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RESEARCH

Gender prediction using geometric morphometry with parameters of the cranium obtained from computed tomography images

Bilgisayarlı tomografi görüntülerinden elde edilen cranium parametreleri ile geometrik morfometri kullanılarak cinsiyet tahmini

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Abstract

Purpose: The gender difference of the cranium skeleton is of great importance in forensic anthropology and forensic medicine sciences. This study is based on this hypothesis and the gender prediction rate was obtained by processing cranium images obtained from computed tomography (CT) using geometric morphometry.
Materials and Methods: CT images of 200 individuals between the ages of 25 and 65 were used in our study. The images were opened at the personal workstation Horos Medical Image Viewer (Version 3.0, USA) program and processed with 3D Curved Multiplanar Reconstruction (MPR). The line passing through the nasion and inion points of the images obtained as a result of the process was determined, and all images were brought to the orthogonal plane. Later, the images were overlapped and saved in JPEG format with 100% magnification. JPEG images saved were converted into TPS format, and 21 homologous landmarks were placed. Generalized Procrustes Analysis (GPA) and Principal Component Analysis (PCA) were applied to the coordinates of landmarks, and shape variations and dimensionality were corrected by gathering the images to the center of gravity. Next, Linear Discriminant Analysis (LDA) was applied to the coordinates, the dimensionality of which was corrected.
Results: The study found that 74.465% of the coordinates of 21 homologous landmarks gathered to the center of gravity could be explained with the first three PCs. As a result of the LDA applied to these coordinates, a gender prediction rate of 86.5% was obtained. In addition, a slight difference was found between the GPA sum of squares and the tangent sum of squares (0.57).
Conclusion: The images of the cranium obtained from CT showed a high dimorphism by geometric

Öz

Amaç: Cranium iskeletinin cinsiyet farklılığı adli antropoloji ve adli tıp bilimlerinde büyük önem taşımaktadır. Bu çalışma bu hipotezden yola çıkılarak bilgisayarlı tomografiden (BT) elde edilen cranium görüntülerinin geometrik morfometri yöntemi kullanılarak işlenmesi ile cinsiyet tahmin oranı elde edilmiştir.
Gereç ve Yöntem: Çalışmamızda yaşları 25 ile 65 arasında değişen 200 bireye ait BT görüntüleri kullanıldı. Görüntüler kişisel iş istasyonu Horos Medical Image Viewer (Version 3.0, USA) programında açıldı ve 3D Curved Multiplanar Reconstruction (MPR) ile işlendi. İşlem sonucunda elde edilen görüntülerin nasion ve inion noktalarından geçen hat belirlenerek tüm görüntüler ortogonal düzleme getirildi. Daha sonra görüntüler üst üste bindirilerek %100 büyütme ile JPEG formatında kaydedildi. Kaydedilen JPEG görüntüler TPS formatına dönüştürülerek 21 adet homolog landmark yerleştirildi. Yer işaretlerinin koordinatlarına Genelleştirilmiş Procrustes Analizi (GPA) ve Temel Bileşen Analizi (PCA) uygulanmış ve görüntüler ağırlık merkezine toplanarak şekil varyasyonları ve boyutsallık düzeltilmiştir. Ardından, boyutsallığı düzeltilen koordinatlara Doğrusal Diskriminant Analizi (LDA) uygulanmıştır.
Bulgular: Çalışmada, ağırlık merkezine toplanan 21 homolog noktasının koordinatlarının %74,465'inin ilk üç PC ile açıklanabildiği bulunmuştur. Bu koordinatlara uygulanan LDA sonucunda %86,5'lik bir cinsiyet tahmin oranı elde edilmiştir. Ayrıca, GPA kareler toplamı ile tanjant kareler toplamı arasında küçük bir fark bulunmuştur (0,57).
Sonuç: Çalışmamız sonucunda BT'den elde edilen cranium'a ait görüntülerin geometrik morfometri analizi ile yüksek bir dimorfizm gösterdiği tespit edilmiştir.

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morphometry analysis.
Keywords: Cranium, computed tomography, geometric morphometry, gender prediction

Anahtar kelimeler: Cranium, bilgisayarlı tomografi, geometrik morfometri, cinsiyet tahmini

INTRODUCTION

Knowing the differences in faces and anatomical structures that make up the faces between genders is of critical importance for forensic anthropology and forensic medicine sciences. In forensic cases, the only remaining structure is the bone tissue if a long time has passed since death. In this context, bone tissue is an essential step for rapid and correct identification. Of the bones that make up the body, the pelvis and cranium are the bones that stand out with their dimorphic feature. In medical sciences, knowing the bone tissue's differences in gender is a guide for morphological and surgical studies[1-4].

For forensic sciences, the cranium is considered the most popular and reliable bone for sex estimation after the pelvis[5]. The main reasons for the popularity of the skull in forensic sciences are that it is more resistant to environmental exposure compared to other bone tissues, significant shape change according to genetic inheritance characteristics and hormonal changes during puberty. In addition, when we look at the studies conducted in the literature, it is possible to obtain high reliability accuracy in terms of gender estimation with both basic statistical methods and advanced statistical methods[6,7].

There are two main methodologies for sex estimation: morphological and metric. Metric methods require less practical experience than morphological methods. However, metric methods require measurement tools and take longer to process than morphological methods. In addition, dimensional variation is an important component of sex estimation, which increases the importance of morphological methods[8-11].

Morphometry is a discipline based on the measurement of shape. The history of this discipline dates back to ancient times, and serious developments have occurred during the process. To name some, Frances Galton developed a method used in face measurements called Bookstein shape coordinates in 1907. In the 1980s, new coordinate-based morphometric methods were developed, which were revolutionary[12-15]. In the following years, a new approach was put forward due to the need for the widespread use of computer-based analysis, the processing of high data, and the analysis of high-quality digital visual materials. In this approach, configurations of images around the geometrical landmark can be made precisely during the analysis, and therefore results that can highly reflect reality can be obtained. This new approach is called geometric morphometry due to these characteristics. Geometric morphometry can easily be applied on 2D and 3D images[12,15].

Morphometric analyses try to answer questions such as "what is the average value of the bone structure?, are there differences according to the population?, what is the significance of the difference found?"[16]. Within the framework of these questions, craniofacial morphometry has examined how environmental factors, population, different periods of the same population, and genetic factors are affected, and differences have been reported[17].

Theere are several main reasons for the predominance of the cranium in geometric morphometry. For instance, the cranium shows a dimensional difference after birth due to the growth of the brain and this dimensional difference is fully revealed during adolescence. Since the cranium protects the brain, central nervous system structures and cerebral vessels, it shows dimensional differentiation and becomes more resistant to environmental factors. The cranium reflects characteristic genetic differences[6,18].

Computed Tomography (CT) is a three-dimensional imaging modality that provides highly accurate imaging of hard tissue. CT is also inexpensive and does not require specialized personnel and is widely used by anthropologists and clinicians. The disadvantage of magnetic resonance imaging is radiation exposure[11,19,20].

The hypothesis of the study was that geometric morphometry, one of the morphologic methods, can be used to predict sex with high accuracy and precision from sensitive CT cranium images. The aim of this study was to determine the sex prediction rate by geometric morphometry using lateral CT images of the cranial skeleton of the Turkish population in the 21st century. The study was conducted on the Turkish population using both CT and geometric morphometry methods. In this respect, it not only presents the sex estimation rate of the population, but also provides a reliable and precise result.

MATERIALS AND METHODS

Sample and MDCT scanning protocol

This study was approved by the decision 727 dated 12.20.2022 of the Local Non-Interventional Ethics Committee of İzmir Bakırçay University. In the study, CT angiography images of the skulls of 100 women and 100 men belonging to the Turkish population living in the 21st century, aged between 25 and 65, were retrospectively scanned and used. Images were obtained retrospectively from the archive system of the Department of Radiology, Faculty of Medicine, İzmir Bakırçay University. Exclusion criteria were surgical intervention in the cranium and any pathology in the cranium. Images were randomly selected from the hospital Picture Archiving and Communication Systems (PACS) archive system according to the exclusion criteria. CT angiography images were obtained by using 16-row multidetector CT (Aquilion 16; Toshiba Medical Systems, Otawara, Japan) in İzmir Bakırçay University Çiğli Training and Research Hospital, Department of Radiology. Scanning protocol values were determined as pitch: 1,0 mm, tube voltage: 120 kV, gantry rotation: 0.75 s, and image section thickness value: 1 mm. 16-row multidetector CT was chosen because the image quality is higher than 4-row multidetector CT. This protocol is the standard protocol for CT images taken in our hospital and allows us to see the sections clearly. The sample size was determined by Power analysis. The margin of error for Power analysis was set at 0.05 and the minimum number of individuals was found to be 86.

Image pre-processing

CT angiography images in Digital Imaging and Communications in Medicine (DICOM) format were scanned retrospectively from the hospital archive system and transferred to the personal workstation Horos Medical Image Viewer (Version 3.0, USA) program. Images were obtained in axial, coronal, and sagittal planes using the program's 3D Curved Multiplanar Reconstruction (MPR) tool. Later, by determining the line passing through the nasion and inion points of the images, all images were brought to the orthogonal plane. The orthogonal alignment minimizes the effect of the minimally different postures of the individuals during shooting. Two prominent points, the nasion and inion, were chosen for the orthogonal plane. The images were superimposed to obtain a single image. This process involves moving the slices closer to each other to obtain a single image. Thus, a real skull shape is created. The overlapped images obtained were saved in JPEG format at 1279x614 pixels through 100% actual magnification. As a result, a 2D image was obtained. The reason for working on the lateral image of the cranium rather than the whole cranium is that in cases of war, natural disasters, etc., not all skeletal remains (e.g. skull skeleton) can be found and some of them need to be worked on. In this study, we focused on the case of lateral cranium. These procedures were performed by an expert radiologist with at least 10 years of experience in radiology.

Image post-processing

Overlapping JPEG images obtained from image pre-processing were converted to TPS format for geometric morphometric analyses[21]. Images converted to TPS format were processed, and homologous landmarks were placed on 21 anthropometric points of the images[22] (Figure 1). The homologous landmarks placed were;

- Nasion
- Glabella
- Midpoint of the frontal bone
- Vertex
- Midpoint of the parietal bone
- Lambdoid suture
- Inion
- Head of mandible
- Angle of mandible
- Base of mandible
- Gnathion
- Alveolar arch
- Oblique line
- Coronoid process
- Anterior nasal spine
- Posterior lower point of pyriform aperture
- Midpoint of pyriform aperture
- Nasal bone endpoint
- Frontal process of zygomatic bone
- Maxillary process of zygomatic bone
- Temporal process of zygomatic bone

When selecting the landmark, care was taken to select the most prominent anthropometric points in the lateral region of the cranium, and all landmarks were evaluated as a single configuration. In addition, the selection of these 21 points was based on osteometric and morphologic studies published in the literature. These points were selected from those affected by ancestral and sex-linked variation.

Obtaining and processing coordinates

The landmark coordinates obtained were saved as TEXT files; translation, rotation, and scaling, which are Generalized Procrustes Analysis (GPA) processes, were applied, and the variational differences of each image not resulting from position or shape were eliminated. They were positioned according to the center of gravity[23,24]. Landmark locations of female and male individuals before and after GPA are shown in Figure 2. The resulting coordinate file in TPS format was transferred to Morpho J (Version 1.07a)[25] programs, and GPA process was repeated here. Principal Component Analysis (PCA) was used to reduce the dimensionality of the data obtained as a result of GPA, and the transformation grid image of Principal Component 1 (PC1) was obtained (Figure 3).

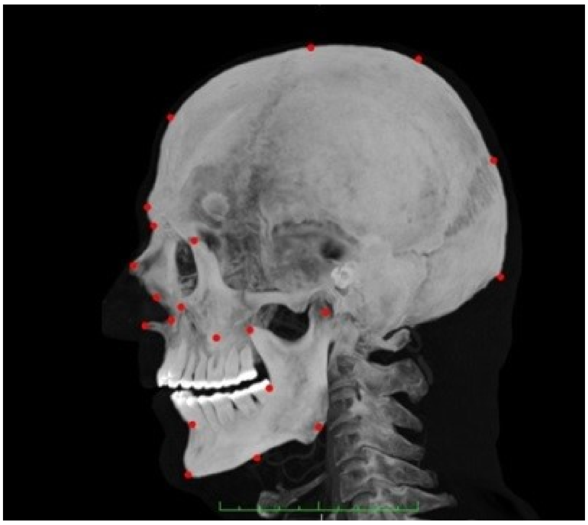

Figure 1. Homologous landmarks.

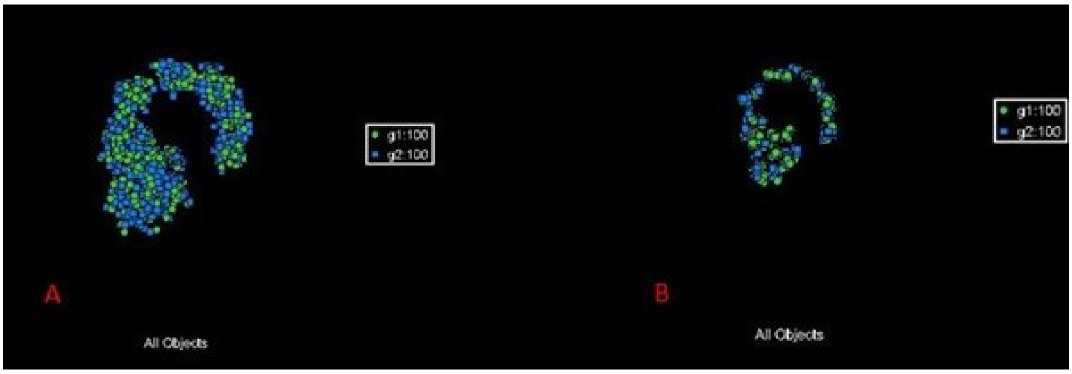

Figure 2. Landmark demonstration before (A) and after (B) Generalized Procrustes Analysis (g1: Male, g2: Female)

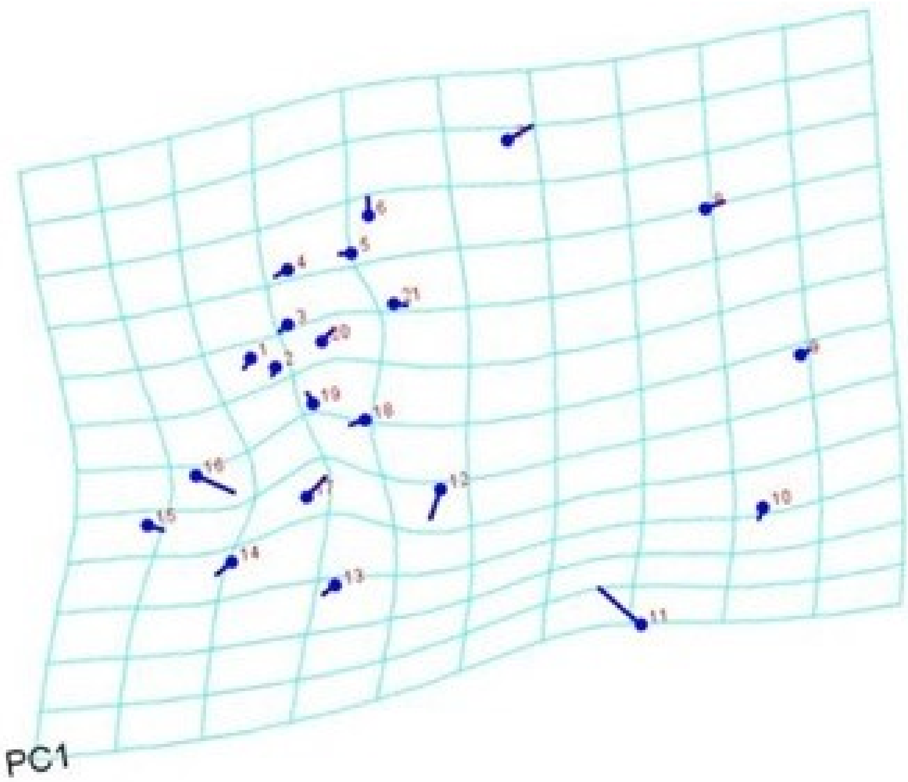

Figure 3. Transformation grid of principal component 1.

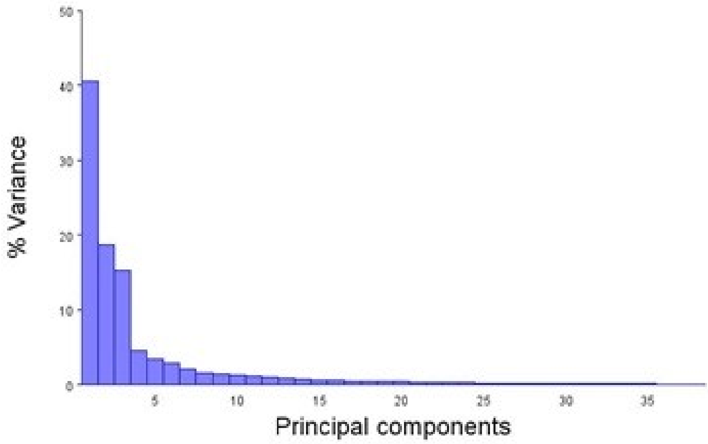

Figure 4. Variance% values

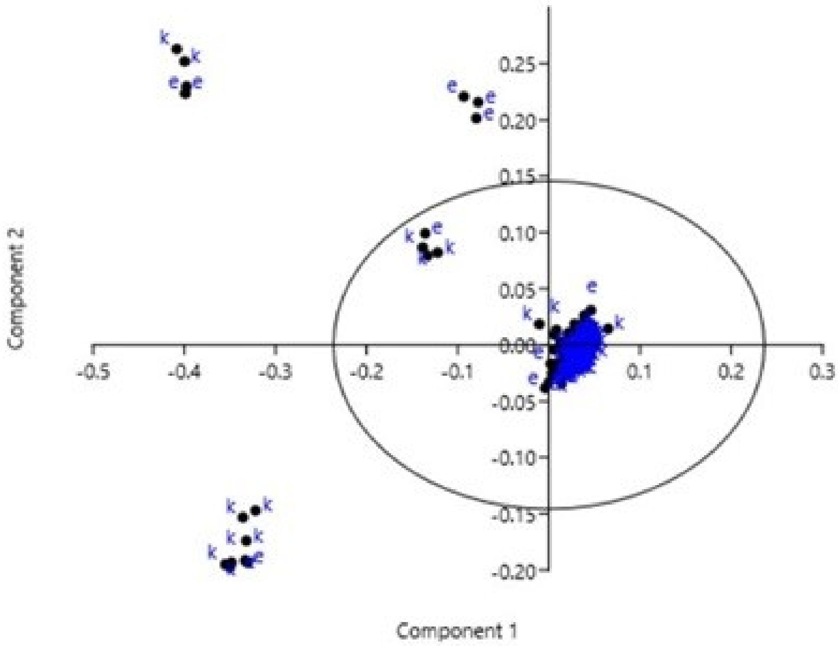

Figure 5. 95% Confidence ellipses (k: Female, e: Male).

Statistical analysis

PAST (Version 4.09), Morpho J (Version 1.07a), R Project (Version 4.0.2), IBM SPSS (Version 21), and Minitab 17 programs were used in statistical analyses. $p \leq 0.05$ value was considered statistically significant. Power analysis was performed using the program G*Power (Version 3.1.9.4).

As a result of PCA, 38 PC were obtained with the formula [(landmark number*2)-4] = PC number and eigenvalues, variance%, cumulative%, total variance, eigenvalue variance scaled by total variance, eigenvalue variance scaled by total variance and the number of variables of these were included. In addition, 95% confidence ellipses of X and Y coordinates obtained as a result of PCA were included. Linear Discriminant Analysis (LDA) was used for gender prediction, and an accuracy rate was given. These programs and analyses, which are also used in statistical analyses, are the necessary programs and analyses to perform geometric morphometry.

RESULTS

As a result of PCA, it was found that 40.549% of total shape variation was explained with PC1, while 18.652% was explained with PC2, and 15.264% was explained with PC3. The remaining 35 PCs explained 25.535% (Figure 4). In short, the first 3 PCs explain 74.465% of the variation in shape.

Table 1 includes eigenvalues, variance%, and cumulative% values of the first 3 PCs obtained due to PCA.

Table 1. Variance%, cumulative% values of the first 3 PCs

PCA	Eigenvalues	Variance%	Cumulative%
PC1	0.00662250	40.549	40.549
PC2	0.00304619	18.652	59.201
PC3	0.00249292	15.264	74.465

*PCA: Principal Component Analysis, PC: Principal Component

Table 2 shows the effects of the variances obtained from PCA on total variance and the sum of GPA squares and tangent squares of the values obtained as a result of rotation. Little difference was found in GPA squares total and tangent squares total (0.57).

Table 2. Variance and sum of squares results

Total variance	0.01633203
Variance of the eigenvalues	0.0000014147940
Eigenvalue variance scaled by total variance	0.00530
Eigenvalue variance scaled by total variance and number of variables	0.20700
Procrustes sums of squares	3.8181312222698063
Tangent sums of squares	3.2500734759906122

In 95% confidence ellipses obtained as a result of PCA, it was found that 6 male individuals and 8 female individuals were outside the ellipses (Figure 5).

The coordinates obtained after GPA were evaluated with Linear Discriminant Analysis regarding gender, and 86.5% accuracy was obtained. The confusion matrix obtained as a result of LDA is shown in Table 3. 87 of 100 males and 86 of 100 females were predicted correctly.

Table 3. Confusion Matrix Table

Gender	Male	Female
Male	87	13
Female	14	86

DISCUSSION

In this study, in which gender was predicted with parameters obtained from the cranium by using the geometric morphometry method, a gender prediction accuracy rate of 86.5% was obtained as a result of the LDA analysis applied to coordinates after GPA. The limitations of our study are that changes in different populations could not be addressed, the cranium was evaluated only from the lateral view, and individuals in the pediatric period were not included in the study.

Different bones, such as the pelvis[26], cranium[3], phalanx[27], patella[28], femur[29], sternum[30], and clavicula[31] have been used for gender prediction, and different accuracy rates have been obtained. However, in most of the studies in which gender prediction is made from bones, the pelvis and cranium, which are considered the most dimorphic, are preferred[32-34].

Morphometry is a method that reveals shape variation and the change of shape depending on certain parameters. This method is today called traditional morphometry, and since it evaluates the data (length, area, angle, etc.) within itself, it cannot fully reveal the difference of the entire shape. This disadvantage has allowed the creation of new methods. One of these methods is the geometric morphometry method, which also allows geometric analysis of data[35]. Geometric morphometry is a shape analysis method and is an extremely powerful statistical method that allows accurate and clear storage of geometric information and allows comparison of initial data with multivariate results[16]. Geometric morphometry using landmarks richly reveals the change between shapes through its graphical representation. Procrustes analysis is one of the stages of geometric morphometry that allows overlaying configurations of landmarks[36].

Chovalopoulou et al. In the study where the skull base and palate morphometry of 94 female and 86 male individuals were analyzed, they obtained a gender prediction rate of 90.4% for the skull base and 74.8% for the palate with the geometric morphometry method[37]. Gillet et al. In their study where they used CT images of the skull and lower jaw of 120 people, they obtained an accuracy rate of 94-100% from the skull and 84.2% from the lower jaw in terms of gender estimation[38]. In our study, we achieved 86.5% accuracy in gender prediction by using the lateral view of the skull. The limitation of our study compared to these studies is that only the lateral cranium image was included.

Toneva et al. They achieved accuracy below 70% in their study using geometric morphometry from viscerocranium. Additionally, in this study, they evaluated the shape and size difference in terms of gender and found that the effect of size was greater[9]. Toneva et al. used 32 landmarks in their geometric morphometry study on neurocranium bones and divided neurocranium bones into 4 different configurations. They obtained accuracy results up to 70% in terms of shape difference. They also stated that size difference is a more important factor than shape difference in gender determination[18]. In our study, we used the lateral CT image of the skull (neurocranium + viscerocranium). Since it allows reconstruction and size adjustment in the CT image, it allows minimizing size differences and orientation to the shape. We think that using both neurocranium and viscerocranium bones increases the accuracy rate.

The disadvantages of our study compared to these studies are the use of a single configuration and the focus on shape variation.

Musilova et al.[39] examined the cranial skeleton of 103 individuals using geometric morphometry analysis and a support vector machine algorithm and obtained a 90.3% gender prediction rate. In their study examining the cranium of 120 individuals, Gillet et al.[40] reported an accuracy rate between 87% and 88.3% by using geometric morphometry analysis. In a study on cranial skeletons of the Greek population, Chovalopoulou et al.[41] used geometric morphometry, logistic regression, and discriminant analysis and obtained an accuracy rate between 68.1% and 82%. Gonzalev et al.[10] examined the craniofacial parameters of 125 individuals using the geometric morphometry method and reported a gender prediction rate between 60.12% and 77.86%. The difference of our study from these studies is that the 21landmark point was determined and performed on the Turkish population.

In a study of 118 American individuals, Kimmerle et al. [42] found that the skull skeleton was sexually dimorphic by geometric morphometry analysis. Toneva et al.[9] analyzed the viscerocranial CT images of 156 males and 184 females with geometric morphometry analysis and showed that viscerocranium is sexually dimorphic. The difference of our study is the use of both neurocranium and viscerocranium bones.

Chatthai et al.[6] used logistic regression analysis in their study on 240 cadaveric donors from Thailand and obtained an accuracy rate of 81.62%. Inoue et al.[43]. In their study on 39 craniometric points of 50 female and 50 male individuals, they obtained an accuracy rate of 86% with discriminant function analysis. In this study, we used geometric morphometry analysis, which has an important place among morphologic methods, and obtained an accuracy rate of 86.5%.

The limitation of the study is that only the lateral view of the head was included in the study, the anterior and inferior views of the head were not included in the study. A higher accuracy rate can be obtained by including the anterior and inferior views of the head in the study.

In our study, 21 homologous landmarks were placed on CT images of 200 individuals from the Turkish population, and the images were configured with geometric morphometry. As a result of the process, it was found that the first 3 PCs explained 74.465% of shape variations, and 86.5% gender prediction rate was obtained as a result of LDA analysis. Studies conducted in the literature and the present study show that the cranium is an important bone in gender prediction. These results also show that population, number of individuals, and the analysis method used after geometric morphometry affect the accuracy rate to a great extent.

As a result of our study, the cranial skeleton of individuals in the Turkish population was found to be sexually dimorphic with the geometric morphometry method. In this respect, our study will be a guide to anthropologists, anatomists, and forensic medicine specialists.

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Ethical Approval: This study was approved by the decision 727 dated 12.20.2022 of the Local Non-Interventional Ethics Committee of İzmir Bakırçay University.
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