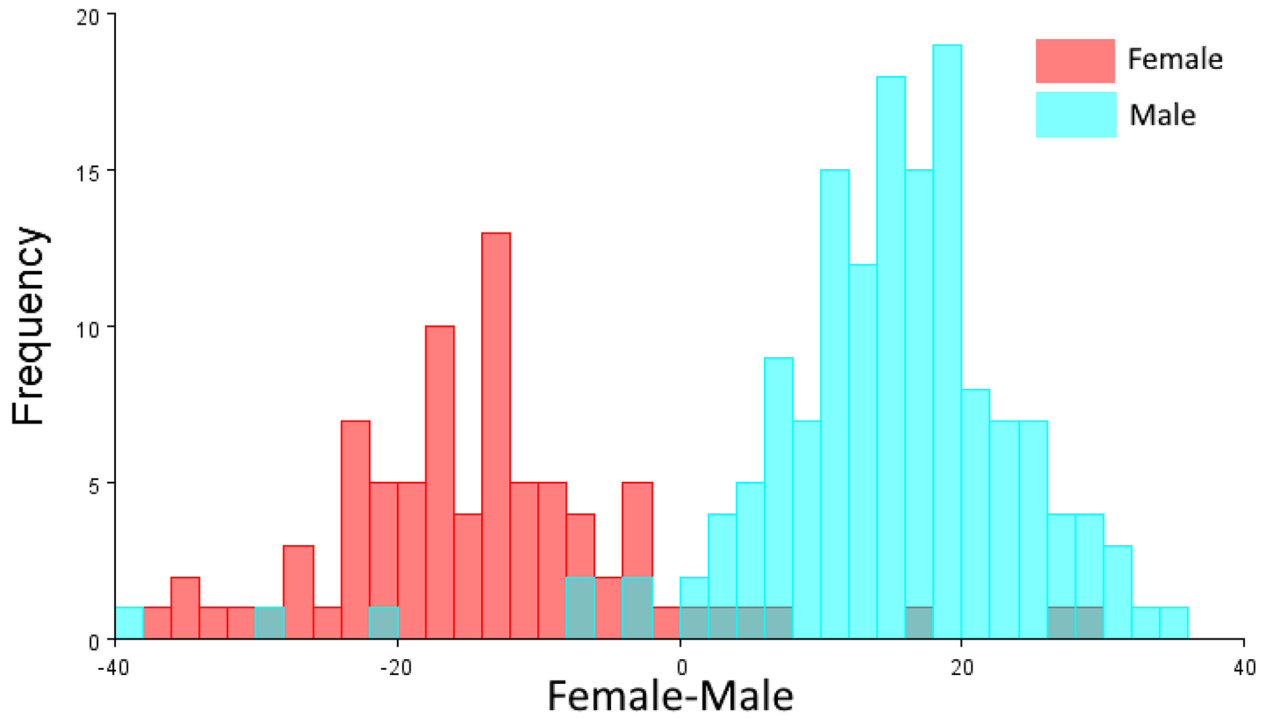

Fig. 5 Cross-validated scores of discriminant function analysis with 10,000 permutations

bone. The Phenice (1969) method is a reliable indicator of sex, and 21% of the changes (Fig. 2) is attributed to the widening of the pubis bone in general. From a practical perspective, teaching sex classification based on the Phenice (1969) method is useful as the fixed views are enough to show differences between males and females. What geometric morphometrics can show is the amount of change associated with each PC which can only be conducted virtually on a computer. Geometric morphometrics can quantify qualitatively the Phenice method region.

Conclusions

With the aid of geometric morphometrics, quantification of the Phenice method is possible, and the region may be useful in assessing sex of an innominate bone, as indicated by the PC1 to PC4 scatterplots. Widening in pubic symphysis in a U shape with a general widening of the border of the true pelvis, which is typically seen in females, accounted for 21.8% (PC1) of the eigenvalues. The Phenice morphology is predominantly dictated by sex. Classifying the region with any other population will yield similar results as indicated in Phenice's (1969) original study. Having the pelvis in fixed regions is useful when dealing with physical and virtual innominate bones as it is an easy method for teaching the differences between the sexes. Geometric morphometric helps in explaining the magnitude of change associated with the region.

Abbreviations

CT	Computed tomography
3D	Three dimensional
PCs	Principal components
PACS	Picture archiving and communication systems
ICC	Intraclass correlation coefficient
PCA	Principal component analysis
DFA	Discriminant function analysis
ANOVA	Analysis of variance
PC	Principal component

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Authors' contributions

MNHH collected data and landmarked the Phenice region. SHMA contributed with the conceptual methodology of the os coxae. FMN contributed to the project administration and reviewing the manuscript. HH drafted the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

Procrustes coordinates are attached with this research.

Declarations

Ethics approval and consent to participate

Ethical approval prior to this research has been obtained with the protocol code USM/JEPeM/18050241 of Universiti Sains Malaysia. This is a retrospective study; hence, consent to participate is not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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