RESEARCH ARTICLE

THREE-DIMENSIONAL MODELS OF HUMAN SKULLS AND THEIR APPLICATION IN SEX DIFFERENCES ANALYSIS OF MIDSAGITTAL LINE

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ABSTRACT

The development of technology and different imaging techniques has contributed to the development of science in general. Imaging has also found application in anatomy. Aim of this research was the application of three-dimensional models of the human skulls in analysis of sex differences of the midsagittal line. The research was performed on 211 three-dimensional models (3D) of human skulls from the Bosnian population (139 male and 72 female skulls). 3D models were obtained by scanning the skulls using a laser scanner. On 3D, seven nonpaired landmarks in the area of the midsagittal line were marked using Landmark Editor program. The position of the marked landmarks was used for analysis of sex differences in the shape of the midsagittal line and for analysis of sex differences of maximum sagittal diameter in the area of the midsagittal line (maximum cranial length, glabella-opisthion). Geometric morphometrics was performed to analyze shape differences of the midsagittal line between the sexes, and the results of correct classification test showed statistically significant differences. Sex determination using the shape of the midsagittal line was possible with 66.19% accuracy for male skulls and 62.5% for female skulls ($p<0.001$). Results of regression analysis showed a statistically significant effect of size of the midsagittal line on its shape. Results of univariate analysis showed statistically significant differences between the sexes ($p<0.001$). The application of three-dimensional models of the skulls for sex determination based on the midsagittal line showed statistically significant differences between the sexes.

Keywords: 3D models, geometric morphometrics, sexual dimorphism, skulls, univariate analysis

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INTRODUCTION

The development of technology and different imaging techniques have contributed to the development of science and humanity in general. Many scientific disciplines are based on imaging or the analysis of an image content. Imaging is an indispensable technique in many branches of medicine. Imaging parts of the body is the basis of radiology, the results of which are used for procedures in almost all areas of medicine. Techniques used in medicine for imaging have developed over time, which has contributed to better and faster disease diagnosis as well as the treatment process itself (D'Errico et al, 2017).

Imaging of body parts can be based on the application of computed tomography (CT), digital radiography (RTG), magnetic resonance imaging (MRI), single-photon emission computed tomography (SPECT) and other imaging technologies that have gradually developed and are widely used. In addition to being used in diagnostics and treatment, new imaging methodologies are also widely used in scientific research in almost all areas of medicine (Almutairi et al., 2017; Hidrovo et al., 2017; Liu et al., 2018; Sun et al., 2018; Pottle, 2019).

Imaging has also found its application in anatomy, where X-ray images have been used from the earliest studies of anatomy to the newer techniques of 3D modelling of the human body. New 3D modelling method has proven to be excellent in understanding interrelationships of organs and organ systems in anatomy. Over the past few years, advanced 3D modelling technology has provided the ability to create realistic printed models of organs, including the bones. Thanks to the precise scanners used for 3D scanning, the three-dimensional models are morphologically indistinguishable from the scanned part of the body. The three-dimensional models obtained in this way have a significant role in education, but also in scientific research (Vaccarezza, 2015). The printed models have significant educational value, where parts of the body can be viewed from all sides, and the interrelationship of organs does not have to be imagined by looking at a 2D image (Hadziomerovic et al., 2023). 3D printed models have shown advantages in anatomical education (Ventola, 2014; Smith et al., 2018; Smerling et al., 2019). In 2020, the results of meta-analysis showed that students who studied on three-dimensional models had better results on anatomy exams compared to students who used the traditional method of studying anatomy (Fleming et al., 2020).

The use of three-dimensional modelling has brought new approaches and technologies to the healthcare industry. Data obtained by CT or MRI can now be processed and converted into 3D models. 3D models can be printed. In addition to the application of 3D modelling for printing organs that will be used for educational purposes, 3D modelling is used for printing and manufacturing of customized prosthetics and implants (Beculic et al., 2023).

Scanning parts of the human body and saving 3D models enable the digitization of data that can be saved for a long period of time, unlike the biological materials. Also, parts of the human body are less accessible for study and scientific research, having their own duration and some important anatomical features destroyed with use. Therefore, their scanning and storage of 3D models enable permanent storage from which 3D models can be obtained over a longer period of time, which facilitates the process of learning and research (Ye et al., 2020).

Three-dimensional models of human body parts in anatomy are used for education and scientific research. All research on macroscopic morphological characteristics of organsperformed on organs themselves, is also performed on three-dimensional models of the examined organs (D'Errico et al., 2017). Thanks to the development of precise statistical programs, the application of three-dimensional models enables much more complex and precise research than classical methodologies used in research directly on parts of the human body.

The aim of this research was to use three-dimensional models of human skulls for the analysis of gender differences in the area of the midsagittal line.

MATERIAL AND METHODS

The research was performed on 211 three-dimensional models of human skulls from the Bosnian population of known sex and age (139 male and 72 female skulls) after an Ethical approval by the Ethics Committee of the Medical Faculty (Number 02-3-4-2377). Three-dimensional models were obtained by scanning the skulls using a laser scanner (HP 3D Structured Light Scanner Pro S2 (DAVID SLS-2), resolution accuracy of 0.05%.). After setting up and aligning the scanner according to the manufacturer's instructions, three-dimensional models of the skulls were taken. The skull for scanning was placed on a rotating stand, and the number of scans to be made was set on a computer connected to the scanner. The distance of the object from the scanner is defined in the manufacturer's instructions and was determined through calibration on the rotating stand. The skull was placed in the Frankfurt horizontal plane and 15 scans were taken, and the stand was rotated 24˚ between two adjacent scans (24x15=360, 360˚- full circle). After scanning in the Frankfurt horizontal plane, the skull was placed on the right side to make 3 scans of the skull base and 1 scan of the skull roof named calvaria, and the process was repeated after the skull was placed on the left side. In this way, a total of 23 scans of the scanned skull were obtained. The scanner contains its own software for automatic or manual scan assembly.

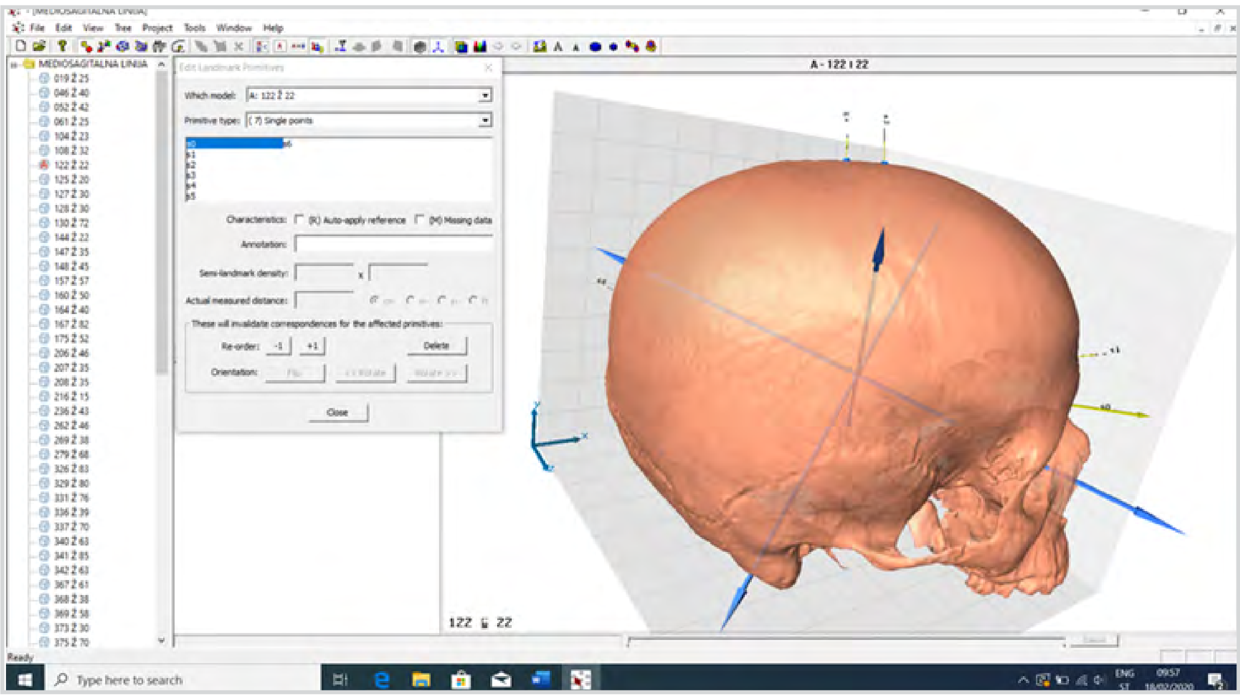

Figure 1 Designation of landmarks in Landmark Editor program on the midsagittal line

The position of the marked landmarks was used for:

1. Analysis of gender differences in the shape of the midsagittal line,

2. Analysis of gender differences of maximum sagittal diameter in the area of the midsagittal line. This diameter is named as maximum cranial length, and that is the distance between two landmarks, glabella and opisthion.

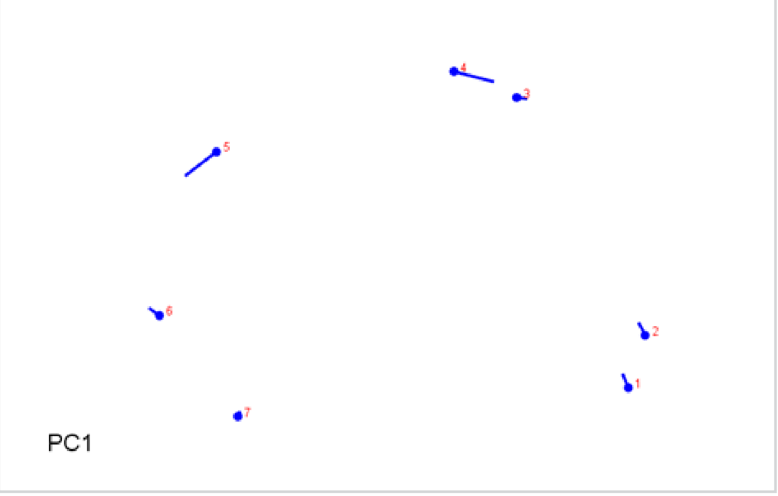

Figure 2 Position changes of landmarks on the midsagittal line described by principal component 1 (PC1) *Blue circles represent mean values of landmarks* Blue lines represent the direction and intensity of changes from the mean values of landmarks (1-nasion, 2-glabella, 3-bregma, 4-vertex, 5-lambda, 6-inion, 7-opisthion)

We provided manual scan assembly. The resulting scans were then cleaned of the artifacts, i.e. everything was removed from the scan except the skull scan itself. The scans were then assembled in such a way that clearly recognizable identical points were observed on two adjacent scans that were joined, which ultimately resulted in the assembly of the entire skull model from the captured scans. After merging the scans, a three-dimensional model was obtained. The procedure was repeated for all skulls from the tested sample. All skull models were given a uniform name, where the first three numbers indicate the serial number of the skull, in the middle is the letter M or Z which indicates the sex of the skull (M- male and Z-female), and the last two numbers indicate the age of the skull (for example 010 M 15). After obtaining three-dimensional models of all skulls from the examined sample, the models for each skull were saved in two formats, a .ply file and a .stl file.

On the three-dimensional models, seven nonpaired landmarks in the area of the midsagittal line were marked using Landmark Editor program (Wiley, 2005). Landmarks are: nasion, glabella, bregma, vertex, lambda, inion and opisthion (Figure 1).

RESULTS

Analysis of gender differences of midsagittal line shape on three-dimensional models of human skulls using geometric morphometric method

Position of the skulls based on the shape of the midsagittal line described by Principal component 1 (PC1) was presented on Figure 2.

Procrustes distances were calculated in MorphoJ program (Klingenberg, 2014). As classifier was entered sex, according to which the differences in the shape and size were analysed anda covariance matrix was generated. The analysis of the principal components (PCs) showed that the first two components (PC1 and PC2) described 52.918% of the total variability of the shape of the midsagittal line (Table 1).

Table 1 Eigenvalues and percentage of shape variability of the midsagittal line described by principal component analysis (PCs)

Number of PCs	Eigenvalues	% Variance	Cumulative %
1.	0.00117335	28.483	28.483
2.	0.00100656	24.434	52.918
3.	0.00070537	17.123	70.041
4.	0.00037235	9.039	79.080
5.	0.00033326	8.090	87.170
6.	0.00026760	6.496	93.666
7.	0.00013078	3.175	96.841
8.	0.00008526	2.070	98.910
9.	0.00002962	0.719	99.629
10.	0.00001526	0.370	100.000

Correct classification tests compare two groups. The test analyzes the mean values of two groups in the form of Procrustes distances or Mahalanobis distances.

Correct classification test was performed, and we analyzed the differences in the shape of the midsagittal line between the sexes. The calculated Procrustes distance was 0.0225, and the p value was less than 0.0001, which showed statistically significant differences between genders. Variability of the skull according to the shape of the midsagittal line defined by the first two principal components was presented on Figure 3.

Table 2 presented the results of correct classification test which correctly classified 92 out of a total 139 male skulls, i.e. as male skulls, which is 66.19% accuracy for male skulls. The correct classification test correctly classified 45 skulls out of a total 72 female skulls, i.e. as female skulls, which is 62.5% accuracy for female skulls.

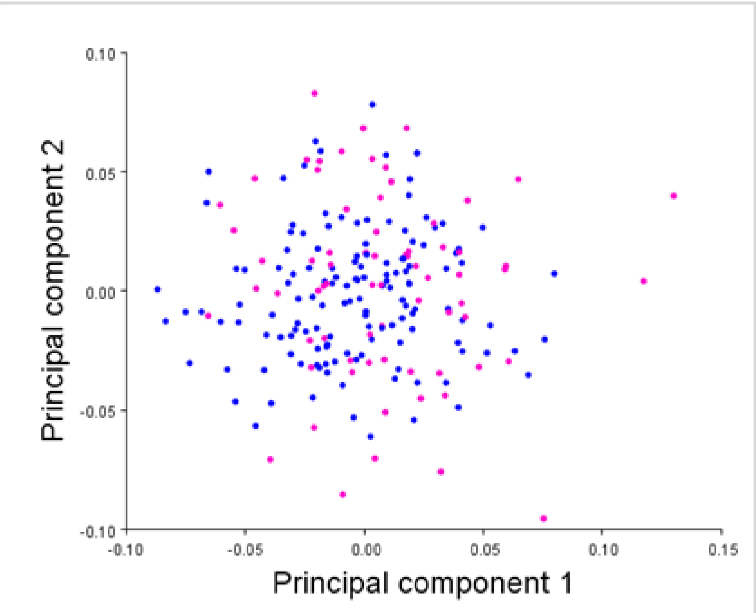

Figure 3 Variability of skulls according to the shape of the midsagittal line defined by first two principal components

Table 2 Results of correct classification test of sex using shape of the midsagittal line

Skulls	Male skulls	Female skulls	Total
Male skulls	**92**	47	139
Female skulls	27	**45**	72

Analysis of effect of size of midsagittal line on its shape using geometric morphometric method

A regression analysis was applied to examine the influence of size on the shape of the midsagittal line. The results showed an influence of 3.5216%. The results of regression analysis was presented in Figure 4.

The interval of the shape changes of the midsagittal line was presented on Figure 5.

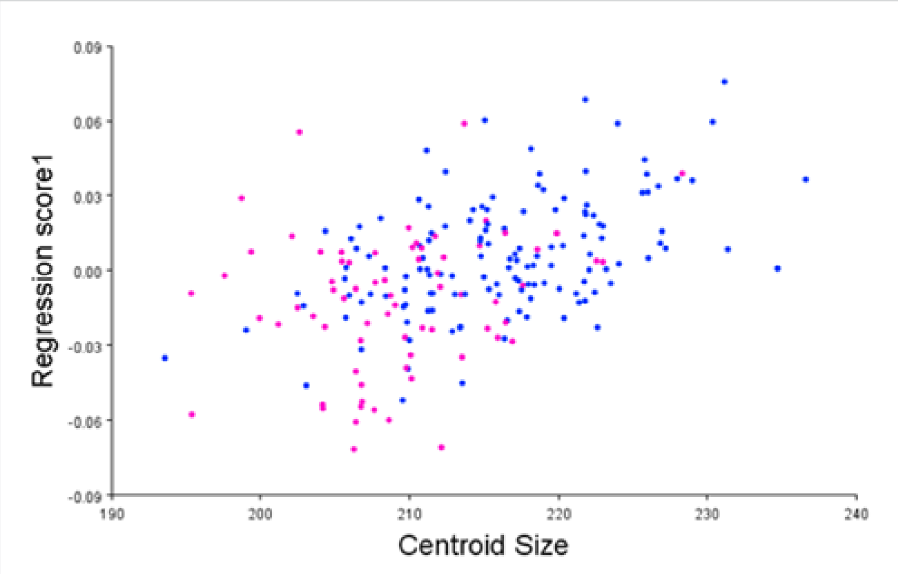

Figure 4 Influence of the size of a region in the area of the midsagittal line on sexual dimorphism of its shape

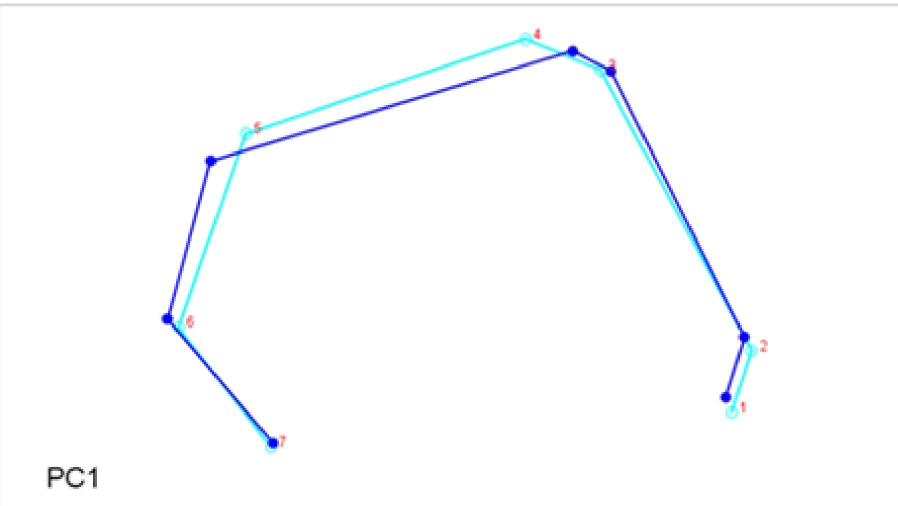

Figure 5 Iinterval of the shape changes of the midsagittal line

Analysis of sexual dimorphism of midsagittal line size on three-dimensional models of skulls using univariate analysis

Gender differences of the size of the midsagittal line on three-dimensional models were assessed by measuring linear diameter maximum cranial length on each three-dimensional model. Maximum cranial length is a diameter between landmarks glabella and opisthion.

Each landmark used to calculate the diameter was marked on three-dimensional models of the examined skulls. Landmark glabella and landmark opisthion have their x, y and z axis values in the coordinate system, based on which their mutual distances are calculated, which represent the linear diameter maximum cranial length (L1). The values of the maximum cranial length for all 211 three-dimensional models of the examined skulls were presented tabularly in Excel, after which statistical processing of the obtained data was performed.

Univariate analysis of gender differences of linear diameter L1 was performed in STATISTICA 10 program.

The results of univariate analysis of sex differences in the length of L1 diameter showed statistically significant sex differences (p value was less than 0.01), Table 3.

Table 3 Univariate analysis of sexual dimorphism of linear diameter L1 (glabella-opisthion)

	B	S.E.	Wald	df	p	Exp(B) DG	95% Confidence interval	
							GG	
L1	-1.641	0.325	25.434	1	**0.000**	0.194	0.102	0.367

DISCUSSION AND CONCLUSION

The study was performed on 3D models of 211 adult human skulls of known sex and age. The skulls belong to the Osteological Collection, Faculty of Medicine, University of Sarajevo. They belonged to individuals who lived on the territory of Bosnia and Herzegovina during the Second World War. One of the goals of this study was to scan the skulls of the osteological collection. Bone material has been exposed to damage over time and due to use. Some of the important anatomical features are missing or have fragmented over time. Therefore, the scanning of existing anatomically preserved skulls, whereby their three-dimensional models are obtained, enables their digitization and permanent preservation. In this way, the osteological material was digitized. Thanks to the precision of the scanner used (resolution accuracy of 0.05%), the obtained three-dimensional skull models are analogous to the recorded skulls. The obtained three-dimensional models can be used for scientific research, and they can also be printed, whereby the printed material can be used for education in anatomy and related disciplines.

In this study, three-dimensional models were used to analyze gender differences in the midsagittal line. In the first part of the research, geometric morphometry was used to analyze gender differences in the shape of the midsagittal line.

After the Procrustes superimposition, generation of the covariance matrix and the introduction of sex as a classification variable, a discriminant functional analysis was applied, which determined the prediction for the male gender with 66.19% accuracy and for the female gender with 62.5% accuracy. The size effect of this region on its shape was examined. Result showed a statistically significant effect of the size on its shape, and that was 3.5216% of the sex variability of the shape of a region in the area of the midsagittal line.

In the second part of the research, maximum cranial length was calculated on the three-dimensional models based on the x, y, and z axis values of two landmarks between which this diameter was measured.

After obtaining the values of the diameter of maximum cranial length for all three-dimensional models of the examined sample, the statistical processing of the data was started. The results of univariate analysis showed statistically significant differences in the length of this diameter between the sexes. Maximum cranial length is significantly longer in three-dimensional models of male skulls.

The area of the midsagittal line is the area of interest for a number of researchers who analyzed the gender differences.

In the investigation of sexual dimorphism of the midsagittal line, Bigoni et al. (2010) used a geometric morphometrics method. Gender determination based on the shape of the midsagittal line was possible with 100% accuracy for males and 98.4% accuracy for females. Our results showed a lower percentage of accuracy in determining sex (66.19% accuracy for the male gender and 62.5% accuracy for the female gender). In their study, the shape of the mediosagittal line was used, which was analyzed using semilandmarks that are more applicable for the analysis of the mediosagittal line, given that the mediosagittal line has only nonpaired anthropometric points in the mediosagittal plane.

We used a geometric morphometrics program based on the analysis of landmarks, not semilandmarks.

In a study conducted in 2016 on the skulls from the Greek population using geometric morphometry, the accuracy of sex determination based on the shape of the mediosagittal line was 68.8%, while the accuracy of sex determination based on the shape of the mediosagittal line (size and shape) was 79.4%. In this study, the authors used the same program as in our study, and the results are approximately equal to our results (Chovalopoulou et al., 2016).

The analysis of gender differences of maximal cranial length showed that there were statistically significant differences in the length of this diameter between the sexes. These results coincide with the results of other studies that conducted similar research.

Supporting the accurate and high-quality scanned three-dimensional models of the examined skulls were the results of this research in comparison with the results of the study conducted directly on the skulls from the examined sample. The results of the examination of gender differences of maximum cranial length of three-dimensional models showed statistically significant differences between the sexes, as did the results of the examination of the gender differences in maximum cranial length of the skulls that were scanned for the current study (Ajanovic, 2017).

Abdelnasser et al. (2017) used three-dimensional skull models obtained from postmortem CT scans of 87 skulls from Malaysia for sex determination. They measured 22 diameters on the obtained three-dimensional models. The results of the study showed that all examined diameters were longer in male skulls, except for the height of the orbit. The accuracy of gender determination was 85.1% in the mentioned research.

Results of the study performed on CT scans of the skulls of patients from Sudan showed that all linear diameters were larger on CT scans of male skulls then the same linear diameters on CT scans of female skulls (Altayeb et al., 2011).

Results of the study provided on the sample of the skulls from Brasilian population showed that all measured linear diameters were statistically significantly longer on male than on female skulls (Zavando et al., 2009).

The results of the studies conducted on skull samples from different populations showed that the linear diameters of the skulls were statistically significantly longer in male skulls compared to the same diameters in female skulls, which is in agreement with our results (Marinescu et al., 2014; Vidya et al., 2012; Saini et al., 2011; Lopez et al., 2009; Franklin et al., 2005).

The application of three-dimensional models of the skulls for sex determination based on the midsagittal line showed statistically significant differences between the sexes in this region with similar results to research conducted directly on the skulls.

CONFLICT OF INTEREST

The authors declared that there is no conflict of interest.

CONTRIBUTIONS

Concept – ZA; Design – ZA; Supervision – ASH; Resources –ED, AL; Materials – ZA, UA; Data Collection and Processing – UA, HH; Analysis and Interpretation – ZA, ASH; Literature Search – LD; Writing Manuscript – ZA; Critical Review – ASH.

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TRODIMENZIONALNI MODELI LJUDSKE LOBANJE I NJIHOVA APLIKACIJA U ANALIZI SPOLNIH RAZLIKA SREDNJE SAGITALNE LINIJE

SAŽETAK

Razvoj tehnologije i različitih slikovnih metoda snimanja su doprinijeli razvoju znanosti u cjelini. Snimanje je pronašlo svoju primjenu i u anatomiji. Cilj ovog istraživanja je primjena trodimenzionalnih modela ljudske lubanje u analizi spolnih razlika srednje sagitalne linije. Istraživanje je provedeno na 211 trodimenzionalnih modela (3D) ljudskih lubanja pripadnika bosanske populacije (139 muške i 72 ženske). 3D modeli su kreirani skeniranjem lubanja korištenjem laserskog skenera. Na 3D modelima je obilježeno sedam neuparenih tačaka u području srednje sagitalne linije korištenjem Landmark Editor programa. Položaj obilježenih tačaka je korišten za analizu spolnih razlika u obliku srednje sagitalne linije i analizu spolnih razlika u maksimalnom sagitalnom dijametru u području srednje sagitalne linije (maksimalna kranijalna dužina, glabela-opistion). Izvršena je geometrijska morfometrijska analiza kako bi se procijenile razlike u obliku srednje sagitalne linije između spolova, a rezultati testa ispravne klasifikacije su pokazali statistički signifikantne razlike. Određivanje spola prema obliku srednje sagitalne linije je izvedeno sa preciznosšću od 66.19% za muške lubanje i 62.5% za ženske lubanje ($p<0.001$). Rezultati regresijske analize su pokazali statistički signifikantan utjecaj veličine srednje sagitalne linije na njen oblik. Rezultati univarijantne analize su pokazali statisitički signifikantne razlike između spolova ($p<0.001$). Primjena trodimenzionalnih modela lubanja pri određivanju spola na osnovu srednje sagitalne linije je pokazala statistički signifikantne razlike između spolova.

Ključne riječi: 3D modeli, geometrijska morfometrija, spolni dimorfizam, lubanje, univarijantna analiza