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Analysis of dimorphic structures of the human pelvis: its implications for sex estimation in samples without reference collections

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Abstract

This work deals with the analysis of pelvic sexual dimorphism in skeletal samples of human prehistoric populations for which adequate reference collections of known sex are not available. We use geometric morphometric techniques based on semilandmarks in order to quantify shape variation of the greater sciatic notch and ischiopubic region. Firstly, intra- and interobserver error associated with the placement of point coordinates in geometric morphometric analyses were evaluated through intraclass correlation coefficient and Kappa index. Our results indicate that such techniques, in contrast to morphoscopic analysis, allow quantification and objective description of sexual dimorphism in pelvic traits, as well as, performing repeated analyses of numerous individuals with no previous observer experience required. Secondly, relative warp analyses calculated based on semilandmarks were used to describe sexual dimorphism pattern of the ischiopubic region and the greater sciatic notch of two unknown sex Amerindian samples from Argentina, and *k*-means clustering analysis was applied to detect two groups within each sample. One sample corresponds to hunter-gatherers from South Argentina ($n = 29$), whereas the other comprises farmers from Northwest Argentina ($n = 30$). The results obtained suggest that: (a) the first relative warps axis obtained for both structures summarizes shape changes due to sexual dimorphism; (b) the individuals grouped into clusters can be assigned as female or male based on their shape; and (c) sexual dimorphism is not equally expressed in both archaeological samples. These findings support the hypothesis that patterns of pelvic sexual dimorphism vary among human populations and thus, criteria for sexing are population-specific.

Keywords: Unknown sex samples; Sciatic notch; Ischiopubic region; Geometric morphometrics

1. Introduction

Modern humans are sexually dimorphic in size as well as in shape, and the differences between sexes are expressed in many osteological elements (Acsádi and Nemeskéri, 1970). Some anatomical structures are used for sexing skeletal samples due to the fact that they display high levels of dimorphism. Accurate sex estimation is a basic issue in bioarchaeological studies since the establishment of sex and age profiles is essential in paleodemography, paleopathology, among others (Meindl and Russell, 1998). The skeletal components often investigated for this purpose are the pelvis and skull, although there is some current consensus to consider the innominate as the most reliable sex indicator because it has long been recognized as the most dimorphic bone, particularly in adult individuals (Genovés, 1959; Krogman and Iscan, 1986; St. Hoyme and Iscan, 1989). Therefore, numerous techniques have been proposed, based either on visual assessment or recording of metric variables of the innominate.

The expression of sexually dimorphic traits varies among human populations; consequently, any attempt to develop standards for estimating sex in human skeletal remains must recognize such variations (Buikstra and Ubelaker, 1994). Most of the known sex samples available, such as Robert

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J. Terry anatomical collection (Smithsonian Institution, Washington DC, USA), Hamann-Todd (Cleveland Museum of Natural History, Cleveland, USA), Christ Church Spitalfields (Natural History Museum, London, England), Raymond Dart Collection (Department of Anatomical Science, University of the Witwatersrand, Johannesburg, South Africa) and Coimbra Identified Skeletal Collection (Museu de Antropologia, University of Coimbra, Portugal), that have been used to built sex criteria, were obtained from medieval to twentieth century populations of European and African ancestry (Holland, 1991; Krogman and Iscan, 1986; Loth and Henneberg, 1996; Molleson et al., 1998; Rocha, 1995). Taking into account that dimorphism is population-specific, the application of criteria for sex estimation derived from such reference samples, to skeletal samples belonging to other populations requires some caution. Unfortunately, the pattern of sexual dimorphism of populations of greater antiquity and different ancestry such as Amerindians is little known, and the accessibility of reference samples from prehistoric times is restricted to some exceptional cases where sex can be estimated on the basis of sex-specific burial artifacts found in association with the skeletons (e.g. in some archaeological sites from Northwest Argentina, pottery is associated with women, whereas projectile points are associated with men; Barboza et al., 2002) or by naturally mummified remains (e.g. Mittler and Sheridan, 1992; Sutter, 2003). In consequence, more research is necessary to address the issue of sexing individuals from archaeological samples for which suitable reference collections of known sex are not available.

Several techniques have been proposed for the analysis of sexual dimorphism that focus either on visual inspection or metric analysis of anatomical structures and traits. Visual or morphoscopic techniques have been largely criticized for their high degree of intra- and interobserver subjectivity (Bruzek, 2002; MacLaughlin and Bruce, 1990). Another problematic aspect of these techniques is the use of dichotomous or ordinal scoring that precludes adequate description of continuous phenotypic traits, reducing the variation to few discrete categories (Novotny, 1988). The metric approach has received increasing attention during the last twenty years (Albanese, 2003; Arsuaga and Carretero, 1994; Bruzek, 1992; DiBennardo and Taylor, 1983; Iscan, 1981; Rissech and Malgosa, 1997; Tague, 1989). Although the generation of unambiguous definitions for some metric variables (e.g. ischium length) is currently problematic, the advantages of such an approach over the morphoscopic one are higher levels of simplicity and consistency in the recording of variables, and availability of powerful statistical methods for the analysis of continuous data (Albanese, 2003; Konigsberg and Hens, 1998). Nevertheless, the different expressions of dimorphic traits in human populations have greater influence in morphometric than in morphoscopic techniques, since the values of discriminant functions are specific for each population and can only be applied to closely related populations (e.g. Patriquin et al., 2002; Rissech and Malgosa, 1991, 1997).

Morphometrics includes two main approaches, the traditional or multivariate (Blackith and Reyment, 1971; Marcus, 1990) based mainly on statistical comparison of distance variables (i.e. linear distances between two anatomical points or landmarks), and the more recent geometric morphometrics, based on the comparison of 2D and 3D coordinates of anatomical landmarks with various degrees of homology (Bookstein, 1991). Whereas some aspects of shape, such as spatial relationships between variables, are usually lost with the application of traditional techniques, geometric morphometrics capture the geometry of morphological structures of interest and preserve this information throughout statistical analyses (Adams et al., 2004). Landmark-based methods are the most widely used, despite the limitation imposed by the fact that a sufficient number of anatomical landmarks may not often be available to capture aspects of curvilinear shapes (Adams et al., 2004). Almost a decade ago, Green (1996) and Bookstein (1997) proposed an approach based on the use of multiple points along a homologous curve called semilandmarks, which permits the analysis of the resulting outlines using the same techniques developed for landmark-based analysis. Although semilandmarks are more useful than landmark-based analysis for the description of sexually dimorphic structures with few landmarks, such as the greater sciatic notch and the ischiopubic region, this method has not yet been applied to the analysis of sexual dimorphism.

Despite the fact that a number of studies assert the existence of population differences with regards to pelvic sexual dimorphism, few systematic efforts have been made to quantify this variation (Patriquin et al., 2003; Rissech and Malgosa, 1991; Steyn et al., 2004). One possible reason is that quantification of size and shape of many pelvic traits, mostly curvilinear and with few conspicuous landmarks such as the greater sciatic notch, is extremely difficult by means of traditional methods (Rosenberg, 2002). In consequence, the purpose of this research is to apply geometric morphometric methods to quantitatively describe the pattern of pelvic sexual dimorphism in two Amerindian archaeological samples of unknown sex, as a contribution to the discussion of sex allocation when no reference sample is available. In particular, we evaluate the efficacy of semilandmark-based techniques to describe and quantify the shape variation of the greater sciatic notch and ischiopubic region, as well as intra- and interobserver reliability of such techniques.

2. Materials and methods

The procedure followed in this analysis involved two steps. Firstly, we assessed intra- and interobserver error associated with geometric morphometric analysis of the greater sciatic notch and ischiopubic region. Particularly, we evaluated the error associated with placement of point coordinates used to describe the shape of these two structures. Secondly, we analyzed and compared the patterns of sexual dimorphism of the greater sciatic notch and ischiopubic region in two archaeological samples of unknown sex by means of geometric morphometrics. Based on these results, we used *k*-means clustering analysis to identify two groups within each sample, which correspond to male and female morphologies under the assumption that sexual dimorphism is the main source of variation of the innominate within populations.

2.1. Samples

Assessment of observer error was performed using a sample of 30 adult human left innominates of unknown sex, from different regions of Argentina (Sample A). This sample was randomly sampled from the anthropological collection of Museo de La Plata, La Plata, Argentina (Lehmann-Nitsche, 1910). Because we were interested in assessing if each observer consistently assigned the same score to the same individual throughout the observations (i.e. reliability), but not in the agreement between the assigned score and the actual sex of individuals (i.e. accuracy), the use of an unknown sex sample was adequate.

The analysis of sexually dimorphic structures was performed on two late Holocene (ca. 3000 to 500 years ^{14}C BP) samples of unknown sex from Southeast Argentina (Chubut valley, Patagonia, Argentina; $n = 29$) and Northwest Argentina (Pampa Grande, Salta, Argentina; $n = 30$), named Sample B1 and B2, respectively. Both samples are also housed in Museo de La Plata. These samples come from two different geographic and ecological regions situated about 2000 km apart from each other, and they belong to prehistoric populations with different organizational properties (mobile hunter-gatherers and less mobile horticulturalist-agriculturalists, respectively; Baffi et al., 1996; Gómez Otero and Dahinten, 1997/98).

2.2. Geometric morphometric analysis

For morphometric analysis we took 2D photographic images of the greater sciatic notch and ischiopubic region of each left innominate with a digital camera (Olympus Camedia C-3030). The right innominate was used when the left innominate was not present or damaged. Each innominate was placed with the auricular surface facing upwards. Sciatic notch photographs were taken with camera lens parallel to ilion surface at 250 mm from the bone. The ischiopubic region was placed parallel to camera lens at 250 mm from the camera. All the innominates were placed in exactly the same position for photography. Two landmarks—i.e. points placed on homologous morphological features (Bookstein, 1991)—and 14 semilandmarks (see below) were digitized on the greater sciatic notch (Fig. 1a). Landmark 1 was placed at the base of the ischial spine, and landmark 2 at the tip of the piriform tubercle. Two landmarks and 19 semilandmarks were digitized on the ischiopubic region (Fig. 1b). Landmark 3 was placed at the intersection of the upper edge of the pubis with the perpendicular line that reaches the uppermost point of the obturator groove, and landmark 4 on the intersection of the lower edge of ischium with a straight line passing between the uppermost and lowest points of the obturator foramen. To digitize evenly distributed points along the contour line of the two structures analyzed, radial guidelines with equal angular spacing, i.e. fans, were placed onto the images using

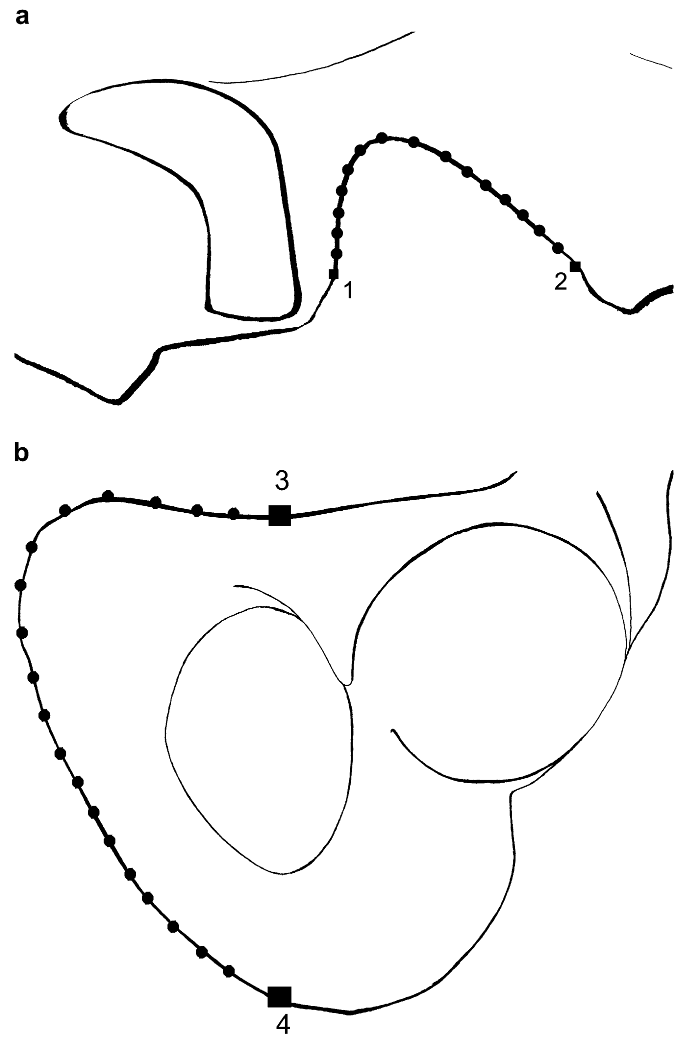

Fig. 1. (a) Allocated landmarks and semilandmarks on sciatic notch. (b) Allocated landmarks and semilandmarks on ischiopubic complex. Drawing by Marina Perez.

MakeFan6 software (Sheets, 2003). Next, both landmarks and semilandmarks were digitized using software tpsDIG 1.40 (Rohlf, 2004).

To convert the evenly distributed points along contours into semilandmarks, they were aligned by means of the perpendicular projection or minimum Procrustes distance criteria (Andresen et al., 2000; Sheets et al., 2004) using the software Semiland6 (Sheets, 2003). This operation extends the standard Procrustes superposition procedure (Gower, 1975; Rohlf and Slice, 1990) sliding the semilandmarks until they match as well as possible the positions of corresponding points along an outline in a reference specimen (Adams et al., 2004), minimizing the Procrustes distance (Sheets et al., 2004). This results in an alignment of the semilandmarks along the curve so that the semilandmarks on the target form lie along the lines perpendicularly to a curve passing through the corresponding semilandmarks on the reference form (Sampson et al., 1996; Sheets et al., 2004).

Thin-plate spline analysis (Bookstein, 1989) was used to quantify shape variations between individuals, and relative warp analysis (Bookstein, 1991; Rohlf, 1993) to describe major trends in shape variation within each sample. Both analyses were performed using software tpsRelw 1.40 (Rohlf, 2004). Relative warps (RW) are principal component vectors of the partial warps variables, the latter being obtained from thin-plate spline analysis. Both uniform (i.e. global change among landmarks and semilandmarks) and non-uniform components of variation (i.e. localized change among landmarks and semilandmarks) were computed in this study (Rohlf, 1993, 1996). The alpha parameter, which determines the relative weighting of the principal warps at different scales, was fixed at 0 (zero) value, as suggested by Rohlf (1993). Shape changes can be seen as deformation grids of each individual relative to the reference configuration (i.e. consensus or mean form).

The first scores of each individual for both structures resulting from the relative warps analysis were used as input in a *k*-means clustering analysis (MacQueen, 1967), which produces exactly *k* different clusters of greatest possible distinction, to classify the individuals into two groups (i.e. probably female and probably male). We have previously demonstrated that *k*-means clustering analysis yields the same results as discriminant analysis with cross-validation when applied to a known-sex sample (Gonzalez, 2005). We analyzed 121 individuals from the Coimbra Collection (Coimbra, Portugal), and the results show that 94.2% of the individuals were correctly assigned by discriminant analysis, whereas 91.7% of the estimations by *k*-means clustering were correct (Gonzalez, 2005). These results allowed us to validate the use of the latter analysis for sex estimation in unknown-sex samples, since no previous information about sex of individuals is required.

Intra- and interobserver error associated with the placement of point coordinates in geometric morphometric analysis were evaluated independently. The former was estimated by the observer (P.N.G.) who digitized the landmarks and semilandmarks of left pelvic structures of samples B1 and B2. In order to assess intraobserver error, P.N.G. digitized the landmarks and semilandmarks on photographic images of Sample A twice, with a week's interval between the scoring sessions. Then, the other two authors (S.I.P. and V.B.) digitized the landmarks and semilandmarks on ample A once to assess interobsever error. These three observers had different previous experience on analysis of pelvic sexual dimorphism, with P.N.G. being the most experienced on the subject. The sets of point coordinates obtained each time were used to perform relative warps analysis and the ordinations obtained were compared to evaluate both intra- and interobserver error. This was made by comparing the score of each individual on the first relative warp, which accounted for the variation allegedly attributable to sex, using intraclass correlation coefficient (ICC; Shrout and Fleiss, 1979). Intraclass correlation assesses rating reliability by comparing the variability of different ratings by the same subject to the total variation across all ratings and all subjects. The ICC values range from 0 to 1, corresponding to lowest and highest agreement, respectively. Significance level was established as $p < 0.05$ and indicates if the agreement is greater than the expected only by chance. Likewise, consistency among classification of individuals into the two clusters of greatest possible distinction obtained by each observer from the relative warps analysis was assessed by means of the agreement ratio (AR) and Kappa index (KI; Cohen, 1960). The latter is appropriate for testing whether agreement exceeds chance levels for binary and nominal ratings; its value is always less than or equal to 1. A value of 1 implies perfect agreement and lower values indicate less than perfect agreement. In rare situations, KI can be negative, thus signifying that the two observations agreed less than what would be expected just by chance.

Statistical analyses were performed using R 1.9.1 (Ihaka and Gentleman, 1996).

3. Results

The values of ICC obtained show excellent agreement (>0.99) (Fleiss, 1981) between the two series of P.N.G., and significant at 0.01 *p* level. Table 1 shows the results of interobserver error associated with the semilandmark-based analysis. The values of ICC for greater sciatic notch and ischiopubic complex indicate excellent agreement and are statistically significant at the same *p* level. Both intra- and interobserver error associated to the two clusters obtained were very low, since perfect agreement between the clusters obtained by observers 1 and 2 (AR = 1; KI = 1) occurred, with only one individual classified in a different cluster by observer 3 (AR = 0.96; KI = 0.94).

Fig. 2 is a plot of the first two relative warps calculated from the landmarks and semilandmarks of greater sciatic notch of the B1 sample (Patagonian sample), which account for 89.58% of the explained variance. The first relative warp explains 63.13% of the variance, and the morphologies at its most negative values are narrower and deeper than those located at the most positive values. Moreover, those morphologies with extreme negative values in the first relative warp have their deepest point at the posterior side of the sciatic notch. The second component describes the variation in sciatic notch depth. Fig. 3 shows the first two relative warps of sciatic notch for the B2 sample (Northwest sample), which account for 91.5% of the explained variance, and the associated morphologies. Morphologies located at the negative end of the first relative warp, which explains 50.84% of all variation, are wider and less deep than those at the positive end. The second component describes the position of the deepest point of the sciatic notch;

Table 1
Interobserver agreement for geometric morphometrics analysis

	Intraclass correlation coefficient	
	Ischiopubic complex	Greater sciatic notch
Observer1 vs. 2	0.978*	0.969*
Observer 1 vs. 3	0.982*	0.923*
Observer 2 vs. 3	0.979*	0.930*

Intraclass correlation coefficients computed from the scores of first principal axis of relative warps analysis.
*$p < 0.01$.

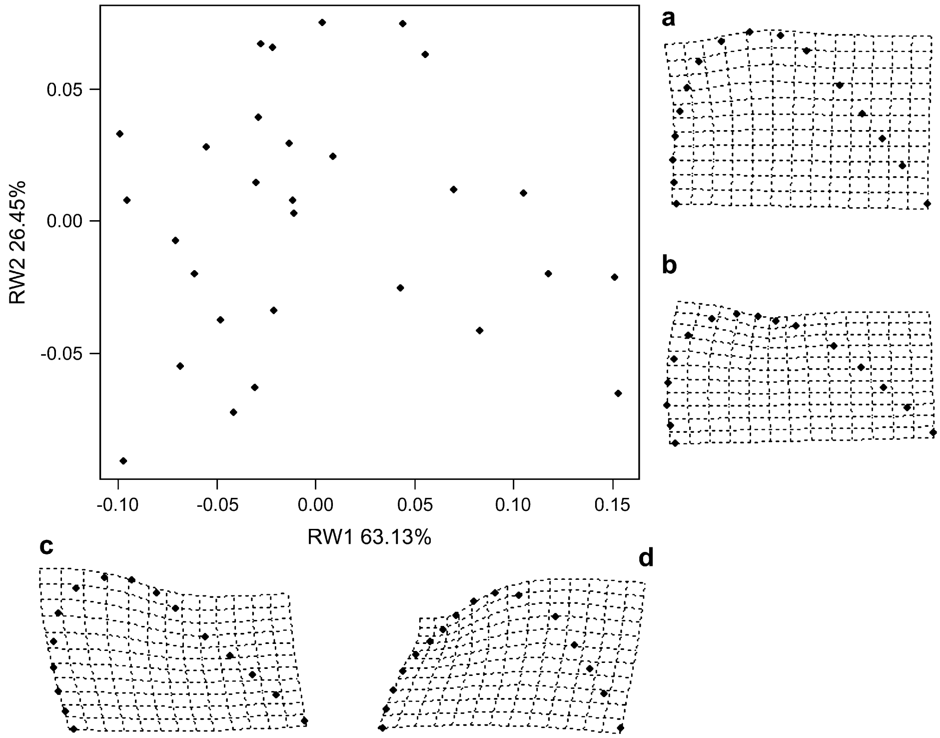

Fig. 2. Relative warps analysis of the greater sciatic notch of B1 (Patagonian) sample. The deformation grids represent variation along the first (c and d) and second (a and b) relative warps axes. Grids a and c correspond to male morphologies; grids b and d, to female ones.

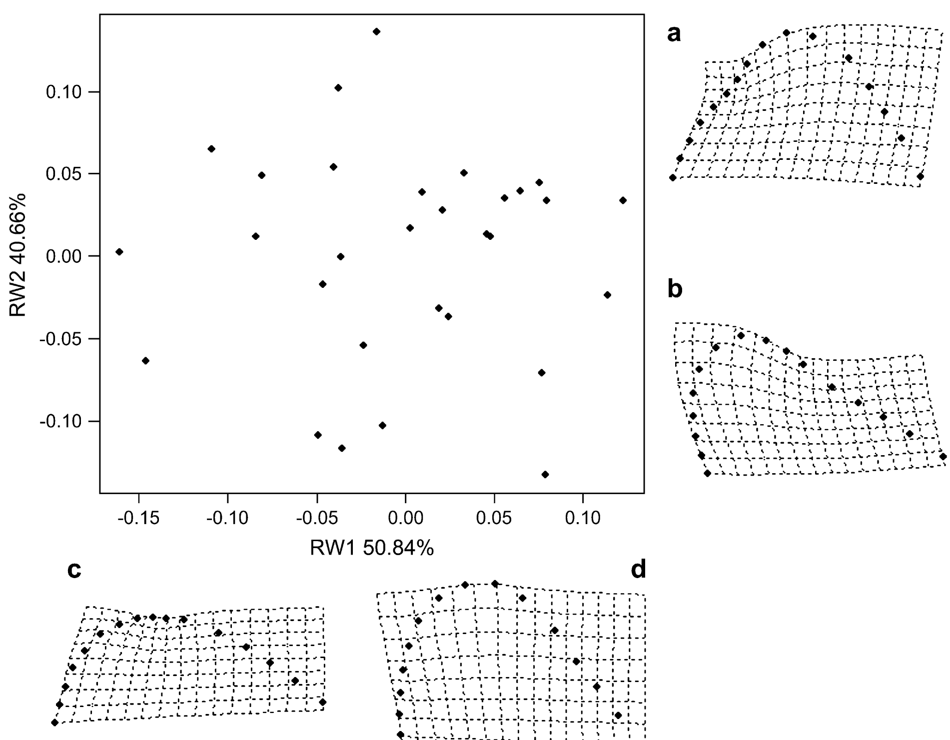

Fig. 3. Relative warps analysis of the greater sciatic notch of B2 (Northwest) sample. The deformation grids represent variation along the first (c and d) and second (a and b) relative warps axes. Grids a and c correspond to female morphologies; grids b and d, to male ones.

the deepest point is located on the posterior side of the sciatic notch in the individuals at the negative end of this relative warp.

Fig. 4 shows the first two relative warps of the ischiopubic region for the B1 sample and the associated morphologies (the explained variation is 77.96%). The first relative warp, which accounts for 64.01% of the total sample variance, comprises subpubic concavity and pubis projection. Fig. 5 displays the first two relative warps of the ischiopubic region for the B2 sample, which account for 81.75% of explained variance. The first component explains 62.04% of the variance and polarizes the same shape differences described for the B1 sample.

Fig. 6 shows the groups obtained by *k*-means clustering for the two samples. Each cluster was assigned as female or male according to its sciatic notch and ischiopubic shape along first RW. For B1 sample, 7 individuals were classified as female and 22 as male (Fig. 6a), whereas in B2 sample, 14 were classified as female and 15 as male (Fig. 6b). The first RWs of each structure obtained with both pooled samples are shown in Fig. 6c. In this figure we also indicate which individuals were assigned as female and male by *k*-means clustering computed for each sample. The results of RW analysis in the pooled sample show extensive overlap between both sexes in B2 sample, whereas the individuals assigned as male and female in B1 sample are far apart. When *k*-means clustering analysis was performed in the pooled sample, the assignation of some individuals to male and female clusters was different with respect to the results of the analysis of separate samples. Two individuals from B1 sample that had been previously clustered as male were classified as female, nine individuals from B2 sample were classified as female instead of male, and finally, three individuals from this latter sample were classified as male instead of female.

4. Discussion

Although it is widely accepted that intra- and interobserver error, related to either visual or metric variables, may produce discrepancies in sexual dimorphism assessment and sex allocation, few works have addressed this issue (Walker, 2005; Walrath et al., 2004). The results of the present analysis of measurement error show that the use of geometric morphometrics results in high intra- and interobserver agreement. In contrast, previous analyses point out that visual assessment is associated with high levels of interobserver error which results from ambiguous definition of variables, strong dependence on previous observer experience and the seriation procedure used to sort the individuals (Bruzek, 2002; Konigsberg and Hens, 1998; MacLaughlin and Bruce, 1990; Steyn et al., 2004; Walker, 2005). Recently, Walker (2005) evaluated intra- and interobserver agreement associated with the scoring of sciatic notch using an ordinal scale of five scores ranging from female

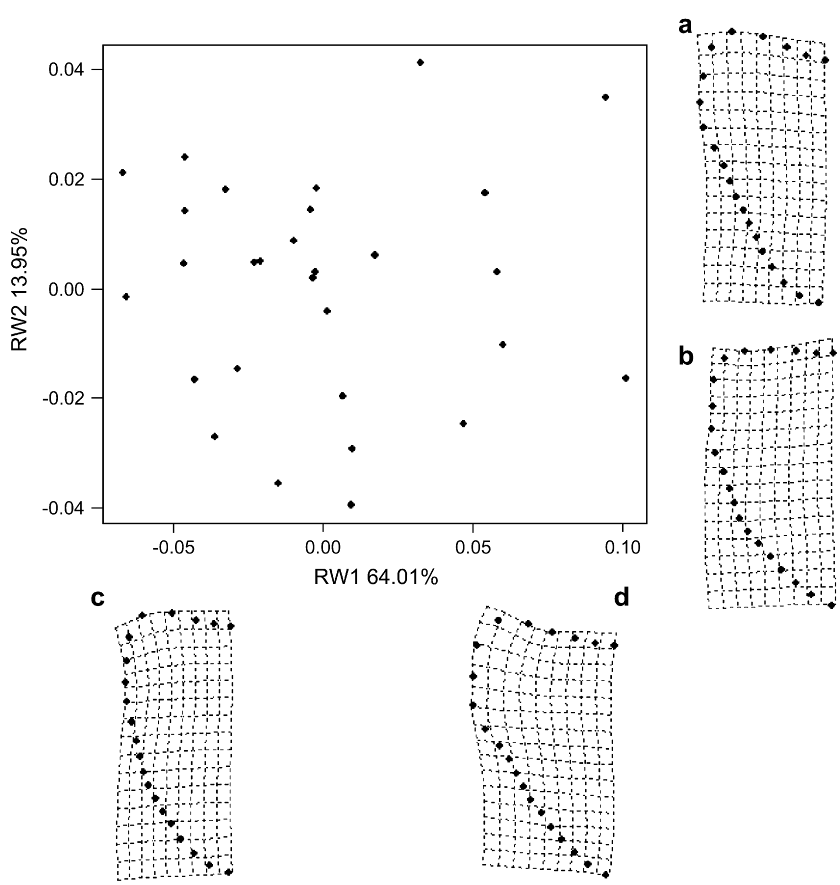

Fig. 4. Relative warps analysis of the ischiopubic complex of B1 (Patagonian) sample. The deformation grids represent variation along the first (c and d) and second (a and b) relative warps axes. Grids a and d correspond to female morphologies; grids b and c, to male ones.

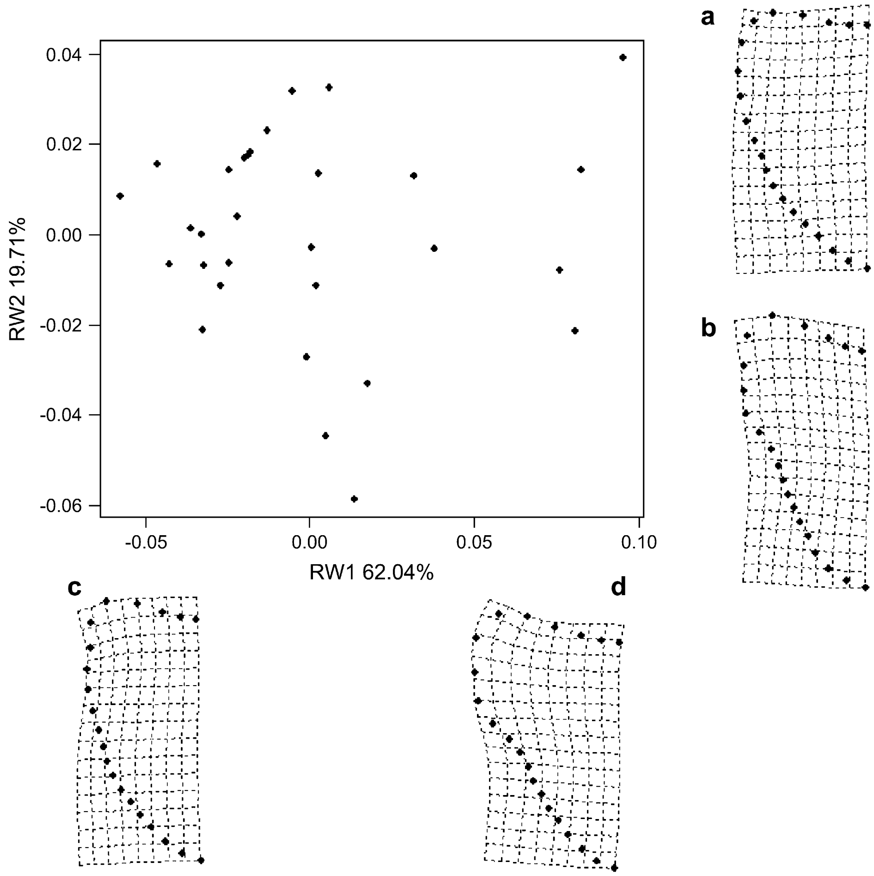

Fig. 5. Relative warps analysis of the ischiopubic region of B2 (Northwest) sample. The deformation grids represent variation along the first (c and d) and second (a and b) relative warps axes. Grids a and c correspond to male morphologies; grids b and d, to female ones.

to male morphologies. In his study, 22 volunteers, with different previous training in osteology, scored the same series of 10 left innominates. His results show that innominates with extreme morphologies can be rated consistently even among observers without any previous experience, but those with intermediate morphologies are very difficult to rate consistently (Walker, 2005). According to Konigsberg and Hens (1998), one problem of seriation is that its application to large samples in a replicable manner is unreliable. Our results support that such factors have less influence in the description of sexual dimorphic structures when geometric morphometrics techniques are used. For instance, although the three observers had different previous experience in the analysis of pelvic sexual dimorphism, they consistently digitized the coordinates of landmarks and semilandmarks. These results indicate that a sufficient number of points can be easily located both in the sciatic notch and ischiopubic region. The fact that the disagreements produced by differences in the digitalization of landmarks and semilandmarks among observations have small influence on the multivariate analyses performed (i.e. relative warps and *k*-means clustering) contributes to enhance the agreement among observations. In consequence, neither the ordination of each individual along the first relative warp axis nor the individuals assigned to each cluster showed important discrepancies among observers. It is noteworthy that the quantitative techniques employed to describe the pelvic structures allowed us to calculate principal components of shape, which can be thought of as linear combinations of the shape coordinates that show greatest variance in the data (St. Hoyme and Iscan, 1989), and at the same time enabled us to visualize the very subtle differences in shape along the first principal component score, which represents variation due to sexual dimorphism within samples. Through the combination of landmark and semilandmark-based techniques with multivariate analyses, the individuals can be consistently ordered; and such results contrast with those obtained by visual ordinations (Konigsberg and Hens, 1998; Walker, 2005).

The relative warps analyses performed on the two structures show shape changes that are concurrent with sexual differentiation. A large percentage of the overall variation in each sample (approximately 60%) is explained by the first relative warps axis, which summarizes the morphological changes due to sexual dimorphism. This statement is supported by the fact that the most important cause of morphological variation in adult pelvis, as well as in other osteological elements, within human populations is sexual dimorphism (Lee, 2001; Rosas and Bastir, 2002). Thus, the greatest variance in the data represented by the first RW axis corresponds to the differences between sexes. Particularly, in the samples analyzed the main variation along this axis corresponds to the width, depth

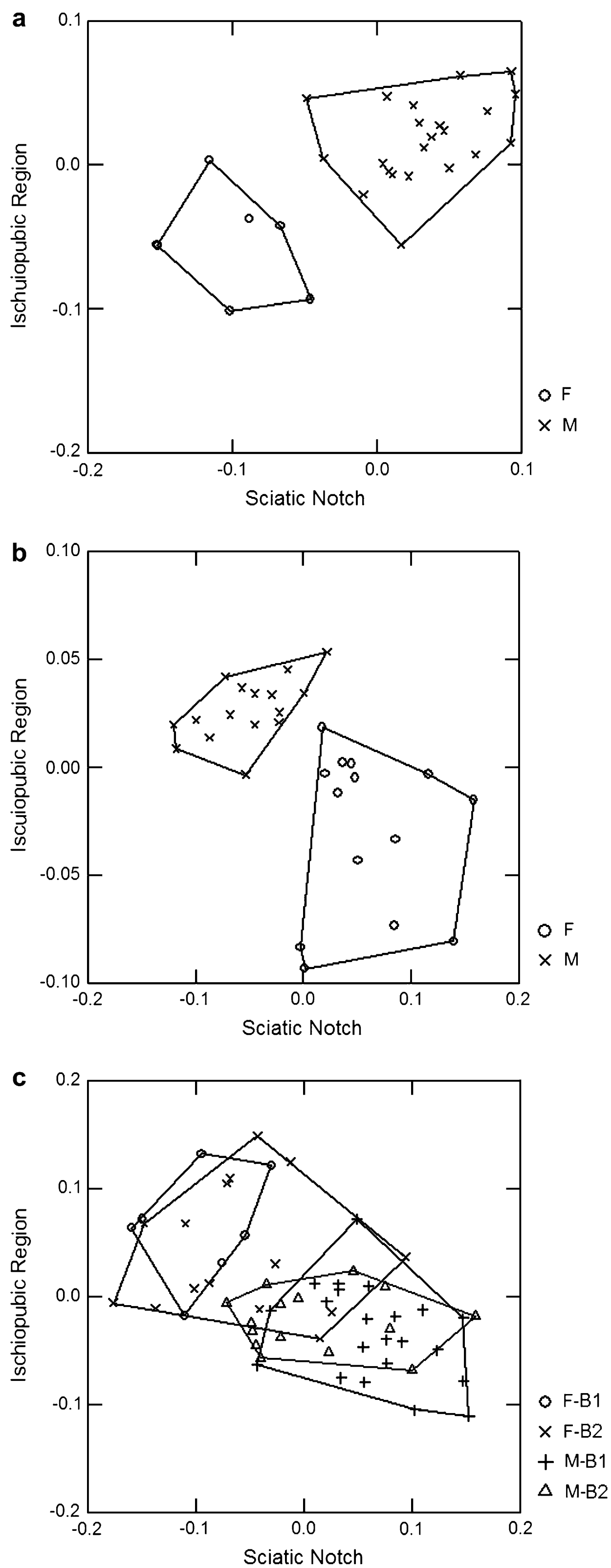

Fig. 6. First two relative warps axes obtained by analysis of greater sciatic notch and ischiopubic complex. The groups represented, designated as female or male, were obtained by *k*-means clustering. (a) Patagonian sample; (b) Northwest sample; (c) pooled sample.

and asymmetry of the sciatic notch, and to the projection of pubis, sub-pubic concavity and length of ischiopubic region (Figs. 2–5). Within each sample, the first axis of relative warps analysis separates sciatic notches that are narrow, deep and asymmetrical from those that are wide, less deep and symmetrical. Such variation is concomitant with the sexual dimorphism of the greater sciatic notch described for *Homo sapiens* and it has been documented, either by visual or morphometric methods, in different known sex samples (Buikstra and Ubelaker, 1994). For instance, Bruzek (2002) found using a visual method that the male sciatic notch is narrow, deep and asymmetrical because the posterior chord is shorter than the anterior chord. Using a different approach based on Fourier analysis, Novotny et al. (1992) showed that the male sciatic notch is always narrow, deep and has a short superior arm, whereas the female sciatic notch is wide, more open and its equally long arms diverge symmetrically forming a parabolic arch. Recently, Steyn et al. (2004), applying landmark-based methods, indicated that the black male sciatic notch is narrow and asymmetrical due to a much shorter posterior aspect of the notch. With respect to the pubis, within each sample, the first axis of relative warps analysis separates morphologies ranging from those with a greater projection of the pubis and marked subpubic concavity to those characterized by absence of such traits (Figs. 4 and 5). These variations in the pubic bone correspond to sexual differences, which have been documented by several authors in known sex samples (e.g. Phenice, 1969). Likewise, several authors have recognized that ischiopubic proportions vary between sexes, with pubic length/ischium length ratio higher in females than in males (Albanese, 2003; Bruzek, 2002). Our results agree with this pattern of variation because there is a change from longer to shorter ischium in relation to pubic length along the first RW axis (Figs. 4 and 5).

Given that the first RW axis summarizes the shape variation due to sexual dimorphism, the clusters obtained within each sample can be assigned as female or male according to their morphology (Fig. 6). Note that the procedure followed to assign the sex to each individual does not need a reference sample; it is based instead on the variation within each sample. The combination of geometric morphometric techniques with *k*-means clustering, allowed us to find underlying subsamples that make up the observer distributions. This approach is widely employed to estimate sexual size dimorphism in samples of unknown sex of fossil species where it is not clear if the same traits used to identify sex in recent populations can be applied to ancestral hominids (Lee, 2001; Plavcan, 1994). The impossibility of calculating percent of correct assignations when using this method could be considered as a weakness of this approach. However, there is evidence that the applicability of both metric and non metric sex determination methods is restricted by the reference sample used to develop the method (Albanese, 2003). For instance, the high allocation accuracy for the Phenice (1969) method based on Terry collection was not duplicated by MacLaughlin and Bruce (1990) on three European samples. Therefore, the percentage of correct assignation always remains unknown when the samples analyzed do not have adequate reference samples, as is the case of almost all archaeological and fossil samples.

Although the variation found within each sample is characteristic of sexual dimorphism in *Homo sapiens*, the relative warps analyses showed that the characteristic male and female shapes are different in both samples analyzed (B1 and B2), mainly with respect to the greater sciatic notch. In the Patagonian sample (B1), the first component describes the variation in position of the deepest point of the sciatic notch and the second shows differences in depth and width (Fig. 2). On the other hand, the variation in the first axis of the Northwest sample (B2) is related to depth and width, while the second reflects the symmetry of the sciatic notch (Fig. 3). Likewise, the sciatic notches with female shape in Northwest sample are wider and less deep than in those innominates assignable to females of the Patagonian sample (Figs. 2 and 3). The differences are more subtle in the ischiopubic region, corresponding mainly to longer pubis and more marked concavity in female morphologies of the Northwest sample than in the Patagonian females (Figs. 4 and 5). Furthermore, the *k*-means clustering analyses performed for each sample show that the two clusters within B1 sample differ primarily along the axis that represents the greater sciatic notch, and thus this structure is more dimorphic than the ischiopubic region (Fig. 6a). In contrast, the clusters in B2 sample are as separated both along the sciatic notch axis and the ischiopubic one, indicating that both structures display similar levels of dimorphism (Fig. 6b). In summary, our results suggest that the expression of pelvic sexual dimorphism in shape is different in the two samples. When B1 and B2 samples are analyzed together these differences become more noticeable (Fig. 6c); whereas the two clusters remain separated for the former, they overlap considerably for the B2 sample When *k*-means clustering is recalculated for pooled samples, the results indicate that some individuals are classified into different clusters depending on whether the samples are analyzed separately or together. Concurrently with the overlap observed in Fig. 6, the B2 samples present more individuals classified in a different cluster. These results indicate that the expression of sexually dimorphic traits is population-specific and thus, the internal variability of each sample should be taken into account for sex estimation.

Even though the presence of populational and regional variations in the pattern of sexual dimorphism is widely accepted, pelvic variation has received relatively little attention in comparison to cranial morphology (Rosenberg, 2002). Although this differentiation in the pelvis has been documented by other authors for modern (MacLaughlin and Bruce, 1990; Steyn et al., 2004; Walker, 2005) and fossil samples (Rosenberg, 2002), there are very few studies based on quantitative analyses that allow the comparison of numerous samples from several regions with a wide range of morphological variation (Steyn et al., 2004). Along these lines, Steyn et al. (2004) analyzed sciatic notch shape of South Africans black and whites using landmark-based methods and found that notch shape in white men is very similar to females of both groups. In contrast, black males differ not only by having a notch that is not only narrower, but also more asymmetrical than those of white and black females and white males. In a recent study based on visual assessment of sciatic notch, Walker (2005) found that the 18th–19th century English sample from St. Bridés Church presents a more feminine morphology than Americans of European or African ancestry. Such results are consistent with those obtained by MacLaughlin and Bruce (1986) who measured the sciatic notches of the St. Bride's sample and compared them with other European collections. According to these authors, sciatic notch size is not equal for all samples. Comparable results were attained by Rosenberg (2002) studying a late Pleistocene human fossil from Liujiang, China. When the sciatic notch measurements of this fossil are compared with either European or Australian standards, the results show that Liujiang's morphology is intermediate between male and female. In contrast, by the standards of a Chinese sample, the individual is clearly male. These findings, as well as those obtained in this study, support the occurrence of dissimilarities in the sexual dimorphism patterns of the human pelvis between populations, although the causes of such differences are not clearly known.

With respect to causal factors of pelvic morphology, phylogenetic and adaptive causes are usually invoked (Weaver, 2002). The latter include the changes produced during individual lifetime (i.e. phenotypic plasticity) or through evolutionary adaptation by natural selection. According to Rosenberg (2002) the ambiguity in sex estimation of the Liujiang fossil reflects variation in the pattern of sexual dimorphism of the pelvis between populations in diverse regions, and she states that the pattern seen today in Asia may have extended into the past. On the other hand, Walker (2005) suggests that an environmental factor such as vitamin D deficiency provides a possible nongenetic explanation (i.e. phenotypic plasticity) of sciatic notch shape dissimilarity between two samples of European ancestry. The samples analyzed in this study differ both in genetic and environmental factors. Sample B1 belongs to mobile hunter-gatherers from Northeast Patagonia, whereas sample B2 belongs to lesser mobile horticulturalists–agriculturalists from Northwest Argentina. Craniofacial analyses (e.g. Cocilovo and Marcellino, 1973; Cocilovo and Di Rienzo, 1984/85; Rothhammer and Silva, 1990) of these archaeological samples have concluded that their genetic differentiation is as expected given their geographical separation (i.e. 2000 km). Hence, any of these factors can be hypothesized as cause of variability in the pattern of sexual dimorphism found between samples. A comparative analysis including several samples that show variations in geographical location, mobility, and subsistence could help to establish the environmental, functional and genetic factors involved.

5. Conclusion

In summary, this research has demonstrated that the use of semilandmark-based techniques makes it possible to quantify and describe objectively sexual dimorphism in the pelvis, while also analyzing many individuals in a replicated manner; additionally, no previous observer's experience of the expression of sexual dimorphism is required. The results of this study suggest that the expression of sexual dimorphism has particular characteristics in each population and that geometric morphometric techniques are useful to describe such differences. Thus, the combination of such techniques with multivariate analyses allows sex allocation considering within-sample variation in cases where a reference sample is not available. As this is the most common situation in most archaeological contexts as well as in fossil hominids, this approach can be successfully applied in such cases. Finally, further studies including greater numbers of samples are required in order to determine which causal factors initiate population variation in sexual dimorphism patterns.

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