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# Estimating osteological sex using predictive geometric morphometric analyses of the greater sciatic notch

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ABSTRACT

Accurately estimating the biological sex of human skeletal remains is crucial in both forensic and archaeological contexts for constructing biological profiles. Presently, one of the most commonly used methods involves an ordinal scale describing the shape of the greater sciatic notch (GSN). However, this approach is limited by variations influenced by temporal, geographic, and ancestral factors affecting pelvic morphology. Consequently, its reliable applicability is restricted to populations resembling the original reference group. Recent advancements in quantitative analyses offer a promising alternative by enabling detailed measurement of subtle morphological changes, thus enhancing the accuracy of sex estimation using skeletal pelvic remains. In this study, we employ 2D landmark-based geometric morphometrics (GMM) to develop a protocol for pelvic sex estimation by quantifying the curve and angle of the GSN. These techniques are applied to both a contemporary population of adult European-Americans of known biological sexes (33 females, 38 males) and an archaeological population (n = 73) from south-west England. Our analysis reveals that our GMM approach achieves a 90 % accuracy rate in modern populations. Results indicate that both GSN morphology and angle are highly indicative of biological sex, allowing confidence in sex estimations of archaeological remains using these features.

## 1. Introduction

Sex estimation is often one of the first parameters explored when assessing human skeletal remains from both forensic and archeological contexts. The pelvis is regarded as the most sexually dimorphic area of the human skeleton (Stock, 2020) and can be used to estimate the biological sex of unidentified skeletal remains (Walker, 2005; White and Folkens, 2005). When the complete pelvis is present, sex estimation based on macroscopic description of morphology ranges from 80–99 % accuracy (Bruzek, 2002). However, not all sexually dimorphic features found on the pelvis are equally reliable (Bruzek and Murail, 2006) and not all anatomical regions are preserved in archaeological or forensic contexts. For example, in supine burials, the pubis, which is considered the most reliable indicator for biological sex on the pelvis (Rösing et al., 2007), protrudes from the skeleton and is particularly susceptible to postmortem damage from taphonomic processes or recovery practices due to its fragile nature (Kjellström, 2004; Walker, 2005). The area of the pelvis that often survives best is the heavy, dense area of the ilium containing the auricular surface and the greater sciatic notch (Waldron, 1987). Thus, the greater sciatic notch, considered to be wider in females and narrower in males, is frequently used to estimate the biological sex of fragmentary remains, with standard methods for sex estimation classifying the form of the notch using qualitative visual scales (Kalsey et al., 2011; Steyn et al., 2004; White and Folkens, 2005).

The current standard for sex estimation of the greater sciatic notch (GSN) is an ordinal scale of five discrete curved shapes ranked from 1 to 5, designed to represent a gradual transition from a hyper-female (i.e., wide, Rank 1) to a hyper-masculine (i.e., narrow, Rank 5) notch, with an average width (Rank 3) being considered indeterminate (Buikstra and Ubelaker, 1994; Walker, 2005). Developed by Walker in 1994, this scale was established using a nineteenth- and twentieth century American population composed of European and African descendants from the Terry and Hamann-Todd collections (Hunt and Albanese, 2005; Walker, 2005). While Walker's (2005) scale is currently widely applied to human remains across the globe from various temporal, cultural and ancestral contexts, the composition of the original sample group used to develop

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the scale does not represent a wide range of the human populace (ANSI/ASB, 2019; Brickley and Buckberry, 2017). Therefore, the subjectivity of relying on these qualitative criteria brings questions into its use and applicability on a global scale.

Walker reassessed his original methodology in 2005, again using the Terry and Hamann-Todd collections, but this time incorporating a seventeenth century English population from the St. Bride's Church collection (Walker, 2005). Using his original scoring system, Walker found that among the seventeenth century English individuals, males tended to exhibit greater variation in the depth and width of the GSN compared to the modern American males, and were more often assigned 'female' scores using his scale (Walker, 2005). In the last decade, researchers have continued to study the accuracy of Walker's (2005) method for sex estimation in non-American populations (Gómez-Valdés et al., 2012), and a growing body of work is expanding our understanding of the impact that population-based differences have on the accuracy of Walker's 2005 scale (see review of these studies in Carrière and Tallman, 2024).

Based on previous studies, it is clear that human variation between and within populations accounts for a wide array of morphological variation in the GSN (Christensen et al., 2014; Cunha and Ubelaker, 2020; Durić et al., 2005). In the development of his scale, Walker (2005) included Americans of African and European descent, but research has indicated that additional sample groups are needed to better represent the variation present in human skeletal remains, as these populations are not representative of all population groups over time (Cunha and Ubelaker, 2020; Gonzalez et al., 2009; Patriquin et al., 2003). Furthermore, Walker's (2005) own assessment calls into question the accuracy of sex estimation in archaeological populations sharing European ancestry using these scales. The English St. Bride's males were assigned a female score 60 % of the time (Walker 2005), compared to 41 % of the time for American males when using Walker's method (Walker 2005). Correct sex assignment for the St. Bride's males, when compared to the nineteenth and twentieth century population, suggests this is not an accurate method for sex estimation in pre-modern populations, even when they likely share ancestry (Walker, 2005).

Despite this growing body of work, almost two decades have passed since Walker's reassessment was published (Walker, 2005), and little has been done to further adjust this methodology, which is still considered the standard for sex determination using the GSN. The sustained appeal of the Walker 2005 scale is likely due to the combination of the simplistic nature of ordinal scales. However, there are more variables involved in sex estimation than a simple visual scale can capture and subtle variations in morphology are difficult to interpret with the naked eye, especially when considering the subjective nature of the criteria and inter- and intra-observer error and bias (Hartley and Winburn, 2021). Some researchers have recognized this issue and have developed various metric protocols for quantifying the shape of the GSN (Mestekova et al., 2015; Raut et al., 2013; Takahashi, 2006), however these are not universally applied.

Advances in morphometric techniques, including geometric morphometrics, for the acquisition and analysis of multivariate shape data have improved our ability to capture high resolution shape data from bioarchaeological remains (for review see Evin et al., 2022; Gunz, 2020). Given the curvilinear shape of the GSN, this feature is well suited to examination with a variety of morphometric approaches and many researchers have developed protocols for the quantification of GSN shape with the aim of predicting biological sex. This has included using permanent landmarks (Gómez-Valdés et al., 2012; Velemínská et al., 2013), sliding semilandmarks (Gómez-Valdés et al., 2012; Velemínská et al., 2013), and outline analysis (Kilmer and Garvin, 2020). Similar to the metric analyses, many of these studies focused on methodological development and only one applied these methods to an archaeological population (Kilmer and Garvin, 2020). Here we present a simplified landmark protocol using 3 permanent landmarks and two curves of sliding landmarks to quantify the shape of the GSN. We test the accuracy of this methodology on a modern population of known sex and then apply the method to estimate the sex of individuals from three archaeological sites in the south-west of England. This was to test this new method of analysis against sex estimations derived from a wider range of sexually-dimorphic features throughout the skeletons.

## 2. Materials and methods

### 2.1. Materials

To test the ability of greater sciatic notch morphology to accurately distinguish the biological sex of skeletal remains, we examined the morphological variation of 144 individuals (Table 1, SI Table 1). Our modern dataset contained 74 European-American individuals of known sex including 36 biological females and 38 biological males ranging in age from 17-91 years old. These individuals were sourced from the New Mexico Decedent Image Database (NMDID) (Edgar et al., 2020).

Alongside this, we assessed the archaeological remains of 73 individuals, including 68 from Exeter Cathedral Green, 3 from Exeter Friars' Gate, and 2 from Gloscat Redevelopment Project, a Roman cemetery site associated with the redevelopment of the Gloucestershire College of Art and Technology (Heighway, 1980) (Fig. 1). All archaeological individuals are part of the human remains collection curated by the University of Exeter, and samples were chosen based on preservation of relevant skeletal elements and access to prior work on the remains. The archaeological remains from both Exeter sites date broadly to the medieval period in England, ranging from the fifth to fifteenth centuries AD (Kingdom, 2019). Individual EXE_448 from Exeter Cathedral Green was previously radiocarbon dated to 661–551 cal BP (Kingdom, 2019). The two individuals from Gloscat Roman cemetery (GAC_K4-A and GAC_H1_A) were selected because they are currently undergoing aDNA analysis which can eventually be used to validate results. Grave goods and radiocarbon dating on several members of the Gloscat population suggest the cemetery was most likely in use between the mid-3rd and late-4th centuries AD (Cotswold Archaeology, 2016). Individuals exhibiting skeletal maturity were included in this study to avoid ontogenetic effects, with dental eruption and epiphyseal fusion of the iliac crest considered to support the identification of young adult and adult individuals in both the archaeological and modern samples (AlQahtani, et al., 2010; Cunningham et al., 2016). For the purposes of this article we are using the term osteological sex to refer to features that are typical of males and females in the archaeological sample and biological sex for known individuals from the modern sample.

### 2.2. Osteological sex estimations

Both modern and archaeological individuals were assigned a value on the Walker 2005 scale and designated as female, probable female, indeterminate, probable male, and male as according to the 5-scale categories. Additionally, for archaeological individuals, blind sex estimation took place on the entire skeleton using standard sex estimation techniques for skeletal remains (White and Folkens, 2005). Where present, the features of the pelvis analysed for sex estimation included the subpubic angle, ventral arc, ischio-pubic ramus of the pubic symphysis, and pelvic inlet shape as these are the most accurate and sexually dimorphic features (Klales et al., 2012). Cranial features included examination of the mastoid processes, the supraorbital ridge, the external occipital protuberance and the mandibular ramus (Walker, 2008; Gülekon and Turgut, 2003; Indira et al., 2012). Previous literature has shown that there is a strong correlation between sex estimates derived from standard osteological analyses and biomolecular methods (Buonasera et al., 2020). Postcranial features included metrical analyses on the femur (maximum length; maximum head diameter) (Steyn and Işcan, 1997).

**Table 1**
Results of the various sex estimation techniques, showing number of individuals assigned as male (M), female (F) or indeterminate (indt.) using the Walker 2005 scale, complete osteological sex estimation, GSN morphology and GSN angle respectively for both modern and archaeological individuals. Individuals were classified as indeterminate if they were allocated a value of 3 on the Walker 2005 scale, or if their probability of sex assignment was below 60% for the GSN analyses.

| | **Walker 2005 Scale** | | | | **Osteological sex** | | | | **GSN morphology** | | | | **GSN angle** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **M** | **F** | **Indt.** | **% Accuracy** | **M** | **F** | **Indt.** | **% Accuracy** | **M** | **F** | **Indt.** | **% Accuracy** | **M** | **F** | **Indt.** | **% Accuracy** |
| **Modern n = 71** | 8 | 47 | 16 | 58 % | 38* | 33* | 0 | 100 %* | 38 | 33 | 0 | 90.2 % | 35 | 36 | 0 | 83.25 % |
| **Archaeological n = 73** | 16 | 40 | 17 | | 43 | 30 | 0 | | 40 | 32 | 1 | | 50 | 23 | 0 | |

*values for modern individuals are taken from their recorded biological sex.

**Fig. 1.** Site Location within Britain of the archaeological individuals.

### 2.3. *Collection of GMM data*

2D morphometric data of the greater sciatic notch were collected from photographs and Computed Tomography (CT) scans of the pelvis. For the archaeological remains, the os coxa was photographed controlling for the orientation of the ilium and the position of the greater sciatic notch (Zelditch et al., 2012). All photographs were taken with a reflex Nikon D5300 camera with a fixed micro lens (AF-S Micro Nikkor 60 mm). The right os coxa was photographed preferentially to ensure a larger sample size, as the Exeter skeletal collection had more right os coxae available. The left os coxa was used only when better preserved. Individuals were only photographed if their full greater sciatic notch curve was present. The modern sample group originated from CT scans downloaded from the New Mexico Decedent Image Database (NMDID) (Edgar et al., 2020). The pelvic CT scans were uploaded and digitally rendered using Slicer 3D (Kikinis et al., 2014). The pelvic 3D model was then oriented to match the positioning of the archaeological 2D photographs to capture the full image of the greater sciatic notch. This image was then exported as a.jpg for further analysis. A single observer collected all photographs and CT captures (LC).

This complete set of digital images were then digitised with a series of 2D landmarks and sliding semi-landmarks using TPS software (Version 2.05) (Rohlf, 2015). The landmark protocol (Fig. 2) includes 3 permanent landmarks placed at the posterior inferior iliac spine (1), the ischial spine (2) and the apex of the greater sciatic notch's arch (3). Two curves of 10 sliding semi-landmarks were digitised along the greater sciatic notch; between the posterior inferior iliac spine and the apex of the arch (landmarks 1 and 3), and between the apex of the arch to the ischial spine (Landmarks 2 and 3). All specimens were digitised by a singler observer (LC) and intra-observer error was 9.44 %. (SI File 2) (Claude, 2008).

### 2.4. *Analysis of morphometric data*

The landmark coordinate data were superimposed using generalised Procrustes analysis (GPA), which removes factors of size, orientation and rotation (Klingenberg, 2011). During this procedure, the sliding semi-landmark position was adjusted following the Procrustes criteria. The resulting Procrustes coordinates were then subjected to principal component analysis (PCA) to reduce the dimensionality of the data and observe overall shape variation within the sample. Next, we performed a MANOVA to determine if the shape of the GSN had a statistically significant difference between the archaeological and modern groups.

### 2.5. *Morphometric assessment of biological sex*

After the data were standardised, we carried out three sets of analyses. First, we explored the shape variation of our modern individuals of known biological sex. We examined whether there were significant shape differences in GSN morphology amongst the modern male and female groups whose biological sex was known, and the ability of our chosen landmarks on the GSN to accurately predict sex assignment using a discriminant function analysis with leave-one-out cross validation corrected for balanced sample sizes (Evin et al., 2013). This analysis was used to determine the robusticity of GSN morphology for predicting sex groups.

Next, to estimate the unknown 73 archaeological individuals, we undertook a predictive linear discriminant analysis following Evin et al., (2015). Modern samples of known biological sex were designated as the reference groups, and the linear discriminant analysis (LDA) assessed which of these groups the archaeological individuals mostly likely belonged to. With two potential groups (male/female), the average percentage for assignment of an individual to one of the sex groups is 50 %, however, we opted for a more conservative assignment value, so archaeological individuals were classified as 'male' or 'female' if their assignment into a group was 60 % or higher. Attributions lower than this deemed the individual unattributable (Boedeker and Kearns, 2019; Evin et al., 2015). The predictive LDA was performed in R using the function 'pldam' (Evin et al., 2015).

### 2.6. *Angle of the GSN as an indicator of sex*

The angle created by the intersection of lines measured between Landmarks 1 and 3, and 2 and 3 (Fig. 2) was calculated for all modern and archaeological populations (Gómez-Valdés et al., 2012; Takahashi, 2006). The robusticity of this metric for predicting biological sex was tested on the modern population using a leave-one-out cross validation, and the assignment of archaeological materials was performed using a predictive linear discriminant analysis as described above.

Finally, we compared the sex ID generated from the LDA, GSN angle and osteological sex identifications to explore the relationship between the morphometric and osteological criteria for sex estimation (SI Table 1).

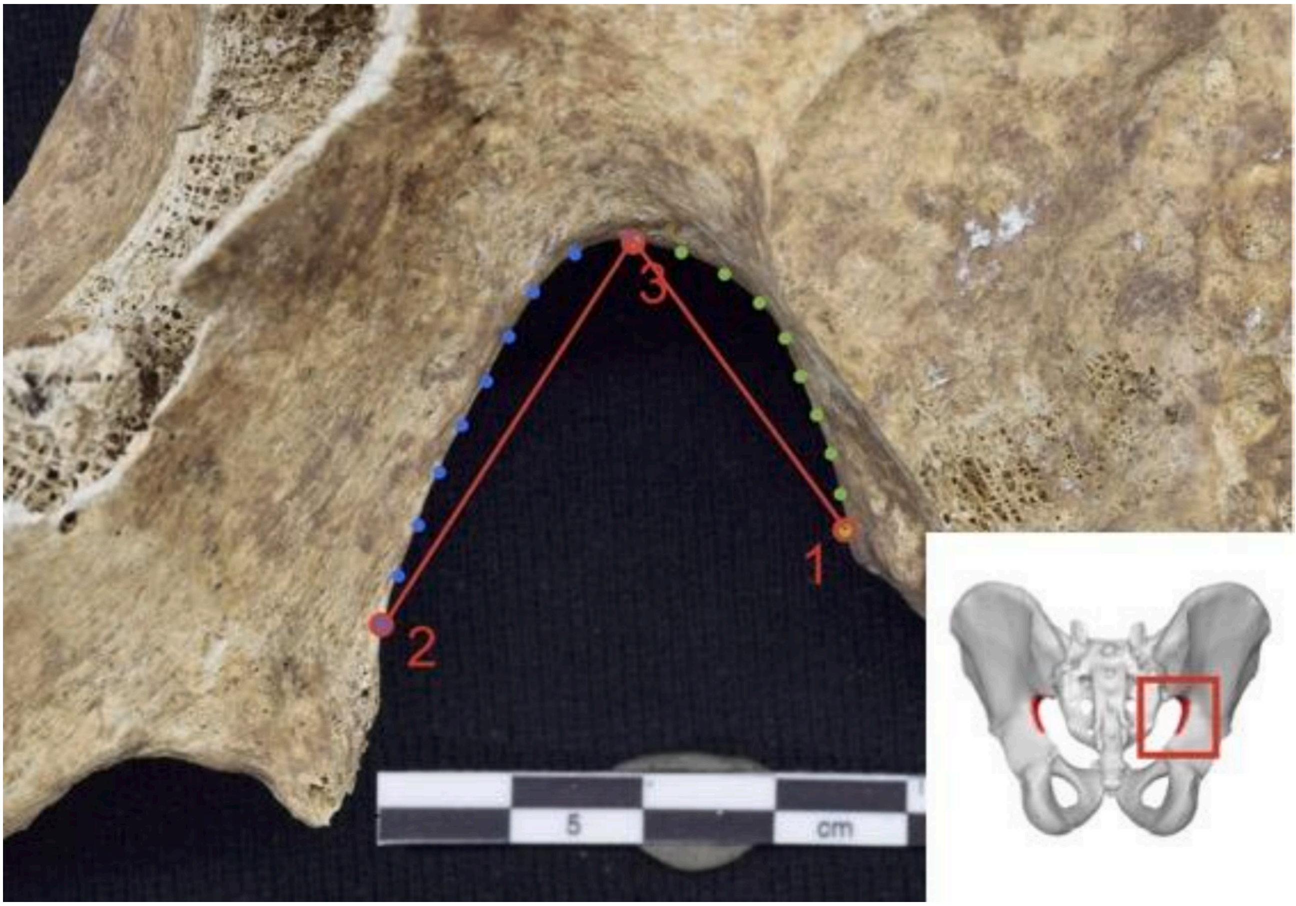

**Fig. 2.** Location of the three landmarks and two curves along the greater sciatic notch, showing the anterior view. The three permanent landmarks are noted in red, while the ten curve points are noted in blue and green. Red lines indicate the distances measured to calculate the angle of the GSN. Inset bottom right shows the location of the greater sciatic notch within the pelvis. (Inset image adapted from "BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 3. Results

### 3.1. *Osteometric sex estimation*

Applying the Walker 2005 scale blindly to the 71 modern individuals of known biological sex, 55 were assigned either 'male' (n = 8) or 'female' (n = 47) (Table 1, SI Table 1). The remaining 16 individuals were given a score of 'indeterminate' (n = 16), as we could not confidently assign them to a sex estimation group using this method. Of the 55 assigned individuals, 75 % (n = 41) were correctly assigned to the sex that matched their recorded biological sex. This accuracy is reduced to 58 % (41/71) if you include the entire dataset of 71 individuals, presuming the indeterminates are incorrectly assigned.

In applying Walker's (2005) Scale to the 73 archaeological individuals, 56 were assigned either 'male' (n = 16) or 'female' (n = 40). The remaining 17 individuals were given a score of 'indeterminate' (n = 17). Using the standard osteological sex estimation techniques outlined in the methodology section above, the archaeological individuals were also classified as 30 females and 43 males, inconsistent with our findings when solely using the Walker 2005 scale. The consistency in sex assignment between the Walker 2005 scale and the osteological sex estimation was 60 % (n = 44) (Table 1, SI1).

### 3.2. *Geometric morphometric sex estimation*

Significant shape differences between known male and female greater sciatic notch shapes were identified (MANOVA F(2,68) = 44.915, p = 4e-13) (Fig. 3 A-D). There was no centroid size difference between modern known males and females (Kruskal-Wallis $X^2 = 3.4024$, p = 0.0651) (Fig. 4B). Differences between the greater sciatic notch morphology of modern individuals of known sex were found to be highly diagnostic, with individuals correctly reassigned to their known group 90.2 % of the time (90 % confidence interval; 86.8–92.6 %).

Of the 73 archaeological individuals, 72 were assigned to a female (n = 32) or male (n = 40) sex group based on GSN morphology using the predictive linear discriminant analysis described above (Table 1, SI1). Only a single individual (EXE_753) was below the threshold of 60 % for assignment to a known modern group, and was classified as 'unattributed'. A further 4 of the 72 attributed individuals were assigned to a group with less than 100 % affinity ranging in confidence from 63-95 % (Table SI1).

### 3.3. *Angle of the GSN*

The angle of the GSN was a highly discriminate indicator of biological sex, with modern individuals correctly reassigned to their known group 83.25 % of the time (90 % confidence interval; 81.81—84.84 %). Osteological sex was assigned to the archaeological individuals based on greater sciatic notch angle using predictive LDA with a high degree of accuracy, and all individuals were classified with a confidence of 95 % or higher (Table SI1). Of the 73 archaeological individuals, 23 were assigned female and 50 male based on GSN angle (Table 1, SI1). The average GSN angle for known females was 93°, and for males 80°. In the archaeological populations, both sexes exhibited relatively narrower angles compared to their modern counterparts (Fig. 4C). Between sexes, both modern and archaeological females had significantly wider GSN

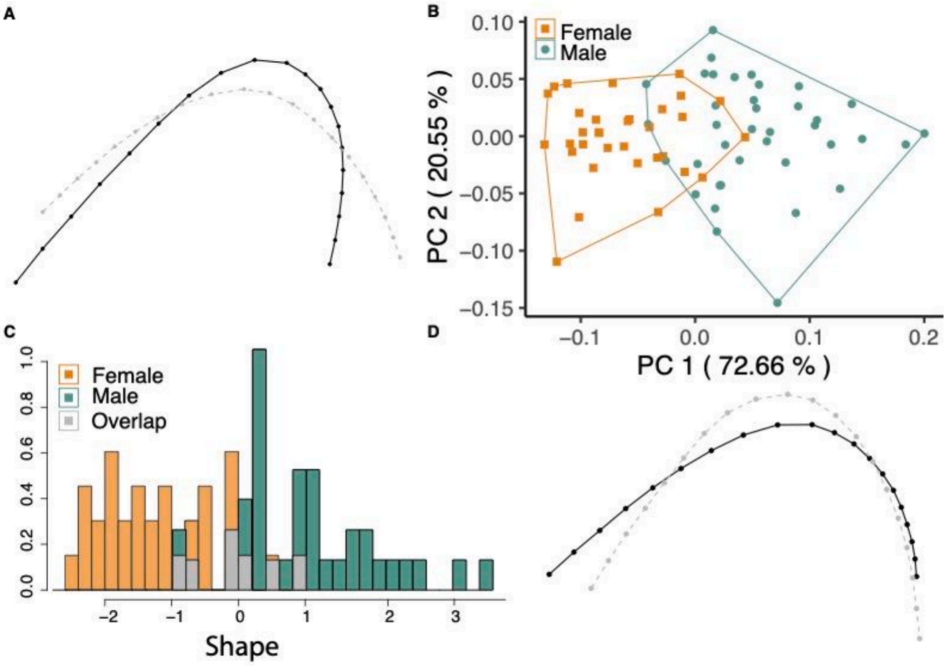

**Fig. 3.** (A) Shape change of the greater sciatic notch (GSN) along the 2nd principal component (Y axis of B; grey negative, black positive). (B) PCA of shape variation of individuals of known osteological sex. (C) Histograms showing frequency distributions of shape. The shape variable corresponds to PC1 of the between group PCA. (D) Shape change of GSN along the 1st PC (x axis of B; grey negative, black positive).

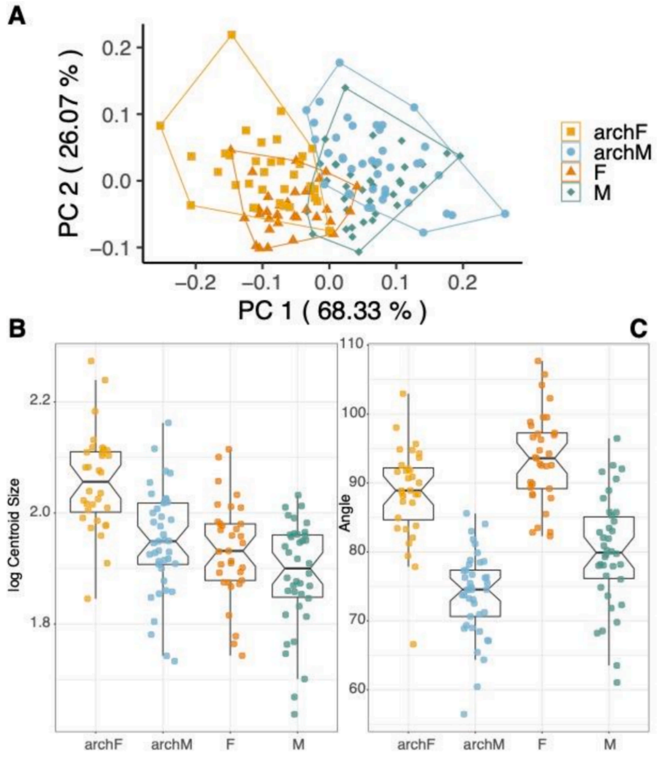

**Fig. 4.** (A) Shape variation across the first two principal components of modern and archaeological individuals, with their LDA sex assignment based on morphometric shape of the GSN. (B) Size of the GSN for modern and archaeological populations grouped by LDA. (C) Angle (in degrees) of the GSN for modern and archaeological populations grouped by LDA assignment.

angles than males in both groups.

### 3.4. Comparing sex estimation methods

Of the 56 archaeological individuals that were assigned a sex using the Walker 2005 scale, 46 were assigned to the same sex using the GMM protocol (82.14 %) (Table 1, SI1). For the 10 remaining individuals with inconsistent assignments, all had been identified as female using the Walker 2005 scale, and male using GMM. These trends are also seen in the assignments using the angle of the GSN, where 39 individuals were given the same sex using Walker (2005) and GSN angle (69.64 %) (Table SI1). The 17 individuals that were inconsistently identified had all been identified as female when using the Walker 2005 scale, but were assigned male when using the angle. In general, there was high agreement between the sex assignments using the GMM and GSN angle methods, with only nine individuals assigned to different categories (i.e. 87.32 % consistency). Each of these nine individuals were assigned ‘female’ using the GMM protocol and ‘male’ with the angle metric (Table SI1).

## 4. Discussion

For a methodology to be considered very reliable in osteometric analyses, it must not misclassify more than 10 % of a sample, and for a methodology to be considered reliable, it must not misclassify more than 15 % of a sample (Novotony et al., 1993). Using this dataset, the Walker 2005 scale fails this reliability test, misclassifying 43 % of modern individuals of known biological sex. Instead, our morphometric analysis of greater sciatic notch shape produced very reliable results, with an average 90.2 % accuracy for modern individuals. The angle estimation is very close to meeting the reliability threshold, with an 83.25 % correct identification rate. It is well established that Walker’s 2005 scale has a varying accuracy rate depending on the population structure of the group it is applied to, with Walker himself finding accuracy rates of between 65–90 % when using his method (Walker, 2005). As Walker’s (2005) method varies widely by sample, it has mixed favorability amongst scholars (Klales et al., 2012). While the GSN is included as one of the main five sex estimation criteria for the pelvis in Buikstra and Ubelaker (1994), it is considered by others as one of the less reliable indicators of sex on the pelvis (Rogers and Saunders, 1994). The sexual characteristics of the greater sciatic notch are difficult to assess by visual examination because the observer is (unconsciously) influenced by the size of the pelvis, and because the morphology of the notch is influenced by developmental variation of features such as the ischial spine or piriform tubercle (Bruzek, 2002; Gonzalez et al., 2009).

The Walker 2005 nominal scale is biased towards the assignment of the female GSN shape, with 85 % of the modern and 71 % of the archaeological individuals described in this paper assigned 'female'. The finding that 16 of the 17 modern individuals assigned as 'indeterminate' by visual analysis using the Walker 2005 scale were biologically known males further supports this.

A further 17 archaeological individuals were also assigned a Walker score of 3 for indeterminate sex. Of these indeterminates, 14 were assigned male, and 3 assigned female using the predictive LDA assignment on GSN shape, while all 17 were assigned male based on GSN angle (SI Table 1).

All together, these results reinforce the variability of greater sciatic notch shape for biological males, which is not accurately accounted for using the Walker 2005 scale criteria. The Walker 2005 scale's bias against variation in the male GSN has been well established. In previous morphological analyses of the GSN in Black and white South African males, it was found that while 84 % of Black males exhibited Walker's (2005) expected narrow morphology, only 33 % of white males exhibited this same narrow shape (Patriquin et al., 2003). Similar results are reflected here. Of the 38 modern males in our dataset, only 8 were assigned as male using the Walker 2005 scale (21 %), 14 modern males were incorrectly assigned female due to a wide GSN morphology, and 16 could not be assigned a sex. This is directly contrasting with our known sex female group which were assigned with 100 % accuracy using Walker's 2005 scale. Furthermore, this study from Patriquin et al. (2003) indicates that the GSN exhibits population variation that is difficult to capture using a static visual scale.

The research undertaken by Gómez-Valdés et al., (2012) examining sex estimation amongst a contemporary Mexican population found the accuracy of Walker's 2005 scale was 62.1 %, while the accuracy for applied GMM methodologies was 82.3 %. Our results support these findings, with 85 % of modern and 71 % of archaeological individuals assigned 'female' according to the Walker 2005 scale. The fact that 16 modern individuals assigned as 'indeterminate' with the Walker 2005 scale were biologically known males further supports this finding. Finally, the asymmetry in the male notch is one of the underlying issues with accuracy surrounding the estimation of males using Walker's 2005 scale. While the visual aids highlight changes to the width of the notch, his reference images are oriented to control for positioning, masking the posterior shift of the deepest point which is a key indicator of male morphology (see Fig. 1 in Walker, 2005). Geometric morphometric analysis is less prone to subjectivity or observer bias by using quantitative analyses to demonstrate robust and clear shape differences between males and females, which discrete and qualitative ordinal scales lack.

There were 12 individuals who were inconsistently assigned a sex estimate across the three methods of sex estimation used in this study, (Table 2, SI Table 1). We investigated if those who were inconsistently classified tended to skew younger in age due to lack of pelvic maturation (Cunningham et al., 2016). Of the 12 individuals, 5 were classified as 18–25 years old at death, 2 36–45, and 4 at 46 + years of age. The only individual who's GSN morphology score was below the 60 % threshold was estimated to be a mature adult over 46 years of age (Kingdom, 2019). Of the 5 18–25 year old individuals, 3 were assigned female scores using the Walker Scale, osteological sexing and GSN morphology, but had a male GSN angle. While the sample size is small, and the age at death estimates are diverse enough that we cannot clearly see a correlation between age and inconsistent sex classifications, previous studies have found that younger males tended to be misclassified as female based on their morphology (Walker, 2005; DesMarais et al., 2024). Our dataset shows that young individuals were more likely to be assigned female when considering GSN morphology, but tended to be assigned male when considering the GSN angle. Further work on the relationship between the angle of the GSN, its overall morphology and pelvic maturation could significantly enhance our understanding of pelvic ontogeny and sexual dimorphism.

**Table 2**
Summary of the sex estimates and age at death (in years) for the 12 individuals who had inconsistent sex assignments across the various methods. Males (M), females (F), indeterminate (I), unknown (NA).

| Individual ID | Age at Death | Walker Score | Osteological Sex | GSN Morphology Sex | GSN Angle Sex |
|---|---|---|---|---|---|
| EXE_531 | 18–25 | 2 | M | F | F |
| EXE_540 | 18–25 | 3 | M | F | M |
| EXE_567 | 18–25 | 1 | F | F | M |
| EXE_635 | 18–25 | 1 | F | F | M |
| EXE_752 | 18–25 | 2 | F | F | M |
| EXE_624 | 36–45 | 3 | F | F | M |
| EXE_740 | 36–45 | 2 | F | F | M |
| EXE_539 | 46+ | 3 | M | F | M |
| EXE_563 | 46+ | 3 | F | M | M |
| EXE_637 | 46+ | 2 | F | F | M |
| EXE_753 | 46+ | 2 | M | I | M |
| EXE_665i | NA | 1 | F | F | M |

Regarding shape variation between the sexes, our results demonstrate that the female GSN shape is broader and more symmetrical than that of the male GSN, which is deeper, narrower and asymmetrical with a posterior shift in the location of Landmark 3 (the deepest point). These findings support the results of previous work (e.g., Gonzalez et al., 2009; Bruzek et al., 2002) which could reflect a functional morphological significance of the greater sciatic notch for successful parturition, in which the female shape with its large posterior component allows the sacrum to move back and out of the birth canal during delivery of the neonate (Hager, 1996; Gonzalez et al., 2009). However, the link between a wider pelvis and parturition has been challenged in recent literature. Increased oestrogen levels can cause female pelvic bones to expand more than their male counterparts, potentially due to the larger volume of space required to support the growth of female reproductive tissues and organs, rather than solely for the purpose of parturition (Dunsworth 2020).

This study shows that multivariate, geometric morphometric analysis using landmark and semi-landmark coordinates to quantify the size and the shape of the greater sciatic notch allows for differentiation between males and females with a high degree of accuracy in both modern and archaeological populations. This protocol presents a robust way to estimate sex from archaeological remains utilising modern populations of known biological sex as the high-resolution shape data derived from GMM analysis captures more biologically informative information than the Walker 2005 ordinal scale which is influenced by population-specific demographic diversity. GMM analysis is of particular use for analysing fragmented or isolated elements from both archaeological and forensic contexts, and further studies should explore fragmentary pelvic remains for sexually dimorphic characteristics. Incorporating other sexually dimorphic elements of the pelvis, such as the subpubic angle or the ischio-pubic ramus of the pubic symphysis, would likely improve the accuracy and robusticity of further GMM analyses.

Modern humans exhibit population-specific morphological variation in the GSN (Patriquin et al., 2003), and scales developed from genetically diverse populations – like the American population used to create Walker's 2005 scale – will not adequately represent all individuals. Such results imply that any 'standard' method of visual sex estimation based on the GSN would not be widely applicable to both contemporary and archaeological population samples. This holds true for the present study, as our GMM techniques proved more effective than standard morphological scales.

## 5. Conclusion

This study has provided comprehensive insights into the challenges of sex estimation methods, particularly focusing on the analysis of the greater sciatic notch in human skeletal remains. The traditional approach, exemplified by the Walker 2005 scale, though widely used, exhibits limitations in accurately estimating biological sex, especially in diverse population groups and archaeological contexts. This research underscores the inadequacies of the Walker 2005 scale, which heavily relies on visual assessment and may exhibit bias towards categorising individuals as female due to its emphasis on wide greater sciatic notch morphology. This bias is evident from the high proportion of individuals assigned as 'female' compared to their known biological sex, highlighting the scale's limited applicability and reliability.

Conversely, GMM analysis emerges as a more robust and accurate method for sex estimation, offering higher precision and reliability. The GMM approach, using landmark and semi-landmark coordinates to quantify GSN morphology, demonstrates superior discriminatory power in distinguishing between male and female individuals in both modern and archaeological populations. This suggests that quantification of GSN morphology could be more accurate when applied to diverse population samples. The GSN angle metrics are also a highly reliable indicator of biological sex, and simpler to measure than the full GMM analysis, potentially introducing a quantitative metric for biological sex estimation that could be widely used by archaeological and forensic practitioners.

Our findings highlight the importance of integrating advanced morphometric and statistical techniques into archaeological investigations for more accurate sex estimation, particularly in cases where a limited amount of well preserved remains affects the ability to conduct a full skeletal assessment. This study underscores the need for ongoing refinement and validation of sex estimation methodologies in both archaeological and forensic contexts when dealing with skeletal remains, particularly in light of advancements in morphometric techniques and the growing recognition of population-specific variations in skeletal morphology (Krishan et al., 2016; Ross and Pilloud 2021). Continued research efforts aimed at refining and standardising sex estimation protocols will contribute to improved estimations, ultimately enhancing our understanding of past populations.

## CRediT authorship contribution statement

**Laura Conner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Allowen Evin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Laura Evis:** Writing – review & editing, Writing – original draft. **Catriona McKenzie:** Writing – review & editing, Writing – original draft, Supervision. **Kimberly Plomp:** Writing – review & editing, Writing – original draft, Formal analysis. **Carly Ameen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data is included in the supplementary files of this manuscript.

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### *Author contributions*

LC and CA designed the study. LC performed all data collection. LC, AE and CA performed the data analysis, with input from KP. LC and CA wrote the manuscript with contributions from all authors.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104745.

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