



## Forensic Anthropology Population Data

Sexual dimorphism in human browridge volume measured from 3D models of dry crania: A new digital morphometrics approach <sup>☆,☆☆</sup>Brian M. Shearer <sup>a,b</sup>, Sabrina B. Sholts <sup>b,c</sup>, Heather M. Garvin <sup>d</sup>, Sebastian K.T.S. Wärmländer <sup>b,e,f,\*</sup><sup>a</sup> Department of Anthropology, The Graduate Center, City University of New York & New York Consortium in Evolutionary Primatology (NYCEP), New York, USA<sup>b</sup> Department of Anthropology, University of California, Santa Barbara, CA 93106-3210, USA<sup>c</sup> Department of Integrative Biology, University of California, Berkeley, CA 94720-3140, USA<sup>d</sup> Center for Functional Anatomy & Evolution Johns Hopkins University School of Medicine, Baltimore, MD 21205, USA<sup>e</sup> Division of Biophysics, Arrhenius Laboratories, Stockholm University, 106 91 Stockholm, Sweden<sup>f</sup> Division of Commercial and Business Law, Linköping University, 581 83 Linköping, Sweden

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## ABSTRACT

Sex estimation from the human skull is often a necessary step when constructing a biological profile from unidentified human remains. Traditional methods for determining the sex of a skull require observers to rank the expression of sexually dimorphic skeletal traits by subjectively assessing their qualitative differences. One of these traits is the prominence of the glabellar region above the browridge. In this paper, the volume of the browridge region was measured from digital 3D models of 128 dry crania (65 female, 63 male). The 3D models were created with a desktop laser scanner, and the browridge region of each 3D model was isolated using geometric planes defined by cranial landmarks. Statistical analysis of browridge-to-cranium volume ratios revealed significant differences between male and female crania. Differences were also observed between geographically distinct populations, and between temporally distinct populations from the same locale. The results suggest that in the future, sex determination of human crania may be assisted by quantitative computer-based volume calculations from 3D models, which can provide increased objectivity and repeatability when compared to traditional forensic techniques. The method presented in this paper can easily be extended to other volumetric regions of the human cranium.

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## 1. Introduction

Sexually dimorphic features of the skeleton are of fundamental importance when constructing a biological profile from unidentified human remains. The most reliable skeletal indicators of sex are located in the pelvis [1–4]. When the postcranial remains of a skeleton are missing or badly damaged, sex is often determined through the visual and tactile assessment of sexually dimorphic traits of the skull [5–8]. In such cases, the mastoid process, the mandibular mental eminence, the nuchal crest, the supraorbital margin, and the glabellar region are particularly diagnostic. In one widely used approach [6] these traits are rank ordered according to five levels of expression, where “one” signifies the most gracile

form of expression (i.e., female) and “five” signifies the most robust (i.e., male) (Fig. 1). This system can predict sex with reasonable accuracy [9], but the rank scores are based on subjective evaluation of qualitative differences and are therefore conducive to both inter- and intra-observer errors [10]. Because traits of varying size and shape may all be given the same score, each of the five rank levels in this system encompasses a broad range of forms. Furthermore, since the trait scoring system was designed for an “average” human population, it does not account for regional or temporal differences in sexual dimorphism. Many factors are consequently excluded when a morphological trait is described by a single subjective integer value, and it is sometimes problematic to assign trait scores to crania from certain geographic regions [9,11–13].

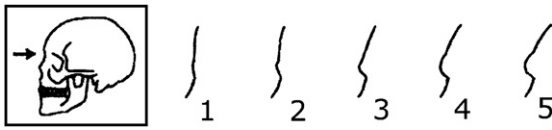
It would therefore be advantageous if male and female crania could be differentiated based on objectively quantifiable parameters. Attempts to use Euclidean distance measurements [14–16] and Cartesian landmark coordinates [12,17,18] to identify and describe sexually dimorphic cranial features so far have not produced a standardized method for sex estimation. An alternative parameter, which has been less explored, is volume. Volumetric analysis of crania has a long-standing tradition in forensic and

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**Fig. 1.** The expression of the glabellar region above the browridge can be rank ordered from one to five for purposes of sex determination.

Source: Image adapted from Buikstra and Ubelaker [6].

anthropological research. The focus of earlier studies, however, has been bony cavities like the braincase and the orbit, in which volumes easily can be obtained by filling the cavities with liquids, seeds, or leadshot [19,20]. Modern imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) have also been used in studies of cranial capacity [19,21], and permit volumetric analysis of less accessible features such as the sinus cavities [22]. Few, if any, research efforts have examined volumetric properties of cranial components or features that are not cavities, such as many of the conventional cranial sex traits. This is surprising, as skeletal features that are more robust arguably occupy a larger volume, suggesting that volumetric measurements of sexually dimorphic regions of the skull may be useful for sex estimation purposes. The dearth of research on the subject might be explained by a lack of suitable techniques for this type of analysis, as the convex morphology of most sexually dimorphic cranial traits does not allow for non-destructive volume measurements with traditional techniques.

We have recently shown that digital three-dimensional (3D) models of human crania created with laser scanners allow for highly precise non-destructive measurements of overall cranial volume [23]. In this study, we investigated if a similar technique can be used for volume measurements of an isolated sexually dimorphic part of the cranium, namely the browridge region. We selected this region because the prominence of the glabellar region, the shape of the supraorbital margins, and the size of the supraorbital ridges are all considered to be among the most reliable indicators of sex in the skull [10,24,25]. Digital 3D models of 63 male and 65 female dry crania from distinct populations were created using a portable and non-invasive 3D laser scanner. The browridge region of the surface 3D models was delimited using four craniometric landmarks and two geometric planes, yielding an isolated browridge component with a well-defined volume. After standardization for overall cranial size, browridge volume ratios for males and females were compared, and the usefulness of this quantitative measure was evaluated.

## 2. Materials and methods

### 2.1. Materials and trait scoring

Crania of 128 individuals of adult age – determined by the presence of a fully erupted third molar if age-at-death was not known – were used in the study. Thirty-six crania (17 females, 19 males) originate from modern Portuguese cemetery remains in the Luis Lopes Collection at the Bocage Museum in Lisbon, Portugal [26]. Thirty crania (16 females, 14 males) originate from modern African-Americans in the Terry collection at the Smithsonian National Museum of Natural History [27]. Sixty-two crania originate from human remains of California Indians, archeologically

excavated from sites on Santa Rosa Island (SRI), California, and currently housed at the Santa Barbara Museum of Natural History. Twenty-nine of these crania (13 female, 16 male) were excavated at the Skull Gulch site (CA-SRI-2) dating to ca. AD 1150–1500 [28,29], and 33 crania (19 female, 14 male) were excavated at the Tecolote Point site (CA-SRI-3) dating to between ca. 5200 and 2000 BC [29,30]. In this paper, the crania from these two sites were used to represent “late” and “early” California Indian populations.

The crania from the Terry and Lisbon collections are of known sex. The California Indian crania were sexed according to standard procedures using cranial traits and, when post-cranial remains were present, pelvic morphology and metric characteristics of the long bones [6]. For the California Indian crania, scores of four sexually dimorphic cranial traits, i.e., the nuchal crest, mastoid process, supraorbital margin, and supraorbital ridge/glabella, were recorded following the system presented by Buikstra and Ubelaker [6] (Fig. 1), using the left side of each cranium or the right side in case the left side was damaged. These cranial traits were used to evaluate the correlation between trait scores and brow volumes. As many of the crania did not have associated mandibles, the trait of mandibular mental eminence was not included in the study.

### 2.2. 3D volume measurements and browridge region definition

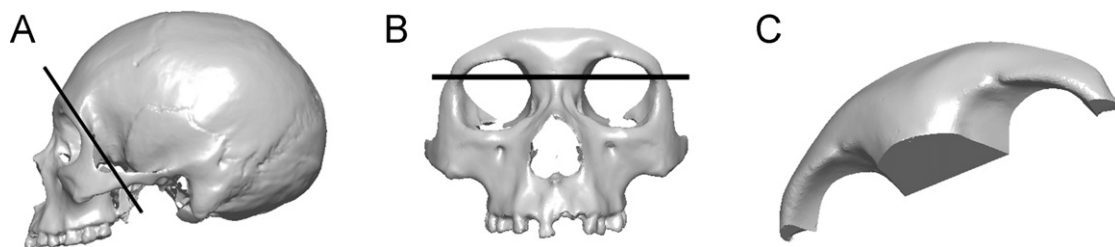
Using previously described protocols [23,31] 3D models of the studied crania were created with a NextEngine 3D laser scanner. A resolution of 75 dots per inch (dpi) was employed, corresponding to a mesh triangle size of 0.23 mm. Geometric analysis of the 3D models was carried out using the Rapidworks software version 2.3.3 and Geomagic version 12.

All 3D models were aligned along the Frankfurt horizontal plane [7] and adjusted for right-left symmetry around the mid-sagittal plane using built-in functions in the editing software. The models were digitally sectioned using a plane defined by the craniometric landmarks supraglabella (the point of deepest midline concavity above glabella) and left and right zygomatic inferior (the most inferior point on the lateral aspect of the zygomatic suture) (Fig. 2A). The portion of the model posterior to this plane was then removed, leaving the anterior portion which was sectioned once more using a plane parallel to the Frankfurt horizontal plane and passing through nasion (the midline point on the frontonasal suture) (Fig. 2B). Removal of all mesh below this plane yielded a final browridge region containing the most significant features of this part of the cranium, i.e., the supraorbital ridge and margins, also known as the trigonum supraorbital (Fig. 2C). As the laser scanner captures only surface data, the thickness of the frontal bone is not manifest in the 3D model, and the boundaries of the isolated browridge component had to be digitally sealed using hole-filling tools in the Rapidworks and Geomagic software. This procedure allows the browridge region to be displayed as a solid body, the volume of which is easily calculated using automated functions within the Rapidworks and Geomagic programs.

In addition to browridge volumes, cranial “bounding box” volumes were calculated by multiplying the length, breadth, and height of each cranium while oriented in the Frankfurt Horizontal Plane (Supplemental material, Fig. S1). These measurements were obtained from built-in features in the 3D-modeling software. When the same 3D model was analyzed with both Rapidworks and Geomagic, the average difference in measured volume was less than one percent. Even though the bounding box volumes do not constitute cranial volumes *per se*, they are proportional to the cranial volumes and therefore useful as proxy measurements. Dividing each browridge volume by the bounding box volume of the same cranium allowed the browridge volumes to be standardized for cranial size in a systematic fashion. These size-corrected browridge volume ratios were the parameters used for statistical analysis.

## 3. Results

The results of the volume measurements and the sex trait scores are presented in Tables 1 and 2, and in the online Supplemental material, Tables S1–S5. The female crania generally display smaller browridge volumes than males, which is expected as female crania are typically smaller in size. However, the size-standardized browridge volume ratios are also smaller for females



**Fig. 2.** A plane passing through supraglabella and right and left zygomatic inferior was used to isolate the craniofacial part of each cranium (A). Next, a transverse plane passing through nasion was used to isolate the final browridge region (B and C).

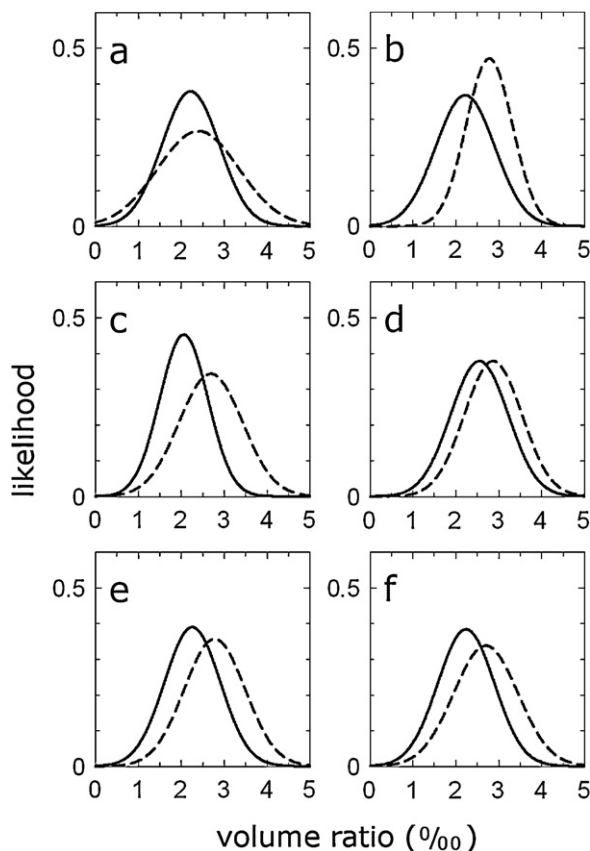
**Table 1**Mean volume ratios in per mil (‰), standard deviations, and *p*-values for the difference between male and female crania from four different populations.

Population	Female	Male	<i>p</i> -Value
Modern African-Americans, Terry collection	2.22 ± 0.69 ( <i>n</i> = 16)	2.40 ± 0.99 ( <i>n</i> = 14)	0.2887
Modern Portuguese, Lisbon collection	2.22 ± 0.69 ( <i>n</i> = 17)	2.78 ± 0.54 ( <i>n</i> = 19)	0.0051
Late California Indians	2.55 ± 0.67 ( <i>n</i> = 13)	2.87 ± 0.69 ( <i>n</i> = 16)	0.1127
Early California Indians	2.06 ± 0.57 ( <i>n</i> = 19)	2.70 ± 0.79 ( <i>n</i> = 14)	0.0083
California Indians overall	2.26 ± 0.65 ( <i>n</i> = 32)	2.78 ± 0.71 ( <i>n</i> = 30)	0.0019
All samples combined	2.24 ± 0.66 ( <i>n</i> = 65)	2.70 ± 0.75 ( <i>n</i> = 63)	0.0002

*n* = sample size; *t*-tests were one-tailed and assumed unequal variances.**Table 2**

Mean trait scores and standard deviations for male and female crania from the early and late California Indians, separately and combined.

Trait being scored	Female	Male
Nuchal crest (both California groups combined)	2.09 ± 0.98	3.23 ± 1.08
Mastoid process (both California groups combined)	2.34 ± 0.89	3.00 ± 1.02
Supraorbital margin (both California groups combined)	1.94 ± 0.62	2.87 ± 0.85
Glabella prominence (both California groups combined)	1.31 ± 0.54	2.53 ± 0.91
Glabella prominence (late California Indians)	1.46 ± 0.49	3.00 ± 0.71
Glabella prominence (early California Indians)	1.21 ± 0.54	2.00 ± 0.86

**Fig. 3.** Likelihood distributions of browridge volume ratios for females (solid lines) and males (dashed lines): (a) modern African-Americans, (b) modern Europeans, (c) early California Indians, (d) late California Indians, (e) California Indians overall, (f) all samples combined.

than for males in all studied populations (Table 1). The differences between male and female browridge volume ratios are statistically significant for the early California Indian and the modern Portuguese crania, but not significant at the  $p < 0.05$  level for the modern African-American and late California Indian crania.

In addition to differences between males and females, the results show differences between the different geographic populations, and between temporally distinct populations from the same location (Fig. 3a–d).

For example, the Portuguese and African-American females have very similar browridge volume ratios (around 2.2‰), but the Portuguese males display more robust browridges (2.78‰) than the African-American males (2.40‰) (Table 1). Furthermore, late California Indians display larger browridge volume ratios than the early group, and this difference is larger for females (2.55‰ versus 2.06‰) than for males (2.87‰ versus 2.70‰) (Table 1). The male/female difference is however highly significant for the combined early/late California Indian sample, and also when all population groups are combined.

Trait scores for the California Indian crania show a clear female/male difference, with females having mean trait scores in the range 1.3 (glabella region) to 2.3 (mastoid process), and with males having mean trait scores ranging from 2.5 (glabella region) to 3.2 (nuchal crest) (Table 2). The late Californian crania generally yield higher glabella trait scores than the early California sample, which is consistent with the overall higher browridge volume ratios of the late group. In Supplemental material, Fig. S2, browridge volume ratios are plotted against the four different sets of trait scores. As the smallest volume ratios correspond to the lowest trait scores, some correlation can be observed, but volume ratios in the range 2–4 per mil can be found corresponding to trait scores in the range 1–4 without a clear pattern for any of the four traits. Correlation coefficients (*r*) between the trait scores and the browridge volume ratios were calculated using all of Spearman's, Kendall's, and Pearson's methods (Supplemental material, Table S5). The correlation coefficients were found to be around 0.4 for glabella, 0.3 for the supraorbital margin, 0.2 for the nuchal crest, and 0.1 for the mastoid process.

#### 4. Discussion and conclusions

Sex determination from skeletal morphology is a hallmark of traditional forensic anthropology. Today many unidentified human remains are sexed through DNA analysis, but a number of situations remain in which morphological approaches are preferred. These situations include cases of genocide or mass fatality where the cost of biomolecular analysis might be prohibitive, cases of ancient human remains where the material may be too degraded to yield amplifiable DNA, and cases where invasive analysis is impermissible on legal or ethical grounds.

The browridge is one of the most sexually dimorphic regions of the skull, and qualitatively scoring the robusticity of this trait is a standard step during skeletal sex determination. Unfortunately, such subjective methods rely on the experience of the researcher

and his or her familiarity with the population sample, leaving them prone to inter-observer errors and ultimately scrutiny in the courtroom. Our recent research suggests that cranial sexual dimorphism can be quantitatively described using geometric shape analysis, thereby minimizing such dilemmas [32].

In this work we demonstrate clear differences in browridge volume ratios between male and female crania, showing that browridge volume accounts for at least some of the variation in supraorbital morphology that exists between adult males and females. Hence, volumetric measurements of local cranial features are potentially useful for sex estimation, and may help in constructing biological profiles for unidentified human remains.

Using the defining equation for the normal/Gaussian function,  $f(x) = (1/(2\pi\sigma^2)^{1/2}) e^{-(x-\mu)^2/2\sigma^2}$ , the browridge volume statistics obtained in this study can be employed to calculate the likelihood that a given cranium is male/female. This allows forensic anthropologists to not only provide a sex estimate, but also a probability reflecting the accuracy of that estimate. However, the browridge volume ratios were found to differ between groups from different geographic regions, and between temporally distinct groups from the same region. Browridge volume reference statistics must therefore be calibrated on regional data sets. For example, an unknown early California Indian cranium with a volume ratio above 3 per mil would have an 88% likelihood of being male (Fig. 3c). If the time period is unknown, the combined early and late sample data are used as reference statistics, and the cranium is given a 75% likelihood of being male (Fig. 3e). Naturally, the separation between male and female volume ratio distributions becomes less distinct when data from a number of populations are combined. Furthermore, all studied populations display substantial overlap in the distributions of the male and female browridge volume ratios in the range between 2 and 3 per mil (Fig. 3). These findings suggest that browridge volume ratios are not sufficient for reliable sex estimation on their own, but, like traditional trait scores, are more useful as a component in a multi-factorial approach to sex estimation.

The trait scores of the California samples show a clear female/male difference (Table 2), yet only weak correlations are observed between the browridge volume ratios and the trait scores (Supplemental material, Fig. S2 and Table S5). Of the four traits examined, the scores for glabella show the highest correlation to browridge volume ( $r \approx 0.4$ ), which is expected since the glabellar trait and the browridge volume describe overlapping areas of the skull. In line with this expectation the late California Indian crania, with higher browridge volume ratios, show higher glabellar trait scores than the early crania with lower browridge volume ratios (Tables 1 and 2). The other three traits – the supraorbital margin, the nuchal crest, and the mastoid process – show decreasingly lower correlations with browridge volume (Supplemental material, Table S5). Thus, traits located further away from the browridge – both in terms of functional and geometric proximity – display a weaker correlation between trait score and browridge size. This observation implies, among other things, that volumetric regions should be defined using landmarks or features located close to the region being studied.

In the present study, the browridge region was defined using glabella, nasion, and right and left zygomatic inferior (Fig. 2). Variation in the location of any of these landmarks will affect the measured browridge volume, but only variation in the location of glabella and nasion are likely to correlate with variation in browridge shape or size. The zygomatic arch is furthermore fragile and not always well preserved in dry crania, and future studies may benefit from replacing zygomatic inferior with a landmark located closer to the browridge.

When selecting landmarks to use in this kind of analysis, it appears preferable to use geometrically defined landmarks such as

glabella, rather than landmarks defined by sutural intersections such as bregma or lambda. We have previously reported that the tools available in 3D-modeling software facilitate accurate identification of geometric landmarks, which can readily be located without tactile assessment and without relying on the sometimes poor color contrast of 3D models [33]. Precise landmark identification is imperative for the kind of analysis presented in this study, since identifying the defining landmarks on the 3D models is the only step that involves human decision-making, and consequently the only source of observer error. The authors are currently planning studies to investigate the degree to which such observer errors affect this type of volume measurements.

As for the bounding box volume, it may be replaced by alternative size measures such as centroid size [36] or overall 3D model volume [23], although such measures can only be obtained for relatively intact crania. We chose to employ the cranial box volume because it has the advantages of being a standardized measure, which (a) is based on three straightforward linear distances, (b) is automatically calculated by most 3D-modeling software, and (c) can be applied to moderately damaged specimens.

During the last decade 3D scanners of various kinds have become more technically sophisticated yet more affordable, and the browridge volumes presented in this work could also be calculated from, e.g., computed tomography (CT) cranial models, which would allow the real bone thickness to be used in the volume calculations. However, CT scanning is a rather expensive technology that damages the biomolecules (e.g., DNA) present in bone [34], and earlier research has demonstrated little variation in overall bone thickness between male and female crania [35]. Thus, as 3D scanners become more frequently used in forensic laboratories, it becomes important to be aware of the pros and cons of different 3D scanning techniques when they are used to modify and improve traditional methods of skeletal analysis [23,31,36,37]. Nevertheless, when used alongside traditional forensic measurements, all 3D scanners allow for more comprehensive documentation of skeletal material and easier data dissemination. Because 3D scanning creates permanent and complete documents of the remains, analysis can continue after a case is closed and the remains have been removed from an investigator, thereby expediting the processes required for interment of remains. In our experience, 3D scanning is a versatile forensic tool that can be used to both document and analyze skeletal material, and we expect 3D scanning to soon become part of the routine examination of human remains.

*In summary*, this study demonstrates that browridge volumes measured from digital 3D models of dry crania exhibit statistically significant differences between males and females, suggesting that such objective volume calculations might be used in place of trait scoring in future systems for cranial analysis. While volume calculations may not necessarily out-perform the subjective judgments of experienced anthropologists, a volumetric measurement constitutes a continuous parameter that is easily incorporated into statistical tests of probability and significance. Hence, volume measurements allow for craniometric analysis that is highly objective, repeatable, and transparent – qualities that have been difficult to achieve in traditional anthropologic practice. The findings that browridge volume ratios differ between geographically different groups, and between temporally distinct groups from the same region, are consistent with previous observations that sexual dimorphism in the cranium can exhibit secular change [13]. The type of volumetric measurements presented in this work will likely prove useful for monitoring such geographic variation and secular changes in cranial features. Furthermore, the method presented can easily be extended to other volumetric regions of the skeleton, such as the other sexually dimorphic traits of the cranium or regions of morphological difference related to disease or ancestral affinity.



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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.forsciint.2012.06.013>.

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