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Sex Estimation Based on Foramen Magnum: A Three-Dimensional Geometric Morphometrics Approach

Estimación del Sexo Basado en el Foramen Magno: Un Enfoque de Morfometría Geométrica Tridimensional

Zurifa Ajanovic[1]; Lejla Dervisevic[1]; Emina Dervisevic[2]; Almira Lujinovic[1]; Uzeir Ajanovic[3]; Jasmina Biscevic-Tokic[4]; Adis Salihbegovic[2]; Aida Sarac-Hadzihalilovic[1] & Nermin Sarajlic[2]

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SUMMARY: The foramen magnum is an important topographic opening which connects cranial cavity and spinal canal. The analysis of the bone material established that there are differences in the shape of the foramen magnum between individuals. The aim of this study was to determine sex based on shape and size of foramen magnum using geometric morphometrics method. A study was performed on three-dimensional models (3D models) of 214 human skulls of known sex and known age (141 male skulls and 73 female skulls). The skulls are located at the museum of Medical Faculty, University of Sarajevo. Skulls belong to Bosnian population from the mid-twentieth century. All examined skulls were scanned with a laser scanner to obtain their 3D models. On 3D models of the examined skulls, four landmarks were marked on foramen magnum. Analysis of sex determination was performed using the MorphoJ program. Results of this study showed that there are sex differences in the shape and size of the foramen magnum. Sex determination based on the shape and size of the foramen magnum was showed 65.25 % accuracy for male and 63.01 % accuracy for female using geometric morphometrics method. Examination of the effect of size of foramen magnum on sexual dimorphism of shape of foramen magnum showed a statistically significant effect. Sex determination based just on the shape of foramen magnum using geometric morphometrics method was possible with 62.41 % accuracy for male and 58.90 % accuracy for female on examined sample. Sex differences on shape and size of foramen magnum were found using geometric morphometrics method on three-dimensional models of the examined skulls. The percentage of accuracy was higher for male based on the shape and size of the foramen magnum than for female.

KEY WORDS: Foramen magnum; Human skull; Sex estimation; Geometric morphometrics method; Three-dimensional models.

INTRODUCTION

The foramen magnum is an important topographic space that connects the cranial cavity with the spinal canal. Through the foramen magnum the intracranial part of the central nervous system continues to the extra cranial part (Samara *et al*., 2017). Topographically, near the foramen magnum is a part of the central nervous system that contains the reflex center for breathing and heart function, and injuries in the area of the foramen magnum can be fatal to patients. Knowledge of the anatomy of the foramen magnum includes interests to many fields of medicine.

Knowing the sex differences of the foramen magnum is important for sex determination in forensic medicine (Madadin *et al*., 2017). Foramen magnum is protected by soft tissue, it is well preserved anatomical position (Gapert *et al*., 2009) in case of mass catastrophes, fire damage or multiple bone fractures. Therefore, foramen magnum is important for sex determination (Ajanovic & Sarac-Hadzihalilovic, 2019).

In the research of skeletal remains, it is necessary to know the existence of population differences. Population standards are determined that show the highest degree of accurate for sex determination if applied to the population from which was tested sample (Sarac-Hadzihalilovic *et al*., 2020).

[1] Department of Anatomy, Faculty of Medicine, University of Sarajevo, Sarajevo, Bosnia and Herzegovina.
[2] Department of Forensic Medicine, Faculty of Medicine, University of Sarajevo, Sarajevo, Bosnia and Herzegovina.
[3] Department of Information Tehnology, Faculty of Engineering and natural sciences, International Burch University, Sarajevo, Bosnia and Herzegovina.
[4] Department of occupational health, Faculty of Medicine, University of Sarajevo, Sarajevo, Bosnia and Herzegovina.

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There are several methods used to sex determination based on skeletal remains. Classical methods are qualitative methods or quantitative methods. Qualitative methods are subjective and descriptive methods. Quantitative methods are based on measuring linear diameters on skeletal remains or on CT scans, as well as radiographic images of skeletal remains or part of skeletal remains. (Sarac-Hadzihalilovic *et al*., 2021).

In literature we can find studies which used classical methods for analysis of sex differences of skeletal remains.

Vinutha & Shubha (2016) used classical methods, for analysis of sexual differences of the foramen magnum on skulls from the Indian population. The authors concluded that all measured diameters were significantly greater in male skulls than in female skulls, while the oval shape of the foramen magnum dominated in both sexes. The authors concluded that the data obtained may be useful to the neurosurgeons (Vinutha & Shubh, 2016).

In the study provided by Burdan *et al*. (2012) founded a significant positive correlation between length and width of the foramen magnum and length and width of the skull. Significant correlations were observed between foramen magnum width and corresponding external cranial diameters in women. Round shape, as well as longitudinal and horizontal oval types of foramen magnum shape were determined according to structure width/length index. All measurements of the skull and foramen magnum were significantly greater in individuals of the round type foramen magnum. Sex differences were found between the examined individuals. It mainly referred to its linear diameters and area, not in the shape of foramen magnum. Unlike men, female skulls had a higher correlation between examined foramen magnum parameters and correct external measurements of the skull, indicating more homogeneous growth in women.

Chovalopoulou & Bertsatos (2017) investigated the sexual dimorphism of the foramen magnum and occipital condyles in a sample from the Modern Greek population using discriminant functional analysis. The study included 154 adult skulls (77 male and 77 female) on which 7 parameters were examined (4 on foramen magnum and 3 on occipital condyles). The result of research showed that the mean values of all parameters are higher in male skulls than in female skulls. The combination of occipital condyle parameters with discriminant functional analysis in this study enabled sex determination with 74 % accuracy in all cases.

Gargi *et al*. (2018) in their study conducted on 110 CBCT scans (55 men and 55 women, 20-80 years) examined sexual dimorphism of foramen magnum between two different groups of the Indian population using discriminant analysis. The authors measured sagittal diameter, transverse diameter, surface area, FMI, and foramen magnum circumference. The foramen magnum area was the best discriminant parameter used in this study to determine sex with an overall accuracy of 90.9 %.

The authors analysed the morphological differences of the foramen magnum as well as the differences in size. The most common forms of foramen magnum in the study were round (22.6 % of cases), egg shape (18.9 % of cases), tetragonal (18.9 % of cases), oval (15.1 % of cases) and irregular (15.1 %). The mean antero-posterior and transverse diameter of the foramen magnum was determined as 31 ± 2.4 mm and 25.2 ± 2.4 mm, respectively. This study determined the various shapes of foramen magnum and its morphometry. The data obtained may be useful for neurosurgeons in the analysis of the morphological anatomy of craniovertebral junction, for anthropologists, morphologists and clinical anatomists (Chethan *et al*, 2012).

Meral *et al*. (2020) conducted study of sexual dimorphism of foramen magnum on human skulls from Turkish population. They analysed 600 (300 males and 300 females) Computerized Tomography (CT) images of Turkish individuals between 21 and 50 years. They measured four measurements on CT images of foramen magnum. All measurements were significantly greater in males than in females, and they provided the higher sex determination accuracy. The area of the foramen magnum calculated by Radinsky's formula was the best measurement for sex determination in this study with a 75 % accuracy. Authors concluded that the CT images of foramen magnum showed sexual dimorphism in Turkish population. They concluded that the use of population-specific data is the most appropriate approach for sex assessment.

Ulcay *et al*. (2022) analysed the coefficient between skull length and foramen magnum length, as well as the coefficient between skull width and foramen magnum width on a sample of 60 adult skulls from the Turkish population. The average of the coefficients of cranial width to width of foramen magnum ratio (4.62 ± 0.35) and the average of the coefficients of cranial length to the length of foramen magnum ratio (4.62 ± 0.50) were found and to be equal to each other. Authors suggested that foramen magnum width and its length could be estimated by using the cranial length and cranial width measurements in the skull by accepting the mean of these coefficients (4.62) as the golden ratio.

New method for analysis of morphological differences is geometric morphometrics method. Geometric morphometrics method is a new method for analysis of morphological differences of the examined structures. It is based on the use of landmarks that are distributed on surface of the examined structures in clearly defined space, on all examined sample. These points are the shapes defined as aligned landmark configurations. The aims of geometric morphometrics method is to reveal differences between morphological objects by their shapes as such, the "size factor" being excluded (Pavlinov *et al*., 2001).

Geometric morphometrics method was used in studies for analysis of sexual dimorphism of skeletal system or parts of the skeletal systems. There are numerous studies which used geometric morphometrics method for analysis of sexual dimorphism of craniofacial region of human skulls in different populations.

Franklin *et al*. (2006) in their study conducted on the crania of indigenous southern Africans used geometric morphometrics method for analysis of sexual dimorphism.

Sarac-Hadzihalilovic *et al*. (2021) used geometric morphometrics method for analysis of sex differences on piriform aperture of human skulls.

The geometric morphometrics method is a technique has been of great value in many biological studies, but does not appear to have been used to examine sex based on foramen magnum of human skulls.

The aims of this study was to determine sex based on foramen magnum using geometric morphometrics method on tested sample from Bosnian population.

Statistical analysis: Examination of the sexual dimorphism of the foramen magnum was performed using geometric morphometrics on three-dimensional models of the examined skulls contained in MorphoJ program (Klingenberg, 2014). Geometric morphometry enables the analysis of differences in the shape and size of the examined structures, as well as the examination of whether the observed differences are statistically significant. Procrustean superimposition with the processes of scaling, centering and rotation, all examined structures placed in the point of origin-“zero” point of the coordinate system, which enables further analysis of morphological differences. Principal component analysis (PCA) highlights statistically significant differences in shape between the examined structures. The first principal component (PC1) describes the largest percentage of present variability.

Multivariate regression analysis (RA) is used to analyse the influence of size on the shape of the examined structures.

The presence of morphological differences between two or more investigated groups was analysed using discriminant functional analysis (DFA). In our study, the presence of differences in the shape and size of the foramen magnum between male and female skulls was analysed using DFA.

MATERIAL AND METHOD

Our study was based on three-dimensional models (3D) of 214 human skulls from Bosnian population (141 males, and 73 female skulls). Three-dimensional models of the examined skulls was obtained using a laser scanner (hp Pro S2). On 3D of the examined skulls, we marked landmarks on foramen magnum for its size and shape analysis. On each 3D model, we marked four landmarks (Table I), two non-paired, and one paired in the Landmark editor program. Data about the position of landmarks we export from landmark editor program as NTSys file and import in the MorphoJ program. MorphoJ program contained statistical tests for analysis of morphological differences of foramen magnum.

Table I. List of landmarks marked on the foramen magnum.

Landmarks	Position
Basion	Point on anterior margin of foramen magnum
Opisthion	Point on posterior margin of foramen magnum
Foraminolaterale	Most lateral point on foramen magnum

RESULTS

Determination of morphological differences between sexes was investigated using geometric morphometrics analysis by statistical tests contained in MorphoJ program. PC1 which describes the largest percentage of present variability described 40.398 % of variability. Total variability (100 %) was described by first three PC (Table II).

Figure 1 showed a clear separation in the form of the foramen magnum between males and females (Difference between means: Procrustes distance: 0.03171698, Mahalanobis distance: 0.7329, T-square: 25.8384, P-value: <.0001 P-value).

Table III and Figure 2 showed results of DFA which investigated accuracy of sex estimation based on form of foramen magnum.

Table II. Eigenvalues and percentage from PCA of foramen magnum form variability.

PC	Eigenvalues	Percentage of variability %	Cumulative percentage of variability %
1.	0.00325091	40.398	40.398
2.	0.00296712	36.871	77.269
3.	0.00182927	22.731	100.000

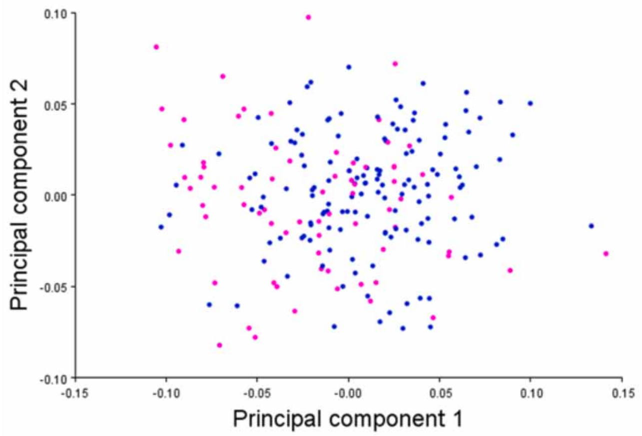

Fig. 1. Scatter plots of the first two principal components (PC1 and PC2) of the specimens separated by sexes (males is marked by blue color, females is marked by pink color).

Results of regression analysis which investigated effect of size of foramen magnum on its shape, was presented in Figure 3. Effect of size was 3.2681 % and have statistical significance on sex dimorphism of the shape of foramen magnum (p= 0.0005).

Table IV and Figure 4 showed results of DFA which investigated accuracy of sex estimation based on shape of foramen magnum.

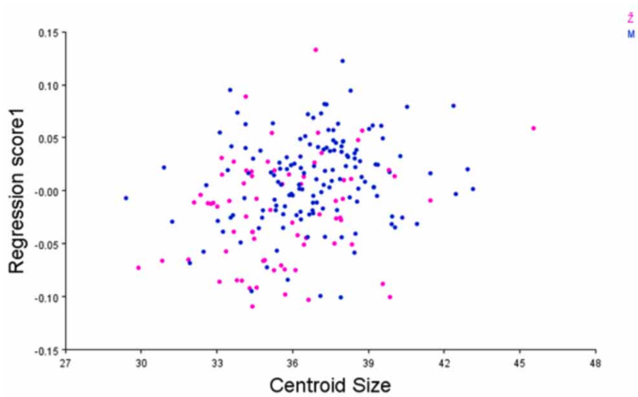

Fig. 3. Regression analysis of the effect of foramen magnum size on sex dimorphism of its shape.

Table III. Sex estimation accuracy based on form of the foramen magnum.

		Sex estimation		Total
Sex	Male	92	49	141
	Female	27	46	73
	Total	*119*	*95*	*214*

Table IV. Sex estimation accuracy based on the shape of the foramen magnum.

		Sex estimation		Total
Sex	Male	88	53	141
	Female	30	43	73
	Total	*118*	*96*	*214*

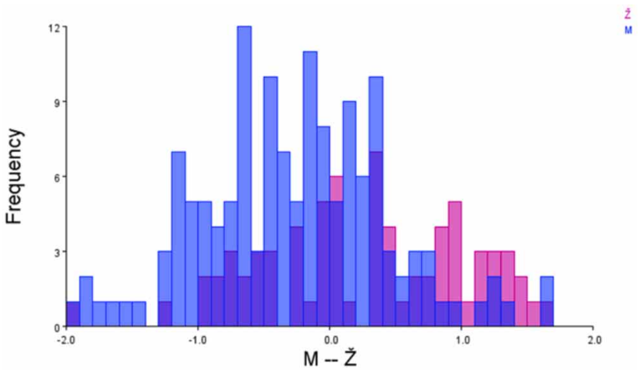

Fig. 2. Histograms of DFA of sex dimorphism of form of the foramen magnum. Males is colored by blue color, females by pink color.

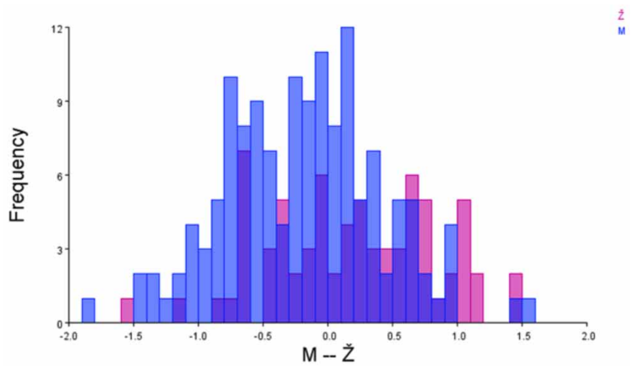

Fig. 4. Histograms of DFA of sex dimorphism of foramen magnum shape. Males is colored by blue color, females by pink color.

DISCUSSION

In our study we analysed sexual dimorphism of foramen magnum using geometric morphometrics method. The analysis of sex differences of foramen magnum was performed on three-dimensional models of 214 human skulls of known sex and known age. The results of the study showed that there are sex differences in the form of foramen magnum (shape and size of the foramen magnum). Sex determination based on the form of the foramen magnum was showed with 65.25 % accuracy for males and with 63.01 % accuracy for females using geometric morphometrics method. Examination of the effect of size of foramen magnum on sexual dimorphism of its shape showed a statistically significant effect. Sex determination based on the shape of the foramen magnum using geometric morphometric method on three-dimensional models of the examined skulls was possible with 62.41 % accuracy for males and 58.9 % accuracy for females.

We compared our results with results of other authors that analysed sex differences of human foramen magnum.

Agarwal *et al*. (2021) in their study analyzed sex differences of foramen magnum on 130 radiological images (65 males and 65 females) using two metric traits. They measured antero-posterior diameter and transverse diameter of foramen magnum. They calculated area of the foramen magnum using these two metric traits. When used individually, transverse diameter had highest predictive value in their study, 67.7 % accuracy, which is similar whith our results (Agarwal *et al*, 2021).

Chandekar *et al*. (2017) in their study analyzed sex differences of foramen magnum on dry skulls from Vidarbha Region, India. They measured two linear diameters (antero-posterior and transverse diameter) on the foramen magnum and they concluded that mean values for both was lesser in female than in male.

Karem *et al*. (2019) provided study about sexual dimorphism of foramen magnum on CT scans of patients from Sulaimani population, Iraq. Sagittal diameter, transverse diameter, calculated the area, index, and circumference of foramen magnum were measured. Authors concluded that women had a lower average value than men. Regarding sex determination, the predictability of the dimensions in sexing the crania for sagittal diameter, transverse diameter, and area of foramen was respectively 76.0 %, 66.0 %, and 74.0 % accuracy.

Lopez-Capp *et al*. (2018) analyzed sexual dimorphism of foramen magnum on sample from Brasilian population using two metric traits and calculating area and circumference of foramen magnumon 100 dyry skulls know sex. The univariate discriminant functions showed an accuracy between 56.0-62.0 %, and the multivariate analysis showed a percentage of accuracy between 60.0-65.0 % in their study. The greatest accuracy was found combining the two linear diameters with 71.7 % accuracy.

Jaitley *et al*. (2016) in their research analyzed sexual dimorphism of foramen magnum using cone beam computed tomography. Authors measured sagittal diameter, transverse diameter, calculated area and circumference of foramen magnum. Results of discriminant analysis showed that sex determination was possible with 72 % accuracy in their study.

Pires *et al*. (2016) in study conducted on dry skulls from Brasilian population used qualitative and quantitative methods for analysis of foramen magnum. They calculated mean values of sagittal and transverse diameter od foramen magnum and concluded that most common shape of foramen magnum was oval.

Raikar *et al*. (2016) analyzed sexual dimorphism of foramen magnum in the South Indian population using digital submentovertex radiographs. Authors measured sagittal diameter, transverse diameter, calculated area and circumference of foramen magnum. They concluded that all parameters were greater in males than in females. The most common shape was an egg shape while hexagonal was the least common morphology. Accuracy for sex determination was 67.3 % what is similar with our results.

Samara *et al*. (2017) in study conducted on computed tomography images individuals from Jordanian population analysed foramen magnum. They measured sagittal diameter, transverse diameter, as well as they calculated foramen magnum index, and analysed shape of foramen magnum. Results showed that the diameters were significantly different between sexes, and most common shape of foramen magnum was irregular.

In their study Sharma *et al*. (2015) and Singh *et al*. (2019) analyzed morphometric characteristics and variation in shape of the foramen magnum on dry skulls of unknown age and sex analysed. They concluded that knowledge of existence of different shape of foramen magnum is important for morphological anatomy of craniovertebral junction in transcondylar approach for brain stem lesion.

Tellioglu *et al*. (2018) analysed sexual differences of foramen magnum on CT scans of 100 patients. Sex determination in their study was possible with 64 % accuracy for women, 70 % accuracy for men and 67 % accuracy for both sexes what is similar with our results.

CONCLUSIONS

1. Sex differences of the foramen magnum were found using geometric morphometrics method on three-dimensional models of the examined skulls.
2. The percentage of accuracy for sex estimation was higher for male based on the form of the foramen magnum and based on its shape.

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RESUMEN: El foramen magno es una importante abertura topográfica que conecta la cavidad craneal y el canal espinal. El análisis del material óseo estableció que existen diferencias en la forma del foramen magno entre individuos. El objetivo de este estudio fue determinar el sexo en función de la forma y el tamaño del foramen magno utilizando morfometría geométrica. El estudio se realizó en modelos tridimensionales (modelos 3D) de 214 cráneos humanos de sexo y edad conocidos (141 cráneos masculinos y 73 cráneos femeninos). Los cráneos se encuentran en el museo de la Facultad de Medicina de la Universidad de Sarajevo. Los cráneos pertenecen a población bosnia de mediados del siglo XX. Todos los cráneos examinados fueron escaneados con un escáner láser para obtener sus modelos 3D. En los modelos 3D de los cráneos examinados, se marcaron cuatro puntos de referencia en el foramen magno. El análisis de determinación de sexo se realizó utilizando el programa MorphoJ. Los resultados de este estudio mostraron que existen diferencias de sexo en la forma y el tamaño del foramen magno. La determinación del sexo basada en la forma y el tamaño del foramen magno mostró una precisión del 65,25 % para los hombres y del 63,01 % para las mujeres utilizando morfometría geométrica. El examen del efecto del tamaño del foramen magno sobre el dimorfismo sexual de la forma del foramen magno mostró un efecto estadísticamente significativo. La determinación del sexo basada solo en la forma del foramen magno utilizando morfometría geométrica fue posible con una precisión del 62,41 % para los hombres y del 58,90 % para las mujeres en la muestra examinada. Se encontraron diferencias de sexo en la forma y el tamaño del foramen magno utilizando morfometría geométrica en modelos tridimensionales de los cráneos examinados. El porcentaje de precisión fue mayor para los hombres en función de la forma y el tamaño del foramen magno que para las mujeres.

PALABRAS CLAVE: Foramen magno; Cráneo humano; Estimación del sexo; Morfometría geométrica; Modelos tridimensionales.

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Corresponding author:
Dr. Sci. Zurifa Ajanovic
Department of Anatomy
Faculty of Medicine
University of Sarajevo
Sarajevo
BOSNIA AND HERZEGOVINA

E-mail: zurifa.ajanovic@mf.unsa.ba