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Sexual dimorphism in human browridge volume measured from 3D models of dry crania: A new digital morphometrics approach☆,☆☆

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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.

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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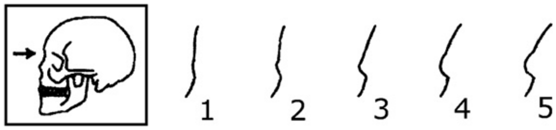

Fig. 1. The expression of the glabellar region above the browridge can be rank ordered from one to five for purposes of sex determination.
Source: Image adapted from Buikstra and Ubelaker [6].

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 zygotemporal inferior (the most inferior point on the lateral aspect of the zygotemporal 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

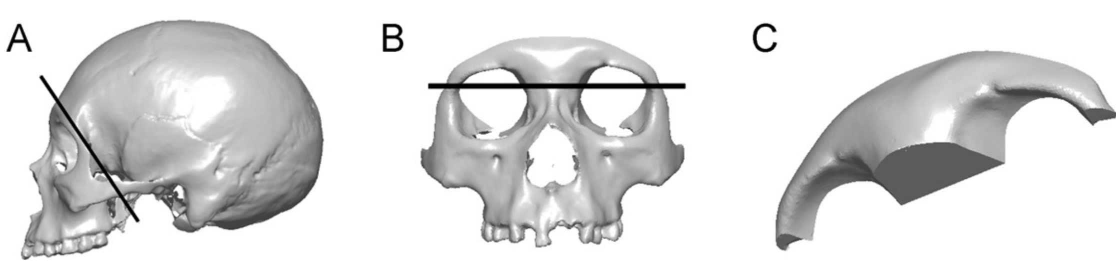

Fig. 2. A plane passing through supraglabella and right and left zygotemporal inferior was used to isolate the craniofacial part of each cranium (A). Next, a transverse plane passing through nasion was used to isolate the final browridge region (B and C).