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Exocranial surfaces for sex assessment of the human cranium

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ABSTRACT

Determination of sex is one of the most important and challenging disciplines in biological anthropology. Creating a robust tool for sexing crania is crucial for forensic anthropology, especially in this period of migration, travel, and globalization, when different populations are mixed together in one region. Many different approaches to sex estimation using the skull have been published; however, population specificity and oscillation of variable sexual dimorphism typically reduces their effectiveness. The aim of this study was to create a robust classifier using virtual anthropology without the use of a CT scanner.

The entire cranial surface was analyzed using coherent point drift-dense correspondence analysis and classification was performed using a support vector machine with a radial kernel, minimizing subjective error. The study sample consisted of 103 CT scans of a recent southern French population. Virtual scans of 52 males and 51 females (age from 18 to 92) were analyzed using 3D software systems (Rapidform, Avizo, Morphome3cs) and innovative approaches in geometric morphometrics. Leave-one-out crossvalidation was also applied. Sex differences in shape and form were displayed by colour scale maps. The whole cranial surface was significantly different between males and females in size (form). Sexual dimorphism was significantly lower in senile skulls. The most exclusive areas were the supraorbital region, orbits, cheek bones, nasal apertures, mastoids, and external occipital protuberances. The method provided a high level of classification accuracy (90.3%) in sexing male and female skulls and is a valuable tool for sex determination.

1. Introduction

One of the first steps in identification of skeletal remains is sex assessment. Determination of sex provides important background for establishing a biological profile with information on age at death, stature, and ancestry of remains [1]. It is possible to evaluate different sexual dimorphic traits on various bones and classify them as masculine or feminine. In general, the highest degree of sexual dimorphism is exhibited in the pelvic bone, which responds with evolutionary adaptation to bipedal locomotion [2] and birth mechanisms, enabling parturition of children with relatively big brains [3–6]. Thus, pelvic bone traits offer a high level of reliability for sex estimation [7]. However, in instances when the hip bone is not preserved due to its fragility, sex is estimated using the skull [8–12]. The human skull reflects the most important evolutionary changes, such as obligatory bipedalism, encephalization, specific nutrition trends, speech capability, and facial recognition of other individuals [13,14]. These trends caused a series of morphological changes in the face. For the purposes of this study, facial recognition of other individuals is particularly important—mating choices and recognition of potential sexual partners influenced cranial structures of both sexes [15,16]. Therefore, these structures have useful traits for sex determination [17,18].

The approaches typically used for sex assessment of skeletal remains oscillate between subjective visual methods and morphometric methods. Morphometry is based on linear measurements and multivariate statistical analysis, such as linear discriminant analysis, logistic regression, or support vector machines [19–22]. Classic visual scoring methods [8,11,23–25] and morphometric studies [26–30] provide satisfying accuracy, but are usually performed on past skeletal material of known sex. Therefore, they are not suitable for recent studies or contemporary forensic applications [31], especially because of changes caused by secular trends [32–34]. Another disadvantage of classic methods is the fact that expression of sexually dimorphic patterns on the

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cranium varies across populations, which makes classification accuracy highly dependent on the target population [35–38]. Also, the approaches to localization of craniometric landmarks differs between researchers [39].

Innovative 3D approaches using virtual imaging are as accurate and reliable as traditional non-computed methods using dry skulls [39–42]. Volume-rendered scans or surface scans can achieve the same or higher accuracy rates despite population specificity and decrease observer error with more independent tools [40,41,43–48]. Virtual anthropology is able to provide a higher perspective on sex assessment by focusing on smaller structures or measurements [10,12], or by examining the entire surface of the studied object. Another advantage is analysis of shape, when size is not included. The most distinctive interpopulation differences in sexual dimorphism are expressed in size [28,49,50].

Excluding the size variable from the analysis allows us to study the shape only. Another advantage of virtual anthropology is that scanning the material takes about 10–20 min, and it is easy to share these datasets with different laboratories and specialists around the world in a very short amount of time [43]. Digital forensic osteology is an innovative field of study that opens up new possibilities and connects various disciplines with the benefit of examination of modern populations and individuals of known identity [40,48].

The aim of this study was to classify sex in our dataset using 3D scans of the exocranial surface. Mesh analysis provided the ability to examine the whole cranial surface, as well as separate structures. Subjectivity was minimized by automatic mesh correspondence methods, hence the classification was not negatively influenced by intraobserver or interobserver error.

2. Material and methods

This study was based on a dataset of 103 cranial CT scans. The population sample from Mediterranean southern France consisted of 51 females 28–90 years of age with a mean age of 58 years; and 52 males aged 18–92 years with a mean age of 52. These data were collected and anonymized with the approval of the ethics committee of Aix-Marseille Université: Faculté de Médicine in Marseille, France. Scans were captured using a Siemens© Sensation 64 scanner (Erlangen, Germany) at the Department of Radiology—North Hospital in Marseille, France. The tomograph was configured as follows: 120 kV, 36–350 mAs, and 1.5 mm pitch.

The scans were manually processed and converted into surfaces in Avizo (version 6.1) software from the Visualization Sciences Group (Burlington, USA; Merignac, France). The resulting triangle meshes were manually trimmed in RapidForm XOS (INUS Technology, Inc., Seoul, South Korea). This step entailed the manual removal of the spine and unrelated objects. We also removed the jaw and teeth due to their variability. Shadow artifacts from dental fillings were also removed. After these steps, the surface model still contained the endocranium and other structures inside the skull. The surfaces were simplified to roughly 50k triangles.

Manual removal of these parts is extremely time consuming; we therefore opted for an automatic procedure that would remove most with as little user interaction as possible. We constructed an axis-aligned cube around the skull; its side was 100 times the distance between the two most distant points of the skull. Furthermore, the centers of the cube and the vertex centroid of the skull were aligned. Then, we let **Q** be the set of 26 points, which included the 8 vertices of the cube, 12 edge mid-points, and six face centers. Finally, we created the exterior surface of the skull by removing the triangles that were not visible from at least two points of **Q**. Point **a** was deemed visible from point **b**, if there was no triangle intersecting the line segment **ab**. This processing was performed in Morphome3cs and took only seconds per skull.

After the exterior surfaces were extracted, a set of eight landmarks was manually placed on each of them. A list of these landmarks is shown in Table 1.

Landmark placement was performed manually in Morphome3cs (www.morphome3cs.com) by an expert anthropologist.

Before statistical processing, vertex homology among the surfaces had to be enforced. There are many applicable procedures, but we opted to use coherent point drift-dense correspondence analysis (CPD-DCA) [52]. This approach first rigidly aligns the meshes using generalized Procrustes analysis (GPA) on landmarks; then uses an automatic nonrigid registration algorithm, coherent point drift (CPD), to compensate for the deformations between the studied meshes and a template, also called the base mesh. After registration, a closest-point search is used to find corresponding vertices. The vertices, also dubbed quasilandmarks, which cannot be matched for whatever reason, are excluded from further processing, as they would only contaminate the results with unwanted variability. In order to reduce the sensitivity of these results to landmark placement error, the surfaces are once more rigidly aligned by performing GPA on all quasilandmarks.

Visualizations were performed by mapping shell distances between the mean male and female surfaces onto the mean surface as colours (Fig. 1a). To detect the areas in which that distance is systematic and statistically significant, we used per-vertex two-sample t-tests on the shell distances from the mean surface and visualized the p-values (Fig. 1b). We also repeated the same procedure for the surfaces with normalized size, i.e. for the shape of the skull (Fig. 1c and d). In order to determine the level of sexual dimorphism in relation to age, we constructed the colour scale maps (Fig. 2) with p-values of per-vertex t-tests separately on adult subgroup (MF0, age < 60 years) and senile subgroup (MF1,

Table 1
List of used landmarks with Martin's handbook definitions [51].

Landmark	Definition
Glabella	The most anteriorly projecting point in the midsagittal plane at the lower margin of the frontal bone, which lies above the nasal root and between the superciliary arches
Inion	The most prominent point of the external occipital protuberance
Opisthion	The point at which the midsagittal plane intersects the posterior margin of the *foramen occipitale magnum*
Nasospinale	The point at which the midsagittal plane intersects lowest point of lower margin of nasal Aperture
Mastoidale dx, sin	The lowest point of the mastoid process
Zygomaticofrontale dx, sin	The point at which the inner orbital margin intersects the *sutura zygomaticofrontalis*