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Sex Prediction Using Geometric Morphometry with Parameters Obtained From Computed Tomography Images of the Seventh Cervical Vertebra

Yedinci Servikal Vertebra'ya Ait Bilgisayarlı Tomografi Görüntülerinden Elde Edilen Parametrelerle Geometrik Morfometri Kullanılarak Cinsiyet Tahmini

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Abstract

Background: The durability of vertebrae increases their likelihood of being discovered in forensic contexts or natural disasters. Identification procedures can also be facilitated through these structures. The aim of this study, based on this hypothesis, is to determine whether it is possible to identify gender with high accuracy and reliability using geometric morphometry on specific points identified on the 7th cervical vertebra.

Materials and Methods: The study was conducted using computed tomography images from 300 individuals aged 18-65. The images were converted into three dimensions and superimposed. The images at actual magnification were then converted to TPS format and 30 landmarks were added. Generalized Procrustes Analysis was applied to these raw coordinates, and the coordinates were repositioned around the center of gravity. Principal Component Analysis was then applied to these repositioned data to reduce dimensionality. Linear discriminant analysis (LDA) was applied to the reduced-dimensionality images to obtain the gender prediction accuracy rate.

Results: The study found that 63.674% of the coordinates clustered around the center of gravity could be explained by the first 6 principal components. LDA analysis applied to the new coordinates yielded an 83.33% gender prediction rate.

Conclusions: The study achieved a high accuracy rate for gender prediction by applying geometric morphometry to points identified on the 7th cervical vertebra.

Keywords: Vertebra prominens, Geometric morphometry, Computed tomography, Sex determination

Öz

Amaç: Vertebraların dayanıklılığı, adli durumlarda veya doğal afetlerde bulunma olasılıklarını artırır. Bu yapılar üzerinden de kimlik tayini işlemleri kolaylaştırılabilir. Kurulan bu hipotez ile yola çıkılan bu çalışmada amaç, 7. servikal vertebra üzerinde belirlenen noktalara geometrik morfometri yöntemi kullanılarak yüksek doğrulukta ve güvenilirlikte cinsiyet tayininin mümkün olup olmadığını ortaya koymaktır.

Materyal ve metod: Çalışma 18-65 yaş aralığındaki 300 bireye ait bilgisayarlı tomografi görüntüleri kullanılarak gerçekleştirildi. Görüntüler üç boyutlu hale getirilerek üst üste çakıştırma işlemi uygulandı. Daha sonra gerçek büyütmedeki görüntüler TPS formatına çevrilerek 30 landmark eklendi. Oluşan bu ham koordinatlara Generalized Procrusters Analysis (GPA) analizi uygulanıp ağırlık merkezi etrafında koordinatlar yeniden konumlandırıldı. Yeniden konumlandırılan bu verilere de Principal Component Analysis uygulanıp boyutsallık azaltıldı. Boyutsallığı azaltılan görüntülere de Lineer diskriminant analizi (LDA) uygulanıp cinsiyet tahmini doğruluk oranı elde edildi.

Bulgular: Çalışma sonucunda ağırlık merkezi etrafında toplanan koordinatların %63,674'ünün ilk 6 principal component tarafından açıklanabileceği bulundu. Yeni koordinatlara uygulanan LDA analizi ile de %83,33 cinsiyet tahmin oranı elde edildi.

Sonuç: Çalışma sonucunda 7. servikal vertebra üzerinde belirlenen noktalara geometrik morfometri yöntemi uygulanarak cinsiyet tahmini açısından yüksek bir doğruluk oranı elde edildi.

Anahtar Kelimeler: Vertebra prominens, Geometrik morfometri, Bilgisayarlı tomografi, Cinsiyet tahmini

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Introduction

Morphometry is a method based on measuring the shape obtained. Although the origins of this method date back much further, it has undergone significant developments over time. With the proliferation of computer-based analysis methods, the need for analyzing high-quality digital visual materials has increased, leading to the emergence of a new approach. In this approach, the configuration of images can be fully realized around geometric turning points during the analysis process. As a result, results that seriously reflect reality can be obtained. This approach has been termed geometric morphometry due to its current characteristics. This approach determines the amount of shape change by identifying differences in the shape and position of objects using landmark (LM) coordinates (1-3). With Generalized Procrustes Analysis (GPA), the homologous LM's of all samples are placed on a common center. This process eliminates the effects of factors such as orientation, position, and size, allowing only shape differences to emerge (3-6). This method can be easily applied to 2D and 3D images (4,7,8). This method, which is also used in archaeological sites, is of great importance in fields such as forensic medicine, anthropology, and anatomy (9).

Following events such as earthquakes, fires, floods, civil wars, and conflicts, which have devastating effects on society, many individuals may lose their lives. After such events, it is necessary to quickly identify individuals. For identification, an analysis of basic information such as race, age, and gender is attempted first. Among these basic details, gender is an area that is frequently focused on. While gender determination can be performed using many structures found in the body, not all tissues have the same chance of being preserved. Many soft tissues can deteriorate very quickly in disasters such as fires or earthquakes. On the other hand, bone tissues are much more durable and can maintain their integrity even in such situations. The robustness of these tissues is also an important reason for their use in identification. For this reason, bone structures are preferred over soft tissue (10-14).

With the advancement of technology, significant developments have occurred in the field of radiology. As a result of these developments, many imaging methods have been introduced. Methods such as X-ray, ultrasound (US), computed tomography (CT), magnetic resonance imaging (MRI), and nuclear medicine techniques are some of these (15). Each method may have advantages or disadvantages depending on the specified purpose. CT has been preferred in a specific segment of anthropological research (16,17). CT is a widely used imaging method that is inexpensive, does not require specialized personnel, and provides high-accuracy imaging in hard tissues (18). Furthermore, CT has become a preferred method due to its advanced image capture capability and the absence of geometric magnification error (19). Furthermore, this method captures information in slices, and these slices can be combined to create a three-dimensional image. The coordinates obtained from CT images are independent of a specific coordinate system with a fixed reference frame, which eliminates the need for data transformations and increases efficiency in geometric morphometric studies (20-22).

This study, which includes a series of highly accessible methods in terms of image acquisition and processing techniques, aims to determine whether gender can be predicted with high accuracy using geometric morphometry on images of the 7th cervical vertebra obtained through computed tomography.

Materials and Methods

Study Population and Computed Tomography Protocol

This study was conducted in accordance with the decision numbered 2025/2235 of the Non-Interventional Local Ethics Committee of Karabük University (approval no: 2025/2235, date: April 16, 2025). The study was performed using CT angiography images from 150 male and 150 female individuals aged 18-65. The CT angiography images were obtained using a 16-row multidetector CT scanner (Aquilion 16; Toshiba Medical Systems, Otawara, Japan) located in the Department of Radiology at the Education and Research Hospital of Karabük University. The scanning protocol values were set as follows: pitch: 1.0 mm, tube voltage: 120 kV, gantry rotation: 0.75 s, and image slice thickness: 1 mm.

Image Processing

CT angiography images in the Digital Imaging and Communications in Medicine (DICOM) format were retrospectively scanned from the hospital archive system and transferred to the RadiAnt DICOM Viewer program, which is a personal workstation. Then, 3D Volume Rendering was applied. These images, now in three dimensions, were flattened so that the midpoint of the vertebral body and the midline of the spinous process remained aligned, and a stacking process was applied. The stacked images obtained using this method were saved in JPEG format at 1,279 x 614 pixels with 100% true magnification.

The images obtained from image processing in the merged JPEG format were converted to TPS format for geometric morphometric analysis. LM's were placed on the images converted to TPS format at 30 points that would reveal the shape of the vertebrae (Figure 1).

The single and paired LM's corresponding to the 30 LM's used to determine the shape of the 7th cervical vertebra are listed separately below.

Unique landmarks;

- The tip of the spinous process

- The midpoint on the anterior aspect of the vertebral body
- The most anterior point of the vertebral canal
- The most posterior point of the vertebral canal

Landmarks located in pairs on both the right and left sides;

- The point where the spinous process begins to narrow
- The point where the spinous process begins to widen
- The posterior projection of the vertebral lamina
- The most lateral point of the transverse process
- The most lateral point on the anterior of the vertebral body
- Midpoint between the lateral and median points of the vertebral body
- Anterior, posterior medial, and lateral points of the transverse foramen
- Anterolateral point of the vertebral canal
- Midpoint between the anterolateral point and the most anterior point of the vertebral canal
- Midpoint between the anterolateral point and the most

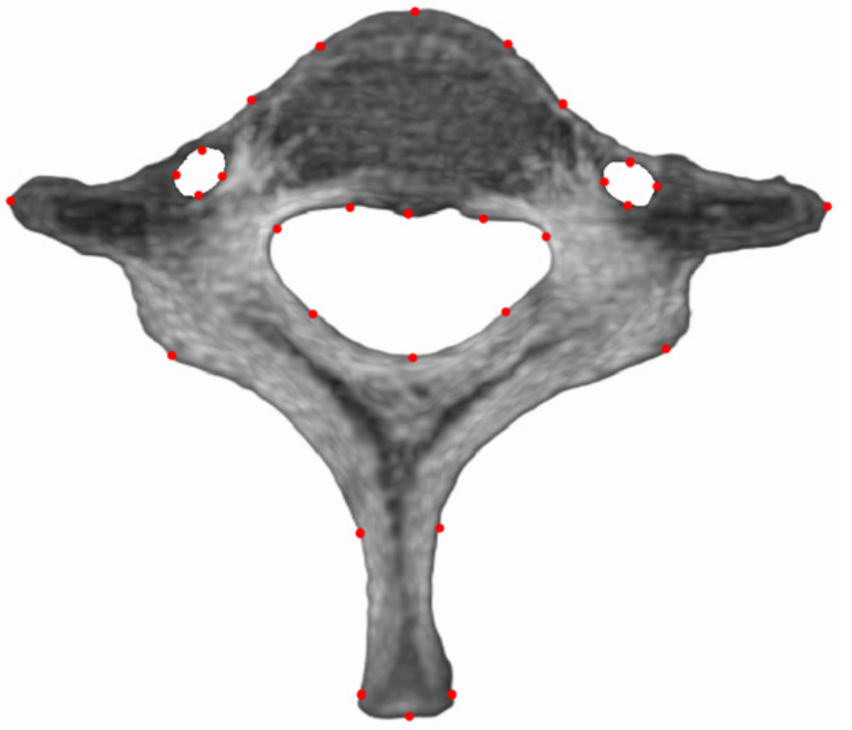

Figure 1. Display of landmarks

Coordinate Processing

All coordinates of the obtained LM's were saved as a TEXT file. Then, the translation, rotation, and scaling processing steps, i.e., GPA, were applied. As a result, the variation in each image that was not due to shape was eliminated, and the images were repositioned according to their center of gravity. After this process, all the points obtained were displayed on the coordinate plane in blue for males and red for females (Figure 2).

Principal Component Analysis (PCA) was used to reduce the dimensionality of the data obtained from the GPA results. As a result of this analysis, transformation grid images corresponding to Principal Component 1 (PC1) obtained for male and female individuals were obtained (Figure 3a, Figure 3b).

Principal Component 2-6 images for male individuals are shown in Figure 4a, while Principal Component 2-6 images for female individuals are shown in Figure 4b.

Statistical Analysis

Statistical analyses were performed using IBM SPSS (Version 21), PAST (Version 4.09), R Project (Version 4.0.2), Morpho J (Version 1.07a), and Minitab 17 software. Values obtained from the analyses were considered statistically significant at $p \leq 0.05$.

As a result of PCA, 56 PCs were obtained using the formula [(number of LM's *2)-4] = number of PCs. The eigenvalues, % variance, total variance, eigenvalue variance scaled by total variance, and number of variables for these were included. In addition, the %95 confidence ellipses of the X and Y coordinates obtained as a result of PCA were included. Linear Discriminant Analysis (LDA) was used for sex prediction, and the accuracy rate was provided.

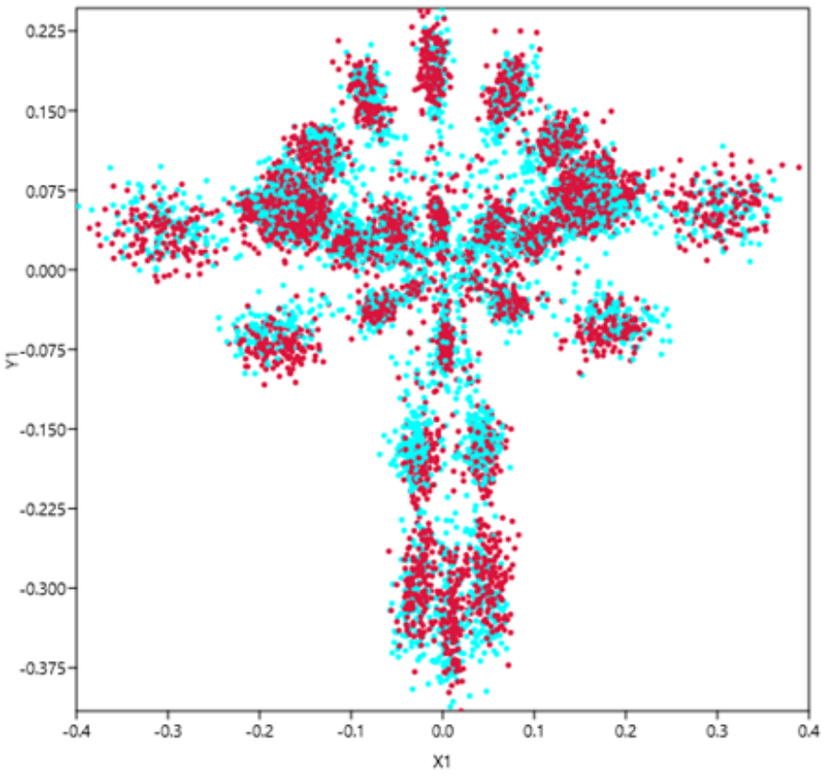

Figure 2. Display of marked points

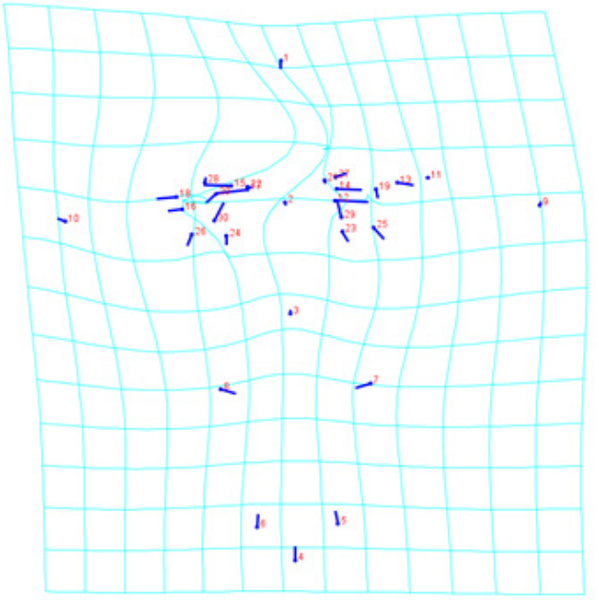

Figure 3a. Transformation grid for Principal Component 1 for female gender

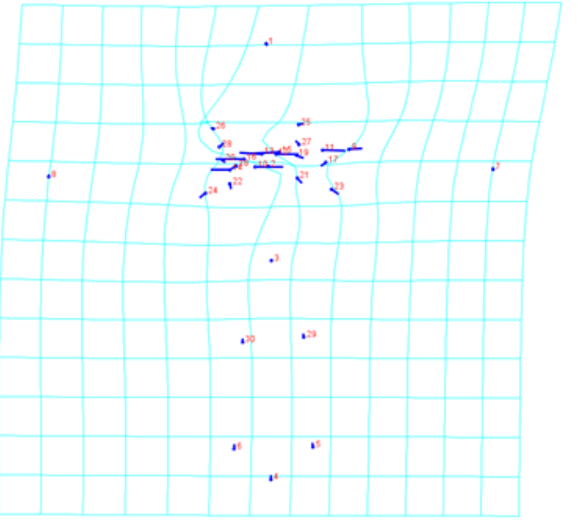

Figure 3b. Transformation grid for principal component 1 for males

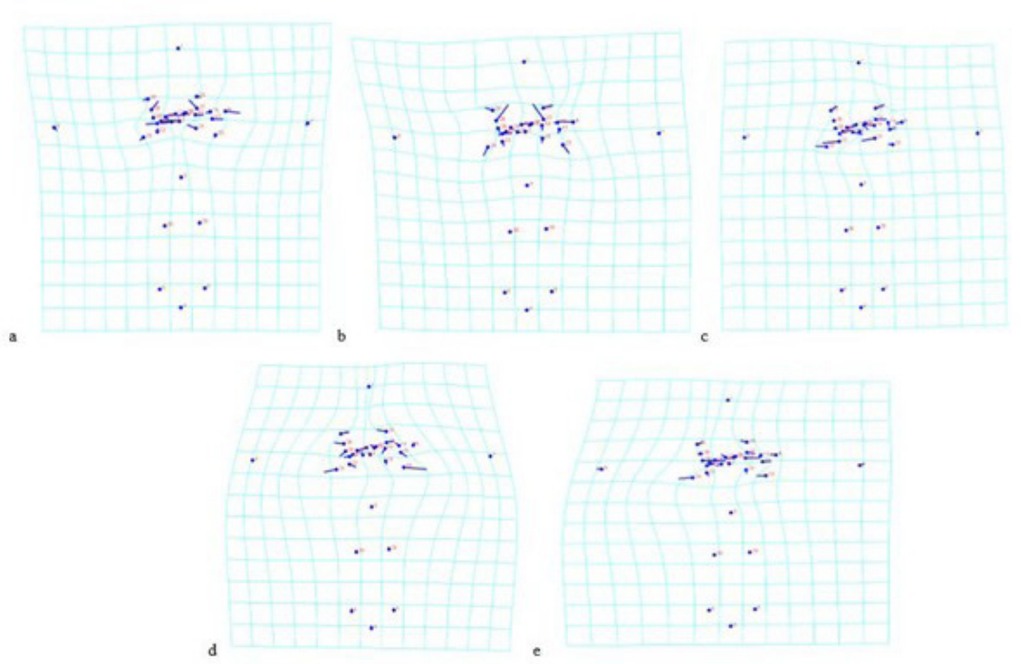

Figure 4a. Transformation grid for principal component 2-6 for males (a: PC2, b: PC3, c: PC4, d: PC5, e: PC6)

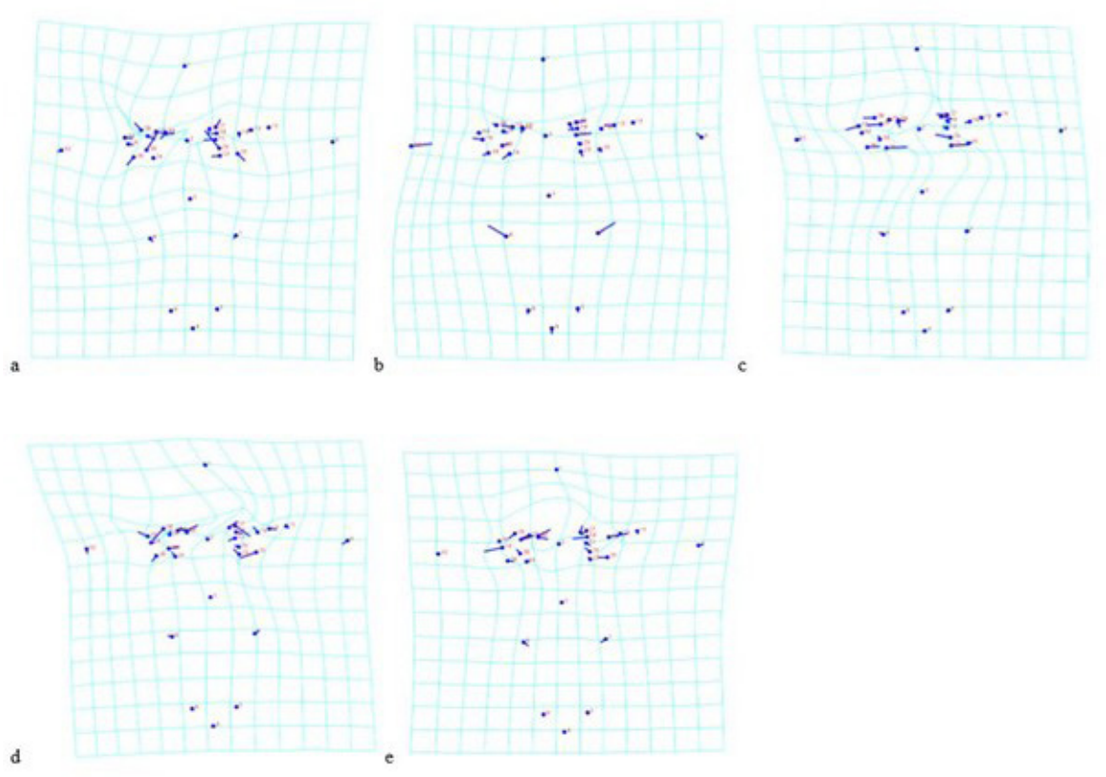

Figure 4b. Transformation grid for principal component 2-6 for females (a: PC2, b: PC3, c: PC4, d: PC5, e: PC6)

Results

The PCA results showed that 18.820% of the total shape variation was explained by PC1, 17.668% by PC2, 8.496% by PC3, 7.042% by PC4, 6.089% by PC5, and 5.559% by PC6. The remaining 50 PCs explained 36.326% (Figure 4). In short, the first 6 PCs explain 63.674% of the shape variation.

The eigenvalues and % variance values of the first 10 PCs obtained from the PCA results are presented in Table 1.

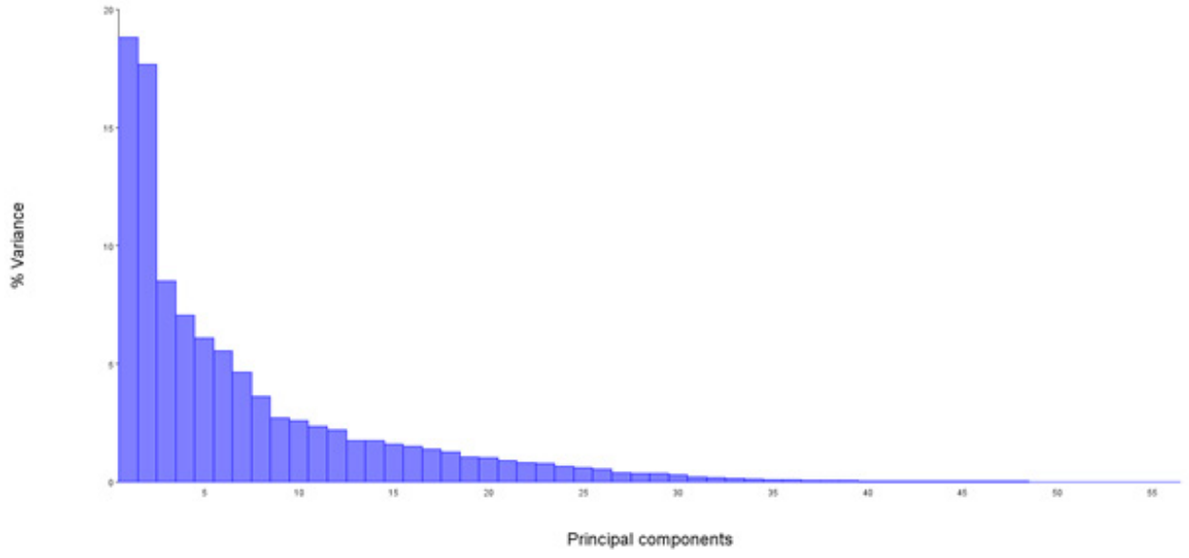

Figure 5. % variance values

Table 1. Eigenvalues and % variance values for the first 10 PCs

PC	Eigenvalue	% variance
1	0.03655858	18.820
2	0.03431943	17.668
3	0.01650337	8.496
4	0.01367977	7.042
5	0.01182725	6.089
6	0.01079836	5.559
7	0.00900772	4.637
8	0.00699999	3.604
9	0.00524925	2.702
10	0.00501748	2.583

PCs: Principal component

The effect of the variances obtained after PCA on the total variance and the values resulting from rotation, the sum of squares of GPA and the sum of squares of tangent, are given in Table 2. The difference between the sum of squares of GPA and the sum of squares of tangent was found to be 85.76035863631684.

The PCA results showed that 5 male individuals and 9 female individuals were outside the 95% confidence ellipses (Figure 5).

Table 2. Results of variance and sum of squares

Total variance	0.19424947
Variance of the eigenvalues	0.0000509841082

Table 2. Continued	
Eigenvalue variance scaled by total variance	0.00135
Eigenvalue variance scaled by total variance and number of variables	0.07704
Procrustes sums of squares	153.16304763536897
Tangent sums of squares	67.40268899905206

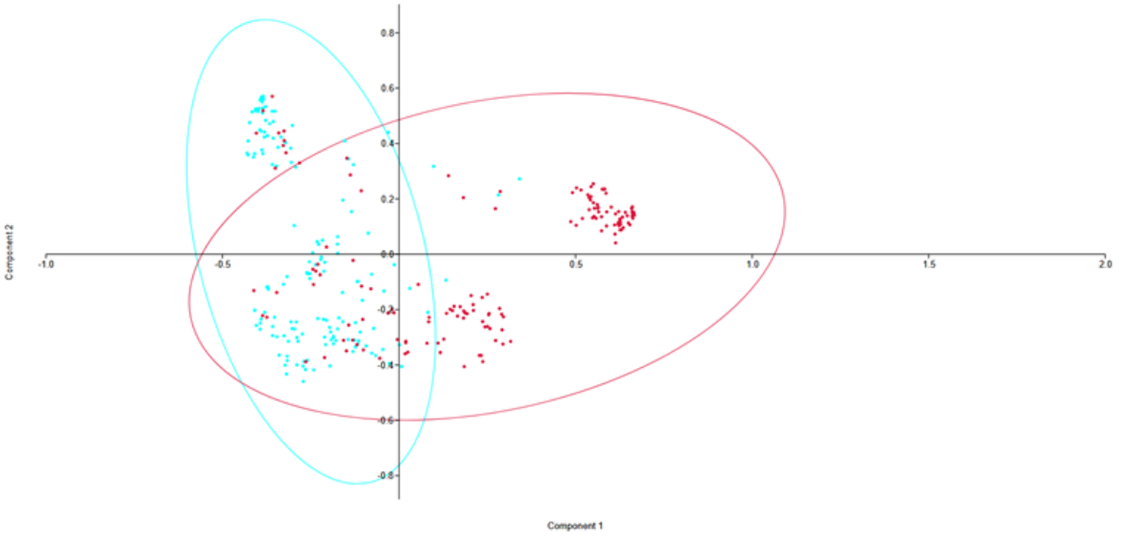

Figure 6. 95% confidence ellipses

The coordinates obtained after GPA were evaluated using LDA in terms of gender, and an accuracy rate of 83.33% was achieved. The confusion matrix obtained from the LDA result is given in Table 3. A total of 131 out of 150 men and 119 out of 150 women were correctly predicted. The ANOVA results showed a significant difference between the parameters for male and female genders (p:<0.0001).

Table 3. Confusion Matrix table		
Sex	**Male**	**Female**
Male	131	19
Female	31	119

Discussion

In our study, parameters obtained from CT images of the seventh cervical vertebra were examined using geometric morphometry in terms of gender, and LDA analysis correctly predicted the gender of individuals at a rate of 83.33%.

One of the most important issues in disciplines such as archaeology, anthropology, or forensic anthropology is identification. In archaeological excavations, natural disasters, or mass events, determining gender is one of the first steps in the identification process. In studies on gender determination, many different methods have been used in different contexts, yielding varying degrees of accuracy (10,23-26). However, bone structures have been used more frequently due to their protectability and durability.

There are many different methods available in areas such as identification and sex determination. Among these, many microscopic and macroscopic methods can be observed. Each method has certain advantages and disadvantages. The geometric morphometry method we selected from among these methods had certain advantages. Some of the advantages of this method include negligible application costs, no need for additional tools or equipment, a very low margin for researcher-related errors, and the ability to achieve reliable results with a minimum number of researchers without requiring a large number of researchers. The geometric morphometry method is also an ideal method in situations where time is limited and sex determination is required within a short time frame (7-9,27,28). These observed advantages have made the geometric morphometry method effective for use in research.

Fauad et al. (29) placed 11 LM's on the C3 vertebra using lateral cervical radiographs of 432 Malaysian individuals over the age of 20 (262 men, 170 women) and correctly predicted gender with a rate of 73.3% using Discriminant Function Analysis (DFA). In our study, we placed 30 LM's on the C7 vertebra and obtained a gender prediction rate of 83.33% using LDA analysis.

In a study by Rozendaal et al. (30) examining the skeletons of 295 individuals (157 men, 138 women) aged 20-99, the researchers examined the 7 cervical vertebrae of the individuals and considered 3 parameters for each vertebra, such as height, length, and width. The researchers found that the success rate of gender prediction using DFA, which examined the vertebrae individually, was 66.9-74% for males and 70.2-79.5% for females. Furthermore, it was observed that the researchers' accuracy rate in predicting gender using a combination of parameters obtained from multiple vertebrae ranged from 80.3% to 84.5% (30). In our study, we only used the 7th cervical vertebra, but we created 30 LM points for this vertebra and achieved 83.33% accuracy from a single cervical bone using LDA analysis. We recommend that our study be developed using other cervical bones and that combinatorial accuracies be created.

In a study conducted by Gama et al. (27) on the bones of 190 individuals (99 men, 91 women) who died between the ages of 20 and 69 and 47 individuals (24 men, 23 women) who died between 1996 and 2001, the second cervical vertebrae were examined, and 13 different measurements were taken. The researchers applied a logistic regression model to the data obtained from the measurements and achieved an accuracy of 82.4% to 89.7% for the training sample and 73.3% to 86.7% for the test sample (27). In a study conducted by Kaeswaren and Hackman (31), they examined 6 different cervical vertebrae (C2-C6) belonging to 25 individuals (13 males, 12 females) aged 49-109 years and measured 3 parameters for each vertebra. DFA results showed that using various parameters together achieved an accuracy rate ranging from 81.8% to 100% (31). In our study, we used the C7 vertebra and obtained a gender prediction rate of 83.33% using LDA analysis.

In a study conducted by Ekizoğlu et al. (32), radiological images from 294 individuals (146 men, 148 women) aged 18-87 were retrospectively examined, and measurements were taken of the C1-7 cervical vertebrae. The data obtained were analyzed for a single vertebra and for groups comprising several vertebrae; the researchers observed a prediction rate of 83.8-91.4% in the training set and a prediction rate of 76.2-91.6% in the validation set (32). In this study, a very wide range of accurate predictions was obtained, and it was observed that high prediction rates were achieved with multiple bone structures.

Based on the data obtained from the study, we found that the 7th cervical vertebra is sexually dimorphic and can be easily applied in forensic cases. Compared to studies in the literature, higher accuracy rates were obtained in some cases, while in others, these results were achieved using much less data or less bone diversity. This accuracy rate is of great importance to anthropologists, forensic experts, and anatomists. We believe that this study will help make the geometric morphometry method more functional in the field of identification.

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Ethical Approval: *This study was approved by the Karabük University Non-Interventional Local Ethics Committee (approval no: 2025/2235, date: April 16, 2025).*

Author Contributions

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Data Acquisition: Y.S., H.Ş.E., N.K.K.

Analysis and interpretation: Y.S., H.Ş.E., N.K.K.

Writing manuscript: Y.S., H.Ş.E., N.K.K., Z.Z., N.Y., S.T.

Critical revision of manuscript: Y.S.

Conflict of Interest: *The authors have no conflicts of interest to declare.*

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