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PAPER

ANTHROPOLOGY

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Virtual Determination of Sex: Metric and Nonmetric Traits of the Adult Pelvis from 3D Computed Tomography Models*,†

ABSTRACT: Examination of the adult os coxae and sacrum is one of the most common methods of sex estimation from bone. Medical imaging, such as computed tomography (CT), provides the opportunity for three-dimensional (3D) imaging of the skeleton from clinical scans of known individuals *in situ*. In this study, a randomly selected subset of abdominopelvic CT-derived models were used to evaluate simple, repeatable metric methods of sex estimation based on a combination of obstetric measurements and the traditionally nonmetric Phenice-derived traits. A four-variable discriminant function for sex estimation was developed based on statistical analyses. Overall, the cross-validated accuracy of this method was 100%, with inter-observer error showing an average of only 2.2%. Comparative analysis was run on the data set using FORDISC 3.0. This study shows that current sex determination standards from the pelvis should be updated to include more *in vivo* data to increase the accuracy of identification.

KEYWORDS: forensic science, forensic anthropology, sex estimation, pelvis, computed tomography, three-dimensional modeling, radiology, virtual anatomy, quantitative anatomy

The importance of developing accurate and reliable techniques for establishing the biological profile from human skeletal remains that meet the *Daubert* guidelines has been well documented (1,2). However recently, with an increased spotlight on the field of forensic sciences, there has been an international initiative toward developing higher standards through more quantitative, reproducible methodologies. In 2009, a congressionally mandated review of the forensic sciences undertaken by the U.S. National Research Council and U.S. National Academy of Sciences (NAS) found severe deficiencies in many of the subdisciplines and immediately issued a call for standardization of methods and reform of current practices (3).

Modern, documented skeletal collections are needed to supplement and improve upon the existing body of knowledge of both global and population-specific methods for sex discrimination. There are a few skeletal collections that are comprised primarily of individuals that were deceased in the last decade or even century. Notable exemptions include but are not limited to the Bass Collection, Maxwell Collection, Pretoria Collection, Athens Collection, and the Wichita State Cadaver Collection (4–8). Numerous studies have discussed the value of current reference samples (9–12). Without quantifiable data, there are obvious implications for the certainty with which even the most highly trained anthropologists can support their assessments in court. Recent studies have introduced novel methods for assessing sex in the pelvis but have focused on existing archaeological osteology collections (13–15). Only by introducing additional data sets that are representative of living subjects can we begin to improve the application of identification techniques.

Traditionally, anthropologists rely on established metric and nonmetric, observational analyses of the actual bone (4,16,17). Medical imaging modalities, like computed tomography (CT), are providing unique data sources for examining modern human variation in a more quantitative manner while extending osteological resources to researchers beyond actual contact (18). In the last decade, there has been a growing trend toward computerized (19) or virtual methodologies. These studies have shown an increase in accuracy and reproducibility over traditional linear methods in establishing a biological profile (20–22).

For the purposes of sex discrimination, it is widely noted that morphological techniques are simple and accurate above chance in correct classifications of most men and women; however, this is highly reliant on the experience level of the observer (23). Numerous attempts at metric classification have been published, but often require complex or time-consuming measurements (24–30). In nonmetric sex estimation of the pelvis, the evaluation is focused on Phenice-defined traits of specific regions of the innominate: ventral arc, subpubic concavity, and ischio-pubic ramus (23,31–36) and may include additional scored traits as well as the morphology of

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the greater sciatic notch. However, while nonmetric methods are a quick means of assessment, they tend to be extremely subjective. Attempts have been made to "metricize" or quantitate nonmetric traits with success (37) in other regions of the body. By "metricizing" specific nonmetric traits in the pelvis, more objective data for sex estimation should be possible and repeatability should increase. Other pelvic indices such as those used in clinical medicine can be used to supplement measurements in the anthropological literature. Medical fields like obstetrics and gynecology regularly use metric measurements of the pelvis in their assessment and treatment of patients (38–40).

This study was undertaken to investigate whether three-dimensional (3D) volumetric virtual models can be used in the estimation of sex from the pelvis and if they can, whether "metricizing" nonmetric sex estimation traits in the pelvis and utilizing current medicine indices will increase the accuracy and reliability of the data over current methods. A sample of pelves from 100 modern, living individuals was evaluated for sex using standard and novel measurements. The study was comprised of a number of elements: (i) landmarking and measurement of the sample; (ii) metric evaluation of inter-observer landmarking error; (iii) inter-observer error using traditional Phenice-derived sex estimation techniques; (iv) discriminant function analysis to predict sex; (v) comparison of sex estimation results from FORDISC 3.0 (41) and this study; and (vi) a preliminary evaluation of untrained observer accuracy.

In light of the recent NAS report (3), it is important to scrutinize current and future practices to ensure that they are robust. By studying individuals contemporaneous with those likely to end up on the anthropologist's examination table, this study attempts to provide data that can lead to more accurate biological profiles of unknown decedents.

Materials and Methods

Clinical Pelves Radiological Scans

For the purposes of this study, a random selection of abdominal CT scans taken of patients (Figs 1 and 2) at the University of South Florida College of Medicine was used per institutional approval. The clinical data were anonymized at the source and collected with informed patient consent.

A total of 100 individuals with known demographics and complete os coxae and sacra were evaluated to test the virtual determination of sex. The age range was 19–83, with a mean age of 49.7 (median 50). The sex distribution for calibration sample was 40 men and 60 women. The average age of the men is 52.8 (range 19–80) and the average age of the women is 47.6 (range 20–83). When selecting the study participants, individuals with large surgical prosthesis, such as hip replacements, were excluded from the study as the implants cause artifacts or "flares" to appear on the DICOM images that occlude the acetabulum and distort other portions of the pelvis. The age and sex information was withheld from the observers during the measurement phase.

3D Computer Reconstruction

Detailed 3D skeletal models were visualized from the DICOM slice data using *Mimics* v 13.1 (Materialise, Leuven, Belgium) (Figs 3 and 4). The original DICOM data were set at a slice thickness of 1.25 mm. A mask was created to select for the bone pixels, and thresholding was adjusted to account for individual variation in bone density. The resultant pixel masks from the transverse (axial), coronal, and sagittal planes were converted to voxels by the software to produce a 3D bone model of the selected region(s) of the skeleton. For older individuals with marked osteoporosis, the threshold was manually entered to account for individual variation in bone density. Pixels from the femora were not selected to allow for observation of the acetabulum. These models can then be measured in *Mimics* or exported into most other 3D packages for further analyses. Accuracy of the virtual models has been verified in previous studies by the authors and other researchers (20).

Virtual Sex Estimation: Osteological Measurements

A selection of both traditional and novel measurements was chosen for use in establishing sex in the pelvis. Decades of literature have demonstrated that features of pelvic morphology such as ventral pubic arc, subpubic concavity, width of the greater sciatic notch, presence/absence of the preauricular sulcus, and the medial aspect of the ischiopubic ramus are highly successful in correct sex classification by trained observers (13,14,23,32–34). However, correct classification suffers using less experienced observers. For this

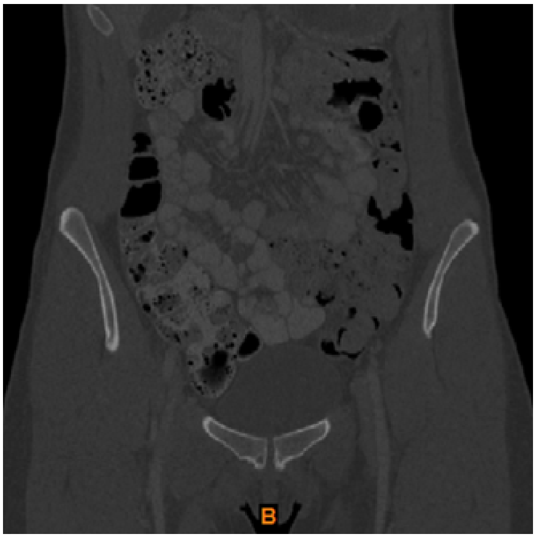

FIG. 1—*Image of a pelvic CT scan in the coronal view.*

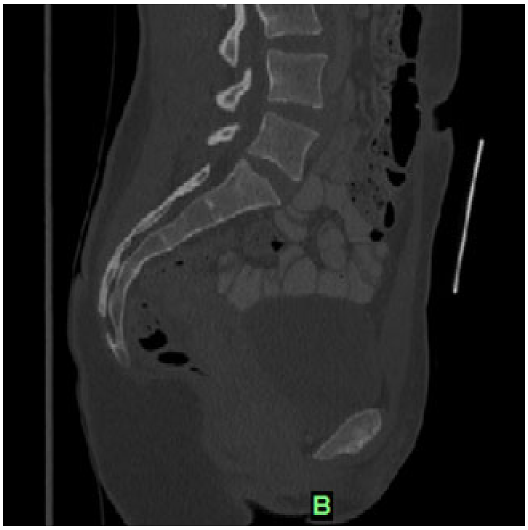

FIG. 2—*Image of a pelvic CT scan in the sagittal view.*

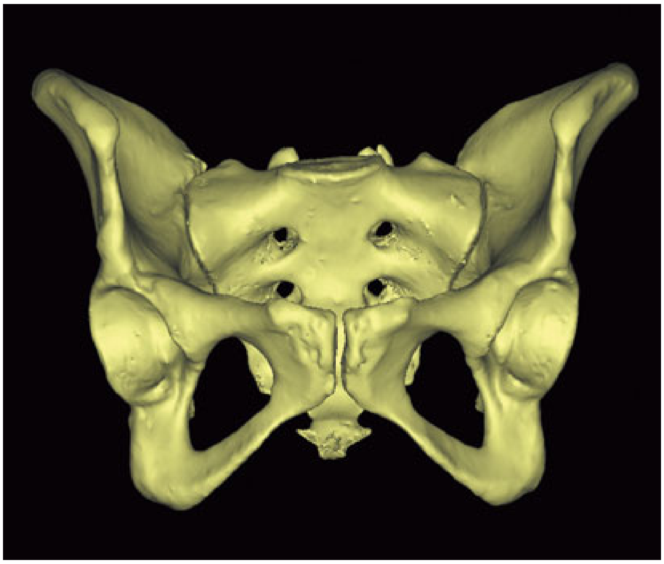

FIG. 3—*A virtual image of the pelvis created from CT data in the anterior view.*

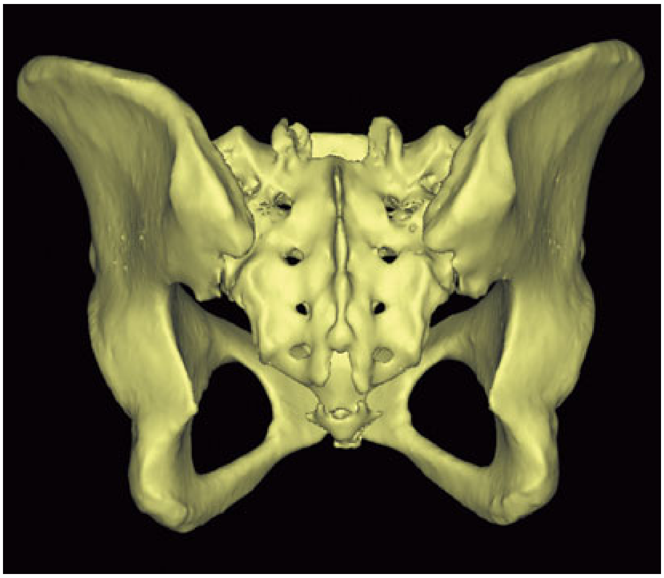

FIG. 4—*A virtual image of the pelvis created from CT data in the posterior view.*

study, the measurements for the calibration sample were chosen to meet one or more of the following criteria: a commonly used measurement reported in the literature (e.g., ischium-pubic index); a "metricized" version of a traditional nonmetric trait (e.g., greater sciatic notch and subpubic angle); or medical indices not traditionally applied to anthropology (e.g., conjugate inlet of true pelvis). A total of 35 landmarks (five midline and 15 bilateral) were placed on each pelvis. Landmarks were located and marked by two trained anthropologists. Definitions are listed in Table 1. From these, 20 distances, angles, and anthropological and medical indices were calculated. The 20 variables listed in Table 2 were tested for their effectiveness in sex estimation.

An osteometric toolkit was designed for landmark placement in the *Mimics* software package (Fig. 5) that allowed the researchers to examine the 20 variables. The observer would simply need to place a landmark at a location defined both in the handbook and in the toolkit itself. The software then calculates linear distances, angles, and indices between specified points. These data are output in a format ready for use in statistical analysis packages.

TABLE 1—*List of landmarks with definitions.*

Landmark	Definition
Midline points	
Coccyx	Most extreme tip of the coccyx
S pubic symphysis	Point at the most superior portion between both pubic symphyses (mark on left—this will be a near duplicate of anterior superior left pubic symphysis)
SCB	Mid-sagittal point on sacral/coccyx border
Sacral promontory	Most superior, anterior point on the mid-sagittal plane
I pubic symphysis	Point at the most inferior portion between both pubic symphyses—*place on the left pubic symphysis*
Bilateral points	
AS pubic symphysis	Most anterior superior point on the symphyseal surface
ASIS	Anterior superior iliac spine
Acetabulum junction	Junction of ilium, pubis, and ischium in the acetabulum
Greater sciatic notch	Deepest point in the GSN
Ischial spine	Ischial spine (base of greater sciatic notch)
Ischial tuberosity	Most inferior point on the ischial tuberosity
Ischiopubic ramus	Lowermost point on the left ischiopubic ramus
Lower pubic symphysis	Most inferior point on the symphyseal surface
PI iliac spine	Most inferior spine on the ilium at the greater sciatic notch
PSIS	Posterior superior iliac spine
Sacral width	The superior portion of the sacrum at its widest point
Sacro-lumbar articular surface	Most lateral point on the superior articular surface between the sacrum and lumbar vertebrae
Sup iliac crest	The most superior point on the iliac crest
Pelvic inlet	Most mediolateral point of the ischium, looking superior to inferior the most lateral points on the interior of the pelvic brim
Pelvic outlet	Most mediolateral point of the ischium, looking inferior to superior

Statistical Analysis

Data collected for this study were analyzed in the software package, SPSS version 18.0 (IBM, Somers, NY). To begin the analysis, measures of central tendency and descriptive statistics (mean, median, standard deviation, etc.) were run to check for any errors in the data. Table 3 provides the mean values and standard deviations for all 20 variables across the sample of 100 individuals. A test of inter-observer error was conducted to verify the repeatability and accuracy of the landmark placement and definitions of the novel measurements. A subset of 10 pelves from the original calibration sample was landmarked by two trained anthropologists (authors SJD and SLD-J). The two observers were in separate locations at the time of landmarking and did not confer during the landmarking sessions. A Cohen's Kappa coefficient was also calculated to determine the level of agreement between observers (Table 4).

TABLE 2—*Measurement descriptions.*

Measurement	Type	Landmark Calculation
Anterior breadth of the sacrum	Distance (mm)	Maximum transverse projection of the sacrum at the anterior projection of the auricular surface
Anterior height of sacrum	Distance (mm)	Distance between the sacral promontory and sacral/coccyx border
Anteroposterior pelvic outlet diameter	Distance (mm)	Distance from coccyx to inferior pubic symphysis
Conjugate pelvic inlet diameter	Distance (mm)	Distance between sacral promontory and superior pubic symphysis
Pubic symphysis length	Distance (mm)	Distance between the most superior and inferior points of the pubic symphysis (taken at left side)
Sub pubic angle	Angle (degrees)	Angle between the iliac spine, deepest portion of the greater sciatic notch and the ischial spine
Transverse diameter of sacral segment 1	Distance (mm)	Distance between the two most lateral points of the first sacral segment
Transverse pelvic inlet	Distance (mm)	Widest medio-lateral points on the plane created by the sacral promontory and the most superior point of the pubic symphysis
Transverse pelvic outlet	Distance (mm)	Widest medio-lateral points on the plane created by the coccyx and the most inferior point of the pubic symphysis
Bilateral measurements		
Iliac breadth	Distance (mm)	Distance from the anterior to the posterior superior iliac spine
Ischium length	Distance (mm)	Distance from the acetabulum junction to the deepest point on the ischial tuberosity
Pubis length	Distance (mm)	Distance from the point on the acetabulum junction to the superior point on the pubic symphysis
Width of greater sciatic notch	Angle (degrees)	Angle between the iliac spine, deepest portion of the greater sciatic notch, and the ischial spine
Innominate height	Distance (mm)	Distance from the most superior point on the iliac crest to the most inferior point on the ischial tuberosity

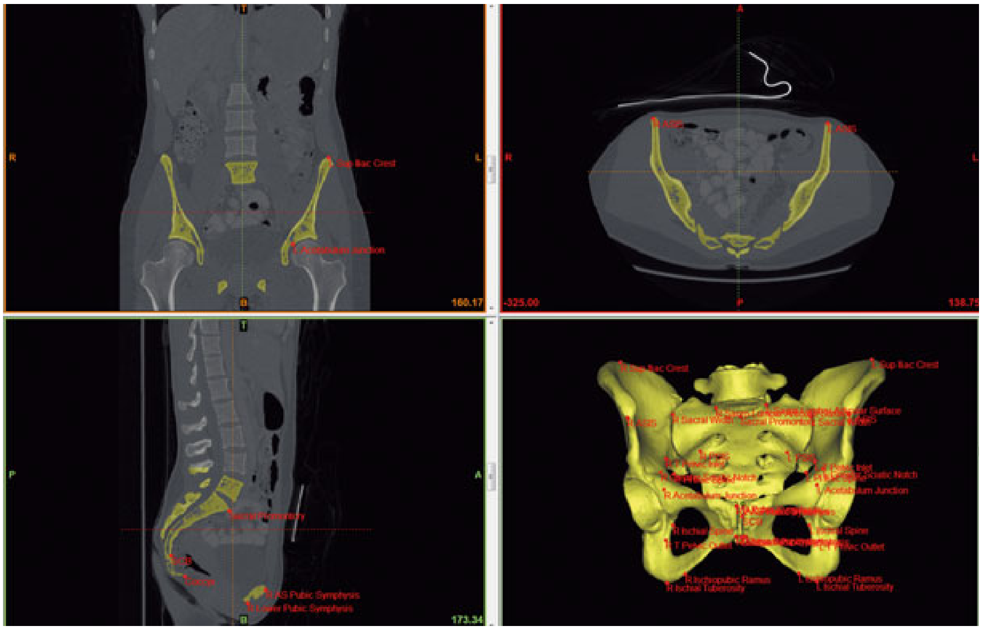

FIG. 5—Mimics *user interface highlighting the 35 landmark points used for pelvimetric assessment indicated on the 2D pelvic mask as well as on the 3D model.*

A Pearson's correlation test was performed to determine which of the variables were the highest predictors of sex. From the correlation study, the four variables with the highest influence were innominate height, greater sciatic notch angle, subpubic angle, and transverse pelvic outlet. These four represented a combination of both anthropological and medical variables. A binary logistic regression was performed using these four variables with men coded as 0 and women coded as 1. This regression was used to develop the four-variable formula for sex estimation. Once the variables were identified, a discriminant function was performed on the four variables to establish cross-validated classification results.

A group of further individuals not included in the calibration sample was landmarked to verify the robustness of the calibration sample findings. This test group consisted of two men and three women, with an age range of 37–54 (mean 48.6). A leave one out cross-validation test was run to determine the robusticity of the results on a holdout sample.

FORDISC 3.0 Analysis

To compare our results to the current field standard, the data were run through the software package, FORDISC *version 3.0*

TABLE 3—*Measures of central tendencies.*

Variable	Measurement Name	Male (Mean)	Male (SD)	Female (Mean)	Female (SD)
ABS	Anterior breadth of the sacrum	116.67	8.89	115.59	7.24
AHS	Anterior height of sacrum	114.22	16.17	109.75	11.24
APOD	Anteroposterior pelvic outlet diameter	104.78	13.09	108.00	11.28
CPID	Conjugate pelvic inlet diameter	119.60	11.71	126.76	8.65
LIB	L iliac breadth	164.85	11.58	155.28	8.55
LIL	L ischium length	95.59	7.58	83.29	5.80
LPL	L pubis length	91.62	8.23	90.67	7.22
LGSN	L width of greater sciatic notch	69.69	8.15	80.70	6.02
LIH	Left innominate height	220.10	13.63	193.04	12.04
PSL	Pubic symphysis length	35.41	4.93	29.87	4.17
RIL	R ischium length	96.46	7.27	83.42	4.77
RPL	R pubis length	89.73	8.81	89.28	8.41
RGSN	R width of greater sciatic notch	68.05	8.02	80.29	6.97
RIB	Right iliac breadth	164.91	12.03	155.49	8.88
RIH	Right innominate height	220.19	14.07	193.20	10.70
SPA	Sub pubic angle	71.37	7.75	82.94	5.72
TDSS	Transverse diameter of sacral segment 1	55.74	6.31	48.83	6.08
TPI	Transverse pelvic inlet	122.34	8.69	130.13	9.26
TPO	Transverse pelvic outlet	100.83	7.13	118.36	9.12
LIPI	L IschPub Index	96.04	7.38	109.15	9.07

All measurements in mm or degrees.

(41). In FORDISC, there are seven variables measured on the os coxae and sacrum with published levels of accuracy. They are sacral length, sacral breadth, sacral breadth at segment 1, innominate height, iliac breadth, pubic length, and ischial length. Results for this portion of the study were compared back to the formula established in the previous portion.

Results

3D Modeling and Virtual Measurements

From the import of the DICOM images to output of the data, the time taken for each specimen was dependent on the type of computer used and the observer's experience and familiarity with the software. The import of the images and the making of the model took approximately 20 min per case. The landmarking and measurements took approximately 10–15 min per case.

Sex Assessment

To establish which measurements were best in assessing sex in the pelvis, averages for the measurements were calculated for each sex. Table 3 displays the averages of each variable used in the study broken down by sex.

In the inter-observer error test, the results of 10 measured specimens from each anthropologist were compared. The error rates ranged from 0.51% to 4.21%. The overall error average between both observers was only 2.22%, which is well below the accepted range of error (23). Table 4 demonstrates the error ranges by variable. The calculated Cohen's Kappa coefficient was determined to be 1.0, which indicates an almost perfect agreement between observers that is not a result of chance.

The Pearson correlation test listed which variables indicated the highest influence on sex estimation. Eleven of the 20 original variables were determined to be statistically significant at the 0.01 level of a two-tailed test. The variables with the highest loadings were selected and narrowed down to innominate height, greater sciatic notch angle, subpubic angle, and transverse pelvic outlet. The Pearson's test demonstrated strong correlations between measurements that were bilateral. Comparisons were made between both left and right innominates, and the variation was found to be negligible. Therefore, only the left side of the pelvis was used for the statistical model to prevent any duplication or artificial inflation of the results.

The binary logistic regression provided a four-variable formula that was useful for calculating sex from pelvis. For this formula, each sex was coded as men = 0 and women = 1. The formula for estimating sex from the pelvis in this study is listed in Table 5. For the calibration sample, the accuracy for the formula was 100% in both men and women with a *p*-value of 0.001 (Table 6). The canonical discriminant function run on the calibration data set had a 100% cross-validated group classification accuracy rate also with a *p*-value of 0.001. Results are shown in Table 7.

The leave one out cross-validation test was run on the five specimen sample that had not been included in the calibration sample. The method resulted in a 100% accuracy classification rate for the specimens.

For the FORDISC portion of the study, all the specimens in the calibration sample were run in the software for all seven variables that are used in the sacral and os coxae analysis. The results showed that the male specimens were correctly classified 67.50% of the time and the women were classified 98.30% of the time. Overall, the FORDISC analysis correctly classified the specimens' sex approximately 86% of the time (Table 8).

The overall accuracy of our model was 100% and indicates an increase in accuracy over current anthropological methodologies. Further studies are needed to confirm these findings using a larger sample of observers.

Discussion and Conclusion

This study demonstrates that it is possible to estimate sex accurately (100% with a *p*-value of 0.001) in 3D virtual pelvic models derived from CT scans. Medical image data provide the opportunity for high-end forensic analysis to be conducted outside the usual confines of traditional anthropological procedures. Imaging modalities such as CT are extensively used in the diagnosis and treatment of patients in a clinical setting. Their reliability has been well documented for years through radiological research. 3D imaging has tremendously expanded in the past few years with increases

TABLE 4—*Measurement error.*

Variable	Measurement Name	Error (Mean), %	Error (SD), %
ABS	Anterior breadth of the sacrum	1.55	1.61
AHS	Anterior height of sacrum	1.58	2.26
APOD	Anteroposterior pelvic outlet diameter	3.10	2.00
CPID	Conjugate pelvic inlet diameter	0.87	0.72
LIB	L iliac breadth	1.12	1.37
LIL	L ischium length	3.93	2.23
LPL	L pubis length	4.21	2.51
LGSN	L width of greater sciatic notch	1.90	1.74
LIH	Left innominate height	2.16	1.30
PSL	Pubic symphysis length	3.48	2.30
RIL	R ischium length	3.07	2.28
RPL	R pubis length	2.90	1.84
RGSN	R width of greater sciatic notch	2.05	1.73
RIB	Right iliac breadth	0.51	0.37
RIH	Right innominate height	2.18	1.78
SPA	Sub pubic angle	3.53	2.44
TDSS	Transverse diameter of sacral segment 1	2.00	1.26
TPI	Transverse pelvic inlet	0.80	0.56
TPO	Transverse pelvic outlet	1.22	1.08
Average N = 10	2.22%		

TABLE 5—*Four-variable model for sex estimation.*

$$\text{Sex} = (0.859 \times \text{LGSN}) + (-1.799 \times \text{LIH}) + (3.867 \times \text{TPO}) + (1.786 \times \text{SPA}) - 244.41$$

Sex, >0 individual is female, <0 is male.

TABLE 6—*Accuracy of four-variable method.*

Accuracy of Four-Variable Method		
Male	40/40	100%
Female	60/60	100%
Total	100/100	100%

TABLE 7—*Four-variable cross-validation test.*

		Classification Results[*,†]		
		Predicted Group Membership		
	Sex	0	1	Total
Original				
Count	0	40	0	40
	1	0	60	60
%	0	100.0	0.0	100.0
	1	0.0	100.0	100.0
Cross-validated[‡]				
Count	0	40	2	40
	1	0	60	60
%	0	100.0	0.0	100.0
	1	0.0	100.0	100.0

[*] 100.0% of original grouped cases correctly classified.

[†] 100.0% of cross-validated grouped cases correctly classified.

[‡] Cross-validation is done only for those cases in the analysis. In cross-validation, each case is classified by the functions derived from all cases other than that case.

TABLE 8—*Accuracy of FORDISC 3.0 method.*

Accuracy of FORDISC		
Male	27/40	67.50%
Female	59/60	98.30%
Total	86/100	86%

in scanner technology. This study utilized medical image data from state-of-the-art 64-slice CT scanners which are quickly becoming the field standard. These scanners are capable of scanning a full body in less than 1 min at a high-resolution slice (0.625 mm). With CT's speed and its ability to capture high-level detail of boney features without having to remove soft tissue, it becomes an ideal tool to save time and to protect remains from physical manipulation. Remains can be examined without the need for defleshing.

Additionally, current studies are showing that medical imaging and modeling are allowing for remote analyses without assuming chain of custody of the evidence (18). This permits local and federal law enforcement agencies to securely transfer data and have access to experts beyond their geographic location. Forensic pathologists are now using medical imaging, 3D modeling, and specialized biopsies to supplement the traditional autopsy in a process called "Virtopsy." These methods also allow for the archiving of case-related data that can be used long past when the remains have been buried (42).

The speed with which the virtual bone models and measurements were generated (20–30 min per case) in this study makes the method a practical alternative to traditional analyses. Our interobserver error test results illustrate the accuracy and repeatability of the method by trained anthropologists. However, beyond accuracy, it is important for new methods of analyses to be accessible enough to be used by practitioners at different levels of training. To investigate this, a preliminary user-friendliness study with student users was conducted with positive initial results. Three upper-level undergraduate students at Liverpool John Moores University who had completed a course in osteology were recruited to explore the impact of experience on our virtual method. None of the students had ever used the software before the test. Each student was independently provided with the same unknown virtual pelvis and training manual. The students were first asked to assess the pelvis using traditional nonmetric traits. The results showed differences between each observer using traditional nonmetric observations. For example, the greater sciatic notch was scored by the students between 2, 3, and 4. Although there were differences in the scorings, each student classified the pelvis correctly. Next, the students were asked to landmark and measure the virtual pelvis using the method outlined in this study. The results could be directly compared and were reasonably accurate with a higher error rate than with the trained observers. While this method was proven to be reproducible for trained practitioners, it is highly recommended that users have training in both forensic anthropological and radiological methods. Future studies may expand the number of observers to test the impact of experience more fully.

This study also highlights the effectiveness of "metricizing" nonmetric traits. Phenice traits in the pelvis have been shown to be significant in the estimation of sex. However, in answering the congressional call for more quantifiable methods in forensic science, "metricizing" nonmetric traits allows researchers to move away from subjective scored (on a scale of 1–5) analyses toward more objective methodologies. The four-variable formula derived in this study illustrates the strength of combining "metricized" traits with medical indices, such as the transverse pelvic outlet. We found that traditional anthropological literature differed from current medical standards in the areas of subpubic angle and pelvic outlets. These discrepancies made a significant difference in the successful classification of sex in our calibration sample. When analyzing the subpubic angle, it is recommended by anthropologists that any pelvis <90° is male (24); however, this study found that a large portion of the women would have been misclassified as men if this standard was followed. The angles in the study for women were found to be closer to 78–83°; this assertion is also reflected in current obstetric literature (38–40).

In FORDISC 3.0 (41), skeletal remains are classified using numerous osteological metric variables. For the innominate and sacral complex, there are seven variables that the software uses to estimate sex. These variables are based on metric measurements that do not completely characterize the unique 3D geometry of the pelvic anatomy needed to distinguish between the sexes. While overall in our study FORDISC correctly classified the specimens' sex approximately 86% of the time, the results showed that the male specimens were only correctly classified 67.50% of the time. It is suggested that this discrepancy in classification rates is attributed to either too much "noise" introduced by the seven variables used by FORDISC 3.0 or the lack of consideration of nonmetric variables. By adding "metricized" nonmetric traits and current medical indices into our four-variable formula, the authors hypothesize that classification rates for sex in the pelvis will increase.

This subsequently brings into question, how does our data set differ from traditional skeletal collections and thus current field data sources? The samples used in this study were a 100% modern population from clinical patients scanned at the University of South Florida College of Medicine. Most anthropological samples are skewed toward older adults because of availability in current collections; however, it has been reported that elderly individuals demonstrate less sexual dimorphism (8,36), so it is theorized that the method for successful sex discrimination in this sample is more robust as they represent a larger sample of younger individuals with wide overall age range (19–83 years). Furthermore, most anthropological osteology collections are archaeological or historical in nature and therefore do not currently best represent the remains that are most common in forensic cases.

One potential limitation of this study is that we used complete, intact pelves. We acknowledge that unlike our data set, in many cases the remains examined in an anthropological setting may be incomplete or fragmented. By utilizing additional aspects of the 3D software in which the remains are measured, fragmented remains can be reconstructed in virtual space. Additionally, the study reveals that the most important characteristics in sex discrimination in this population (innominate height, greater sciatic notch angle, subpubic angle, and transverse pelvic outlet) require only the presence of one innominate and the sacrum.

To increase the value of data sets like the one utilized in this study, more information should be gathered such as ancestry of the patient. The anonymized patient data did not include the patient's ancestral background so it is unclear at this time what role, if any, race played in the classification of sex of this calibration sample. By collecting more clinical data, we will be able to better understand patterned phenotypic variation in modern human populations.

In summary, the establishment of the biological profile (age, sex, stature, and ancestry) from human remains is at the core of the forensic anthropologist's training and practice. This study demonstrates the value of CT data for making detailed virtual models of the pelvis that can be analyzed beyond contact with the actual bone. From these 3D models, a novel, accurate formula for sex estimation was developed using "metricized" nonmetric traits and medical indices. The proposed method in this study represents a quick, reliable alternative to traditional anthropological methodologies used in establishing sex from the pelvis.

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