Detection of sexual dimorphism in the human neurocranium at local scale

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Detection of sexual dimorphism in the human neurocranium at local scale

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***Abstract* – In physical anthropology sexual dimorphism refers to the morphological differences observed in female and male individuals belonging to the same species. In the human cranium a number of anatomical traits are known to be sexual dimorphic. In this work, we present a geometric morphometric approach to automatically detect the most sexual dimorphic on skeletal collections. We applied the workflow on the human neurocranium and we defined, without an a priori definition of modules, which portions are most sexually dimorphic. We used a large sample of sex-known human 3D skulls to analyse the rate of sexual dimorphism found in the human neurocranium. We applied the Procrustes ANOVA on the best dimorphic patch found using the proposed workflow. We calculated the accuracy in discriminating sex in a sex-known sample by using our proposed model and the traditional approach.**

I. INTRODUCTION

The study of archaeological populations is a crucial step to reconstruct the lifestyles in the past. In addition, the morphological analysis of human remains returns essential information about the biological profile of populations. In bio-archaeology, the recognition of sex is essential to increase our knowledge about the culture of ancient populations, their funerary rituals and their gender concepts e.g. [1], [2]. In physical anthropology the analysis of sexual dimorphic traits is performed by distinguishing males and females by a visual assessment or metric estimation [3].

Standard anthropological approaches briefly associate a score to masculine and feminine morphology at specific anatomical traits. Optionally a weight could be associated to the score of skeletal features[4]–[6][7]. On the human neurocranium the traits taken into account include the morphology of the glabellar region, the supraorbital torus, frontal eminence, bregma, parietal eminence, mastoid shape and size, neurocranial architecture and frontotemporal constriction.

In the last years, a number of papers focused on the use of innovative shape analysis (Geometric Morphometrics, GM) method to classify a human specimen as male or female [8]–[10]. GM is a landmark-based method and it requires the definition a priori of the anatomical traits under investigation by acquiring the geometrical topology in the sample. In GM the anatomical region is described by the acquisition of anatomical (landmarks) and geometrical (semilandmarks) points [11]. The use of semilandmarks requires a sliding step to establish the geometric correspondence of the semilandmarks by removing the effect of the arbitrary initial spacing minimizing the TPS bending energy between each individual and the Procrustes mean shape [12]. The neurocranium shape can be analysed to investigate the human variability and the principal axes of variations can be used as input to classify the specimens regarding to categorical variables as the sex. In this paper, we present a GM based approach capable to identify locally which portions of skeletal surface are most sexual dimorphic. We tested the approach on a large collection of sex-known human specimen analysing the neurocranial morphology. This approach does not require an a priori definition of anatomical modules. It discretizes the surface in triangles and it analyse locally the entire topology calculating through a Procruste ANOVA [13] which triangles are related to a categorical variable: sex in our case study.

II. DIGITAL ACQUISITION

The arising of Virtual Anthropology development of computerized technologies based on X-rays, structured-light, and photogrammetry, allows us to acquire and digitally process osteological collections. Further analytical tools based on statistical and multivariate methods for the study of skeletal variability allow an assessment of evolutionary and functional of human collections. The sample used in this study consists of acquisition via CT-scan and photogrammetry. X-ray tomography provides a series of 2D slices spaced by a constant distance which defines the resolution of the scan. Information about the radio density of the object comes from attenuation of radiation, resulting from absorption and scattering, caused by the object itself. By setting a proper radio density range is set, it is possible to calculate a 3D model [14], [15][16]. Photogrammetry is a method able to reconstruct 3D model starting from the acquisition of multiple images. Via photogrammetry the operator acquires a series of images of the specimen in different views. The collected images are then aligned, a sparse point cloud is generate allowing the calculation of a 3D model [17]. The quality of the models acquired thorough CT-scan and photogrammetry are comparable. Usually 3D model acquired via photogrammetry required post-production steps as smoothing and decimation [18].

III. MATERIALS AND METHODS

The sample size consisted of 163 crania (75 female and 88 male) belonging to four digital osteological repositories: i) the Lynn Copes digital Collection [19], [20], ii) the Museum of Anthropology "G. Sergi" from Sapienza University of Rome [21], iii) the Oloriz Collection from Spain and iv) the Anthropological Museum of Florence (University of Florence) [22]. The collections consisted of 3D models of crania of adult specimens of known-sex. The 3D models were obtained via photogrammetry and via CT scan as explained in the "Digital Acquisition" section. Each 3D model composing the sample of study has been decimated to 500.000 facets; no smoothing algorithm has been applied in order to avoid loss of anatomical information[23].

On each specimen, we collected 50 landmarks (Table 2) placed on the entire cranial morphology by using Avizo software (version 7). We defined on a specimen, chosen as reference, a net of geometric points (semi-landmarks). The patch of semi-landmarks consists of 500 bilateral and symmetric points.

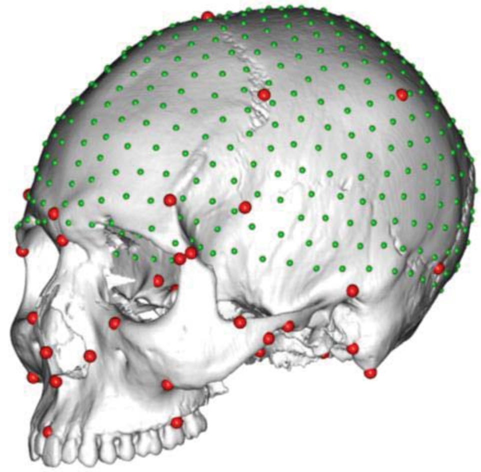


Fig. 1. Landmark (red) and semi-landmarks (green) shown on the reference specimen (grey).

We analysed the shape of the entire neurocranial region by performing a PCA on the scaled and rotated landmark and semi-landmark configuration after the Generalized Procrustes Analysis. We reported in figure 2 the PCA of the first two PC scores.

Methodological design

We devised an approach to detect dimorphic sexual signal into a very small local scale. First, we built a triangulation starting from the entire semi-landmark configuration (500 points); second, we performed on the three vertices composing each triangle of the triangulation a Procrustes ANOVA test (function procD.lm of the geomorph R package) [13] and we calculated at each triangle the p-value and the R-squared value.

We built a semi-landmark patch by using only the vertices belonging to those triangles presenting a p-value lower than 0.05. The semi-landmark patch so defined is the best sexual dimorphic patch (BDP) in the neurocranium.

By using the procedure described below, we are able to find morphological patches responding to categorical variables as sex in this study. We tested the goodness of fit of the procedure by creating 1000 random patches formed by N contiguous semi-landmarks of the same size of the BDP. The connection between semi-landmarks has been extrapolated from the triangulation of the entire set of semi-landmarks. At each iteration we calculated the R-squared value. We counted the number of iterations in which the R-squared value is lower than that observed in the BDP and we divided by the number of total observed values (number of iterations + BDP). In this way, we properly defined the p-value.

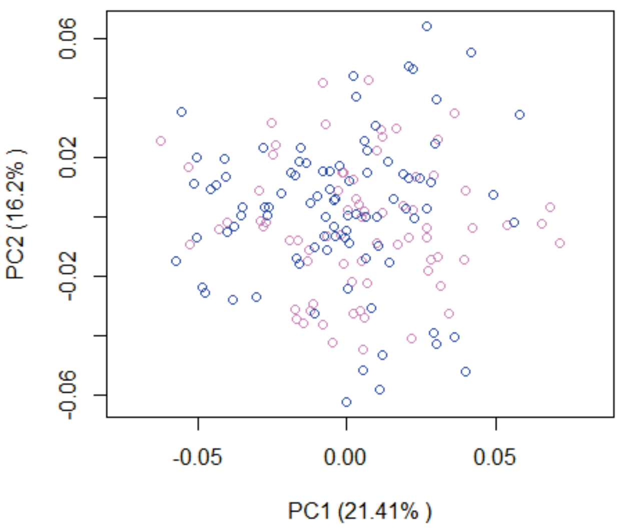
Detection of sexual dimorphism in BDP

On the entire neurocranium and in the BDP we performed a Linear Discriminant Analysis (LDA) considering in the model the 75% of the shape information (PCscores), the Centroid Size (CS) and the sex variable. Subsequently, we calculated the accuracy of the model to discriminate, within the sample, the female and the male individuals.

IV. RESULTS

The PCA performed on the landmark and semi-landmark configurations highlights the presence of an overlapping between female and male morphology. The first two PC scores accounts for 37.61% of the total variance.

We calculated at each triangle of the triangulated patch of semi-landmark (500 vertices and 952 facets) the relation between shape and sex variable. For each triangle we extracted the p-value and R-squared after applying the Procruste ANOVA. We selected only the vertices belonging to the facets associated to a p-value lower than 0.05. This collection of vertices defined the Best Sexual Dimorphic Patch (BDP). As stated in the section "*Methodological design*" we calculated the Procrustes ANOVA on the BDP and on 1000 random contiguous patches sampled with same number of semi-landmarks (N=208). In Figure 4 is reported the R-squared distribution for the random patches. These values are bracketed between 0.010 and 0.018. The R-squared calculated on the BDP is equal to 0.029 and statically significantly lower than random patches (p-value = 0.001).



Fig, 2. PCA of the first two principal components performed on the entire neurocranium. Female and male specimens are reported in violet and blue respectively.

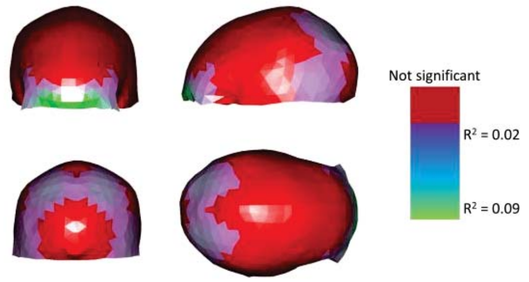


Fig. 3. Detection of local sexual dimorphism in the human neurocranium. In red triangles not sexual dimorphic (p-value greater than 0.05). The gradient of sexual dimorphism is reported in a colour gradient ranged from violet (low sexual dimorphism) to green (high sexual dimorphism).

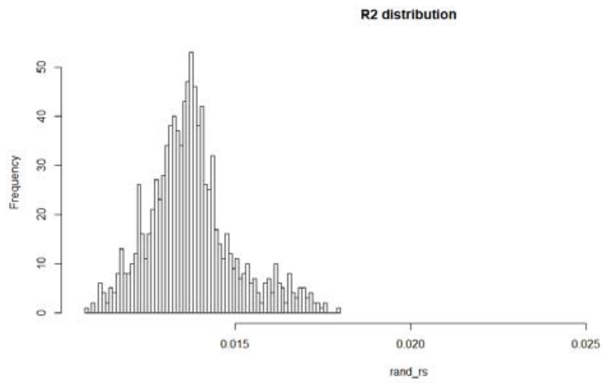


Fig. 4. Histogram showing the distribution of R-squared calculated on random and contiguous semi-landmark patches. The vertical line indicates the R-squared calculated on the best dimorphic patch.

The linear discriminant analysis performed on the entire neurocranium shows an accuracy equals to 0.79, while the precision to discriminate correctly females and males is equal to 75% and 83% respectively.

The same analysis performed on the BDP return a value of accuracy equals to 0.84. The precision to correct identify females is equal to 82%, the precision to classify male specimens is equal to 85%.

V. DISCUSSION

The study on sexual dimorphism landmark-based traditionally requires the definition of a model to be tested against the sex variable. For what concerns the skull the rate of expression of some anatomical feature are easily recognisable such as development of supraorbital torus, the glabellar region, presence of the frontal eminence, orbital margin shape, shape of the zygomatic bone, mastoid size, the nuchal crest. In detail for the neurocranium only a few numbers of landmarks are detectable. For this reason, until now a quantitative approach is not possible. We overcome this issue by using a semi-landmark approach without a definition of modulus a priori.

Our results show as the neurocranium is not entirely sexual dimorphic despite in literature its globular architecture is associated to female morphology. We found as the major anatomical traits sexual dimorphic are found in correspondence with the supraorbital torus, the frontal-temporal constriction, the parietal eminence. We need to consider that the sample used in this study coming from different populations and the population affinity variable should influence the neurocranium morphology in some traits more than sex variable.

The advantage of using the approach reported in this study, is the chance to visualize the shape variations of the modules found related to sexual dimorphism only, deleting all the shape information not directly related to sexual dimorphism (fig. 5). In addition, a more extensive study of the entire cranial morphology could be taken as reference by physical anthropologists to correctly detect sex in sex-unknown archaeological populations.

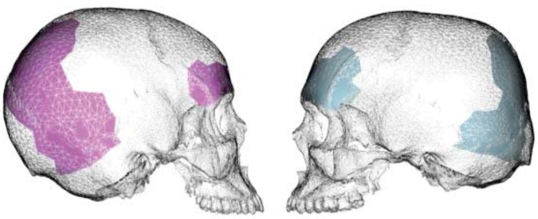


Fig. 5. Shape variations associated to the best dimorphic patch in females (left) and males (right)

VI. CONCLUSION

The potentiality of synergy between advances in technology (Virtual Anthropology) and shape analyse (Geometric Morphometrics) techniques has been shown in this case-study. Traditionally, physical anthropologists analyse the "real" skeletal collections in order to extrapolate information about the population as sex, age, paleopathology. This case-study showed as the use of digital models instead of physic ones could be a real alternative way to infer on the life history of human populations.

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