TECHNICAL NOTE

ANTHROPOLOGY

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Quantification of Maxillary Dental Arcade Curvature and the Estimation of Biological Ancestry in Forensic Anthropology

ABSTRACT: Previous studies suggest that palate shape is a useful indicator of biological ancestry in human remains. This study evaluates interobserver error in ancestry estimation using palate shape and explores palate shape variation in Gullah (descendants of West Africans) and Seminole (Indigenous American) population samples using geometric morphometric analysis. Ten participants were asked to ascribe biological ancestry and shape to 28 dental casts based on a classification scheme employed in previous studies. The mean correct classification was 42.0%, indicating that the likelihood of assigning the correct ancestry is very poor and not significantly different from random assignment (p = 0.12). The accuracy analysis based on categorical classification of the casts was complemented by geometric morphometric analysis of nine 3D landmarks reflecting palate shape of 158 casts. Principal component analysis results show no difference between populations regarding palate shape, and cross-validated discriminant function analysis correctly classified only 62.0% of the specimens. Combined, these results show that previous methods to estimate ancestry are inaccurate and that this inaccuracy is probably due to a lack of palate shape differences between groups, rather than limitation of the analytical method per se. Therefore, we recommend caution should be used when choosing to apply the analysis of palate shape in forensically relevant contexts.

KEYWORDS: forensic science, human variation, geometric morphometric analysis, discriminant function analysis, principal components analysis

There are a number of anatomical skeletal traits that may be used to estimate ancestry in the construction of a biological profile for unidentified human remains (1,2). One trait that has traditionally been used to inform ancestry estimation is palate shape (1,3–6). Qualitative analyses have suggested that individuals of African ancestry tend to have a hyperbolic (i.e., widely arched) palate shape, individuals of European ancestry tend to have a parabolic (i.e., a moderately arched) palate shape, and people of “American Indian” or Indigenous American ancestry tend to have an elliptical (i.e., narrowly arched) palate shape (1,7). The purpose of this study was, first, to evaluate the accuracy of ancestry estimation using the shapes outlined in previous studies and, second, to explore shape variation in Gullah African American and Seminole Indigenous populations using a geometric morphometric analysis of maxillary dental casts.

The Gullah are descendants of West Africans (8) who were brought to South Carolina and Georgia and enslaved between 1670 and 1807 (9). After the slave trade became illegal, the Gullah continued to live on the Sea Islands off the coast of South Carolina where, until recently, they were culturally and genetically isolated (8,9).

The Florida Seminole are descendants of Creek, Yemassee, Yuchi, and Oconee Indigenous Americans (10). The colonization of North America by Europeans decimated Indigenous American populations, and the fractured groups that survived consolidated to form the Seminole (11).

Despite historical accounts of cultural integration between African Americans and the Seminole Indigenous Americans, biological evidence has shown that the amount of population admixture is small (12,13). Huoponen et al. (12) performed a mitochondrial DNA (mtDNA) analysis and a Y chromosome analysis on members of the Florida Seminole. They found no evidence of African patrilineal admixture (12). Results also suggested only minimal African matrilineal contribution (12).

Bolnick and Smith (10), in a later study, analyzed haplogroup frequencies among the Florida Seminole and found that the degree of African admixture among the Seminole was small. These studies show that the effects of cultural integration between African Americans and the Seminole were not biologically significant. Consequently, while historical sources may suggest otherwise, the Florida Seminole are genetically and phenotypically representative of Indigenous Americans (10,12,13). Furthermore, it is unlikely that the genes affecting palate shape were preferentially incorporated into the Seminole from such minimal African American admixture. The Florida Seminole and the Gullah therefore comprise an appropriate comparative sample for this study.
Materials and Methods

This study was divided into two parts. The first part of the study was an accuracy test to assess the effectiveness of Gill’s method (1,7) on the Gullah and Seminole for classifying individuals according to palate shape. The accuracy of osteological classification tests can be a result of the inefficiency of the method (i.e., the method does not allow for a reliable classification of the biological variation in the specimens) or due to a false assumption about the existence of discernible differences (i.e., the biological variation is not structured in a way that significant differences exist among ancestries). Therefore, to explore the cause of the lack of accuracy of Gill’s qualitative method as applied to these sample populations, the second part of the study consisted of a quantitative analysis of morphological shape variation in these sample populations. The purpose of this second part of the study was to determine whether better classification rates based on palate shape can be achieved using an objective and quantitative method to assess morphological variation. The sample for the first part of the study consisted of 28 maxillary dental stone casts from the Renee M. Menegaz-Bock Dental Anthropology Collection housed at The Ohio State University (OSU). All casts in this collection were collected from living individuals. This sample consisted of 15 male and female individuals from the Gullah African American population and 13 male and female individuals from the Florida Seminole population. The Florida Seminole sample in the Menegaz-Bock dental anthropology collection is comprised of casts from individuals from the Brighton, Dania, and Big Cypress reservations (11). Individuals from the Brighton reservation were studied in the summer of 1964, and individuals from the Dania and Big Cypress reservations were studied in the winter of 1964 (11). Ancestry for the Seminole was self-reported in interviews conducted at the time the casts were taken (11,14). The Gullah data derive from dental casts of a single population of Gullah, African Americans from the outer banks of South Carolina, living on St. James Island during the 1950s (15). The dental casts were made as part of a larger study of Gullah biology and ancestry (15). All specimens were selected at random from the complete collection housed at OSU. Only intact casts with permanent dentition and normal occlusion were included in the sample. While casts often do not capture the most distal portion of the palate, the differences between hyperbolic and elliptical palate shapes are present in the shape of the anterior palate (16). Specifically, in a 2013 study of dry crania, Maier (16) found that the anterior curvature of hyperbolic, elliptical, and parabolic palates is flat, founded, and pointed, respectively (16). In addition, Maier (16) found that the angulation of the sides of the palate is markedly different in the hyperbolic, elliptical, and parabolic palate shapes. While a parabola has acutely angled sides, the hyperbola has nearly parallel sides. The sides of the elliptical assume an intermediate angle (16). The casts used in this study are therefore an appropriate tool to evaluate palate shape, even though they occasionally do not capture the portion of the most distal portion of the palate.

To test the accuracy of ancestry estimation according to Gill’s method (1,7), ten graduate students, including MA and PhD students, with advanced knowledge in human osteology at The Ohio State University’s Department of Anthropology were provided with sketches of the shapes outlined by Gill (1,7) to assess biological ancestry. Each observer was presented with a copy of the drawings (Gill 1,7) for elliptical and hyperbolic palate shapes and their corresponding ancestries (Indigenous American and African, respectively). Participants were permitted to keep and refer to these sketches throughout the duration of the study. It was then explained verbally that individuals of Indigenous American ancestry typically exhibit elliptical palate shapes, and people of African ancestry typically exhibit hyperbolic palate shape. Participants were then given the 28 maxillary dental casts and asked to classify each cast, first, according to shape (i.e., hyperbolic or elliptical) and, then, according to ancestry (i.e., African or Indigenous American). Participants were asked to classify casts by shape, first, to ensure that the shapes represented in the sketches (i.e., hyperbolic and elliptical) were, in fact, present in the specimens analyzed and, second, to ensure that the observers were relying primarily on shape to assess ancestry rather than dental morphology that could not otherwise be controlled for. It was anticipated that if the results for ancestry and shape classification were significantly different, those results would have indicated that participants were relying on dental morphology (i.e., incisor shoveling and winging) rather than palate shape to estimate ancestry. When all of the participants had completed the questionnaires, their responses were checked against the documented ancestries. In the first case (shape identification), an answer was marked as correct when the shape selected matched the expected shape for the ancestry of the cast. In the second case (ancestry identification), correct answers were answers that correctly estimated the ancestry of the specimens. The reliability of Gill’s classification scheme (1,7) was assessed for each participant and then for all participants on average. To test the hypothesis that there is an association between palate shape and ancestry, chi-square tests were applied. In this case, the observed frequency of each classification (African or Indigenous American) was contrasted with the expected frequency of selecting answers at random in the questionnaire. Consequently, Gill’s classification scheme (1,7) is an accurate method for ancestry estimation if it provides a significantly higher classification rate than would be expected by chance alone.

The sample for the second part of the study consisted of 158 maxillary dental casts from the Renee M. Menegaz-Bock Dental Anthropology Collection. Of the 515 total casts from the Gullah population in the collection, 88 were included in this study. Of the 346 total casts from the Seminole population in the collection, 69 were included in this study. The remaining casts were excluded from the sample because they exhibited deciduous dentition, incomplete eruption, or abnormal occlusion. Additionally, casts that were fractured, incomplete, or did not extend to the second molar were also excluded.

Three-dimensional surface scans (Fig. 1) of each cast were obtained with a NextEngine 3D scanner with a MultiDrive following the suggested protocol established by the manufacturer for scanning dental casts (17). All casts were scanned in high resolution (44,000 points/inch³). The surface scans were used as the basis for all morphometric analyses in this study.

For the morphometric comparisons, nine anatomical landmarks (Fig. 1) were collected with the software LANDMARK EDITOR 3 (Institute for Data Analysis and Visualization, UC Berkeley, California). These landmarks were placed on the distolingual aspect of the gum line of each second molar, and along the lingual side of the palate between each first molar and second premolar, each first premolar and canine, each canine and second incisor, and between each first incisor (Fig. 1). These points were selected because together they approximate palate curvature. These landmarks were then projected onto a plane defined by the two most posterior (left and right second molars)
landmarks and the most anterior (between first incisors) landmark. By projecting the landmarks on a plane, a better approximation of palate arc shape was obtained that also allowed us to explore shape variation using thin plate splines (18). General Procrustes analysis was used with these two-dimensional landmarks to remove difference that occurs due to rotation, translation, and size among individuals (19).

Morphological affinity between Seminole and Gullah palate shape was assessed with principal components analysis and discriminant function analysis. Principal components analysis (PCA) is a variable reduction procedure used to represent the similarities between cases (e.g., dental casts) by condensing large amounts of information into a few meaningful variables (20). The casts were plotted in the morphospace defined by the first two principal components. The shape variation in these axes was represented using thin plate splines that represent deformation grids from the average shape in the dataset. Discriminant function analysis (DFA) is similar to PCA in principle because it also condenses comparative data into a few meaningful variables (21). However, while PCA evaluates the variation in the sample as a whole, DFA will partition the variation in those axes that best discriminate groups defined a priori. DFA was used to create a classification matrix to assess the percentage of individuals correctly classified given the discriminatory power of the shape variables (defined by the nine two-dimensional landmarks) included in this study. To test for the reliability of the results, a leave-one-out cross-validation (21) was also conducted and the resulting classification matrix compared to the original results. By quantifying morphological affinity, DFA eliminated the problem of subjectivity in qualitative analyses. In this study, DFA allowed us to classify the individuals and compare these classifications to the actual groups to which the individuals belonged. Analyses in the second part of the study were conducted in R (22), with functions written by MH and complemented by functions from package geomorph (23).

This study qualified for category two and category four exemptions through the OSU IRB. These exemptions refer in the first instance to research involving the use of educational survey procedures and in the second case to research involving the study of existing data that cannot be linked to subjects through identifiers. All IRB guidelines were followed.

### Results

#### Accuracy Test

The summary of the accuracy tests is shown in Tables 1 and 2. As can be seen, overall the participants’ classification rate was poor both in terms of ancestry estimation (Table 1) and in terms of shape estimation (Table 2). The results of the analyses based on shape and ancestry estimation returned similar results: Correct classifications of ancestry ranged from 21.4% to 60.7%, with an average of 42.9% (Table 1), and correct classification of palate shapes ranges from 25.0% to 57.1%, with an average of 42.1% (Table 2). By chance alone, it would be expected that each observer would correctly assign ancestry to 9.33 casts (28 casts/3 choices). Additionally, by chance alone, each observer would describe 9.33 casts as having the expected shape (28 casts/3 choices). The mean correct classification rate in both analyses is not statistically higher than what would be expected by chance ($\chi^2 = 0.76; p = 0.38$ for ancestry and $\chi^2 = 0.65; p = 0.41$ for palate shape). In fact, only two participants (1 and 5; Table 1) correctly estimated the ancestry more than one casts/3 choices. The results suggest Gill’s methodology is not an accurate means by which to discriminate between African American and Native American ancestry, especially if it is taken into consideration that all participants in this study are graduate students with advanced knowledge in human osteology.

<table>
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In bold – individuals that classified correctly significantly more ($p < 0.05$) casts than expected by chance alone.
Figure 2 shows the scatter plot of the individuals according to the first two principal components. Together, the first two principal components account for 59.0% of the total shape variation. PC 1 is associated with the relative width of the palate arch, with lower values in this axis having wider arches and positive values narrower arches. PC2 is mainly explaining the expansion of the anterior part of the palate, with positive values associated with narrower, more V-shaped anterior regions, and negative values indicating wider, rectangular, anterior regions. These shape variations correspond well with the palate shape features used by Gill (1,7) to discriminate ancestry based on this trait.

Yet, as can be seen there is absolutely no differentiation between the Gullah and the Seminole individuals included in this analysis, with a remarkable overlap in their distributions.

<table>
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</table>

In bold – individuals that classified correctly significantly more ($p < 0.05$) casts than expected by chance alone.

**Morphological Shape Analysis**

Figure 2 shows the scatter plot of the individuals according to the first two principal components. Together, the first two principal components account for 59.0% of the total shape variation. PC 1 is associated with the relative width of the palate arch, with lower values in this axis having wider arches and positive values narrower arches. PC2 is mainly explaining the expansion of the anterior part of the palate, with positive values associated with narrower, more V-shaped anterior regions, and negative values indicating wider, rectangular, anterior regions. These shape variations correspond well with the palate shape features used by Gill (1,7) to discriminate ancestry based on this trait. Yet, as can be seen there is absolutely no differentiation between the Gullah and the Seminole individuals included in this analysis, with a remarkable overlap in their distributions.
Table 3 shows the classification matrix based on the discriminant function analysis. Using palate shape to estimate ancestry produced a low classification rate; 67.7% of the individuals were correctly classified when the shape data were analyzed, and this rate fell to 62.2% in the cross-validation. This is not a significant improvement from the classification rate expected by chance alone (50%) and is thus in strong agreement with the results obtained in the first part of the study. These results illustrate that it is not necessarily Gill’s method applied in the first experiment that is at fault, but rather the assumption that palate shape differs between these two ancestry groups that is wrong.

Discussion and Conclusions

The questionnaires in the first part of this study illustrate the low accuracy rate produced using palate curvature as an indicator of biological ancestry in this sample. Irrespective of the type of question asked (identification of shape or ancestry directly), the ability of the participants to identify correctly the ancestry of the dental casts was not larger than what would be expected by chance alone. In fact, even the best observers did misclassify c. 40% of the casts, and the average rate of correct classification was only slightly higher than 40% in both questionnaires. These results suggest that Gill’s method is inaccurate and that most of the time trained observers cannot associate expected palate shape to the sample of Native Americans and African Americans used in this study.

The morphological shape analysis carried out in the second part of the present study corroborates the inaccuracy of the classification scheme by showing that there is not enough differentiation in palate shape between the groups and that there is significant variation in palate shape within each group. Consequently, the correct classification rate is relatively low (c. 62.0% in the cross-validation test). This classification rate is even more problematic when compared to classification rates obtained for the skull, which can be above 85% correct when enough variables are considered (e.g., 24,25). This lack of between-group differences can be easily observed in the PCA results (Fig. 2). Moreover, the PCA results show that the overall shape differences, namely the pointed and rectangular shapes of the anterior dentition and the angulation of the sides (16), are captured by the casts and are represented in this sample. The PCA results therefore illustrate that it is not necessarily Gill’s method that is inaccurate, but rather that this is a case where the biological variation of the trait under consideration (palate shape) is not partitioned according to differences between groups, and consequently, the largest differences in palate shape exist within each group. This is also true for cranioetric studies (e.g., 26), and as a result, large numbers of anatomical regions are required even in the skull to reach high correct classification rates (24). Therefore, our results suggest that palate shape is not an accurate method to estimate ancestry, at least for the groups examined in the present study, and its use should be considered with caution in a forensic context.

While Gill’s original scheme (1,7) suggested that it would be possible to reliably differentiate among European, “American Indian,” and African palate shapes, our results are limited to the differentiation only between the latter two groups, and therefore, this is a limitation of our study. However, even though this study does not test the accuracy of Gill’s method (1,7) for differentiating among European, “American Indian” and African palate shapes, we believe that our study has forensic relevance. African Americans and Indigenous Americans are important components of actual North American populations and are more likely than European Americans to fall victim to violent crime (27,28). Therefore, discrimination between these two ancestry groups is relevant in forensic situations. Given the current knowledge that African Americans disproportionately make up the annual number of homicide victims (29), a test that is not accurate in differentiating this ancestry from others common in the country (Indigenous Americans in this case) should be applied with caution.

Finally, these results further illustrate the obligation of forensic anthropologists to consistently re-evaluate methods for estimating ancestry. In fact, the results presented here indicate that it is not necessarily the method designed by Gill (1,7) that is at fault, but rather the assumption that ancestry will be significantly associated with discrete palate morphologies. Palate shape cannot be easily sorted into discrete categories because, like most other human morphologies, it is continuous. Future studies should continue to evaluate the usefulness of palate shape in other populations not included in this study, namely Europeans and populations with significant admixture. However, the substantial within-population variation and minimal between-population variation in palate shape found in the present study suggest that palate shape “types” in ancestry estimation are not likely to perform at the Daubert level of reliability.

In his 2013 study on dry crania, Maier (16) found that the likelihood that an observer would correctly classify a palate by ancestry (into “white,” “black,” or “Asian” categories) was 40%; this percentage is not much higher than random assignment to these three categories (33.3%). According to Maier, the result of his observer accuracy test is not statistically significantly different from the result of his accuracy test for his computer palate recognition program, which yielded an overall accuracy rate of 58% (16). Although Maier argues that 40% is “better” than 33% and that the computer recognition program’s higher classification rate might have practical (as opposed to statistical significance), his results, like those of the present study, indicate that palate shape as an estimator of ancestry fails to meet Daubert reliability standards. In consideration of the substantial within-population variation found in the present study, the results of a parallel study by Maier on dry crania (16), and the continuous nature of palate shape variation, it would be surprising if palate shape types were to perform well as reliable indicators of ancestry in other groups.

In conclusion, the lack of accuracy in the estimation of ancestry using palate shape that is demonstrated here and elsewhere (16) is not appropriate in the field of forensic science, failing the standard for reliability set forth by Daubert v. Merrell Dow Pharmaceuticals, Inc. (1993) (30). Given the weight of forensic science in the courtroom, it is necessary that the reliability of
forensic methods be maintained. The scientific community needs to continue to ensure the accuracy, reliability, and validity of forensic methods. Furthermore, the methods used in forensic anthropology need to be reliable so that forensic anthropology will be continued to be viewed as both a practical and academic discipline that is valued for its rigor in the legal, medical, academic, and professional spheres.

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References


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