Forensic Science International 221 (2012) 156.e1–156.e7

Contents lists available at SciVerse ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Forensic Anthropology Population Data

Comparison of methods to determine sex by evaluating the greater sciatic notch: Visual, angular and geometric morphometrics

Jorge A. Gómez-Valdés [a,b,*], Mirsha Quinto-Sánchez [c], Antinea Menéndez Garmendia [a], Jana Veleminska [d], Gabriela Sánchez-Mejorada [a], Jaroslav Bruzek [d,e]

[a] Departamento de Anatomía, Facultad de Medicina, Universidad Nacional Autónoma de México, Circuito Interior, Ciudad Universitaria, Coyoacan, Distrito Federal 04510, Mexico
[b] Posgrado en Antropología, Universidad Nacional Autónoma de México, Circuito Exterior, Ciudad Universitaria, Coyoacan, Distrito Federal 04510, Mexico
[c] Laboratorio de Osteología, Licenciatura en Antropología Física, Escuela Nacional de Antropología e Historia, Periférico Sur y Zapote S/N, Colonia Isidro Fabela, Tlalpan, Distrito Federal 14030, Mexico
[d] Department of Anthropology and Human Genetics, Faculty of Sciences, Charles University, 12844, Vinicna 7, Prague, Czech Republic
[e] PACEA-LAPP, UMR5199, Centre National de la Recherche Scientifique, Université Bordeaux 1, Avenue des Facultés, 33405 Talence, France

ARTICLE INFO

Article history:
Received 4 March 2011
Received in revised form 20 February 2012
Accepted 25 April 2012
Available online 16 May 2012

Keywords:
Forensic anthropology population data
Forensic osteology
Sex diagnosis
Greater sciatic notch
Geometric morphometrics

ABSTRACT

Sex estimation is the first step for biological profile reconstruction of an unknown skeleton (archaeological or contemporary) and consequently for positive identification of skeletal remains recovered from forensic settings. Several tools have been developed using different osseous structures. With the intention to provide an objective method comparison, we reported the analysis of three different methods (visual, metric and geometric morphometrics) for sex assessment of the greater sciatic notch. One hundred and thirty pelvic bones (45.4% females and 54.6% males) from the National Autonomous University of Mexico Skeletal Collection pertaining to the contemporary Mexican population were analyzed.

We used the ROC-analysis to test between desired false positive thresholds (1-specificity) and expected true positive rates (sensitivity) in order to predict the best approach to sex assessment. The comparison of the area under the ROC-curves shows significant differences among visual and metric methods. At the same time, the analysis suggested that higher morphological variation among the sexes is independent of the methodological approach.

The results indicate that the metric (angle), with a high percent of indeterminate cases (34.6%), and visual, with 26.2% of the cases allocated as intermediate cases, were poorly accurate; we cannot recommend these techniques for sexing an unknown specimen. On the other hand, the geometric morphometrics approach improves sex estimation in 82.3% of correctly classified individuals with more than 95% of posterior probability.

In addition to the method comparison, the major sexual variation of the greater sciatic notch was determined to be located on its posterior border.

1. Introduction

Assessment of sex from human skeletal remains plays an important role in human skeletal analysis. Sex diagnosis is one of the most important components of bioarchaeology. In forensic osteology, individual biological attributes, such as sex, are fundamental to establish the individual-identity of human remains [1].

The degree of sexual dimorphism varies among anatomical structures according to functional implications [2–4]. In general, the pelvis and skull are considered like the best skeletal parts to carry out a reliable sexual diagnosis. Recent publications supported the idea of the different elements from the postcranial skeleton perform equally higher sexual estimations [5,6]. Additional opinions suggest the implementation of comparative analysis from various aspects of the skeleton (multifactorial method); however, in many cases, the commingled, isolated, fragmented and incomplete remains may also reduce the number of possibilities for consensus. Methods for sex assessment from human bones are given in traditional osteology manuals developed by different authors [1,7–10]. Based on a visual approach, Genovés [11,12], Phenice [13], Novotny [14], Bruzek [15], Bruzek and co-workers [16,17] and Walker [18] have suggested the considerations to follow for sex assessment in mature human pelvic bones.

The greater sciatic notch is especially valuable to sex assessment because it is highly sexually dimorphic. Female sciatic

* Corresponding author at: Departamento de Anatomía, Facultad de Medicina, Universidad Nacional Autónoma de México, Universidad 3000 C.P. 04510, Mexico. Tel.: +52 56232425; fax: +52 56232425.
E-mail address: pollosapiens@yahoo.com.mx (J.A. Gómez-Valdés).

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http://dx.doi.org/10.1016/j.forsciint.2012.04.027

notches are wider, open and with a lower width-to-depth ratio; while in males, the greater sciatic notch tends to be narrow and U-shaped [18]. The greater sciatic notch usually forms an angle of approximately 60° in females and 30° in males [8].

Genovés [11,12] stated that major sexual variation of the greater sciatic notch involves chord segmentation of the posterior border of the notch. Novotny [14] and Bruzek [15] also proposed an extreme sex form showing nearly equal anterior and posterior chords in females and a shorter posterior chord segmentation in males.

More sophisticated metric methods for approximation of the sexual shape variation of the greater sciatic notch based on angle, curvature and other geometric transformations have been developed by Singh and Potturi [19], Segebarth-Orban [20], Marchal [21], Patriquin et al. [22], Takahashi [23] and Isaac [24]. In recent studies the geometric morphometrics approach was introduced to sex analysis in order to quantify sexual shape variation of the greater sciatic notch [25–27].

This paper combines different kinds of morphological analyses to investigate the sexual differences of the greater sciatic notch. We applied visual, metric and geometric morphometrics techniques to evaluate the sciatic notch sexual and morphological variation. The relationship with each method was quantitatively explored. The aim of this analysis was to acquire the visual, metric and shape accuracy values of the sex assessment and compare the results.

2. Materials and methods

One hundred and thirty adult left coxal bones (45.4% females and 54.6% males) from Physical Anthropology Section, Department of Anatomy, School of Medicine, National Autonomous University of Mexico (UNAM), Skeletal Collection were analyzed (Table 1).

The age-at-death distribution of the skeletons used in this study are in the range from 21 to >67 years old. The female mean was 50.5 years and standard deviation 18.2 and male 41.9 in average and 12.1 from the standard deviation.

The skeletons belong to a contemporary Mexican population (1990–2010) and were obtained from bodies collected after anatomical dissection practices of the students in the School of Medicine from the National Autonomous University of Mexico.

All decedents were residents of Mexico City at the time of death and it is difficult to assess their socioeconomic status, nevertheless, in part correspond to the no-name and unclaimed bodies.

The UNAM Skeletal Collection consists of 194 males and females and was formed following Article 4° and 5° from the third chapter of "Human Dead Bodies Research" of the National Autonomous University of Mexico Legislation (http://info4.juridicas.unam.mx/unijus/). From the total, only adult cases without any osteopathology or *postmortem* modifications caused by peeling were analyzed.

To compare the different techniques, the data acquisition occurred in three steps: (a) visual shape analysis, (b) metric analysis via greater sciatic notch angle and (c) shape analysis by geometric morphometrics approach.

Visual analysis was performed following the Walker [18] proposal, who developed a set of greater sciatic notch diagrams and scoring procedures. The Walker diagrams represent drawings of the gradual transition between the extreme sciatic notch morphology of females and males.

Walker [18] created scores between 1 and 5 (1 = hyperfeminine, 2 = feminine, 3 = intermediate, 4 = masculine, and 5 = hypermasculine) to classify sexual variation based on a modification of the Acsádi and Nemeskeri [28] standard. Finally, significant sexual differences are tested by the Chi-square test ($p < 0.01$).

For angular and geometric morphometrics analysis, standardized images from each specimen were obtained in the dorso-lateral view. For this purpose, a NIKON© D50 digital camera (6.1 megapixels and 300 dpi) with an AF-S NIKKOR© 18–55 mm f/3.5–5.6 standard zoom lens was used. With the aim of orthogonalize the pictures and minimize the parallax error of the digital camera a photo reproduction table FIRENZE©, a fixed 100 mm focal point and an optical axis orthogonal to the bone was used and we considered the position when the bone is placed on its dorsal side and the orientation was helped for a container with mustard seeds. Similar approach was used in the previous studies of greater sciatic notch analysis [14,15].

For angle definition, three landmarks [11,12,23] were used directly over the images and greater sciatic notch angle was acquired using Meazure© software (http://cthing.com) (Fig. 1a).

Angular sciatic notch values and Walker's scores were not comparative; consequently, the angular raw measurements were arranged into nominal variables. We used the difference between the minimum and maximum values of the angle to estimate a range. Subsequently, we constructed five class intervals where the minimum angular value is 49°, the maximum is 104.7°, and the range was equal to 55.7° with the growth of 11.14°. With these values, we found that the first class is given by [≥93.56°], second [<93.56° & ≥82.42°], third [<82.42° & ≥71.28°], fourth class with interval [<71.28° & ≥60.14°] and [<60.14°] at the end. Lastly, a Chi-square ($p < 0.01$) test was applied comparing the angles between males and females.

The greater sciatic notch shape analysis was processed applying geometric morphometrics techniques. Two bony markers were identified on the images, Marker-1 and Marker-2, with the same criterion that was previously employed in the angle definition. Using MakeFan6© software [29] (http://www3.canisius.edu/~sheets/morphsoft.html), a virtual line was placed based on the two initial markers. A circular fan was located at the midpoint of this line, and 64 lines (with two of exaggeration value) were drawn. Based on this fan, 32 equidistant points were placed where the lines intersect the border of the notch. This occurred for every fan start direction in marker-1 and ending in marker-2 (Fig. 1b and c). For landmark coordinate acquisition, the tpsDig 1.4© software was used [30] (http://life.bio.sunysb.edu/morph/).

In order to overcome homology within equidistant landmarks [31] we slide the points along the tangential direction which allowed to us align semi-landmarks based on the minimum bending energy criterion [32].

With the semi-landmark information a Generalized Procrustes Analysis (GPA) [33,34] was carried out using tpsRelw© [35] (http://life.bio.sunysb.edu/morph/) and Relative Warp Analysis (RWA) was taken like a descriptor of shape variation. The Discriminant Function Analysis (DFA) from the weight matrix was performed, and the individual posterior probabilities of group membership were calculated in each case with an equal probability for female and male groups. Only cases with posterior probabilities equal or superior to 0.95 were classified as male or female, any value below was taken into account as intermediate [36].

Finally, thin-plate splines was conducted to visualize the gradient of shape variation from the average shape to different cut points at the minimum 5, 10, 15, 20, 50, 80, 85, 90, 95 and maximum percentile values of the relative warps scores.

Receiver Operating Characteristic (ROC) analysis was used to compare the diagnostic performance of the three (visual, metric and geometric morphometrics) sexual assessment methods [37].

For five possible cut-off points (hyper > female > intermediate > male > hyper), the intermediate discriminate value was selected between the two sexes. There will be some cases where the sex was correctly classified as positive (true positive), but

Table 1
Overall global accuracy results over predicted sex for all three methods.

	True	Allocated to						Total (n)
		Female		Male		Intermediate		
		n	%	n	%	n	%	
Visual	Female	55	93.2	1	1.7	3	5.1	59
	Male	6	8.5	34	47.9	31	43.7	71
	Total	61	46.9	35	26.9	34	26.2	130
Angle	Female	50	84.7	2	3.4	7	11.9	59
	Male	5	7.0	28	39.4	38	53.5	71
	Total	55	42.3	30	23.1	45	34.6	130
GM	Female	50	84.7	1	1.7	8	13.6	59
	Male	4	5.6	57	80.3	10	14.1	71
	Total	54	41.5	58	44.6	18	13.8	130

Cross-tabulation from original or true sex (rows) and sexual allocation (columns) after the application of each method. Visual corresponds to the Walker [13] proposal, angle to the metric approach and GM to geometric morphometrics. Correct classification of sex 68.5% from visual, 62.1% from angle and in geometric morphometrics 82.3% after discriminant analysis (with >95% of probability). Shape analysis provides the best accuracy to evaluate the greater sciatic notch sexual differences.

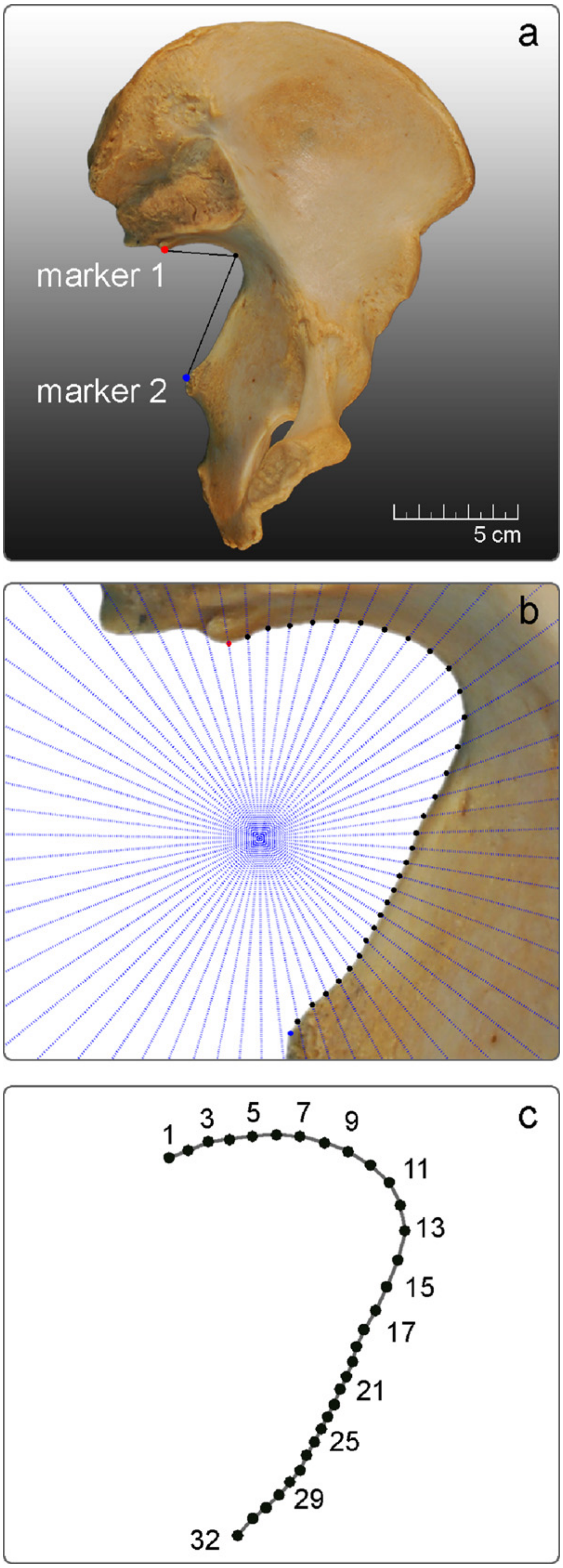

Fig. 1. Metric (angle) and geometric morphometric procedures for sex difference evaluation in the greater sciatic notch. (a) Marker-1, marker-2 indicators used in angle definition and in virtual diameter projection for the fan in geometric morphometrics. (b) Circle fan representation where the 30 semi-landmarks were located on the intersection of the notch border and 2 additional anatomical markers are placed at the tip of the notch. (c) Shape configuration. (Marker-1) Tubercle of the pirifomis, (marker-2) at the ischial spine level and (point-C) the most sharply curved point of the notch.

some cases were classified negative (false negative). Taking into account the female-like focal sex, sensitivity represents the probability that a test result would be positive in this sex direction (true positive rate, expressed as a percentage). Specificity is the probability that a test result would be negative (true negative rate, expressed as a percentage). Depending on the criterion value assigned like a cut-off point, the false positive fraction will decrease with increased specificity. On the other hand, the true positive fraction and sensitivity will decrease.

In a ROC-curve, the true positive rate (Sensitivity) is plotted as a function of the false positive rate (100-Specificity) for different cut-off points. Each point on the ROC plot represents a sensitivity/specificity pair corresponding to a particular decision threshold. A test with perfect discrimination (no overlap in the two distributions) has a ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity). Therefore, the closer the ROC plot is to the upper left corner, the higher the overall accuracy of the test.

With the intention to test the significance of the differences of the methods, the area under the ROC-curves (AUC) was used. For this purpose, MedCalc 11.3.8.0© software was utilized (http://www.medcalc.be) following the De Long et al. [38] methodology.

3. Results

In relation to visual analysis, our results show a greater separation between sexes in the distribution of Walker's sciatic notch scores [18]. A total of 68.5% correct classifications regarding sex were obtained. Females presented the highest percent of hyperfeminine (score 1) (64.4%) and feminine (score 2) (28.8%) typical morphologies; in contrast, the males notch morphology tends to be at the middle of the distribution, with the major percentages from indeterminate features (43.7%) and less from masculine (score 4) (33.8%) and hypermasculine (14.1%). In total 34 of the cases (26.2%) are located in the intermediate morphology (Table 1). The sexual differences in sciatic notch scores are highly significant ($p < 0.01$).

In Fig. 2a, it is possible to determine the correct female classification in relation to the 1 and 2 scores after the Walker [18] proposal. Most of the females show broad typical notch morphology; on the other hand, males depict narrower shapes.

The greater sciatic notch angle class shows a consistent separation between the sexes where the female angle is more open in relation to the males.

In contrast to the visual analysis, the histogram of the angle class (Fig. 2b) shows a more symmetrical distribution from both sexes. A great majority of the cases are grouped around the mean values (female mean = 90.06 and male mean = 72.57).

In the female cases, 33.9% have an angle greater than 93.56°, and 50.8% have an angle between 82.42° to 93.56°. On the other hand, greater percentages of males are located between 71.28° to 82.42° (53.5%) and 60.14° to 71.28° (35.2%) intervals (Table 1). The correct sex allocation concerns only 78–130 individuals (62.1%).

Great overlapping of the sexes happens in the central values of the greater sciatic notch angle class; 45 males and females (34.6%) have approximately the same angular values, nevertheless, significant differences between the sexes was obtained after applying the Chi-square test ($p < 0.01$) (Fig. 2b).

Geometric morphometrics results permitted us to visualize the morphological trajectories followed by the sexes in each relative warp and prove regionalization of morphological changes.

The relative warp analysis was used like multivariate exploratory method. The percentages of variability, explained by the first three relative warps among sexes, were substantially high (95%) (Fig. 3).

The first relative warp (RW1) explains a common morphological variation between the sexes and is enclosed for the latest landmarks that correspond with the anterior (dorsal) border of the greater sciatic notch. Contrarily, the second relative warp (RW2) shows a clear separation by sexes suggesting that the major shape changes in sex are related to the posterior border of the greater sciatic notch. Relative warp 3 (RW3) explains the randomized residual variation in overall notch shape (Fig. 3).

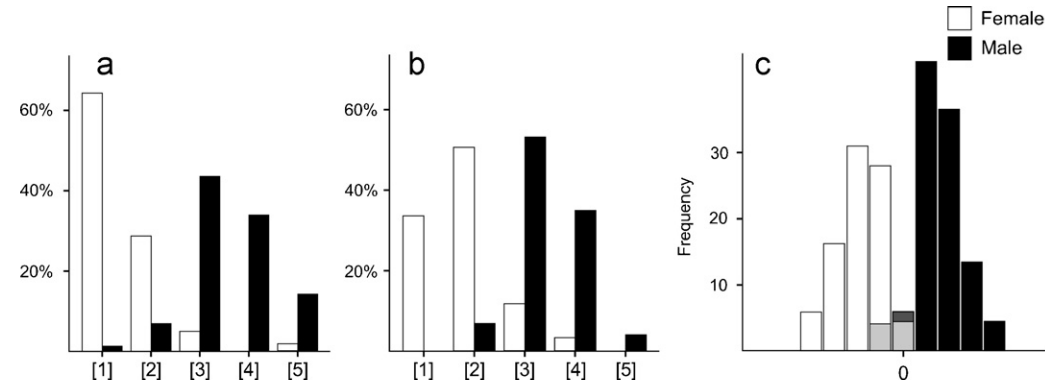

Fig. 2. Comparison of distribution of methods to determine sex by evaluating the greater sciatic notch. (a) Walker's scores in the female and male samples (Chi-square value = 95.779; $p < 0.001$ and Phi value = 0.858; $p < 0.001$), (b) angle scores in the female and male samples (Chi-square value = 81.39; $p < 0.001$ and Phi value = 0.791; $p < 0.001$), (c) first discriminate function for greater sciatic notch shape analysis via geometric morphometrics. Females are shown in white, and males are shown in black. It should be noted the distribution male scores is skewed in female direction according to Walker [13]; (a) more symmetrical distribution of the angle in both sexes (b) and that a few cases overlap each other (gray) in geometric morphometrics (c).

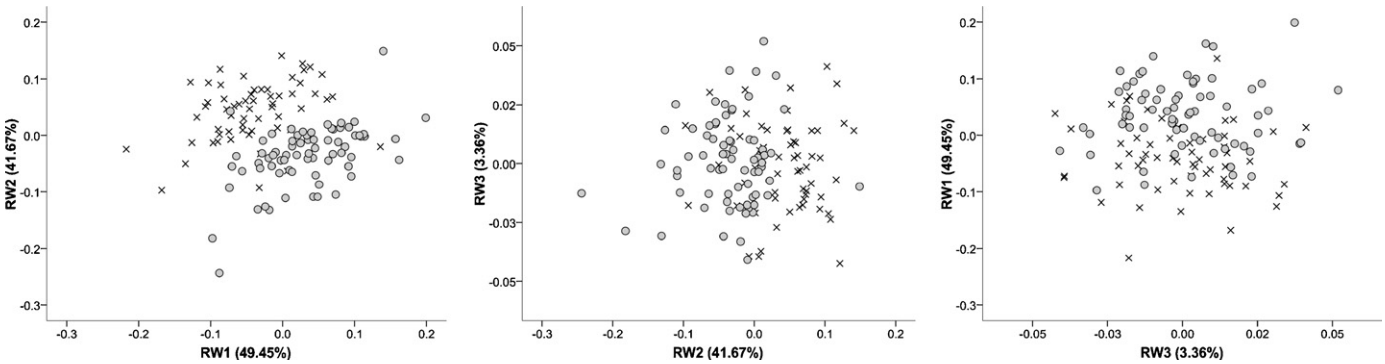

Fig. 3. Two dimensional scatter plots of the RW1, RW2 and RW3 from Procrustes coordinates matrix. Female sex is indicated by black crosses and male sex by gray-filled circles (top). Most of the greater sciatic notch shape variations are not related to sex. Greater separation by sexes occurred in RW2.

Shape variation among sexes, explored by geometric morphometrics, is presented in Fig. 4; the trajectories followed by notch morphology in extreme percentile values across each relative warp are reflected. Visual observation of RW1 provided data revealing that the female notch is deep, broad, and obtuse; contrarily, male morphology is narrower and with a smaller angle. The results highlight the RW2, where the females are grouped at the positive coordinates and males in the negative. The posterior curve is increased, and the deep of the notch decreases. On the other hand, the males show a curved posterior border. Shape variability primarily concerns the posterior border and anterior region appears to have less variation (Fig. 4).

Discriminant function analysis was used to determine the sexual differences in the greater sciatic notch. Sex was correctly assigned in 82.3% (without intermediate cases which have <0.95 posterior probability) of the cases using full-shape information.

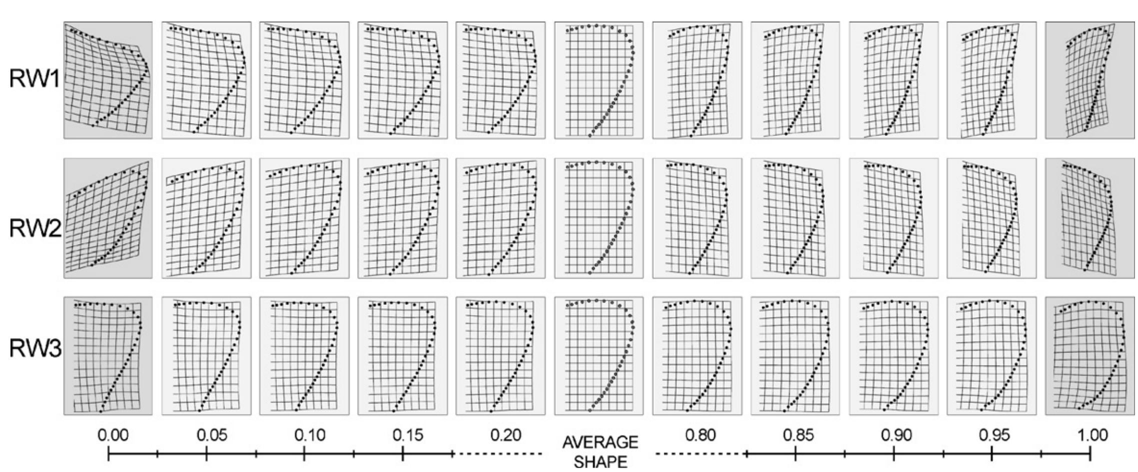

Fig. 4. Greater sciatic notch shape variation across each relative warp (RW). TPS of greater sciatic notch in ventral view related to the percentiles of the three first relative warps. They show each shape on extreme values of the percentile distribution of the negative and positive relative warp scores. Sexual differences are mainly due to a curved posterior border.

The information obtained from the graph's distribution of the discriminant function offers additional evidence to support greater sexual differences (Fig. 2c).

In addition to the results of each method, as can be seen in Fig. 5, the ROC-curves analysis confirms significant differences among Walker's proposal and the other two approaches: the Walker's scores shows an AUC = 0.623; the angle of the greater sciatic notch of AUC = 0.918 and AUC = 0.922 from geometric morphometrics, which can be interpreted as an increase in probability to correct sex diagnosis in geometric morphometric direction and angle data. Fig. 5 confirms that there is no overlapping of the distributions for each curve where the metric and geometric morphometrics approaches follow approximately the same trends. A sensitivity of 63.38 and specificity of 59.32 were determined from visual data. On the other hand, angular approach shows a 92.96 of sensitivity and 84.75 of specificity and geometric morphometrics shows a sensitivity and specificity with a value of 92.96 and 83.05, respectively. Taking into account the intermediate cut point, the ROC-analysis can be read with more precision and accuracy in the metric (angle) and shape (geometric morphometrics) approaches when compared to the visual technique.

Pairwise comparison of the area under the curve permits us to test the hypothesis stating that the difference between the two AUCs is 0. From this aspect, we did not observe significant differences ($p \geq 0.01$) between the metric and geometric morphometrics methods; nevertheless, the visual does have a greater difference ($p < 0.01$) in relation to the other two approaches (Fig. 5).

4. Discussion

Several works have described the principal sex variation in the human greater sciatic notch. Our results, based on different methodological approaches, are consistent with the previously

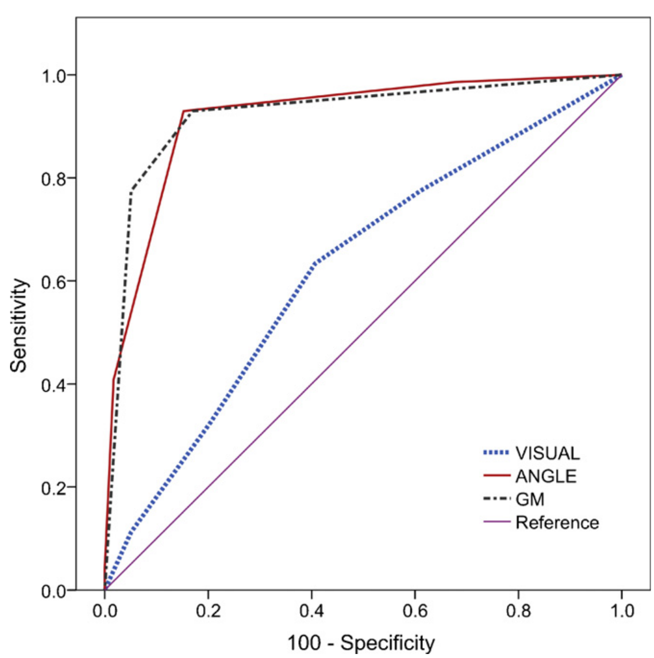

Fig. 5. Comparison of ROC-curves from three greater sciatic notch sexual assessments. Solid thick line = angle classification; dotted line = visual (Walker's scores); and dashed-dotted line = geometric morphometrics. Where the positive group is equal to female. AUC (visual) = 0.623, $p = 0.0107$; AUC (angle) = 0.918, $p < 0.0001$; and AUC (gm) = 0.922, $p < 0.001$. When there is a perfect separation of the groups, the area under the ROC-curve is equal to 1. Pairwise comparison visual *vs.* angle $z = 5.215$, $p < 0.001$; visual *vs.* geometric morphometrics $z = 5.594$, $p < 0.001$; angle *vs.* geometric morphometrics $z = 0.174$, $p = 0.8618$.

reported sexual changes verifying a major distinctive feature among sexes in the posterior border of the notch [11,12,14,15,18,19], and a powerful discrimination by sexes can be shown based on the notch morphology.

Valuable information was provided by visual shape analysis. Both sexes have an abundant intra-group variation and cover all of the morphological changes, but the females tend to have an asymmetrical distribution slanting to the opening morphologies from the Walker's classification (scores 1 and 2). On the other hand, most of the males gather around the intermediate morphology with a narrower shape. From these aspects, Walker [18] recorded very little overlap between the sexes at the extremes of the distribution and mentioned that male notch morphology is more variable than female notch morphology; the distribution of their scores is skewed in the female direction. Several works reported considerably higher percentages of correct sex classification using notch morphology [9,18]. In our work, significant sexual differences were evaluated in spite of higher intermediate morphology among the sexes.

As were expected, the results of angular projection showed more opening of the sciatic notch in females than in males. In addition, a more symmetrical frequency distribution was obtained between the sexes using this approach; nevertheless, the trends of angle class revealed that 34.6% of intermediate sexual variation was common for both sexes. Some authors previously noted values among 75% to 87.1% of correct sex classification using the metric evaluation of the sciatic notch [19,23].

Using angle technique, it is important to consider only 5.2% of the total cases in our work were misclassified (3.4% in females and 7% in males) (Table 1); nevertheless, a significant percentage of intermediate angle cases or non-classified cases were produced for both sexes.

Geometric morphometrics analysis permitted us to obtain a maximum separation by sex using full-shape information. As is evident in Fig. 2c, few cases were misclassified, and the highest probabilities for sexual diagnosis were obtained from discriminant analysis. We achieved an accuracy rate of 96.2%. As can be followed in specialized literature [39,40], shape-based analysis permits more detailed shape descriptions.

The patterns of shape variation for sexual dimorphism of the greater sciatic notch, explored from relative warp analysis, are characterized in the RW1 by a common intra-sex variation. The RW2 supply information related to sexual changes characterized by a notch that reflected an increase of the posterior curve and a decrease of the deepest in the female trajectory.

Allocation of major changes in the posterior border is interesting because functional aspects are related to birth canal configuration and restricted on illium position [20,41]. In females, the pelvis also serves as a birth canal, and thus it may be inferred that the evolution of pelvic dimorphism is associated with parturition [42]; nevertheless, the opening notch is intrinsically related with the greater or false pelvic cavity (inferior abdominal region) and not by the lesser cavity (ischium and pubis); therefore more related with bipedal locomotion [43–45].

The patterns of variation depending on sex are heterogeneous in the hip bones, but we can consider allometric, independent sacro-iliac functional segments, which can explain the scattering across the entire plot of sexes in the first relative warp (Fig. 3) when using the greater sciatic notch.

In our results, the first relative warp (RW1) explaining a common morphological variation among sexes is related to functional aspects of the notch segment (anterior and posterior border). This can be interpreted like a pattern of dimorphism of the greater sciatic notch among human groups by drawing asymmetric trajectories of variations among sexes; nevertheless, these don't have to be taken like patterns of generalized morphology of the pelvis. Previous works have supported the hypotheses that pelvis sexual variation is not structured into population-specific manner [36,46].

Our results clearly confirm that the most general aspects of the greater sciatic notch morphology are related to sex dimorphism, but it is important to consider other additive and stochastic effects related to functional implications from bipedal locomotion and population variability of the pelvis.

Furthermore, these findings are congruent with previous works based on geometric morphometrics considering a more reliable approach to quantify shape changes on the greater sciatic notch when compared to the traditional visual and classical methods [25–27]. The semiplane, small shape, easily anatomical orientation and measuring of the greater sciatic notch in osteology has become a standardized tool with a considerable correct percentage of sexing via traditional methods like Walker's [18]. Percentages from 65% to 90% of correct sex assessment have been described from the greater sciatic notch [18]. The results obtained from the present study reflect tendencies where the angle represents the less accurate method with 62.1% correct sex classification; 68.5% was obtained by visual counts and 82.3% (excluding cases with posterior probabilities equal or inferior to 0.95) with geometric morphometrics. These findings indicate, on one hand, that there is not strict concordance among methods; on the other hand, there was greater accuracy and reliability of quantitative (geometric morphometrics) shape methods compared to the other approaches.

Visual, angle and shape methods analyzed are conducive to the assessment of sex from the greater sciatic notch; nevertheless, the ROC-curve analysis permits us to confirm the reliability and accuracy of the geometric morphometrics methods. This greater sciatic notch shape analysis suggests an intermediate sex criterion with greater sensitivity and specificity values.

ROC-curve analysis detected dependent trends to posterior distribution after visual, metric and geometric morphometrics approaches for sex assessment. In other words, it is possible to determine that each method produces randomized dissimilar results in the estimation of sex, which means that each method does not produce an individual estimation of sex.

The comparison of methods shows that the geometric morphometrics performs approximately 20% more successful classification rates in comparison with angle data and Walker's proposal. As can be seen in Fig. 5, geometric morphometrics and angle approaches have more or less the same AUCs in the ROC-diagram, nevertheless, in geometric morphometrics more sensitivity represents high probability in correct sex assessment.

In our work, the implementation of geometric morphometrics approach was conducted to quantify and describe sexual dimorphism in the notch, considering this tool very valuable in forensic osteology because of the high accuracy to assess the sex difference.

5. Conclusions

Our study confirms the strong sexual dimorphism of the sciatic notch as indicated by previous studies. Using the three techniques of sciatic notch evaluation (visual scoring after ordinal scale, sciatic notch angle and geometric morphometrics approach), different results (despite the existence of significant sex differences) were obtained in a sample of 130 pelvic bones of known sex. Visual scoring of the sciatic notch morphology allows 68.5% correct sex classification. In the male subsample, we found a high proportion of indifferent cases. We cannot recommend this technique for sexing an unknown specimen. Its importance is only in extreme cases of variation. Using the sciatic angle, the correct sex allocation reaches only 62.1%. The misclassification rate is low (5%), but 34.6% of the specimens are indeterminate. This method is also not considered appropriate for sex determination. Only the geometric morphometrics approach has achieved a satisfactory high number of correctly classified individuals (82.3%), but this approach is time consuming. When comparing diagnostic tools and measuring the performance weight of various diagnostic methods, the using of ROC analysis is recommended.

Acknowledgments

The authors thank Professor Douglas Ubelaker for his initial contribution to this work and anonymous reviewers for their comments that improved the quality of the work.

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