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The frontal bone as a proxy for sex estimation in humans: a geometric morphometric analysis

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THE FRONTAL BONE AS A PROXY FOR SEX ESTIMATION IN HUMANS: A
GEOMETRIC MORPHOMETRIC ANALYSIS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Anthropology

in

The Department of Geography and Anthropology

By Lucy A. E. Hochstein
B.A., George Mason University, 2009
May 2014

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ABSTRACT

Physical anthropologists have a toolkit for determining sex from skeletal remains composed of visual and metric techniques concerning the pelvis and the skull. However, complete elements are not always available and results can be indeterminate. The present study combines visual assessment of the skull with statistical methods of shape analysis, geometric morphometrics, to reach a better understanding of how cranial variation of the frontal bone is influenced by sex. The three-dimensional coordinates of frontal bone curvatures of 204 skulls from the Terry Collection were collected using a Microscribe digitizer. These data were used to assess the ability of this technique to estimate sex. Results of a Procrustes distance analysis of variance (ANOVA) suggest that variation in frontal bone curvature is explained best by sex compared to variables of ancestry and visual score. A discriminant function analysis (DFA) cross-validation test of sex classification showed the DFA correctly assigns frontal bones as female with 88.3% accuracy and males with 70.4% accuracy. These results suggest that this technique may be useful in future sex estimation software.

CHAPTER 1. INTRODUCTION

Sexual dimorphism has been an important pursuit in physical anthropology research for many years. The ability to classify sex in anthropology gives a picture of the demographic composition of a past culture, can give information about warfare, and helps develop other theories of archaeological importance. In forensic anthropology, sex estimation is extremely important in finding the identity of decedents. General differences in size and robusticity and specific morphological traits in the skull and postcranium indicate the sex of skeletal remains. These general features and specific traits have been researched, and the classification criteria established, based on visual and metric observations. However, quantifying sex estimation can be difficult as variation exists on a continuum, not separated by distinct boundaries.

Accuracy rates for sex estimation vary according to which elements are used. In the postcranium, Phenice (1969) developed a set of three visually assessed morphological features of the pelvis that estimate sex with 95% accuracy. Also, a combination of measurements of 12 postcranial elements yields 92-94% accuracy (Spradley and Jantz, 2011). In the skull, sex estimation is primarily based on size, because female skulls are generally smaller and more gracile than male skulls (Krogman, 1962). Metric sex estimation based on a discriminant function analysis of eight measurements from the cranium alone is between 90-91% accurate (Spradley and Jantz, 2011). Although the accuracy of cranial sex estimation has been found to be fairly high in some studies, the reliability and repeatability of visual assessments are not absolute (Giles and Eliot, 1963). Geometric morphometric analysis presents a way to metrically classify groups based on shape, not linear measurements.

The frontal bone of the cranium has three morphological features used to estimate sex: prominence of glabella and the supraorbital ridge, sharpness of the supraorbital margin, and angle of the forehead (Hrdlička, 1920; Keen, 1950). Although variation exists due to ancestry (Krogman, 1962; Walker, 2008; SWGANTH, 2010) and age (Walker, 1995; Burns, 2009), the first two of these features are well established in standard physical anthropology methodologies (Buikstra and Ubelaker, 1994; Bass, 2005). The present study combines visual assessment of the skull with statistical methods of shape analysis, geometric morphometrics, to reach a better understanding of how cranial variation of the frontal bone is influenced by sex. Additionally, these data were used to assess the ability of this technique to classify sex based on a single curve collected from the midline of a human frontal bone.

CHAPTER 2. LITERATURE REVIEW

Study of sexual dimorphism in the human skeleton as a means to estimate the sex of an individual has a long history in physical anthropology. The pelvis and the skull are the main regions of interest in research and forensic applications. The former is the most sexually dimorphic area in the skeleton and the latter has traditionally been considered the second most accurate area for morphological sex estimation (Bass, 2005). However, recent analysis of combined measurements of postcranial elements, not including the pelvis, yields up to 94% accuracy, compared to 90-91% using skull measurements (Spradley and Jantz, 2011). Previous metric studies of the skull consider prominence of the brow ridge of the frontal bone to be important in sex estimation (Rosas and Bastir, 2002; Walker, 2008; Garvin and Ruff, 2012; Shearer et al., 2012); yet, few studies address the overall contour shape of the frontal, from nasion to bregma. Different methods of classifying frontal bone shape in modern sex estimation and metric studies of cranial shape variation will be discussed below.

Morphological Sex Estimation

Estimation of sex from the frontal bone is dependent upon size and prominence of two features: supraorbital ridge and the glabellar region (Hrlicka, 1920; Krogman, 1962; Acsádi and Nemeskéri, 1970; Buikstra and Ubelaker, 1994; White, 2000; Rosas and Bastir, 2002; Bass, 2005; Walker, 2008; Garvin and Ruff, 2012; Shearer et al., 2012). Glabella is the most anteriorly projecting point on the frontal bone, located in the midline between the supraorbital ridges (Hrdlička, 1920). The supraorbital ridges, also called superciliary arches, are the bony ridges directly above the eye orbits (Hrlicka, 1920; White, 2000). In this paper, “brow ridge” will be used to describe the combination of the glabellar region and the supraorbital ridges.

Visual assessment of the frontal bone had an early start in physical anthropology. In 1920, prominence of the supraorbital ridge was classified as “traces,” “slight,” “moderate,” “pronounced,” or “excessive” (Hrdlička, 1920). Male supraorbital ridges were said to range from “moderate” to “excessive” and, in females, from “traces” to “moderate” (Hrdlička, 1920). By 1950, the female frontal bone was described as being “wider and ris[ing] more steeply” than the male frontal bone (Keen, 1950:66). Of the two areas, size of the supraorbital ridges is a more reliable classification of sex than prominence at glabella due to the greater variation between males and females at glabella (Krogman, 1962).

Multiple studies have found variation in the curvature and angle of the forehead based on sex. Woo (1949) and Krogman (1962) elaborated on sexual dimorphism by classifying the curvature of the forehead. Males have “steeper, less rounded” frontal bones while females have “rounded, full, infantile” frontal bones (Krogman, 1962:192) that are more curved than in males (Woo, 1949). The frontal eminences, bosses in the frontal bone located superiorly to the brow ridge (White, 2000), are said to be large in females and small in males (Krogman, 1962). A later study by Russell and colleagues (1985) found variation in the angle of the forehead. From 140 Australian Aboriginal crania, they found that female frontal bones tended to be more vertical while males had “very angled faces with receding foreheads” (Russell et al., 1985:348). Later researchers have not investigated forehead contour for sex estimation, but have developed scoring methods of the brow ridge and estimates based on overall cranial measurements (Buikstra and Ubelaker, 1994; Walker, 2008; Steckel et al., 2010). Considering these studies were completed on different continents, investigation into the implications of ancestry is worthwhile. Krogman (1962) found that frontal bone morphology varies by ancestry. The

“frontal contour” of black individuals is more rounded, while in white individuals, the frontal bones “have a steeper frontal curve” (Krogman, 1962:274).

Metric Sex Estimation

Visual sex estimation methods have been complemented by the emergence of metric techniques. Giles and Elliot (1963) discussed the need for metric techniques due to the variation in visual cranial sex estimates by experienced physical anthropologists. To address this concern, Giles and Elliot (1963) developed a set of multivariate discriminant functions from 11 cranial measurements of black and white skulls to determine the probability that an individual skull would be classified as male or female. Resulting accuracy rates ranged between 82% and 89% within a known population of black and white individuals and 89.4% in a test on 85 chimpanzees. Additionally, Giles and Elliot (1963) tested their discriminant functions on a historic Irish population and three prehistoric Native American populations with visually assessed sex estimates. Although the functions were able to discriminate between sexes in these different populations, the accuracy increased with population-specific sectioning points.

Another important development in sex estimation occurred with the creation of FORDISC 1.0 in 1993 by Ousley and Jantz (Ubelaker, 1998). FORDISC is a computer program widely used among forensic anthropologists in the United States that provides a metric alternative to morphological assessments of sex and ancestry. Discriminant functions based on various populations from around the world give the probability that an individual fits within specific sex or ancestry groups (Ousley and Jantz, 2006). Although FORDISC allows for much greater ease in quantifying sex assessments in the United States, applicability in European populations for sex assessment has not been as successful. Ramsthaler and colleagues (2007)

found that 86% of individuals in a German forensic collection were classified correctly using FORDISC compared to 94% from a visual scoring method.

While 86% is better than chance, a study applying FORDISC to French and Thai samples found accuracy in sex estimation to be 55.6% (Guyomarch and Bruzek, 2011). Accuracy increased when ancestry group selections were made. The sex assessment of the French sample increased to 89.3% when the white group was selected, while the Thai sample became 60.7% when the Asian groups were selected. Discriminant functions in FORDISC are based on measurements of approximately 3,400 individuals from the Forensic Anthropology Data Bank, composed of skeletal material from the United States, China, Japan, Guatemala, Central America, Mexico, and Vietnam (Forensic Anthropology Center, n.d.; Jantz and Ousley, 2005) and 2,504 human crania from 28 countries in the Howells dataset (Howells, 1996). Considering the large number of populations utilized in FORDISC, the European and Thai tests indicate the importance of studying sexual dimorphism within populations. The ability to support a morphological sex assessment with “generally accepted” statistical accuracy in forensic cases is important for presentation of evidence in court (Wiersema et al., 2009).

Scoring Techniques

Quantification of sexual dimorphism in the frontal bone also has taken the form of a categorical scoring method that assigns numbers to the degree of prominence at glabella. This method was first introduced by Acsádi and Nemeskéri (1970), but became standardized in Buikstra and Ubelaker’s Standards for Data Collection (1994) and later by Steckel and colleagues (2010). In this method, examining the skull from a lateral view, the outline shape of the frontal bone is scored from one through five: one being almost flat at glabella (i.e., female)

and five, protruding (i.e., male) (Buikstra and Ubelaker, 1994). The skull is held up and compared to a line drawing featuring typical expressions of each of these scores.

Walker (2008) applied a discriminant function analysis to the cranial scoring method for sex estimation. He tested the accuracy of individual and combined traits, including “nuchal area,” “orbital margin,” “glabellar area,” “mastoid process,” and “mental eminence” on 304 individuals from multiple collections. He found that classifying sex based on the glabellar area alone resulted in the greatest univariate logistic regression accuracy of 82.6%. When all five cranial traits were combined, accuracy increased to 90.1% in the quadratic discriminant model (Walker, 2008). These studies illustrate that morphological traits, especially the brow ridge, can be quantified and used to produce useful sex classification boundaries.

Geometric Morphometrics

To address the issues of objective morphological sex assessment and quantification of sex through flat measurements, the current study will utilize geometric morphometrics. Geometric morphometric analyses allow shape to be quantified using a set of points, called landmarks. The relationship between these points in a specimen can be statistically compared to other specimens of similar shape and size. Multivariate statistics then are used to investigate group differences (Bookstein, 1991). Additionally, geometric morphometrics has a visualization component that allows researchers to present statistical shape variation, not only in number tables, but also as combined pictures that show the variation between individuals and groups (Bookstein, 1991, 1997; Bookstein et al., 1999; Rosas and Bastir, 2002; Shearer et al., 2012). Considering the importance of frontal bone shape in sex estimation, this visualization component has potential for recognizing population variation and increasing accuracy.

In anthropology, geometric morphometrics has been used in the quantitative analysis of hominin skull morphology to study growth and evolution. Bookstein et al. (1999) used CT scans of five Neanderthal crania and 16 modern humans to capture outline data of the inner and outer table of the frontal bone for comparison. They placed a series of semilandmarks and landmarks around the exterior and interior of each skull, creating an outline of each skull. Multivariate statistical analyses were conducted to determine the areas of greatest variation between the two groups. Resulting graphs of the shape differences showed statistically significant variation among modern humans, Neanderthals, and primates at the brow ridge (Bookstein et al., 1999). More recently, geometric morphometric studies have been conducted to assess the affinity of a single Neanderthal cranium to other specimens (Friedline et al., 2012), to estimate the development of a subadult Neanderthal cranium (Gunz and Bolygina, 2012), and in the reconstruction of hominin crania (Gunz et al., 2009).

Geometric morphometric techniques also have been applied to the evaluation of sexual dimorphism in modern humans. Rosas and Bastir (2002) collected 29 landmarks with a Microscribe 3DX digitizer around the entire lateral profile of 52 adult female and 52 adult male skulls from the Coimbra collection. They found that with increased prominence of glabella and more angular nasals in males, the nasal aperture increases in size. In females, glabella is much less prominent and the nasal aperture smaller (Rosas and Bastir, 2002). However, only three landmarks comprised their data capture of the frontal profile: nasion, glabella, and bregma. As such, overall curvature of the frontal profile is not addressed. Statistically confirming the influence of glabellar prominence on sexual dimorphism and providing insight on nasal aperture size as a sexually dimorphic feature demonstrate the potential for geometric morphometric studies of frontal profiles.

Recently, two studies have examined the brow ridge with geometric morphometric techniques using three-dimensional laser scans of complete crania. Garvin and Ruff (2012) studied the brow ridge and mental eminence in a sample of 119 black and white, male and female crania from the Terry collection. To isolate the brow ridge from the three-dimensional scans, they used the supratotal sulcus as the superior boundary, placed points at the deepest superior points of the supratotal sulcus at “ $\frac{1}{4}$ of the minimum frontal breadth from the midline” to form the lateral constraints, and used nasion as the inferior delineation (Garvin and Ruff, 2012:663). ANOVA of the volume and surface area of this isolated shape showed a significant difference in size between males and females. Brow ridge shape was quantified by placing five lines of sagittally-oriented semilandmarks from the inferior to the superior borders of the isolated shape, including one at midline. Garvin and Ruff (2012) found that degree of sexual dimorphism within ancestry groups is not significantly different. However, their findings indicate that white male brow ridges tended to be more prominent than black male brow ridges. Females followed the same pattern. Morphometric sex estimation based on the semilandmarks yielded 91.6% accuracy, but only 79.8% when cross-validated. Their morphometric analysis also showed that in males with very prominent brow ridges, projection at glabella is reduced. Alternatively, females display more uniformity in brow ridge projection.

Shearer and colleagues (2012) conducted a similar isolated feature analysis on the brow ridges of 128 adult crania from multiple ancestry groups using 3D scan data, but included the complete lateral expression of the trait. They defined the brow ridge shape by forming lines around glabella, nasion, and right and left zygotemporal sutures inferiorly. Volume ratios of individual brow ridges then were compared. Their results reinforced that females have smaller brow ridges than males because females exhibit lower brow ridge volumes (Shearer et al.,

2012). The authors emphasize the need to compile regional data on brow ridge shape and suggest that 3D shape data be incorporated into regular analysis of human skeletal remains.

CHAPTER 3. MATERIALS AND METHODS

A sample of 204 crania from the Terry Collection at the Smithsonian Institution's National Museum of Natural History was used in this study. Male and female individuals of black and white ancestry were selected to encompass sexually dimorphic variation between these ancestries (Table 1). Individuals in the Terry Collection are of known sex and ancestry and were born between 1828 and 1943 (Hunt and Albanese, 2005). Their ages at death range from 14 to 101 years old. Since sex characteristics in the skull change with age (Walker, 1995; Burns, 2009), individuals who died between 40 and 60 years of age were chosen for this study. These ages were chosen because they represent the narrowest range with at least 200 individuals with the above sex and ancestry characteristics.

Table 1. Distribution of sample based on sex and ancestry.

	Black	White	Total
Female	47	53	100
Male	52	52	104
Total	99	105	204

Data Collection

A MicroScribe G2x digitizing system was used to capture the frontal outline of individual skulls to quantify frontal slope and brow ridge prominence. A visual assessment of cranial sex was performed using the glabellar scoring technique from Buikstra and Ubelaker (1994) prior to the digital capture to document how each skull would be classified without the digitizer.

Individuals with little or no glabellar prominence were scored as either 1 or 2, suggesting a female. Those skulls with greater glabellar prominences were given scores of 4 or 5, suggesting

males. A score of 3 indicates moderate prominence of glabella that could signify either sex. Known sex and ancestry of each individual also were recorded. The digitizer is currently utilized as an alternative to traditional calipers for completion of standard forensic anthropology ancestry and sex estimation in the morphometric program, 3D-ID (Slice and Ross, 2009). 3D-ID assesses landmark data to give the probability that an individual belongs within a specific group. The present study demonstrates the ability of this digitizer technique to quantify the shapes assessed by strictly visual techniques and suggests the potential for incorporating geometric morphometrics into forensic sex estimation methods.

The digitizer has a base, a multi-jointed arm, and a stylus with a sharp point at the end of the arm. The stylus tip collects three-dimensional points with x-, y-, and z-axes. Placing the stylus on a specific feature of an object and pressing a button collects a point to represent that feature. Dragging the stylus along an object creates a line composed of multiple three-dimensional points that are recorded at set intervals. Following the example of previous cranial and brain outline studies, landmarks and semilandmarks were collected from the frontal bone to form an outline of the frontal profile (Bookstein, 1997; Bookstein et al., 1999; 2003). Specifically, standard osteological landmarks, nasion and bregma, were used as start and end points for the traced contour, as recommended by Gunz and colleagues to reduce distortion (2005), and sliding semilandmarks composed the remainder of the outline. Glabella also was used to record the greatest prominence of the brow ridge. Table 2 provides definitions for landmarks used in this study and Figures 1 and 2 show where landmarks are located.

Table 2. Landmark definitions (Hrdlička, 1920; Martin, 1956:444-451)

Bregma (b)	The point at which the coronal and sagittal sutures come together in the midsagittal plane (Figure 1)
Glabella (g)	The most anterior point on the frontal located directly above nasion between the supraorbital margins in the midsagittal plane (Figure 1)
Nasion (n)	The midsagittal point in the naso-frontal suture (Figure 1)

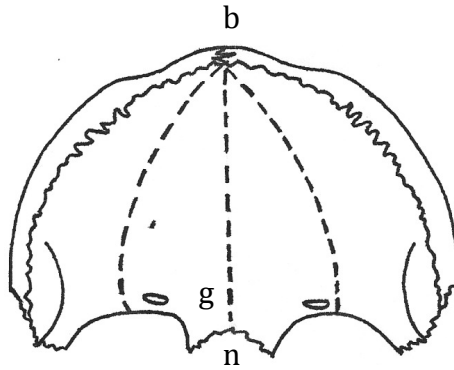


Figure 1. Anterior view of frontal bone. Medial line is traced from bregma (b) to glabella (g) and a point placed on nasion (n). Lateral lines are traced from bregma to greatest prominence of the supraorbital ridge.

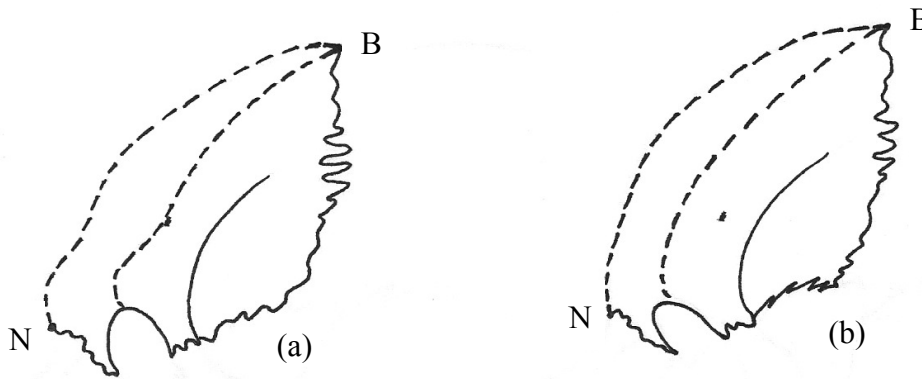


Figure 2. Lateral view of frontal bone. Frontal profile and lateral data collection lines on estimated male (a) and estimated female (b) skulls.

During data collection, each skull was placed on a foam mat resting on its inferior maxilla and mastoid processes with eye orbits facing the researcher (Figure 3). It was not

necessary to place the skulls according to the Frankfurt plane because the collected curves were aligned in a later process mathematically. Three curves were recorded from each skull with the digitizer. Round stickers were placed on each skull at the osteological landmarks and curve endpoints the digitizer was to collect (Figure 3). A flexible curve drafting tool was held against the frontal bone as a straight edge for the digitizer stylus to follow (Figure 3). Setting the digitizer to “stream” mode when tracing the frontal curve collected points at five millimeter intervals for all outlines. One curve was recorded by tracing the frontal contour at midline from nasion to bregma (Figs. 1 and 2). Garvin and Ruff (2012) caution against solely analyzing mid sagittal outlines of the skull, because lateral variation in the brow ridge may be excluded. In their three-dimensional volume study of the brow ridge, they found the feature to be slightly depressed at glabella and more prominent over the eye orbits in some males (Garvin and Ruff, 2012). To account for this, two additional lateral lines, composed of semilandmarks, were traced from bregma to the greatest prominence of the supraorbital ridge and the midline of the supraorbital ridge (Figure 1). The inferior point of one contour was determined by placing one endpoint of a set of spreading calipers on lambda and the other at glabella. While holding one tip on lambda, the other was traced along the supraorbital ridge until the greatest length was reached and a sticker was placed on this point.

Data Preparation

All curve data were collected into a plain text file. These data files for individual crania had to be compiled and re-coded before import into Morpheus et al., a 3D geometric morphometric visualization and analysis software package (Slice, 2013). The raw frontal bone outlines, composed of three landmarks and a curve resulting from varying numbers of points spaced every five millimeters, appear to visually represent frontal curvature well.



Figure 3. Setup of data collection. Shown is the flexible curve drafting tool, landmark stickers, and scale for use in documenting outlier specimens.

However, raw outline data had to be converted to semilandmarks for geometric morphometric analysis (Figure 4). The number of semilandmarks during statistical analysis should be consistent to compare variation at specific point locations that, together, represent the entire shape of the object (Bookstein, 1997). Choosing a specific number of equally spaced semilandmarks before data collection; however, can result in inaccurate warps when data are prepared for statistical analysis (Gunz et al., 2005). A previous geometric morphometric

study of 24 individuals comparing the frontal bones of modern humans and their hominid ancestors took 10 semilandmarks and three landmarks (Bookstein et al., 1999).

For the current study, Morpheus et al. was used to place 12 semilandmarks along the frontal curve to represent the shapes in more detail (Figure5).

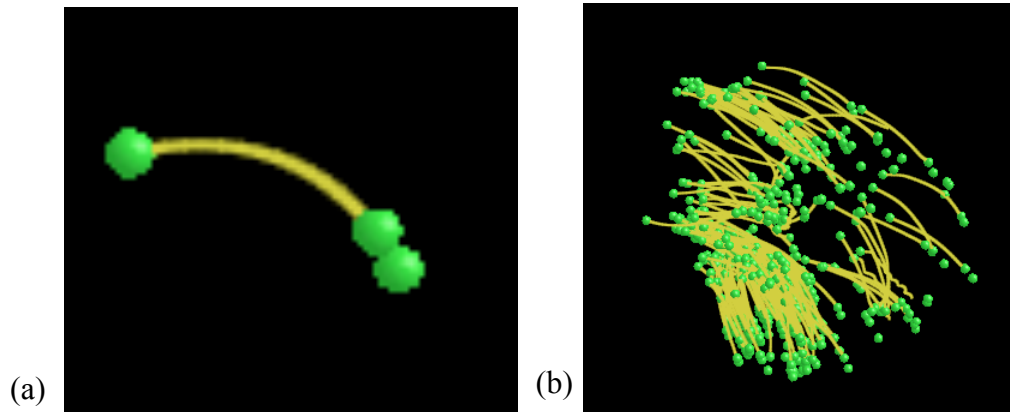


Figure 4. Curves visualized before resampling. Single curve (a) and collection of all curves (b) visualized in Morpheus et al. Green points represent the landmark points.

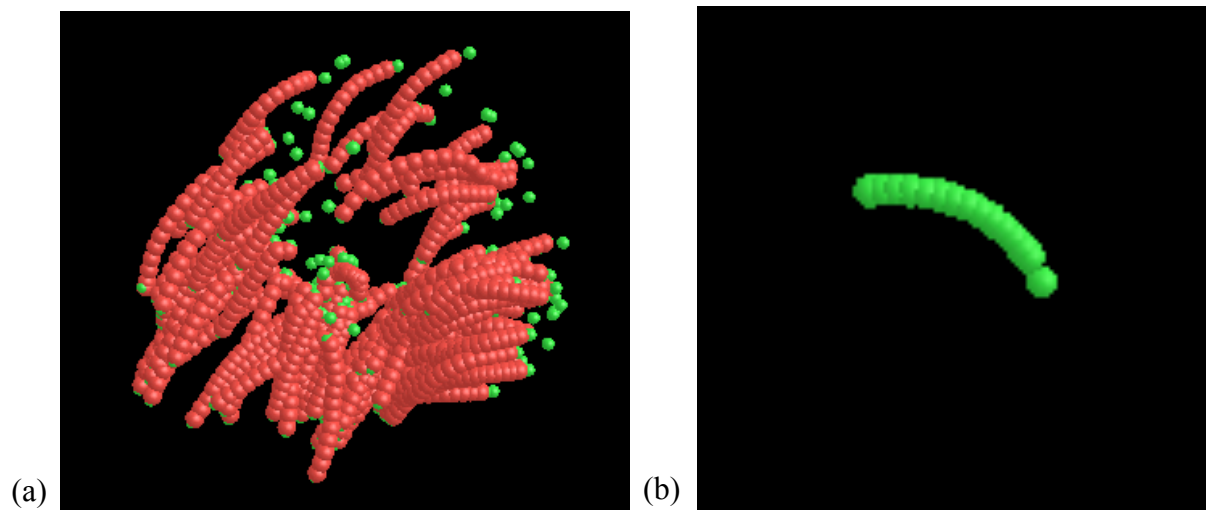


Figure 5. Curves visualized during resampling process. The points are red for the researcher to check if the number of semilandmarks adequately represent each specimen (a). The single curve with green points is one accepted resampled curve (b). All specimens now have three landmarks and 12 semilandmarks.

To focus on shape variation, differences in size, position, and skull orientation were removed through a Generalized Least Squares Procrustes analysis (GPA) superimposition algorithm (Bookstein, 1997) in Morpheus et al. (Slice, 2013). Curve shape was standardized by shrinking or stretching the individual curves, based on a calculated average curve length from nasion to bregma (Figs. 6 & 7). As can be seen in Figure 6, some of the curves did not appear to represent any natural frontal bone shape and were deleted, leaving 192 outlines for analysis (Figure 7).

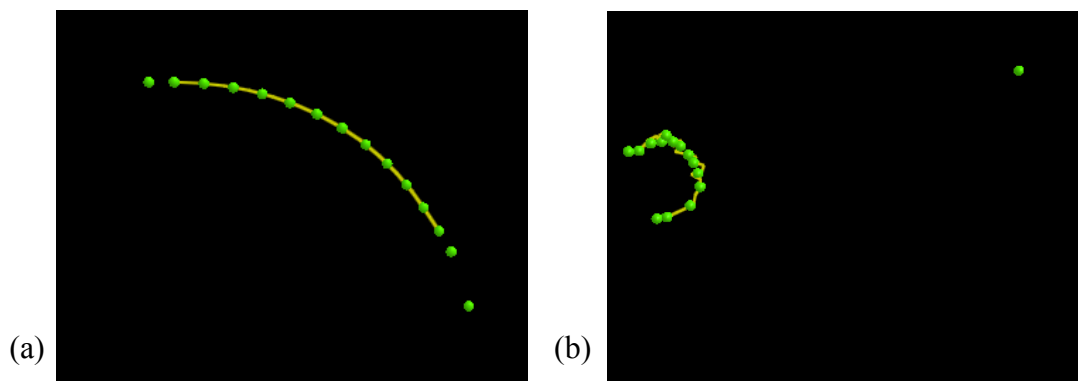


Figure 6. Visualization of individual curves post-GPA. Right curve (b) was deleted from the dataset as it does not accurately represent a frontal curvature probably due to a collection error.

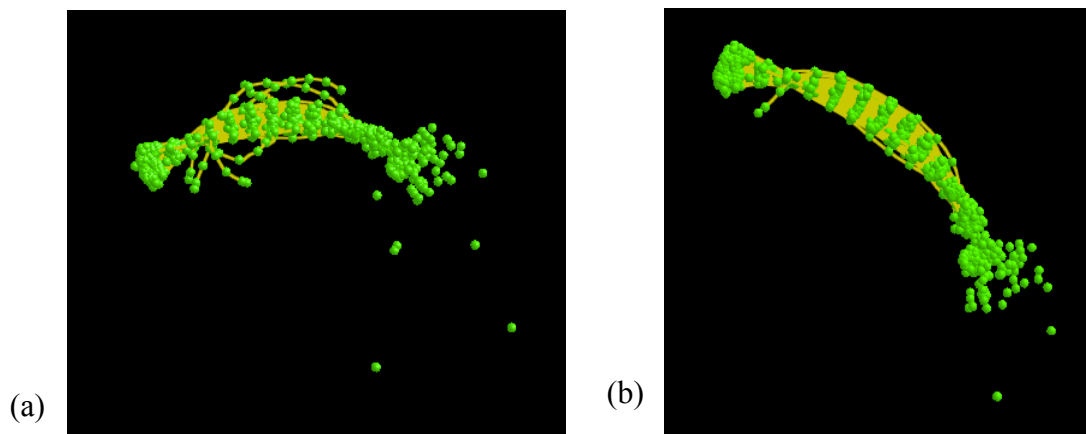


Figure 7. Visualization of all GPA aligned curves. Figure (a) includes all 204 curves. Figure (b) includes only 192 curves after the problem curves were deleted.

Data Analysis

For the 192 remaining specimens (Table 3), two geometric morphometric statistical packages, geomorph (Adams and Otárola-Castillo, 2013) and MorphoJ (Klingenberg, 2011), were used to conduct five statistical analyses to understand variation in the collected frontal bone outlines and suggest the potential of this digitizer method for use in sex estimation. For all tests, significance was determined if $p < 0.01$. Geomorph (Adams and Otárola-Castillo, 2013) was used to perform a principal components analysis (PCA) to show where shape variation exists between individuals regardless of prior group affiliation, like the sex or ancestry of the skulls.

Table 3. Distribution of crania used for statistical analyses.

	Black	White	Total
Female	46	48	94
Male	49	49	98
Total	95	97	192

Second, a canonical variates analysis (CVA) was conducted using MorphoJ (Klingenberg, 2011) to explain variation among group means. The CVA showed how well each group (female/male, black/white, and score) explains variation in the data. An additional test of group variation, a Procrustes distance analysis of variance (ANOVA), was performed in geomorph (Adams and Otárola-Castillo, 2013), as it is especially useful for datasets that include semilandmarks. A pairwise group comparison was completed in geomorph after the Procrustes distance ANOVA had identified the factors that explain shape variation. Euclidean distances among the group means were used as test statistics to see if the factor, in this case sex, is significant based on permutation. The pairwise group comparison “performs pairwise comparisons among groups using the Euclidean distances among group means” (Adams and

Otárola-Castillo, 2013). Lastly, a discriminant function analysis (DFA) was conducted in MorphoJ (Klingenberg, 2011) to test the classification ability of the digitizer frontal bone curve collection in assigning sex.

CHAPTER 4. RESULTS

Results of the PCA are presented in Table 4 and Figs. 8 and 9. Table 4 shows the percent of variation along each principal component (PC) axis. Any proportion of variance less than 5% is not considered to significantly contribute to the variation in frontal bone curvature. PC1 explains 54.922 % of the variation, while PC2 explains 35.927%. The remaining 40 principal component scores explain less than 4% of the variance and are not included in the table.

Table 4. Principal component scores for PC1-PC5.

	Standard Deviation	Proportion of Variance	Cumulative Proportion
PC1	0.06931	0.54922	0.54922
PC2	0.05606	0.35927	0.90849
PC3	0.01698	0.03296	0.94144
PC4	0.01349	0.02082	0.96226
PC5	0.00952	0.01036	0.97262

The range of variation in PC1 is visualized in Figure 8, which shows the frontal bone profiles at the minimum and maximum ends of the range of variation. Plotting of principal component scores for all specimens shows distinct clustering when the sex of individual skulls is labeled (Figure 9.a). Males are more scattered and females cluster in the negative portion of the graph. This suggests that using the digitizer has the possibility of being useful in sex identification since most of the variation in PC scores is explained by sex. No pattern is evident in the PCA plot labeled by ancestry (Figure 9.b).

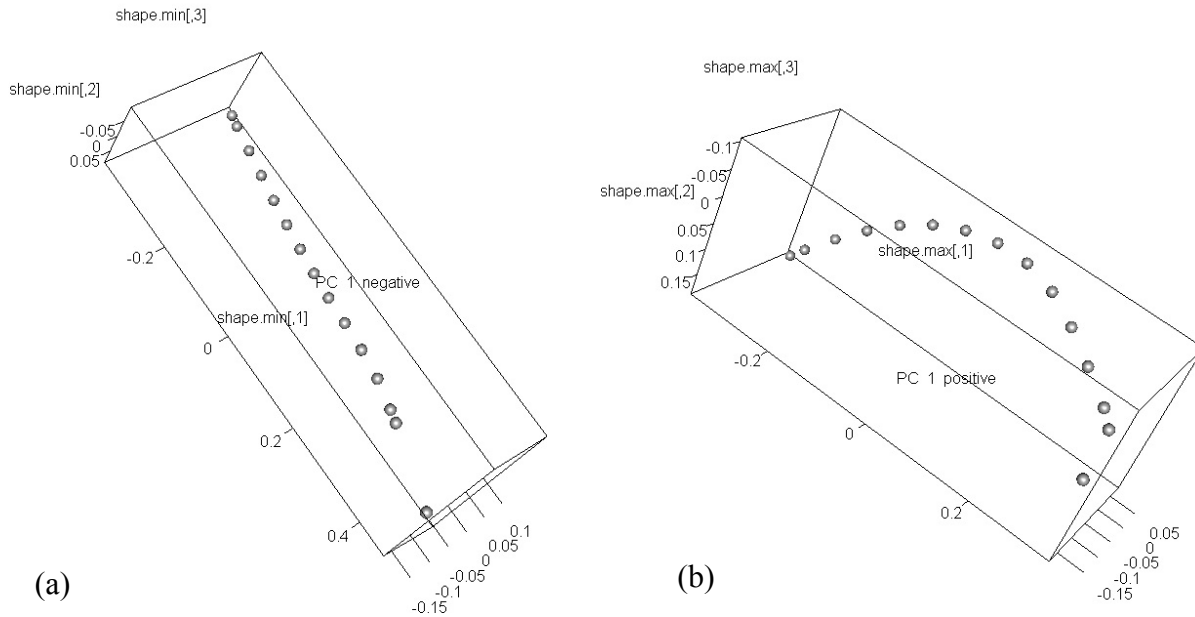


Figure 8. Variation in PC1. These curves show the extreme ends, the minimum (a) and maximum (b) shapes. They are rotated to reflect the angle of a skull with nasion located inferiorly and bregma superiorly.

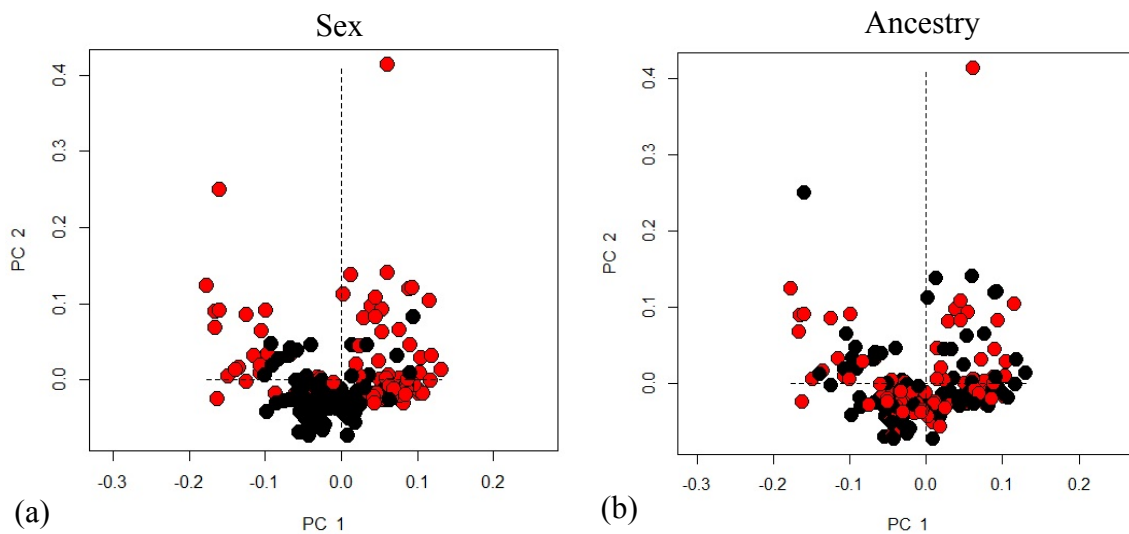


Figure 9. Plots of the principal component scores for each specimen. The specimens in plot (a) are labeled by sex without regard to ancestry. Red points represent males and black points represent females. The specimens in plot (b) are labeled by ancestry without regard to sex. Black points represent black individuals and red points represent white individuals.

Figure 10 presents three scatterplots of canonical variate scores for specific groups. In Figure 10(a), all groups are included and a pattern is difficult to decipher. Figure 10(b) includes

both sex and ancestry groups and 10(c) includes just males and females. Both 10(b) and 10(c) graphs show a distinction between the males and females. Similar to the PCA plot, males are more widely distributed and females cluster.

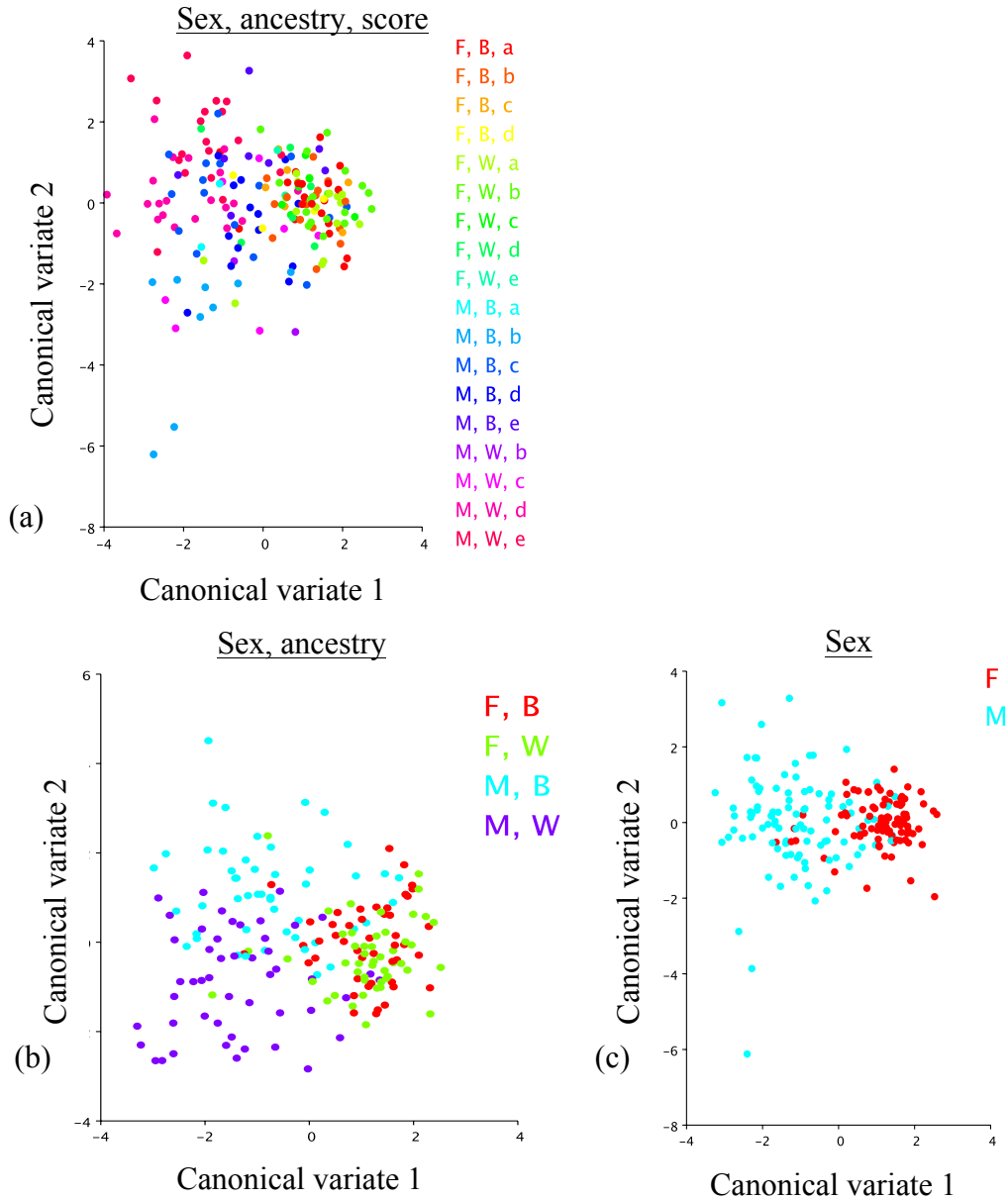


Figure 10. Scatterplots of canonical variate scores for each individual. Plot (a) describes the variation among all groups within the factors sex, ancestry, and score. Plot (b) shows the variation between sex and ancestry groups. Plot (c) shows the variation in scores between males and females.

The lollipop graphs in Figure 11 show the landmarks and semilandmarks captured by the digitizer and the amount of variation at each point. Points 1, 2, and 3 are the landmarks nasion, glabella, and bregma, respectively. Points 4 through 15 are the semilandmarks. From the graphs, it is apparent that the greatest variation in all groups is at nasion (1), followed by bregma (3), and the most posterior semilandmark (15). There is also large variation in the middle semilandmarks, 8 through 11, which may represent the area of a frontal bone that indicates in a visual assessment whether a skull was male with a sloping forehead or female with a vertical forehead. Figure 11(d) shows that ancestry creates the least variation, though nasion remains the most variable landmark.

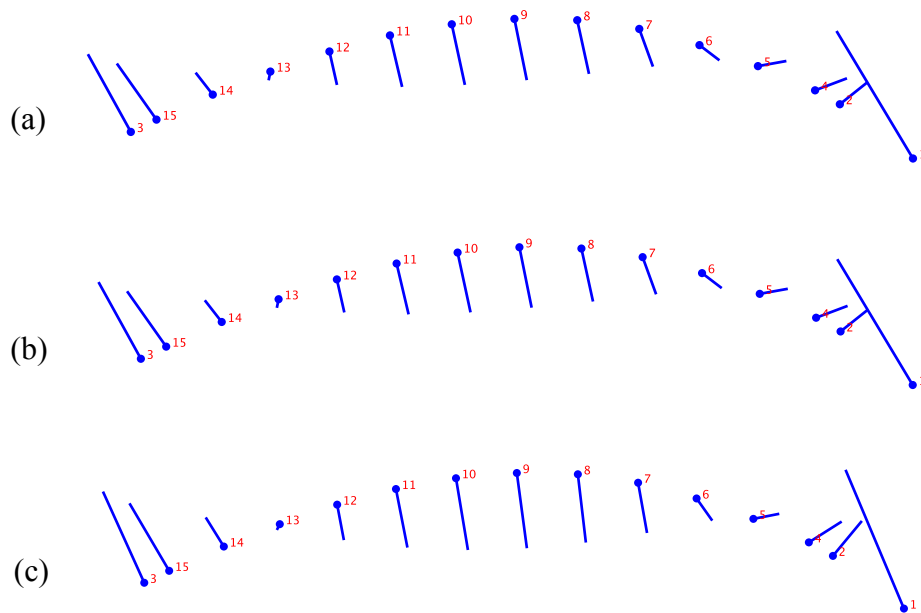
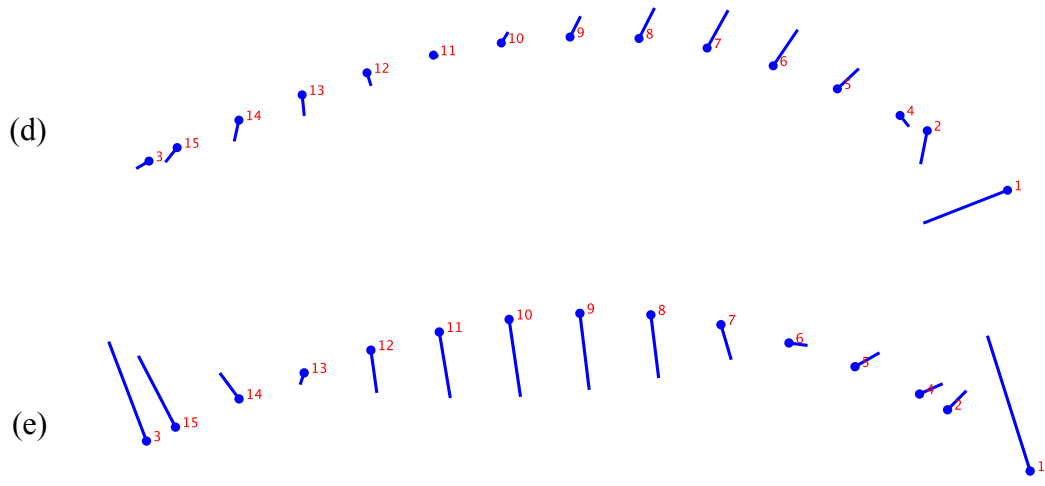


Figure 11. CVA lollipop graphs of frontal bone curvature configurations. Plots represent the variation in canonical variate scores of groups at each point along CV1. Graph of sex, ancestry, and score (a). Graph of sex and ancestry (b). Graph of sex (c). Graph of ancestry (d). Graph of score (e).



(figure continued)

Results of the Procrustes distance ANOVA are presented in Table 5 and show sex to be the only significant factor that explains shape variation in the frontal curvatures at $p < 0.01$. As such, the pairwise group comparison was conducted on sex as the significant grouping factor. Results of the pairwise group comparison are presented in Table 6. Sex is shown to be significant at $p < 0.01$.

Table 5. Procrustes distance analysis of variance. SS: sum of squared Procrustes distances for that variable. MS: mean sum of squares.

Factor	df	SS.obs	MS	P.val
sex	1	0.181054596	0.181054596	0.001
sex:ancestry:score	4	0.034658048	0.008664512	0.07
sex:ancestry	1	0.014809268	0.014809268	0.178
ancestry	1	0.012656389	0.012656389	0.252
sex:ancestry:age	20	0.122546945	0.006127347	0.26
sex:age:score	80	0.005659084	7.07E-05	0.508
ancestry:age	20	0.159858444	0.007992922	0.578
sex:age	20	0.142635962	0.007131798	0.72
ancestry:score	4	0.023458441	0.00586461	0.725

(table continued)

Factor	df	SS.obs	MS	P.val
sex:score	4	0.022612557	0.005653139	0.737
age:score	80	0.352766435	0.00440958	0.766
age	20	0.123225205	0.00616126	0.937
ancestry:age:score	80	0.003271675	4.09E-05	0.958
score	4	0.009959313	0.002489828	0.987
sex:ancestry:age:score	80	0	0	1
Total	191	1.670822971	0.008747764	NA

Table 6. Results of pairwise group comparison of sex. Dist.obs presents the Euclidean distances among group means. Prob.Dist. presents the pairwise significance level.

Sex	Dist.obs.F	Dist.obs.M	Prob.Dist.F	Prob.Dist.M
F	0	0.061429705	1	0.001
M	0.061429705	0	0.001	1

Tables 7 and 8 give results of the DFA of known sex from the frontal bone curvatures collected. Both the initial DFA and the leave-one-out cross-validation show that the classification method presented in this paper is better able to accurately classify females than males. In the cross-validation, females were correctly classified 88.3% of the time compared to males at 70.4%.

Table 7. Classification by sex from discriminant function.

	Female		Male		Total
	Number	Percent	Number	Percent	
Female	86	91.5%	8	8.5%	94
Male	18	18.4%	80	81.6%	98

Table 8. Cross-validation of classification by sex.

	Female		Male		Total
	Number	Percent	Number	Percent	
Female	83	88.3%	11	11.7%	94
Male	29	29.6%	69	70.4%	98

Results of sex assessment based on the visual scoring technique corresponded fairly well to known sex (Table 9). Out of the 192 curves, 69 (73.4%) of the 94 females were scored correctly as 1 or 2 and 13 (13.8%) were intermediate. Of the 98 males, 62 (63.4%) were scored correctly as 4 or 5 and 23 (23.4%) were intermediate.

Table 9. Count of assessed score of all specimens against known sex.

Score	1	2	3	4	5	Total
Female	34	35	13	10	2	94
	36.1%	37.2%	13.8%	10.6%	2.1%	
Male	2	11	23	35	27	98
	2.0%	11.2%	23.5%	35.7%	27.6%	

CHAPTER 5. DISCUSSION AND CONCLUSION

The present study tests the ability of the digitizer technique to quantify with semilandmarks the shapes assessed by strictly visual techniques and demonstrates the potential for incorporation into forensic sex estimation methods. The results of the score-based assessment show that more than half of the individuals in each sex were scored correctly, but many were intermediate or did not match the known sex (Table 9). Age may be a factor in the distribution of these scores, since the dataset includes many women over 45. Walker (1995) found that post-menopausal women over 45 years old had significantly larger brow ridges than women under 45. However, the Procrustes ANOVA did not find that age is a significant factor in the grouping of frontal curvatures collected with the digitizer (Table 5).

Variation within the non-grouped three-dimensional frontal curves does not appear large from the GPA plot of all specimens (Figure 7). The two-dimensional PCA plots suggest that sex may be a factor in explaining variation as the females are in a cluster and the males are widespread (Figure 9). The Procrustes distance ANOVA suggests that sex is related to the shape of the frontal bone contour as collected by the digitizer (Table 5). That sex was the significant variable in explaining the Procrustes distance variances is encouraging. The digitizer technique was able to divide the dataset into groups based on sex. It was surprising that score, age, and ancestry do not play significant roles in grouping the frontal curvatures. This finding may indicate that the midline of the frontal bone, as captured by the digitizer, is not affected by brow ridge prominence, but simply the anterior-posterior curvature of the overall bone and that the scoring technique describes the brow ridge.

Results of the canonical variates analysis show that most of the variation in the frontal bone curvatures lies at nasion, bregma, and near the middle of the curve. The cross-validation

test showed the promise of this technique for sex estimation compared to the accuracy of the scoring technique found by Walker (2008) of 82.6%. The Procrustes ANOVA shows there is potential for a sex estimation technique that will not be skewed by ancestry or adult age.

The practical use of this method for sex estimation has great potential, but the amount of time it took to learn various statistical software and process the raw data means it is not ready yet. Someone with more experience conducting geometric morphometric analyses on semilandmarks may find the task easy. Lateral curves collected by the digitizer were not analyzed due to time constraints but will hopefully be used in later studies. An additional drawback is that digitizers may not be widely available to all researchers. Fortunately, geometric morphometric statistical software packages are widely available and usually free on the Internet, but it can be time consuming to find the correct one for a particular project.

Conducting this study laid the foundation for a future software package that may involve only a simple stroke of a digitizer pen on a frontal bone and the likelihood of that individual being male or female will be given immediately. This is dependent on developing user-friendly software and consistent protocol that is able to estimate sex even in the case of obliterated sutures or a shifted bregma on specific skulls. The present study accounted for these by using the flexible curve drawing tool to estimate a straight line from nasion to the coronal suture. Future research should expand the dataset to broader ancestry and age groups and include more modern (i.e., contemporary) individuals, before testing begins on forensically significant collections. Additionally, this geometric morphometric technique has potential to explore cranial sex differences in sub adults, as has been demonstrated in innominates (Vollner et al., 2010).

Refinement of this method and inclusion of a broader sample will help improve the classification rates of males and females and make this a useful technique to complement visual assessments of sex from the skull.

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