JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, May 2012, Vol. 57, No. 3
doi: 10.1111/j.1556-4029.2011.02009.x
Available online at: onlinelibrary.wiley.com

PAPER

ANTHROPOLOGY

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Human Coxal Bone Sexual Dimorphism and Multislice Computed Tomography: Geometric Morphometric Analysis of 65 Adults

ABSTRACT: The authors studied sexually dimorphic differences in coxal shape using geometric morphometric analysis of 15 osteometric landmarks recorded by multislice computed tomography (MSCT), based on three-dimensional reconstructions of 65 Caucasian adults. Geometric morphometric analysis, principal component analysis, canonical variates analysis, and other discriminant analysis (Goodall's *F*-test and Mahalanobis distance) were performed for the three separate bones of the left innominate (pubis, ilium, and ischium), the modified pubis (pubis and ischiopubic ramus), the modified ilium (ilium and ischial spine), three bone complexes (ischiopubic, iliopubic, and ilio-ischial), and the complete innominate. A cross-validation test was also performed. All areas studied were dimorphic, but results for sexual dimorphism in decreasing order were as follows: the modified pubis, followed by the ischiopubic complex, the iliopubic complex and the complete innominate, the pubis, the modified ilium, the ilio-ischial complex, the ilium, and finally the ischium. These results show the potential of this approach for future anthropological research.

KEYWORDS: forensic science, forensic anthropology, geometric morphometry, sexual dimorphism, coxal bone, multislice computed tomography

Many techniques already exist for skeletal sex determination. Currently, the adult hip bone is known to provide the highest levels of accuracy because of its marked sexual dimorphism, which results mainly from selective constraints on men and women imposed by locomotion and childbearing (1,2). A variety of methods are described in the textbooks, and several studies using multiple measurements and characteristics of the pelvis have been conducted worldwide with varying degrees of accuracy (2–11). These classic methods are based on morphological traits relating to the shape of the pubis, greater sciatic notch, obturator foramen, and acetabulum, or on metric parameters. Recent methods of sexual dimorphism determination, both metric and morphological, have been developed and preexisting standards tested (12–14). Two recent methods for coxal bone sexing were reported as having a high accuracy in sex determination (15,16). Morphological characteristics of the skeleton are often difficult to assess because of a number of factors such as inter- and intra-observer errors, observer experience, and problems of standardization and statistical analysis (17,18). Geometric morphometric analysis permits quantification of morphological characteristics (19–21). The main advantage of geometric morphometrics over traditional morphological approaches is that it provides a shape space, geometrically preserved, which is statistically interpretable (22). Geometric morphometric analysis combines the powerful and flexible tools of multivariate statistics and makes possible investigation of morphological variations, with direct reference to the anatomical context of the structure studied (23). Geometric morphometric analysis has been developed to quantify the shape of rigid structures that have curves and bulges that are not easily analyzed by traditional metric methods (19,20). It provides extremely useful visual information when applied to the study of differences between skeletal features. The exact areas of the morphological structure that cause the variation between specimens or groups can be visually identified. It has been used for this purpose since the late 1980s, but has only recently started to become popular in physical anthropology (24,25). This technique has already been used to study sexual differences of the complete pelvis or segments of the pelvis (26–28). Marchal (26) proposed morphometric analysis of the pelvic bone based on a two-dimensional (2D) photographic method. Bouhallier (27) used Procrustes analysis to compare the pelvic cavity of australopithecines with humans and chimpanzees to clarify the obstetrical mechanism. Several authors have performed 2D geometric morphometric analysis on isolated parts of the innominate bone (17,28). Some publications have used three-dimensional (3D) geometric morphometric analysis, but they either concerned the cranium or were based on Microscribe data (29,30). Although it could enable more precise evaluations than 2D photographic methods and offers many post-processing possibilities, 3D multislice computed tomography (MSCT) reconstructions have never previously been used for

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Received 27 July 2010; and in revised form 4 Feb. 2011; accepted 1 Mar. 2011.

geometric morphometric analysis of human adult coxal sexual dimorphism.

The aim of this study was to demonstrate that sexually dimorphic differences in adult coxal shape can be identified and visualized objectively with geometric morphometric analysis based on 3D MSCT reconstructions.

Materials and Methods

Materials

Population—We carried out a retrospective study of coxal bones from adult patients undergoing clinical MSCT in our institution between April 2005 and April 2009 (Toulouse, France). The MSCT examinations were mainly requested in a clinical context of abdominal diseases. Patients with a known history of bone disease were excluded. The patients were of various ethnic origins and were globally representative of the present-day population of southwestern France. A total of 65 MSCT examinations were included, consisting of 30 men (mean age, 24.8 years; SD, 5.5 years), 35 women (mean age, 27.3 years; SD, 6.7 years). The data and images were recorded anonymously.

MSCT—Examinations were performed on a Sensation 16 Scanner (Siemens, Erlangen, Germany) with 16 × 1.5 mm collimation. The image matrix was 512 × 512 pixels. A bone filter and a soft-tissue filter were used. Depending on the purpose of the examination, axial 3-mm (or 2 mm) reconstructions were performed every 2 mm (or 1 mm).

Postprocessing—Scans were saved as Digital Imaging and COmmunications in Medicine (DICOM) files, and postprocessing was performed with Amira 4.1.1® (Mercury Computer System, Inc., Chelmsford, MA).

Methods

Morphological 3D Analysis—Based on standard anthropometric techniques and literature, 15 osteometric landmarks were selected by convention on the left coxal bone (5,31–34) (Table 1). These landmarks were chosen as an adequate summary of those used in classic osteometric methods for coxal bone sexing, in order to allow comparisons with previously published results. The landmarks were all type I landmarks, which have an anatomical definition (19,20). The landmarks were positioned using Amira® on the MSCT reconstructions with the volume rendering technique (VRT) mode and the multi-planar reconstructions (MPR) mode. The corresponding 3D coordinates (x, y, and z) for each landmark were subsequently recorded. Anatomically, the adult innominate is formed by the fusion of three separate bones: the ilium, the ischium, and the pubis. These three bone parts meet in the acetabulum and fuse during puberty to form the single adult bone (1). Consequently, the three separate bones were first studied individually: the pubis, the ilium, and the ischium. Additionally, a modified ilium shape (consisting of the ilium and the ischial spine) and a modified pubis shape (consisting of the pubis and the ischiopubic ramus) were studied. The different parts of the following bone complexes were then analyzed individually: the ischiopubic complex (consisting of the modified pubis and the ischium), the iliopubic complex (consisting of the ilium and the pubis), the ilio-ischial complex (consisting of the ilium and the ischium), and finally the complete coxal bone. All the landmarks used for each bone or bone segment are illustrated in Fig. 1. In summary, the ilium consisted of nine landmarks, the pubis five landmarks, the ischium four landmarks, the modified ilium 10 landmarks, the modified pubis five landmarks, the iliopubic complex 12 landmarks, the ilio-ischial complex 10 landmarks, the ischiopubic complex seven landmarks, and the complete coxal bone 11 landmarks.

Precision Studies—Data used in this study were collected by two observers working under a common data collection protocol. To examine the effects of intra-observer error, the principal observer (MFB) carried out five observations of five randomized specimens from the sample of 65 adult pelvises 1 month after the first examination. To assess inter-observer error, the second observer (FD) carried out one observation of five randomized specimens. For each observer, landmark deviations were calculated relative to the landmark mean. As previously described, percentage errors were calculated for the 15 landmarks (Table 1) (35–37). Previous authors suggested that the results are acceptable when the percentage errors do not exceed 5% (35–38).

Procrustes Analysis—All morphometric geometric analyses and statistical analyses were carried out with Morpho J software and R 2.2.0 software (39,40). The landmarks chosen for the region of interest characterized the shapes of the corresponding areas (Fig. 1). For each bone and bone complex a generalized Procrustes analysis (GPA) was used. The GPA minimizes the sum of squared

TABLE 1—*Intra- and inter-observer variabilities of the 15 landmarks positioned on the MSCT pelvic reconstructions. The results are expressed in percentage errors.*

Landmark Abbreviations	Location on the Coxal Bone	Intra-Observer Variability (%)	Inter-Observer Variability (%)
HIC	Superior point of the iliac crest	1.98	2.08
II	Most inferior point of the ischium	2.81	2.85
LIC	Most lateral point of the iliac crest	2.26	2.49
ASS	Anterior superior iliac spine	1.94	2.27
AIS	Anterior inferior iliac spine	1.95	1.93
PSS	Posterior superior iliac spine	1.12	1.59
PIS	Posterior inferior iliac spine	2.11	2.35
IS	Ischial spine	2.60	2.95
HP	Superior point of the pubic symphysis	2.15	1.9
IP	Most inferior point of the pubic symphysis	2.47	2.43
AA	Most anterior point of the acetabulum	2.20	2.65
PA	Most posterior point of the acetabulum	1.75	1.65
CA	Center of the acetabulum	2.10	2.09
FO	Most anterior point of the obturator foramen	2.54	2.52
GSN	Widest point of the greater sciatic notch	1.81	2.02

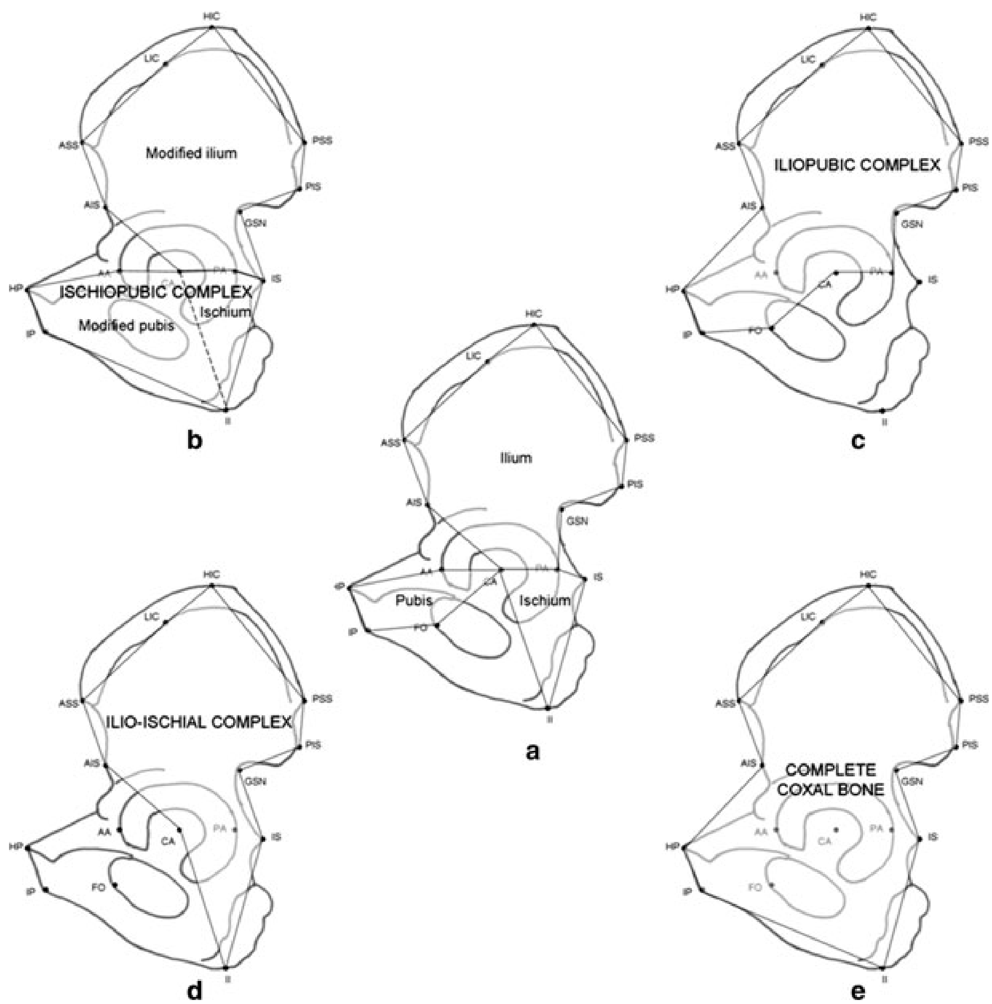

FIG. 1—*Drawing of the left coxal bone: position of the landmarks. (a) View on the left coxal bone of the landmarks used for the delimitation of the ilium, the pubis, and the ischium. (b) View on the left coxal bone of the landmarks used for the modified ilium (ilium and ischial spine), the modified pubis (pubis and ischiopubic ramus), and the ischiopubic complex. (c) View on the left coxal bone of the landmarks used for the iliopubic complex. (d) View on the left coxal bone of the landmarks used for the ilio-ischial complex. (e) View on the left coxal bone of the landmarks used for the complete coxal bone.*

distances between homologous landmarks by translating, rotating, reflecting, and scaling them to best fit (20,23,41,42). Scaling is according to centroid size (CS), the square root of the sum of squared Euclidean distances from each landmark to the centroids, which is the mean of the landmark coordinates. CS was used in this study, as a biologically meaningful expression of the overall scale of the landmark configuration, and thus of the bones studied, and permitted to examine allometry (21). The allometry is the shape variation that correlates with size (42). In this study, the static allometry was studied, corresponding to the shape variation that correlates to size (21, 42). With GPA, size effects related to isometry were removed, but allometric size differences were retained and visible (42). A consensus configuration, or mean shape configuration, was produced for men and women, so that differences between male and female configurations could be compared. These superimposed mean male and female landmark configurations (consensus configuration shape) were represented graphically as wireframes, that is, lines between landmarks with a 3D representation, individually for men and women. No deformation grid (thin plate spline analysis) was produced because those are used to illustrate graphically 2D deformations and not 3D representations.

The landmark coordinates were analyzed for the entire coxal bone, separate bones, and bones' complexes using principal components analysis (PCA) and canonical variates analysis (CVA) to describe major trends in shape variation within the sample. The PCA is an ordination technique that summarizes the variation among individuals on different axes calculated in multivariate space (41–43). The CVA assessed the ability to assign specimens in a data set to groups (i.e., men or women), rather than asking whether the two groups have a different shape (42, 44). The CVA differs from a PCA in that it describes the differences between groups rather than individuals. Where a PCA will determine the axis with the most variation among every specimen in the analysis, a CVA will determine the axis with the most variation between predetermined groups (41,43). A discriminant analysis with leave-one-out cross-validation was performed to compare the percentages of cases, in which the estimated sex of individuals correctly matched their true sex (i.e., the percent of correct classification) (42). A Pearson's chi-squared test (with a p-value determination) was also performed on the percentages of correct sex classification for men and women and for each bone area studied, in order to determine whether the differences were statistically significant (with $p < 0.05$). To determine whether the shape distances were statistically significant, a p-value was also calculated using the Goodall's F-test and Mahalanobis D^2 matrices (20,23,41,44–46). The Goodall's F-test allows testing for overall shape difference between

TABLE 2—*Principal components 1–13 of the PCA for the bones and bone complexes studied.*

	Eigenvalues, and Proportion of Total Variance (%) of the Bones, Parts of Bones, and Bone Complexes Studied								
Component	Ilium	Pubis	Ischium	Modified Ilium	Modified Pubis	Iliopubic Complex	Ilio-ischial Complex	Ischiopubic Complex	Complete Coxal Bone
1	8.7024	1.0181	1.0903	9.1107	3.3166	9.4950	9.2533	3.8685	10.6794
	31.04%	28.42%	38.23%	29.37%	47.25%	24.67%	26.83%	35.93%	25.81%
2	4.8004	NS	0.7772	5.2831	1.4312	6.0259	5.1043	1.7440	6.1561
	17.12%		27.25%	17.03%	20.39%	15.66%	14.80%	16.20%	14.88%
3	2.6227	NS	NS	2.7343	NS	4.1381	3.8080	0.9894	4.2491
	9.35%			8.81%		10.75%	11.04%	9.19%	10.27%
4	2.2415	NS	NS	2.3780	NS	2.8134	2.7999	0.8242	3.1639
	8.00%			7.67%		7.31%	8.12%	7.66%	7.65%
5	1.8078	NS	NS	2.0123	NS	2.2354	2.4362	NS	2.5351
	6.45%			6.49%		5.81%	7.06%		6.13%
6	1.2651	NS	NS	1.4349	NS	2.0165	1.8237	NS	2.1638
	4.51%			4.63%		5.24%	5.29%		5.23%
7	1.1326	NS	NS	1.2557	NS	1.7851	1.4827	NS	1.8565
	4.04%			4.05%		4.64%	4.30%		4.49%
8	0.9470	NS	NS	1.0529	NS	1.4540	1.1600	NS	1.4760
	3.38%			3.39%		3.78%	3.36%		3.57%
9	0.7905	NS	NS	0.8356	NS	1.2148	1.0834	NS	1.3777
	2.82%			2.69%		3.15%	3.14%		3.33%
10	NS	NS	NS	NS	NS	0.9495	0.9275	NS	1.1239
						2.47%	2.69%		2.72%
11	NS	NS	NS	NS	NS	0.8019	NS	NS	0.9435
						2.08%			2.28%
12	NS	NS	NS	NS	NS	0.7339	NS	NS	0.8740
						1.91%			2.11%
13	NS	NS	NS	NS	NS	NS	NS	NS	0.7081
									1.71%

The results are presented with eigenvalues and total variance (in percentage). As Jolliffe previously stated, the threshold of 0.70 was applied to the eigenvalues, which were considered as nonsignificant if under 0.70 (47). NS, nonsignificant value (eigenvalue <0.70).

groups and takes into account all the sample variables. The statistic is based on the ratio of the squared Procrustes distance between the means of each group, to the sum of the squared Procrustes distance of each specimen to its group means (41). The test assumes that the landmarks are symmetrically distributed around the Procrustes mean. Observations of the 3D scatterplots of these data sets indicate that this is a reasonable assumption (20,41). The test generates F and $p(F)$ values. Whereas discriminant analysis scores can provide a visualization of group separation, Mahalanobis distances (D^2) measure the distances between group centroids on a scale that is adjusted to the within-group variance in the direction of the group difference (41,42). This Mahalanobis distance is the squared generalized distance of the generalized statistical distance between means of two groups relative to the variance within the groups (41–43). This distance takes into account the correlations among variables when computing the distance between means. The generalized distance is used in Hotelling's T^2 test (42).

To study static allometry, the male and female CS were compared with an analysis of variance and determination of the F and $p(F)$ values. This permitted to determine whether the male and female CS means differed. It has already been demonstrated that principal component (PC) 1 well represents ontogenetic shape changes (21,36). The relationship between the size and the shape of the bones studied was investigated by looking for evidence of a significant correlation between the scores of individuals on PC 1 and log CS with determination the r^2 and p-values.

Results

Table 1 presents the percentage errors of the intra- and interobserver variabilities. None of the percentage errors exceeded 3%. Table 2 shows PCs 1–13 of PCA for the different bones and parts of bones studied. As Jolliffe (47) previously stated, the eigenvalue threshold was 0.7. The graphical representation of the PCA, which permitted the best discrimination in terms of sexual dimorphism, was PC 1 against PC 2 for all bone areas studied. Table 3 presents percentages of correct sex assignment obtained with the original CVA and the discriminant analysis with cross-validation test. All the p-values of the males and females' percentages of correct sex assignation were greater than 0.05, and consequently considered as nonsignificant. This result indicated that there was no sex difference concerning the correct percentage sex assignation performed after the cross-validation test. Table 4 presents the Goodall's F-test and the Mahalanobis distance values with their corresponding p-values for the different bone structures and areas studied.

Shape Study of the Three Separate Bones and Modified Separate Bones of the Innominate

Ilium and Modified Ilium—The Goodall's F and the Mahalanobis distance values indicated that the shape of the male and the female ilium and modified ilium differed significantly ($p < 0.0001$) (Table 4). PCA of the ilium provided sexual shape discrimination with PC 1 and PC 2 representing 48.16% of the explained variance (Fig. 2*a*, Table 2). The CVA revealed globally 94.04% of correct sexual assignation and the cross-validation revealed 73.81% of correct sexual assignation (Table 3). The Mahalanobis distance value of the ilium was greater than those of the pubis and the ischium and similar to that of the modified pubis (pubis plus the ischiopubic ramus). PCA of the modified ilium revealed shape discrimination with PC 1 and PC 2 representing 46.40% of the explained variance (Fig. 2*b*, Table 2). The CVA revealed globally 94.24% of correct sexual assignation, what was quite similar to the ilium, but the

TABLE 3—*Results of the original CVA and the cross-validation for the bones and bone complexes studied.*

		Original CVA			Cross-Validated		
Areas studied	Sex	Correctly Assigned	Incorrectly Assigned	% Correctly Assigned	Correctly Assigned	Incorrectly Assigned	% Correctly Assigned
Ilium	F	32	3	91.43	26	9	74.29
	M	29	1	96.67	22	8	73.33
	Total	61	4	94.04	48	17	73.81
Pubis	F	34	1	97.14	33	2	94.29
	M	24	6	80.00	24	6	80.00
	Total	58	7	88.57	57	8	87.14
Ischium	F	28	7	80.00	25	10	71.43
	M	18	12	60.00	15	15	50.00
	Total	46	19	70.00	40	25	60.71
Modified ilium	F	31	4	88.57	27	8	77.14
	M	30	0	100.00	28	2	93.33
	Total	61	4	94.29	55	10	85.24
Modified pubis	F	33	2	94.29	32	3	91.43
	M	28	2	93.33	28	2	93.33
	Total	61	4	93.81	60	5	92.38
Iliopubic complex	F	35	0	100.00	31	4	88.57
	M	30	0	100.00	26	4	86.66
	Total	65	0	100.00	57	8	87.62
Ilio-ischial complex	F	35	0	100.00	30	5	85.71
	M	30	0	100.00	25	5	83.33
	Total	65	0	100.00	55	10	84.52
Ischiopubic complex	F	34	1	97.14	33	2	94.29
	M	30	0	100.00	27	3	90.00
	Total	64	1	98.57	60	5	92.14
Complete coxal bone	F	35	0	100.00	31	4	88.57
	M	30	0	100.00	26	4	86.66
	Total	65	0	100.00	57	8	87.62

F, females; M, males.

TABLE 4—*Values of Mahalanobis D^2 distance and of the Goodall's F-test for the bones and bone complexes studied.*

Areas Studied	Mahalanobis Distance (D^2) p-Value	Goodall's F-test (F value) $p(F)$ Value
Ilium	2.90	3.39
	$p < 0.0001$	$p < 0.0001$
Pubis	2.34	2.93
	$p < 0.0001$	$p < 0.0001$
Ischium	0.96	4.21
	$p < 0.0246$	$p < 0.0001$
Modified ilium	3.37	3.82
	$p < 0.0001$	$p < 0.0001$
Modified pubis	2.90	3.39
	$p < 0.0001$	$p < 0.0001$
Iliopubic complex	5.21	5.67
	$p < 0.0001$	$p < 0.0001$
Ilio-ischial complex	4.13	5.97
	$p < 0.0001$	$p < 0.0001$
Ischiopubic complex	3.57	4.69
	$p < 0.0001$	$p < 0.0001$
Complete coxal bone	6.37	5.87
	$p < 0.0001$	$p < 0.0001$

cross-validation test revealed 85.24% of correct sexual assignation, what was better than the ilium (Table 3). The Mahalanobis distance value of the modified ilium was lower than those of the bone complexes and of the complete coxal bone, but the greatest of the three isolate bones. On 3D graphic representation, there were differences in ilial shape between the sexes, with a higher ilium for men (HIC-PA length), and greater anteroposterior width for women (ASS-PPS length) (Fig. 2*c*). Concerning women, posterior landmarks (PSS, PIS) were higher than those of men, the anterior landmarks (ASS, AIS) more anterior than those of men, and superior landmark (HIC) more posterior, lower, and external. Additionally, the female PIS landmark was more internal than the male and the PSS landmark more external. On 3D representations, inclusion of the ischial spine yielded additional data, showing differences at the greater sciatic notch, which were wider and deeper in women (position of GSN, and angle formed by IS-GSN-PIS). Furthermore, 3D locations of the IS-GSN-PIS landmarks differed between men and women, with external displacement of the landmarks GSN and IS.

Pubis and Modified Pubis—The Goodall's F and the Mahalanobis distance values indicated that the male and female pubis and modified pubis differed significantly in shape ($p < 0.0001$) (Table 4). PCA of the pubis provided no results and only PC1 had an eigenvalue higher than 0.7, which represented 28.42% of the explained variance (Fig. 3*a*). The CVA revealed globally 88.57% of correct sexual assignation, and the cross-validation revealed globally 87.14% of correct sexual assignation (Table 3). The Mahalanobis distance value of the pubis was greater only than that of the ischium. PCA of the modified pubis revealed shape discrimination with PC 1 and PC 2 representing 67.64% of the explained variance (Fig. 3*b*, Table 2). The CVA revealed globally 93.81% of correct sexual assignation, and the cross-validation revealed globally 92.38% of correct sexual assignation, better than the pubis (Table 3). The Mahalanobis distance value of the modified pubis was greater than those of the pubis and the ischium taken alone, but similar to the ilium taken alone. On the 3D graphical representation, the male pubis differed from the female: the symphyseal height (HP-IP length) was greater in males, and the pubic length (IP-CA and HP-AA lengths) was shorter than in females (Fig. 3*c*). Furthermore, the position of female HP and IP landmarks tended to be more medial and lower than those of males. Inclusion of the ischiopubic ramus provided additional data: the male ischiopubic length (IP-II length) was shorter and more steeply inclined than the

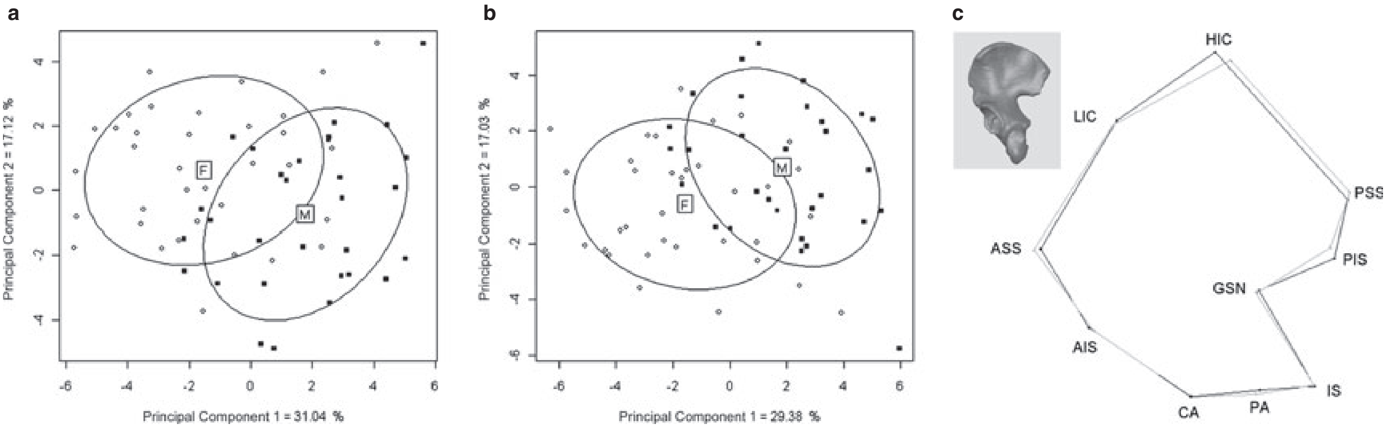

FIG. 2—*Geometric morphometric study of the ilium and modified ilum. (a) PCA obtained for ilium shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females. (b) PCA obtained for modified ilium shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females. (c) Variations of the modified ilium shape in 3D secondary to sexual differences (males: black lines; females: gray lines). For a better comprehension of the view, a 3D VRT reconstruction of the left coxal bone is also presented. See Table 1 for definitions of landmark abbreviations.*

female, and globally, the female ischiopubic ramus tended to be more horizontal and more sagittal than the male.

Ischium—The Goodall's *F* and the Mahalanobis distance values indicated that the male and the female ischium differed significantly in shape ($p < 0.0001$), but the Mahalanobis distance value was the lowest obtained (Table 4). PCA of the ischium provided bad sexual shape discrimination with PC 1 and PC 2 representing 65.48% of the explained variance (Fig. 4*a*, Table 2). The CVA revealed globally 70% of correct sexual assignation, and the cross-validation revealed globally only 60.71% of correct sexual assignation, which are the worst values of our study (Table 3). However, on the 3D representation, the male ischium was longer (PA-II length) than the female (Fig. 4*b*).

Shape Study of the Bone Complexes

Iliopubic Complex—The Goodall's *F* and the Mahalanobis distance values indicated that the male and female iliopubic complex differed significantly in shape ($p < 0.0001$) (Table 4). PCA of the iliopubic complex provided sexual shape discrimination with PC 1 and PC 2 representing 40.33% of the explained variance (Fig. 5, Table 2). The CVA revealed globally 100% of correct sexual assignation, and the cross-validation revealed globally 87.62% of correct sexual assignation (Table 3). The Mahalanobis distance value was lower only than that of the complete coxal bone.

Ilio-Ischial Complex—The Goodall's *F* and the Mahalanobis distance values indicated that the male and the female ilio-ischial complex differed significantly in shape ($p < 0.0001$) (Table 4). PCA of the ilio-ischial complex provided sexual shape discrimination with PC 1 and PC 2 representing 41.63% of the explained variance (Fig. 6, Table 2). The CVA revealed globally 100% of correct sexual assignation, and the cross-validation revealed globally 84.52% of correct sexual assignation (Table 3). The Mahalanobis distance value was lower than that of the iliopubic complex and the complete coxal bone and only greater than the ischial and ilial values.

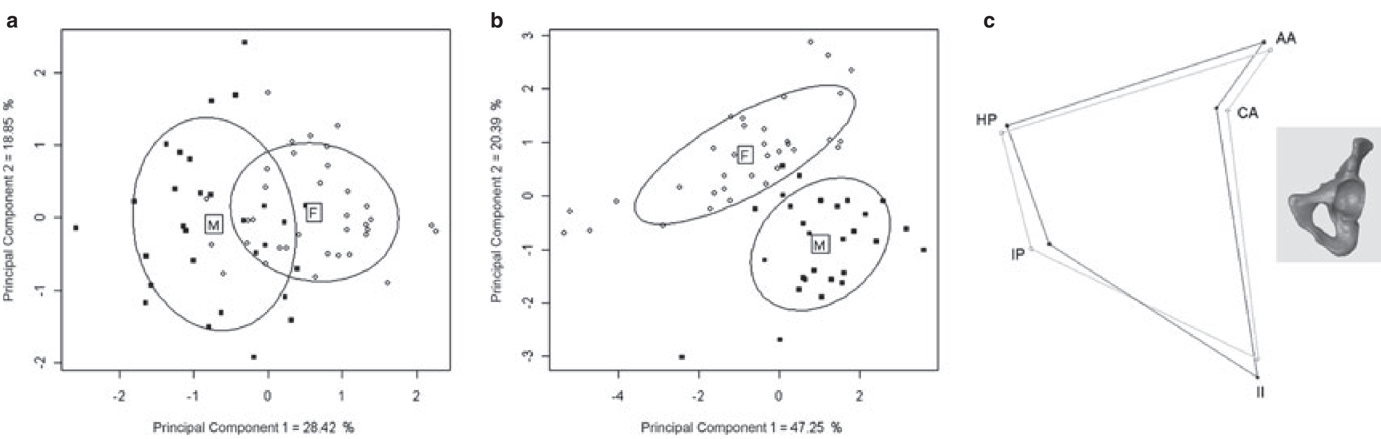

FIG. 3—*Geometric morphometric study of the pubis and the modified pubis. (a) PCA obtained for pubis shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females. (b) PCA obtained for modified pubis shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females. (c) Variations of the modified pubis shape in 3D secondary to sexual differences (males: black lines; females: gray lines). For a better comprehension of the view, a 3D VRT reconstruction of the left coxal bone is also presented. See Table 1 for definitions of landmark abbreviations.*

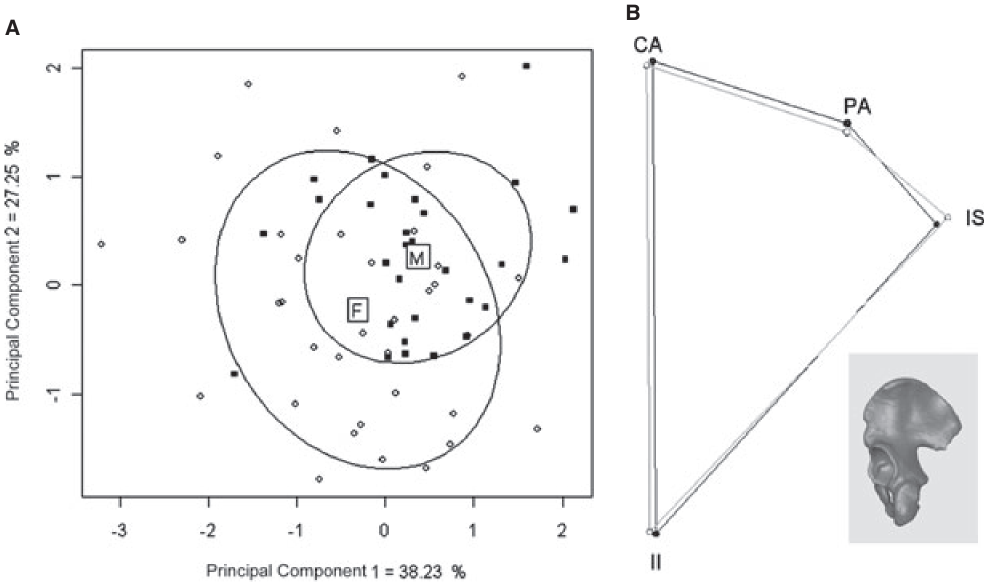

FIG. 4—*Geometric morphometric study of the ischium. (a) PCA obtained for ischium shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females. (b) Variations of the ischium shape in 3D secondary to sexual differences (males: black lines; females: gray lines). For a better comprehension of the view, a 3D VRT reconstruction of the left coxal bone is also presented. See Table 1 for definitions of landmark abbreviations.*

Ischiopubic Complex—The Goodall's *F* and the Mahalanobis distance values indicated that the male and the female ischiopubic complex differed significantly in shape ($p < 0.0001$) (Table 4). PCA of the ischiopubic complex provided sexual shape discrimination with PC 1 and PC 2 representing 52.13% of the explained variance (Fig. 7, Table 2). The CVA revealed globally 98.57% of correct sexual assignation, and the cross-validation revealed globally 92.14% of correct sexual assignation (Table 3). The Mahalanobis distance value was lower than that of the iliopubic and ilio-ischial complexes and the complete coxal bone. There were differences in ischiopubic complex shape between the sexes, as revealed with the modified pubis, but inclusion of the ischium revealed an antero-posteriorly shorter male ischiopubic complex (IS-HP length), but higher than females (AA-II, CA-II, PA-II, IS-II lengths).

Complete Coxal Bone—The Goodall's *F* and the Mahalanobis distance values indicated that the male and the female complete coxal bones differed significantly in shape ($p < 0.0001$) (Table 4). PCA of the left coxal bone provided sexual shape discrimination

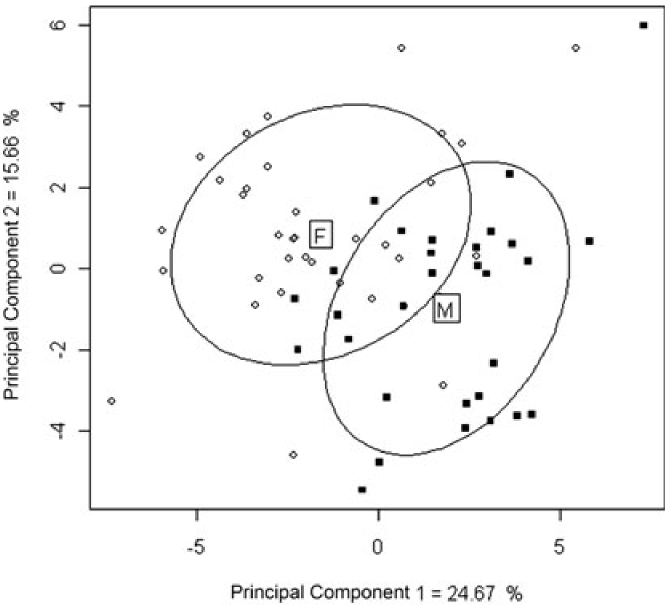

FIG. 5—*Geometric morphometric study of the iliopubic complex. PCA obtained for iliopubic complex shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females.*

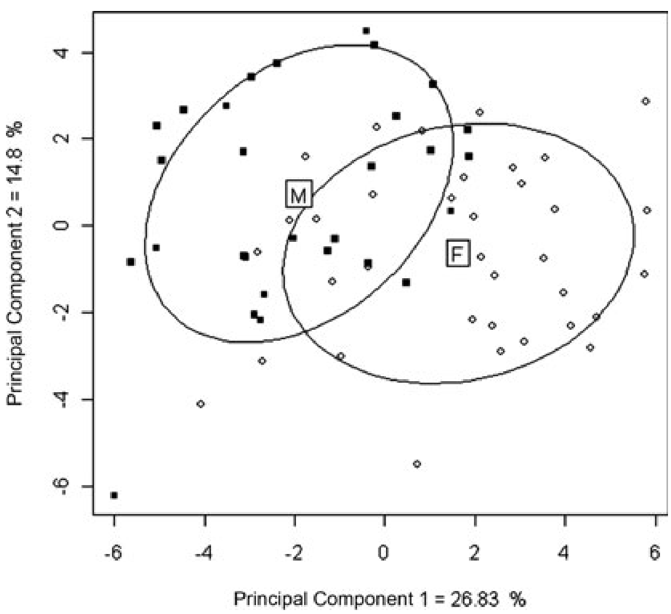

FIG. 6—*Geometric morphometric study of the ilio-ischial complex. PCA obtained for ilio-ischial complex shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females*

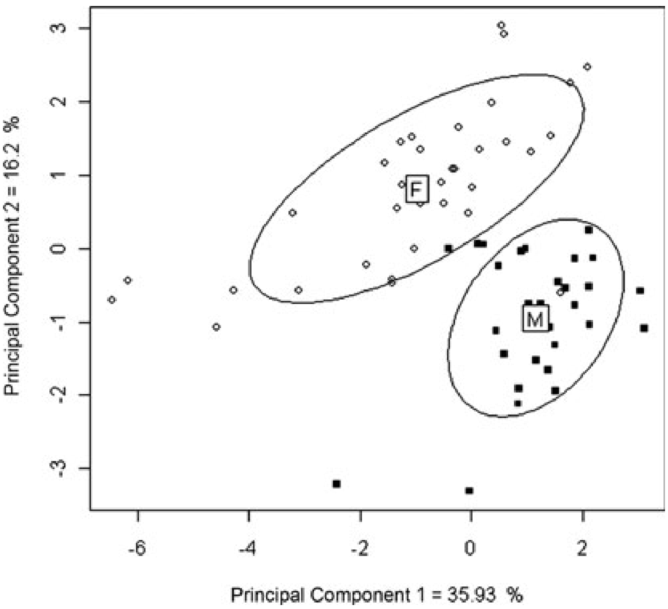

FIG. 7—*Geometric morphometric study of the ischiopubic complex. PCA obtained for ischiopubic complex shape variables. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females.*

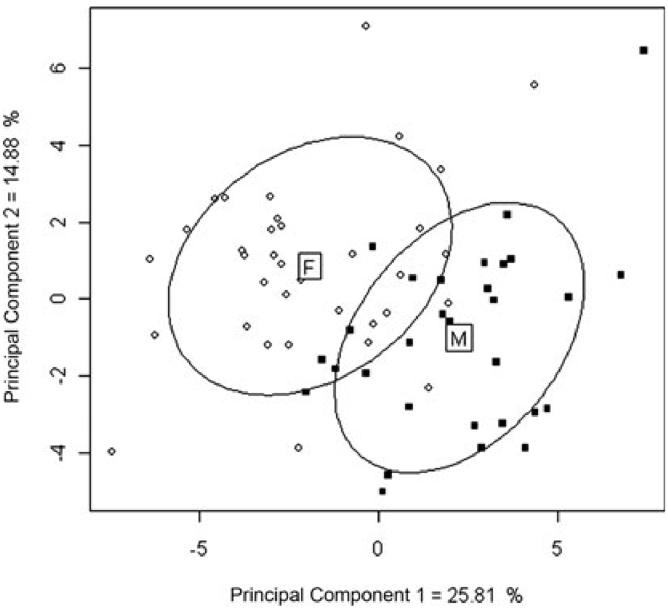

FIG. 8—*Geometric morphometric study of the complete coxal bone. PCA obtained for the complete coxal shape. Males are shown as a solid black square (■) and females as an open circle (○). The ellipses represent 68% confidence intervals for males and females.*

with PC 1 and PC 2 representing 40.69% of the explained variance (Fig. 8, Table 2). The CVA revealed globally 100% of correct sexual assignation, and the cross-validation revealed globally 87.62% of correct sexual assignation (Table 3). The complete coxal bone had the highest Mahalanobis distance value (Table 4). This indicated that the innominate had the most pronounced sexual dimorphism of all the bones of the population that we studied. The male 3D mean shape was significantly different from the female with male coxal bone higher (HIC-II length) but narrower than the female bone (ASS-PSS, IP-IS and HP-IS lengths). Furthermore, the ilium compared with the inferior part of the coxal bone tended to be more externally inclined in females.

Size Effects

The Table 5 illustrates the mean values (and standard deviations) of the male and female CS for all bones and bone complexes studied. All the *p*-values were greater than 0.05, attesting of their nonstatistically significant differences. Table 6 shows coefficients for the reduced major axis regression of PC 1 on log CS across all individuals by bones and bone complexes. The r^2 varied from 0.56 to 0.91, but all the *p*-values were highly significant (<0.001). Furthermore, PC 1 accounted from 47.25% for the modified pubis of total shape variance to 25.81% for the complete coxal. A strong linear relationship between PC 1 and CS was visible, proving that PC 1 largely summarized size-correlated bones and bone complexes variations and established that allometric scaling was present.

Discussion

Our results showed that intra- and inter-observer variabilities were less than 3%, attesting of the accuracy and reproducibility of the technique, which is acceptable (35–37,44,45). Based on our results, all the part of bones (modified or not), bones complexes, and complete coxal bone presented a sexual dimorphism (*p*-values of the Goodall's *F*-test and the Mahalanobis distances <0.0001), which is in accordance with previous classical osteoscopic or metric studies (2–11,28). However, some bones or bones complexes appeared to be more dimorphic than others. The modified pubis and the modified ilium were more sexually dimorphic than original bones (which are defined by a precise embryological origin). This was obvious for the *modified ilium*, with an increased percentage of correct sexual assignation obtained after cross-validation when compared with the *ilium*. The result of 85.24% of correct sexual assignation for the modified ilium can be compared with that obtained with the 2D semi-landmarks study focused on the greater sciatic notch, which has previously been estimated at 90.9% (17). Our percentage results are slightly inferior maybe because of the inclusion of landmarks that did not concern the greater sciatic notch, but other ilial landmarks may be less sexually dimorphic, introducing disturbance and consequently reducing the percentage of correct sexual assignment. On 3D representations, there were differences in iliac shape between the sexes, with a higher ilium in men, and greater antero-posterior length in women, and deeper and wider the greater sciatic notch in women. These features were in accordance with classic physical anthropological descriptions of the ilium (2,3,5–11,48). 3D location of the three landmarks defining the greater sciatic notch showed also further differences between men and women, with external displacement of the landmarks GSN and IS, and internal displacement of the PIS. The ilial index (which is the percentage ratio between width and height) has already been described as dimorphic in adult populations, with mean values always higher in women than men (48). Furthermore, morphometric geometric analysis also illustrates the fact that the crestal point (HIC landmark) is located further back in women than in men (48).

For the *pubis*, it is important to note that the PCA had only the PC 1 had a significant value of its eigenvalue. The inclusion of the ischiopubic ramus permitted to obtain two significant PC scores. The results of the CVA and of the cross-validation were also improved by this inclusion. The percentage of correct sexual

TABLE 5—*Values of the centroid sizes (CS) for males and females for the bones and bone complexes studied.*

Areas Studied	Male CS [Mean (SD)]	Female CS [Mean (SD)]	*F*-value	*p*-Value
Ilium	22.92 (2.80)	23.46 (3.33)	0.3704	0.5451
Pubis	18.13 (4.82)	20.59 (5.54)	2.9597	0.0906
Ischium	18.45 (4.74)	20.08 (5.43)	1.2149	0.2749
Modified ilium	24.66 (2.81)	25.03 (2.82)	0.1497	0.7002
Modified pubis	20.63 (4.70)	22.63 (5.40)	2.0693	0.1556
Iliopubic complex	30.11 (2.77)	30.57 (3.16)	0.3189	0.5744
Ilio-ischial complex	27.52 (2.73)	27.49 (3.21)	0.0143	0.9052
Ischiopubic complex	22.40 (4.46)	24.12 (5.15)	1.7028	0.1970
Complete coxal bone	32.09 (2.74)	32.22 (3.10)	0.018	0.8938

TABLE 6—*Effects of the allometry. Values of the r^2 and p-values after reduced major axis regression of principal component 1 on log centroid size.*

Areas Studied	r^2	*p*-Value
Ilium	0.73	$<2.2\ e^{-16}$
Pubis	0.56	$1.826\ e^{-12}$
Ischium	0.90	$<2.2\ e^{-16}$
Modified ilium	0.72	$<2.2\ e^{-16}$
Modified pubis	0.89	$<2.2\ e^{-16}$
Iliopubic complex	0.66	$9.096\ e^{-16}$
Ilio-ischial complex	0.65	$3.480\ e^{-15}$
Ischiopubic complex	0.91	$<2.2\ e^{-16}$
Complete coxal bone	0.61	$5.633\ e^{-14}$

classification for the *modified pubis* after the cross-validation was the highest of our study attesting of its high sexual dimorphism (92.38%). The modified pubis had a Mahalanobis distance value similar to that of the ilium. This feature has never previously been described in the literature. On 3D representation, the male pubis differed from the female: the symphyseal height was greater in men, and the symphyseal length shorter than in women. These features completely agreed with previous descriptions (15,28,49). The male ischiopubic length was shorter than the female, which also agrees with the classic physical anthropological literature (2–11,28,49). Including the ischiopubic ramus with the pubis increased highly its sexual dimorphism. Differences in orientation of the ischiopubic ramus were clearly visualized on 3D reconstructions of consensual shape. The female ischiopubic ramus appeared more horizontally and sagittally oriented than the male, and also tended to be longer than the male.

Although the *ischium* presented a sexual dimorphism, the results of the CVA, of the cross-validation, and of the Mahalanobis distance were the worst of the isolate bones and of our study. This weakness was surprising, as the ischium has previously been described as sexually dimorphic for the adult population, with male ischial lengths classically being longer than the female (what we also noted on the 3D representations) (50). We explained this result by the fact that the ischial length, which is classically the maximum distance from the acetabular point to the ischiatic tuberosity, was not comprised within our isolated ischial shape but was comprised within the ischiopubic complex (28).

Within these *bone complexes*, however, some appeared to be more dimorphic. Most adult sexual dimorphic bone complex was first the ischiopubic, followed identically by the iliopubic complex and the complete innominate, and the ilio-ischial complex. Some of our results agree with classic sex determination data (28). Steyn and Iscan have previously found that measurements of the *complete coxal bone* varied from 83.3 to 95.4% accurate to determine sex (28). In our case, the percentage of correct assignation was 100% after CVA and 87.62% after cross-validation. The consensus shapes (men or women) are intrinsically composed of all these differences of lengths or length ratios, and explain the high sexual dimorphism of the innominate. Globally, the innominate was higher and narrower in men and the greater sciatic notch was wider and deeper in women, which agrees with classic anthropological data (2–11).

Concerning the *ischiopubic complex*, Steyn and Iscan previously described the high accuracy for determining sexual dimorphism based on pubic and ischial measurements, with an accuracy that was calculated at 89.% (28). In our case, the percentage of correct assignation was 98.57% after CVA and 92.14% after cross-validation. In their 2D semi-landmarks study of the ischiopubic complex, Gonzalez found a similar percentage of correct sex assignation of 90.10% (17). It could be surprising that those percentages are quite similar because in theory, semi-landmarks bring more data than landmarks. We interpreted this by the fact that our data were based on 3D configurations and not 2D configurations. Morphological sex differences are better studied and visible in 3D mode. Of course, realization of 3D semi-landmarks could improve our results. Our results demonstrate the high sexual dimorphism of the ischiopubic complex. However, it is important to note that the addition of the ischium and the modified pubis (forming the ischiopubic complex) do not increase results obtained only by the modified pubis study, but do not dramatically decrease it, which could be suggested because of the weak ischial results in terms of sexual dimorphism. We observed differences in ischiopubic complex shape between the sexes, with an antero-posteriorly shorter ischiopubic complex for men, but higher than women. This also agreed with conclusions based on the classic ischiopubic ratio (4,15).

Our results concerning the *iliopubic* and *ilio-ischial complexes* were noteworthy. As far as we are aware, these complexes have not previously been described as sexually dimorphic. We found them to be less dimorphic than the previously described ischiopubic complex. However, the *iliopubic* complex, consisting of the superior and infero-anterior parts of the innominate, was as sexual dimorphic as the complete innominate, with correct sexual assignation after cross-validation of 87.62%. This result is not surprising because of the weak sexual dimorphism of the ischium in our study, which certainly reduces the performance of the innominate. The *ilio-ischial* complex, consisting of the superior and infero-posterior parts of the innominate, presented the worst accuracy percentage of the bone complexes in terms of correct sexual assignation (84.52%). This percentage was worse than the modified ilium percentage, probably decreased by the addition of the ischium, for same reasons previously explained.

Concerning the *static allometric* effects, our results demonstrated a strong linear relationship between PC 1 and CS, with PC 1 largely summarized size-correlated bones and bone complexes variations. We established that allometric scaling was present but not equal for all bones and bone complexes. The r^2 varied from 0.56 for the pubis to 0.90 and 0.91, respectively, for the ischium and the ischiopubic complex, but all the *p*-values were highly significant (<0.001). Those results indicated that it well represents aspects of static allometry common to all populations in this analysis.

We used 3D MSCT reconstructions and geometric morphometric analysis to evaluate sexual dimorphism in adult human coxal bones. Our results suggest that geometric morphometric analysis is an objective method revealing sexual dimorphism, which clearly quantifies classic osteological traits previously described and published, that are known to be difficult to assess objectively (17). Furthermore, some of our results summarized in Tables 3 and 4 are interesting, and our findings relating to the iliopubic and ilio-ischial complexes, which were sexual dimorphic areas, are new observations. We demonstrated the reliability of this method and determined areas with the greatest shape sexual dimorphism: the modified pubis followed by the ischiopubic complex, identically the iliopubic complex and the complete innominate, the pubis, the modified ilium, the ilio-ischial complex, the ilium, and finally the ischium. Inclusion of the ischial spine in the iliac shape analysis provided higher sexual dimorphism than the ilium alone. Inclusion of the ischiopubic ramus in the pubis shape analysis provided higher sexual dimorphism than the pubis alone, identical to that of the ilium alone. Although the isolated ischium was dimorphic, the results were weak. All our findings were in accordance with those of previous studies, but in addition they provide new data on sexual dimorphism. Further studies will be undertaken on more adults and also on immature populations. Moreover, dimorphism analysis of the innominate shape with 3D type III landmarks (semi-landmarks) will be an additional path of research (17). The use of clinical MSCT investigations for anthropological purposes, after validation of the methods applied, also opens new fields for anthropology. The number of subjects who could be studied by MSCT for anthropological purposes is potentially much greater than those available in the classic osteological collections and a worldwide virtual osteological collection could be created, rendering the concept of virtual anthropology more concrete (51,52).

Acknowledgment

Sincere appreciation is expressed to Nina Crowte for her assistance in the preparation of this manuscript.

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