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Sex and ancestry assessment of Brazilian crania using semi-automatic mesh processing tools

Mikoláš Jurda *, Petra Urbanová

Laboratory of Morphology and Forensic Anthropology, Department of Anthropology, Faculty of Science, Masaryk University, Kotlarska 2, 611 37 Brno, Czech Republic

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ABSTRACT

The present paper aims to test performances of semi-automatic tools for mesh-to-mesh processing while assessing sex and ancestry in documented human crania. The studied sample of 80 human crania, which originated in two documented Brazilian collections (São Paulo, Brazil) was digitized using photogrammetry and laser scanning. 3D cranial morphology was quantified by computing inter-mesh dissimilarity measures using in-house freeware FIDENTIS Analyst (www.fidentis.com). Numerical outputs were further processed using Discriminant Function Analysis and Canonical Variant Analysis in order to classify models into sex and ancestry groups. In addition, cranial morphology was described by a set of 37 landmarks, processed by a Procrustes analysis and confronted with the inter-mesh comparison. Patterns of sexual dimorphism and ancestral group-specific variation were interpreted using average meshes and further emphasized by employing advanced visualization graphics. The mesh-to-mesh processing was capable to detect shape differences related to sex and ancestry. The highest accuracy levels for sex determination were obtained for meshes representing the facial skeleton and the supraorbital region. For both, analysis correctly assigned 82.5% of the crania. Ancestry-related differences were manifested primarily in the global cranial features (observed accuracy rates reaching 63%). The advanced visualization tools provided a highly informative insight into sexual dimorphism and ancestry-related variation. While in the current state the technique cannot be considered suitable for being implemented into the everyday forensic practice, the extent of automatization proved to be perspective, especially for assessing skeletal features that cannot be properly quantified using discrete variables.

1. Introduction

In the framework of forensic anthropology, information encoded in craniofacial morphology is traditionally exploited by two main concepts – visual and metric. The former is based on the assessment of skeletal morphology in qualitative terms, i.e., classifications into pre-defined developmental stages, categories or types. The latter is grounded on the acquisition of standardized measurements, inter-landmark distances or spatial data [1–4]. As an ongoing trend in the field, novel variants established on both concepts are being constantly developed in order to maximize reliability of biological profile if assessed from skeletal remains. This particularly applies to assessment of sex and/or ancestry.

One of the strategies how to boost precision and reliability is to combine multiple predictive features into a single complex descriptor. Nowadays, this strategy is generally linked to multivariate statistical algorithms [5]. In regards to multivariate statistics, the visual and metric approaches have been treated rather unevenly. As Hefner and Ousley [6] point out, visual traits, qualitative in nature, have not been given the statistical rigor adequate to that given to metric traits. Measurements, on the contrary, are processed standardly by various statistical methods, from those grounded in linear parametric statistics to machine learning algorithms, such as classification trees or neural networks [7–9].

In the recent years, substantial development has been made in three-dimensional acquisition technologies as well as computation performances, which increased availability and affordability of various scanning systems [10]. Current off-the-shelf recording devices have allowed creating accurate three-dimensional models with resolutions of thousands points per square centimeter [10]. Consequently, realistic 3D digital models of skeletal remains have become gradually employed in the course of forensic anthropological examination as truthful replicas to physical evidence [11], which are easily displayable [12] or usable for various documentation and presentation purposes [13]. But, first and foremost 3D models are sources of abundant quantitative and qualitative data [4,14,15].

* Corresponding author.
E-mail address: mikolasju@gmail.com (M. Jurda).

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In order to explore skeletal variations linear measurements and other discrete features extracted from 3D digital models have been utilized for more than twenty years [16–19]. Following the technological progress, however, traditional metric traits started being replaced by advanced geometry-derived variables such as three-dimensional landmarks, outlines or curves. These variables processed by methods of geometric morphometrics or statistical shape analysis have been shown to increase the amount of morphological information and ultimately to improve significantly sex or ancestry assessments [20]. However, it has been also noted that while advanced statistics-based methods are capable of increasing levels of accuracy [3,21], under unfavorable conditions they can equally provide highly biased and unreliable results. For instance, an employment of an inadequate reference sample [21–23] or an improper recording technique prone to an erroneous acquisition [24] can seriously skew acquired results.

Only recently morphological studies started focusing on information encoded in a three-dimensional (polygonal) mesh as a whole [14,24,25]. Statistical shape modeling or active shape models have been one of the techniques proposed to deal with global morphological variations. Studies based on statistical shape modeling demonstrated an improvement in performances while exploring ethnic and sex variability of various skeletal parts including femur [26], cranium [25] and patella [27]. Alternatively, quantification of mesh curvatures has been employed, for example, as a measure of complexity of the pubic symphysis surface [15,24]. Absolute distance deviations computed between aligned surfaces has been vastly preferred in studies of human face variation [28–31]. In these studies, the alignment is frequently conducted by the Iterative Closest Point (ICP) algorithm whereas the deviations are expressed in terms on closest vertex-to-vertex or vertex-to-polygon distances.

One of the setbacks of mesh-to-mesh comparisons is that inter-mesh deviations can be computed only on surfaces aligned pairwise. This limits their employment in cases where multiple meshes are to be processed. Software application FIDENTIS Analyst [32] introduced recently into the field allows multiple mesh processing based on a modified Iterative Closest Point (ICP) algorithm. According to the authors, the application is primarily designed to process 3D shell facial scans [33] and its performance has been demonstrated in studies by Urbanová [34] and Chalás et al. [35]. In essence, the program offers multiple functionalities employable in processing diverse mesh-to-mesh comparisons in user-friendly fashion. This may open new possibilities for mesh comparisons in skeletal anthropology [14,36,37].

The present study tests the applicability of semi-automatic mesh-to-mesh analysis as performed by FIDENTIS Analyst software while assessing morphological variation and manifestation of sex and ancestry specific morphology in human crania.

2. Methods

2.1. Data acquisition and pre-processing

The studied sample consisted of 80 human crania that originated in two documented Brazilian collections – a series curated by the Museum of Human Anatomy, University of São Paulo (N = 15, referred to as USP sample) and a cranial collection housed in the Paulista School of Medicine, Federal University of São Paulo (N = 65, referred to as UNIFESP sample). The crania were labeled with documentation regarding sex and ancestry derived mostly from autopsy reports. Although the information provided often contained detailed records on individual's geographic origin (such as stating country of origin, e.g., Italy, Portugal, Spain), a simplified classification of the ancestral background was adapted following a paper by Urbanová et al. [23]. For the present sample, three ancestral groups – African Brazilians, European Brazilians and Admixed Brazilians were recognized. Altogether, the sample consisted of 49 male and 31 female crania (Table 1). If tested, no statistically significant differences in age among collections and sex and ancestry categories were revealed (one-way PERMANOVA, 9999 permutations; $p_{collection} = 0.575$; $p_{sex} = 0.902$; $p_{ancestry} = 0.5193$).

Only adult crania were included into the studied sample. The adult status was verified by the fused sphenooccipital synchondrosis. Numerous crania showed minor damage in the alveolar region represented mainly by fractured alveolar juga. Furthermore, multiple cranial vaults exhibited saw cuts suggesting the autopsy-related braincase removal. In order to restore the original morphology the complementary cranial pieces were re-attached using a duct tape.

Two types of quantitative spatial data were collected for each cranium, surface 3D scans and 3D coordinates of discrete landmarks. Firstly, a set of 3D Cartesian coordinates for 37 landmarks were collected with a MicroScribe G2X digitizer. The landmarks followed definitions by [38,39] and covered the entire exocranial surface (Fig. 1).

Secondly, 3D polygonal models were created using two techniques. The UNIFESP crania were digitalized using single-camera photogrammetry for which traditional photographs are required as input images. Therefore, a set of 80–134 photographs per cranium was taken with a Nikon D7000 digital camera equipped with Nikon 60 mm AF-S Micro lens. The image acquisition was conducted under standard lighting conditions (ceiling fluorescent lamps) in full manual mode, with an aperture and exposure time set to values of f/27 and 3 s respectively. A tripod and self-timer was employed in order to avoid the occurrence of motion blurs. For each cranium, two sets of images were taken while the cranium was positioned in two different positions; one position coincided approximately with the Frankfurt horizontal while the second, reverse, position placed the basicranium upwards (basal view). In each case, the images were taken in a circle-like manner. Although spaced regularly images were not set to respect strict intervals. Altogether approximately 40 images per cranial position were taken. The two sets of images were combined and processed together in PhotoScan v.1.0.4 application employing Masking and Chunk tools using a protocol established in Urbanová et al. [11]. 3D digital models were generated under the "high accuracy" option of image alignment and dense cloud generation. The point clouds were converted into polygonal meshes using the interpolating algorithm and the "Mesh type" preference set to "Arbitrary". The resulting meshes were decimated to approximately one million vertices and appended by texture files (jpeg, 4096 × 4096 pixels). Finally, the photogrammetry-generated models were scaled according to paper scales included in photographs in order to adjust size to the real world dimensions.

The crania derived from the USP collection were scanned with a MicroScan laser scanning system, composed of a scanning head attached to a MicroScribe G2X digitizer. Each cranium was scanned in multiple positions to cover the entire exocranial surface. Acquired partial scans were aligned using a 3-point alignment function, then adjusted automatically and eventually merged into a raw 3D model. Subsequently, the merged 3D models were converted into point clouds, removed from a background noise, smoothed (with density set to 0.15 mm), re-meshed into open 3D models and finally reduced to approximately 500 k vertices. In all cases, the post-processing was performed using MicroScan Tools program.

All polygonal models were further edited with GOM Inspect v8.0 and MeshLab v1.3.3 [40]. The meshes were cleaned of isolated polygonal artifacts and records corresponding to inner bony structures. As a result, the final edited models composed of the