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Sex estimation by size and shape of *foramen magnum* based on CT imaging

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ABSTRACT

Foramen magnum (FM) has a well-protected position, which makes it of particular interest in forensic research. The aim of the study is to assess the sex differences in size and shape of FM, develop discriminant functions and logistic regression models based on the FM measurements, compare the accuracy results of the measurements obtained through different measuring approaches, and establish the most reliable variables for sex estimation in Bulgarian adults. Head CT scans of 140 Bulgarian adults were used in the study. The segmentation of the skulls was performed in the software InVesalius. The length, breadth, circumference, and area were measured based on the 3D coordinates of definite landmarks and semi-landmarks. The circumference and area were calculated regarding the foramen as a 2D and 3D structure. Two additional variables (λ_2 and λ_3) corresponding to the least square errors along the length and breadth directions at the fitting of the 3D coordinates to a plane were examined for their sex discriminating ability. The FM shape was classified based on the values of the FM index. The significance of the sex differences was assessed. Discriminate function analysis and binary logistic regression were conducted. Significant sex differences were established in the FM size and shape. The eigenvalue λ_3 is the best discriminating parameter applying discriminant function analysis. The acceptance of FM as a 2D or 3D structure does not provide substantial information for its sex discrimination. The measurements of FM do not offer sufficiently high predicting rates for sex estimation in the Bulgarian population.

1. Introduction

The identification of skeletonized human remains is a challenge in forensic expertise. Sex is one of the main characteristics of the biological profile of the individual and its estimation is an essential part of medico-legal investigations. The more available bones there are, the better opportunity will be for reliable results in sex assessment. However, a whole and well preserved skeleton is a rare finding; therefore methods for sex estimation were developed based on different bones and bone parts. This increases the possibility for correct sex estimation and successful identification of the deceased. Thus, the parts of the skeleton which are more likely to remain integral and undamaged are very useful in personal identification and are of significance in forensic studies. The cranial base has been reported to stay intact although the other parts of the skull can be compromised [1]. Since the cranial base along with the *foramen magnum* (FM) is protected by a large amount of soft tissue, mainly muscles and ligaments [2], it can remain less affected by physical injuries, proving a considerable merit of its utilization for the purposes of sex estimation [3].

The FM is an anatomical area traversed by the medulla oblongata, the meninges, the ascending portion of the spinal accessory nerve, and the vertebral and spinal arteries [4]. It provides a pathway for the constant flow of fluids and nerve impulses between the neurocranium and spine, and thus possesses specific hemodynamic, hydrodynamic, and locomotor functions [5]. The length of the FM attains its adult dimensions by 5 years of age, whereas the growth in the breadth continues until the end of the first decade [5]. Therefore, both size and shape of the FM undergo modifications until 10 years of age [6]. Hence,

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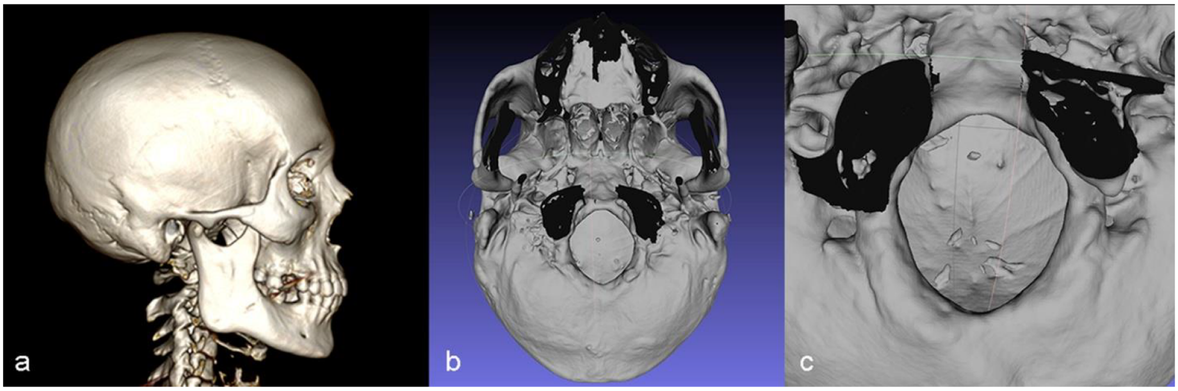

Fig. 1. 3D visualization of a skull: (a) Lateral view of a skull and vertebrae captured in a head CT-scan, visualized in the software InVesalius; (b) Bottom view of a 3D model (STL) of a skull in the software MeshLab with deleted vertebrae; (c) Close view of *foramen magnum*.

the FM shape and size could be influenced by factors associated with its formation and development, such as variations in the rate of suture closure as well as simultaneous development of neural structures in the FM region [7,8].

The value of the FM measurements for sex prediction in forensic investigations has previously been evaluated. Most of the studies in the extant literature assess the significance of the FM in sex estimation via direct examination of dry skulls [3,9–18]. Computed tomography (CT) [8,19–29] and digitizer [30] have also been used for this purpose and the CT is suggested as a reliable and useful tool in the FM studies [20]. Although modern technologies have recently been applied, the FM has been regarded as a two-dimensional (2D) structure for its measurements, and thus the area calculation depended on simple formulas based on the main FM diameters or was computed using a given tomogram. Still, the FM is a 3D structure. Hence, we decided to take the measurements considering the foramen as a 3D structure using landmark-based approach as well as to project it onto a plane and to compare the accuracy results of the measurements obtained through the different approaches.

Based on the different techniques of examination and the set of measurements used, discriminant functions and logistic regression models for differentiation of the sex by the FM measurements have been developed for various population groups, though there have been no such data for the Bulgarian population. Therefore, the present study aimed to assess the sex differences in the size and shape of the FM, develop discriminant functions and logistic regression models based on the FM measurements, compare the accuracy results of the measurements obtained through different measuring approaches, and establish the most reliable variables for sex estimation in Bulgarian adults.

2. Material and methods

2.1. Sample

CT head scans of 140 Bulgarian adults (70 males and 70 females) were used in the study. The mean age of the males was 61.5 ± 15.5 years and of the females was 64.4 ± 14.3 years. The CT scans were carried out using a Toshiba Aquilion 64 CT scanner. The scanning protocol was as follows: 32 × 0.5 mm detector configuration, tube voltage of 120 kV, tube current ranging from 165 to 500 mA, exposure time of 0.5 s, total scan time of 6.5–7 s, and helical pitch of 0.625. Images were reconstructed with a 512 × 512 reconstruction matrix, 0.5 mm slice thickness and 0.3 mm reconstruction interval using convolution kernel FC63. Individuals with traces of trauma, surgery or pathological lesions in the FM region were not included in the sample. The study was approved by the Ethics Committee at the IEMPAM-BAS.

2.2. 3D models generation

The segmentation of the skulls was performed in the open source software InVesalius [31] (Fig. 1a). Initially, the predefined “Bone” threshold was selected for the mask for generation of the 3D surface of each skull. Afterwards, the 3D surface was created and the produced 3D model was exported in STL format. Each 3D model was imported into free software MeshLab [32], where the vertebrae were deleted and the FM region was exposed (Fig. 1b and c).

2.3. Digital measurements

The FM length (FML), breadth (FMB), and circumference (FMC) were measured digitally based on the 3D coordinates of definite landmarks and semi-landmarks. The FML was measured between the landmarks *basion* and *opisthion*, i.e. the points where the midsagittal plane intersects the anterior and posterior margins of the foramen, respectively. The FMB was measured between the most laterally located points on the lateral margins of the foramen. The 3D coordinates of the four landmarks were recorded using the Pick Point function in the software MeshLab (Fig. 2a). Both linear measurements were calculated as Euclidean distances based on the 3D coordinates of the corresponding landmarks using the software PAST [33]. The FMC was measured using the Curve option in the free software Landmark Editor [34], since the 3D models were exported in PLY file format beforehand. Two curves were constructed on the right and left side of the FM outlining the contour of its margin. The first curve was built with placement of the first landmark on *basion*, the second one on the visual halfway of the lateral margin and the third one in the region of *opisthion* (Fig. 2b). The second curve was built as the first landmark coincided with the last landmark of the first curve, its second landmark was placed in the halfway of the lateral margin of the foramen and the third landmark ended in *basion* (Fig. 2c). Both curves consisted of 41 semi-landmarks, therefore a total of 80 landmarks were used to outline the foramen circumference, because two of them are common for both curves. The 3D coordinates of all landmarks and semi-landmarks were exported in NTS format. After that, the Euclidean distances between each pair of consequent landmarks were calculated and summed up to obtain the total circumference of the foramen (FMC-3D).

The FM area (FMA) was computed using the 3D coordinates of the landmarks and semi-landmarks, located on the foramen margin. Two approaches were used for its calculation. At first, the FM was considered as a 3D structure (Fig. 3a and b). Using the coordinates of all 80 points, the center of mass for each polygon formed by the landmarks was computed as a weighted average of the midpoints of the 80 polygon sides with weights equal to the length of the corresponding side. Afterwards, each 3D polygon was split into 80 non-overlapping triangles, having the center of mass as a common vertex, and the surface