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Sex Determination Using Craniometric Parameters: A Computed Tomography-Based Assessment

Kraniyometrik Parametrelerle Cinsiyet Tayini: Bilgisayarlı Tomografi Temelli Bir Değerlendirme

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Öz

Amaç: Bu çalışma, bilgisayarlı tomografi (BT) görüntülerinden elde edilen kraniyal ölçümlerin cinsiyet belirlemedeki etkinliğini değerlendirmeyi amaçlamıştır. Yedi lineer kraniyal parametre, erişkin Türk popülasyonunda cinsiyet sınıflandırmasındaki bireysel ve kombine ayırt edici güçleri açısından incelenmiştir.

Yöntem: Cinsiyeti bilinen erişkin bireyler, üçüncü basamak bir hastanede arşivlenen kraniyal BT görüntülerinden retrospektif olarak seçildi. Maksimum kraniyal uzunluk, nazo-oksipital uzunluk, kraniyal taban uzunluğu, basion–bregma uzunluğu, bizigomatik genişlik, biorbital genişlik ve interorbital genişlik olmak üzere yedi kraniyometrik parametre, multiplanar rekonstrükte BT görüntüleri kullanılarak ölçüldü. Cinsiyete göre karşılaştırmalar yapıldı ve sınıflandırma doğruluğunu değerlendirmek için kuadratik diskriminant analiz (QDA) uygulandı.

Bulgular: Çalışmaya 20–75 yaş aralığında toplam 200 birey (100 erkek, 100 kadın) dahil edildi. Tüm kraniyal ölçümler, interorbital genişlik dışında ($p = 0.047$), erkeklerde kadınlara göre anlamlı derecede daha yüksek bulundu (tüm diğer parametreler için $p < 0.001$). Cinsiyetler arası en belirgin farklar, bizigomatik genişlik (erkeklerde 132.82 ± 5.00 mm, kadınlarda 124.06 ± 4.90 mm) ve maksimum kraniyal uzunluk (erkeklerde 182.17 ± 7.42 mm, kadınlarda 171.51 ± 6.86 mm) parametrelerinde gözlendi. QDA modeli, erkeklerde %83 ve kadınlarda %89 doğruluk ile toplamda %86 sınıflandırma doğruluğu sağladı. İnterorbital genişlik yaş gruplarına göre anlamlı farklılık gösteren tek parametreydi ($p = 0.002$), diğer ölçümler yaşa göre etkilenmedi.

Sonuç: BT görüntülemelerinden elde edilen kraniyal parametreler, örneklemimizde %86 doğrulukla biyolojik cinsiyet tahmini sağlamış ve adli antropolojik değerlendirmelerde kullanılabilirliğini ortaya koymuştur. Bu bulgular, BT tabanlı lineer kraniyometrik analizlerin, özellikle ileri düzey 3D veya yapay zekâ temelli yöntemlerin uygulanmasının mümkün olmadığı durumlarda, invaziv olmayan ve tekrarlanabilir bir yaklaşım olarak değerini pekiştirmektedir. Ayrıca, bu çalışma erişkin Türk popülasyonuna özgü referans veriler sunarak literatüre populasyon-spesifik standartlar açısından katkıda bulunmaktadır.

Anahtar Kelimeler: Adli antropoloji, Kraniyometrik analiz, Cinsiyet tayini, Bilgisayarlı tomografi, Türk popülasyonu, Diskriminant analiz.

Abstract

Objective: This study aimed to evaluate the effectiveness of cranial measurements obtained from computed tomography (CT) scans in determining sex. Seven linear cranial parameters were assessed to investigate their individual and combined discriminative power in sex classification within an adult Turkish population.

Methods: Adult individuals of known sex were retrospectively selected from cranial CT scans archived at a tertiary care hospital. Seven craniometric parameters—including maximum cranial length, naso-occipital length, cranial base length, basion–bregma length, bizygomatic width, biorbital width, and interorbital width—were measured using multiplanar reconstructed CT images. Sex-based comparisons were performed, and a quadratic discriminant analysis (QDA) was conducted to assess classification accuracy.

Results: A total of 200 individuals (100 males and 100 females), aged between 20 and 75 years, were included in the study. All cranial measurements were significantly higher in males compared to females ($p < 0.001$ for all parameters except interorbital width, $p = 0.047$). The most prominent sex-based differences were observed in bizygomatic width (132.82 ± 5.00 mm in males vs. 124.06 ± 4.90 mm in females) and maximum cranial length (182.17 ± 7.42 mm vs. 171.51 ± 6.86 mm). The QDA model achieved an overall classification accuracy of 86%, with 83% accuracy in males and 89% in females. Interorbital width was the only parameter showing significant variation by age group ($p = 0.002$), while the remaining measurements were unaffected by age.

Conclusion: Cranial parameters obtained from CT imaging demonstrated a classification accuracy of 86% in sex estimation within our sample, supporting their utility in forensic anthropological assessments. These findings reinforce the value of CT-based linear craniometric analysis as a non-invasive and reproducible approach, particularly in settings where advanced 3D or AI-based methods may not be feasible. Additionally, this study provides reference data specific to an adult Turkish cohort, contributing to population-specific standards in the literature.

Keywords: Forensic anthropology, craniometric analysis, Sex determination, Computed tomography, Turkish population, Discriminant analysis

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INTRODUCTION

Identification in forensic medicine is of critical importance for both deceased and living individuals and constitutes a fundamental step, particularly in mass fatalities, natural disasters, fires, explosions, and war scenarios. In cases involving decomposed, fragmented, or charred bodies, conventional identification methods such as fingerprinting, DNA analysis, and dental records often become unusable (1). Under such circumstances, the durability and resistance of bone tissue against postmortem degradation highlight the relevance of anthropological analysis based on the skeletal system (2).

In forensic anthropology, it is important to distinguish between the concepts of sex and gender. While sex refers to biological and anatomical attributes such as chromosomal, hormonal, and skeletal features, gender encompasses sociocultural identity, roles, and behaviors. Since the present study is based on craniometric analysis of skeletal features derived from CT images, the appropriate term is sex estimation (2-4). Therefore, all references throughout the manuscript are aligned accordingly to ensure terminological accuracy and scientific rigor.

Sex estimation based on skeletal remains is the first and one of the most crucial stages in constructing the biological profile (3). Determining the sex provides a foundational reference for subsequent steps, including age and stature estimation (4). In this context, bones with high sexual dimorphism—such as the skull, pelvis, and femur—are frequently analyzed (5). However, in cases where full skeletal access is not feasible, region-specific morphometric analysis of well-preserved structures, particularly the skull, becomes highly valuable (6).

The skull displays distinct metric differences between males and females, shaped by embryonic development, hormonal influences, and genetic factors (7). In recent years, the use of modern radiological imaging techniques—especially computed tomography (CT)—has become increasingly common alongside traditional osteometric methods in assessing these differences. CT imaging enables the acquisition of high-resolution bone images, allows for non-invasive measurement, and yields reproducible data (8).

Among the craniometric parameters, maximum cranial length, naso-occipital length, cranial base length, basion–bregma length, bizygomatic width, biorbital width, and interorbital width are metrics that have been proven effective in sex estimation across both the literature and forensic practice (9-11). Researchers have demonstrated that these parameters can distinguish sex with 80–90% accuracy in various populations (7,10).

However, sex-related metric differences can vary across ethnic, geographic, and population-specific factors (12,13). Therefore, the development of population-specific reference standards is essential to improving the accuracy of forensic anthropological analyses (14).

Despite the presence of more complex methodologies in the literature, there is still a practical need for reliable and accessible approaches in populations with limited reference data. This study addresses that need by providing population-specific linear craniometric reference values for the adult Turkish population using routine CT imaging.

The objective of this study was to evaluate the utility of craniometric parameters obtained from computed tomography (CT) images for sex estimation, both individually and in combination. Metric data derived from craniofacial structures were statistically analyzed using quadratic discriminant analysis, and the discriminative power, accuracy rates, and individual contributions of each parameter were compared. The study aimed to provide highly reliable, reproducible, and population-specific measurement data applicable to forensic practice. The findings are expected to contribute to forensic anthropological analyses in Turkey and serve as a reference for standardized measurements in identification processes.

METHODS

This study was designed as a retrospective, cross-sectional observational analysis. Ethical approval was obtained from the Clinical Research Ethics Committee of AAA University Faculty of Medicine between 09/03/2022 and 04/01/2023 (Approval No: 2022/35). Only anonymized CT images archived in the hospital's database were used, and no identifiable patient information was accessed at any stage of the study.

Sample Selection

The study included adult individuals selected from brain CT and CT angiography scans taken between 2016 and 2021 for various clinical indications, archived in the Radiology Department of AAA University Research and Training Hospital. All images were retrospectively retrieved and reviewed via the hospital's PACS system.

Inclusion criteria consisted of:

• Individuals aged over 20 years (to ensure completed skeletal development).

Exclusion criteria included:

• Scans without visualization of the frontal sinus and mandibular regions,

• Images with artifacts, craniofacial fractures, or significant deformities,

• History of craniofacial surgery,

• Absence or hypoplasia of the frontal sinus.

Imaging Protocol

The CT scans were acquired using 64-slice GE VCT LightSpeed and 80-slice Canon Aquilion Prime SP multidetector computed tomography (MDCT) systems. Imaging parameters were as follows:

• Slice thickness: 0.5–0.625 mm

• Voltage (kV): 120 kV

• Tube current (mAs): 45–175 mAs

• Rotation time: 0.5 seconds

• Spiral pitch: 0.8–1.0

• Matrix size: 512 × 512

• Field of view (FOV): 210–270 mm

Multiplanar reformation (MPR) was applied to the axial source images to generate sagittal and coronal planes, on which all measurements were performed.

Measurement Parameters and Techniques

Craniometric measurements were obtained based on seven parameters previously reported in the literature to exhibit high discriminative value in sex estimation. All measurements were performed in millimeters using digital calipers on the CT workstation.

The seven craniometric parameters were measured on sagittal, axial, and coronal planes of the CT images.

• Maximum cranial length (MCL): Measured in the sagittal plane as the longest distance between the glabella and the opisthocranion.

• Naso-occipital length (NOL): The distance between the nasion and the opisthocranion, measured sagittally.

• Cranial base length (CBL): The distance between the basion and nasion in the sagittal plane.

• Basion–bregma length (BBL): The perpendicular distance from the basion to the bregma, also in the sagittal plane (Figure 1).

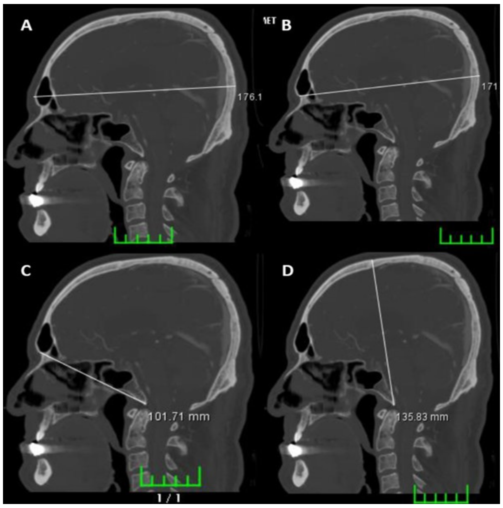

Figure 1. Demonstration of maximum cranial length (A), naso-occipital length (B), cranial base length (C), and basion–bregma length (D) on sagittal and axial CT sections.

- Bizygomatic width (BZW): Measured in the axial plane as the widest transverse distance between the lateral aspects of both zygomatic arches.

- Biorbital width (BOW): The distance between the ectoconchion points of both orbits, measured in the coronal plane.

- Interorbital width (IOW): The distance between the dacryon points on both sides, also measured coronally (Figure 2).

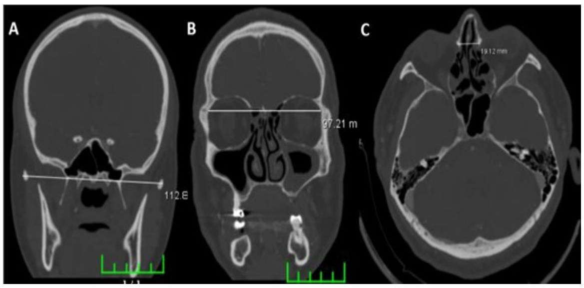

Figure 2. Digital representation of bizygomatic width (A), biorbital width (B), and interorbital width (C) on axial and coronal CT sections.

These parameters were used as primary morphological indicators in assessing cranial dimorphism between sex.

All measurements were independently performed by a radiology specialist and a trained researcher. Two months later, the researcher repeated the measurements to assess intra-observer and inter-observer reliability. Reliability was evaluated using the intraclass correlation coefficient (ICC), which demonstrated high (ICC > 0.85) to excellent (ICC > 0.95) agreement across all parameters.

Statistical Analysis

Statistical analyses were performed using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). For numerical variables, descriptive statistics including mean, standard deviation, minimum, maximum, and median values were calculated. The normality of data distribution was assessed using the Shapiro–Wilk test. Depending on the distribution, either the Student's t-test or the Mann–Whitney U test was used for sex-based comparisons. For comparisons across age groups, one-way ANOVA or the Kruskal–Wallis test was applied as appropriate. Quadratic Discriminant Analysis (QDA) was employed to evaluate the predictive power of craniometric parameters in sex estimation and to calculate classification accuracy. Prior to performing discriminant analysis, Box's M test was used to assess the equality of covariance matrices across groups. The result indicated a statistically significant difference ($p < 0.001$), supporting the use of QDA over Linear Discriminant Analysis (LDA), which assumes equal covariance. The performance and reliability of the discriminant model were evaluated using Wilks' Lambda, chi-square statistics, the canonical correlation coefficient, and overall classification accuracy. Additionally, Receiver Operating Characteristic (ROC) analysis was conducted for the two most discriminative parameters—bizygomatic width and maximum cranial length—to determine their individual classification performance. Area Under the Curve (AUC) values, as well as optimal cut-off points, were calculated using the Youden Index. Sensitivity and specificity values corresponding to these thresholds were also reported. A p-value < 0.05 was considered statistically significant.

RESULTS

A total of 200 individuals were included in the study, equally distributed by sex with 100 females and 100 males. Participants were stratified into five distinct age groups based on 10-year intervals: 20–29, 30–39, 40–49, 50–59, and 60–75 years. A homogeneous sample was created by including 20 females and 20 males in each age group.

Descriptive statistics of the craniometric parameters are presented in Table 1. The parameter with the highest mean value was maximum cranial length (MCL) at 176.84 ± 8.91 mm, followed by naso-occipital length (NOL) at 173.91 ± 8.57 mm, and basion–bregma length (BBL) at 136.88 ± 5.98 mm. The lowest mean value was observed for interorbital width (IOW), measured at 20.36 ± 2.47 mm. The median and range values showed a similar distribution: MCL had a median of 176.4 mm (range: 157.6–200.0 mm), NOL had 173.0 mm (150.5–197.5 mm), and IOW had 20.0 mm (13.0–32.6 mm) (Table 1.).

Sex-based comparisons of the craniometric measurements are presented in Table 2. When stratified by sex, all craniometric parameters were found to be significantly higher in males compared to females. The most pronounced difference was observed in bizygomatic width, which measured 132.82 ± 5.00 mm in males and 124.06 ± 4.90 mm in females (p < 0.001). Similarly, maximum cranial length was significantly greater in males (182.17 ± 7.42 mm) than in females (171.51 ± 6.86 mm) (p < 0.001). Other parameters—including naso-occipital length, cranial base length, basion–bregma length, and biorbital width—also exhibited significantly higher values in male participants, with all comparisons reaching statistical significance (p < 0.001). Although the difference in interorbital width between sexes was less marked, males still showed slightly higher measurements, and this difference was also statistically significant (p = 0.047)

Table 1. Descriptive statistics of the craniometric parameters

Parameter	Mean ± SD (mm)	Median (Min–Max) (mm)
Maximum cranial length (MCL)	176.84 ± 8.91	176.4 (157.6–200.0)
Naso-occipital length (NOL)	173.91 ± 8.57	173.0 (150.5–197.5)
Cranial base length (CBL)	101.21 ± 5.31	101.0 (89.0–114.0)
Basion–bregma length (BBL)	136.88 ± 5.98	136.6 (121.1–152.0)
Bizygomatic width (BZW)	128.44 ± 6.61	128.45 (114.4–143.2)
KBiorbital width (BOW)	93.31 ± 4.24	93.0 (81.4–102.6)
Interorbital width (IOW)	20.36 ± 2.47	220.0 (13.0–32.6)

Table 2. Gender-based comparisons of the craniometric measurements

Parameter	Male (Mean ± SD) (mm)	Female (Mean ± SD) (mm)	p-value
Maximum cranial length (MCL)	182.17 ± 7.42	171.51 ± 6.86	< 0.001†
Naso-occipital length (NOL)	178.00 ± 7.99	169.82 ± 7.08	< 0.001†
Cranial base length (CBL)	103.76 ± 5.04	98.67 ± 4.26	< 0.001†
Basion–bregma length (BBL)	139.36 ± 5.34	134.39 ± 5.56	< 0.001†
Bizygomatic width (BZW)	132.82 ± 5.00	124.06 ± 4.90	< 0.001†
Biorbital width (BOW)	95.18 ± 3.84	91.45 ± 3.78	< 0.001†
Interorbital width (IOW)	20.67 ± 2.23	20.05 ± 2.67	0.047‡

(Table 2.).

The results of the discriminant analysis based on craniometric measurements are presented in Table 3. The model's ability to distinguish between sex was found to be statistically significant (Wilks' Lambda = 0.401; $p < 0.001$), with an overall classification accuracy of 86%. The canonical correlation coefficient was 0.774. According to the structure coefficients, bizygomatic width (SC = 0.727) had the highest discriminative power for sex differentiation, followed by maximum cranial length (SC = 0.613), cranial base length (SC = 0.449), naso-occipital length (SC = 0.445), biorbital width (SC = 0.402), and basion–bregma length (SC = 0.375). Although interorbital width showed statistically significant differences between sex in previous analyses, it contributed less to the discriminant function (SC = 0.103). When comparing the standardized discriminant function coefficients for male and female groups, bizygomatic width (3.220) and basion–bregma length (3.001) had the highest impact in males, whereas the corresponding values for females were 2.855 and 2.989, respectively. Notably, the interorbital width had negative coefficients in both sexes, suggesting that lower values in this parameter are more strongly associated with the female group. This model correctly classified 83% of male and 89% of female participants (Table 3.).

Table 3. The results of the discriminant analysis based on craniometric measurements

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Parameter	Structure Coefficient (SC)	Male Coefficient	Female Coefficient
Bizygomatic width (BZW)	0.727	3.220	2.855
Maximum cranial length (MCL)	0.613	1.769	1.156
Cranial base length (CBL)	0.449	–0.404	–0.476
Naso-occipital length (NOL)	0.445	0.642	1.090
Biorbital width (BOW)	0.402	2.740	2.844
Basion–bregma length (BBL)	0.375	3.001	2.989
Interorbital width (IOW)	0.103	–3.094	–2.801
Constant		–719.365	–648.858
Discriminant Model Indicators	Value		
Wilks' Lambda	0.401		
Eigenvalue	1.495		
Chi-square	177.796		
p-value	< 0.001		
Canonical Correlation	0.774		
Classification Accuracy (%)	86.0%		

Sex classification accuracy based on craniometric measurements is presented in Table 4. The discriminant analysis model developed from craniometric data successfully classified individuals by sex with an overall accuracy rate of 86%. Specifically, the model correctly identified 83% of male individuals (n = 83) as male, while 17% (n = 17) were misclassified as female. In contrast, the model demonstrated higher accuracy for female participants: 89% (n = 89) were correctly classified as female, whereas 11% (n = 11) were incorrectly classified as male (Table 4.).

Table 4. Gender classification accuracy based on craniometric measurements

Actual Gender	Predicted: Male (n)	Predicted: Female (n	Total (n)	Correct Classification (%)
Male	83	17	100	83.0
Female	11	89	100	89.0
Total	94	106	200	86.0

Comparisons of craniometric parameters across age groups are presented in Table 5. When the distribution of craniometric parameters was examined according to 10-year age intervals, no statistically significant age-related variation was observed in most measurements. Maximum cranial length (MCL), naso-occipital length (NOL), cranial base length (CBL), basion–bregma length (BBL), bizygomatic width (BZW), and biorbital width (BOW) did not show significant differences across age groups (all p > 0.05). However, interorbital width (IOW) demonstrated a statistically significant difference with respect to age (p = 0.002). Notably, individuals in the 60–75 age group had higher IOW values, and this group was found to differ significantly from individuals in the 20–49 age range (Table 5.). ROC analysis was performed for bizygomatic width and maximum cranial length, which were identified as the most effective variables in the discriminant model. The AUC was 0.923 (95% CI: 0.888–0.959) for bizygomatic width and 0.902 (95% CI: 0.864–0.940) for maximum cranial length, indicating excellent classification performance. Using the Youden Index, the optimal cut-off value for bizygomatic width was determined to be 128.3 mm, with a sensitivity of 88.0% and specificity of 85.0%. For maximum cranial length, the optimal cut-off value was 176.0 mm, yielding a sensitivity of 85.0% and specificity of 82.0%. Additionally, a confusion matrix of the QDA model is shown in Figure 4, indicating correct classification of 83% of males and 89% of females (Figure 3.).

Table 5. Comparison of craniometric parameters by age group (Mean ± SD).

Parameter	20–29 yrs	30–39 yrs	40–49 yrs	50–59 yrs	60–75 yrs	P-value
Maximum cranial length (MCL)	178.05 ± 7.45	178.09 ± 8.87	176.05 ± 9.21	175.60 ± 8.99	176.42 ± 9.21	0.612§
Naso-occipital length (NOL)	175.34 ± 7.33	175.21 ± 7.83	172.92 ± 9.41	172.97 ± 8.24	173.12 ± 9.87	0.498§
Cranial base length (CBL)	102.10 ± 4.38	102.50 ± 4.13	100.56 ± 6.29	100.39 ± 5.52	100.32 ± 5.91	0.219§
Basion–bregma length (BBL)	137.17 ± 4.76	138.03 ± 6.22	136.76 ± 7.44	136.44 ± 6.25	136.07 ± 6.48	0.636§
Bizygomatic width (BZW)	128.20 ± 7.20	128.03 ± 6.26	129.06 ± 6.47	127.64 ± 7.03	129.29 ± 6.31	0.757§
Biorbital width (BOW)	92.68 ± 4.59	93.53 ± 4.61	92.00 ± 4.16	93.38 ± 3.98	94.09 ± 3.85	0.611‡
Interorbital width (IOW)	19.66 ± 2.38	19.85 ± 1.99	19.97 ± 2.61	20.67 ± 2.22	21.66 ± 2.67	0.002‡

§ ANOVA test, ‡ Kruskal–Wallis test

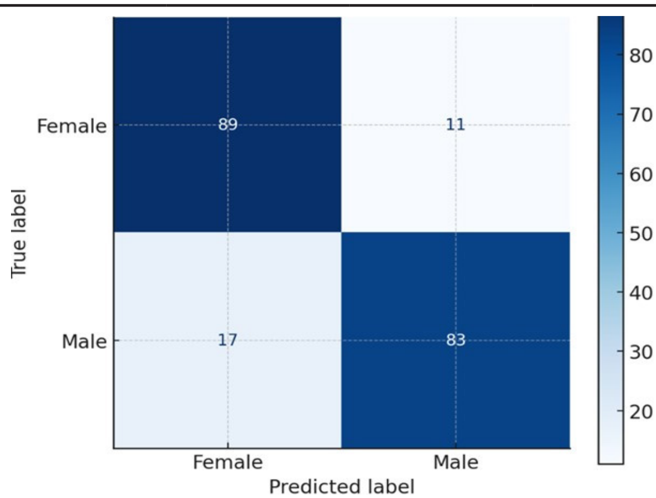

Figure 2. Digital representation of bizygomatic width (A), biorbital width (B), and interorbital width (C) on axial and coronal CT sections.

DISCUSSION

This study demonstrated that selected cranial parameters are effective in estimating biological sex, achieving an overall classification accuracy of 86% using quadratic discriminant analysis. In our analysis of seven different craniometric measurements, all parameters were found to be significantly higher in male individuals, and a discriminant model constructed solely from these metrics achieved an overall sex classification accuracy of 86%. Notably, bizygomatic width (BZW), maximum cranial length (MCL), and cranial base length (CBL) were identified as the parameters contributing most significantly to sex differentiation.

Cranial morphometric analysis has long served as a fundamental tool for sex estimation, particularly in postmortem identification processes. In this context, the findings of our study are largely consistent with existing literature. Kranioti et al. reported an 81% accuracy rate in sex estimation using similar craniometric parameters in a Greek population, identifying bizygomatic width as the most discriminative variable (15). Swift et al., in their study on an Australian population, emphasized the presence of strong sexual dimorphism in zygomatic, orbital, and cranial length measurements (14).

In our study, bizygomatic width emerged as the most powerful variable in terms of both structure coefficient and discriminant function coefficient. The zygomatic arches, which are more pronounced in males due to higher exposure to androgenic influence, serve as a highly distinctive region for sex differentiation (16,17). Similarly, maximum cranial length reflects skeletal growth differences and thus represents a significant indicator of sexual dimorphism. These findings have been consistently reported in both anthropological and radiological studies (18,19).

Our findings were further compared with similar studies conducted in different populations, as shown in table 6. While bizygomatic width and maximum cranial length consistently emerged as the most discriminative parameters, slight variations in absolute values and accuracy rates were observed across populations. For instance, Kranioti et al. reported 81% accuracy in a Greek population, while Toy et al. achieved over 90% using machine learning techniques in another Turkish cohort. These differences may reflect methodological variations (e.g., ML vs. QDA), sample composition, or population-specific craniofacial characteristics.

The observed differences in cranial dimensions between sexes are primarily attributable to underlying biological and developmental processes. Male skulls tend to be larger due to the prolonged influence of androgens during puberty, which enhances periosteal bone growth, particularly in the zygomatic arches and cranial vault. These hormonal effects result in more prominent facial skeletons in males. Additionally, sex-based variation in craniofacial growth trajectories contributes to increased sexual dimorphism in adulthood. Functionally, wider zygomatic arches in males are thought to support larger masticatory muscles, an evolutionary adaptation associated with dietary and mechanical demands.

Interestingly, although IOW showed a statistically significant difference between males and females in our sample, it had the lowest structure coefficient in the discriminant model. This suggests that, despite its statistical significance, the discriminative power of IOW may be limited—potentially due to age-related variation within the sample. Indeed, IOW was the only parameter that exhibited a significant difference across age groups ($p = 0.002$). This finding implies that certain craniometric dimensions, particularly in the orbital region, may change with advancing age. Previous studies have reported subtle age-related craniofacial remodeling, including widening of orbital dimensions due to bone resorption at the medial and inferior orbital walls (20,21). Additionally, slight measurement discrepancies may result from soft tissue changes or variation in imaging angles, particularly in older individuals. These findings underscore the importance of considering age-related variability when utilizing IOW in sex estimation models.

In our discriminant model, which demonstrated high classification accuracy, 89% of female and 83% of male individuals were correctly classified. This suggests that the model was more effective in identifying female individuals. The difference may be attributed to greater homogeneity in cranial measurements among females or a broader range of anatomical variation in males. This pattern has also been observed in previous studies, where female cranial dimensions tend to exhibit tighter clustering around the mean, resulting in more consistent classification outcomes. In contrast, greater anatomical dispersion in males may lead to overlap between classes and reduce prediction precision. These observations suggest that sexual dimorphism, although more pronounced in some male features, may be expressed with more statistical consistency in females. Similar findings have been reported in the literature, where classification accuracy tends to be higher in female populations (22-25).

While deep learning and machine learning models have achieved classification accuracies above 90% in some studies (22,23), they often require large datasets, complex feature extraction, and high computational resources. In contrast, our use of QDA offers a more interpretable, accessible, and statistically sound approach—particularly in small-to-medium-sized datasets with well-defined linear measurements. Previous studies using QDA or linear discriminant analysis have reported accuracies ranging between 75% and 85%, placing our model (86%) among the higher-performing conventional approaches (9,14,15).

One of the key contributions of our study is the presentation of CT-based craniometric reference data specific to the Turkish population. While many previous craniometric analyses have been conducted using cadaveric specimens or manual measurements (10,26,27), our study utilized CT, a high-resolution, non-invasive, and reproducible imaging modality, to obtain objective and standardized data. This approach offers a valuable advancement for both clinical applications and forensic anthropological evaluations.

Although the parameters and statistical methods used in our study may appear similar to those employed in previous research, this study provides significant value by focusing on a Turkish cohort using CT-based linear measurements. While advanced methods such as 3D geometric morphometrics and machine learning have shown promise in sex estimation, they often require sophisticated equipment, specialized software, and complex processing pipelines that may not be accessible in routine forensic or clinical practice. In contrast, our approach offers a practical, reproducible, and cost-effective method using widely available CT imaging data. Furthermore, craniometric reference standards specific to the Turkish population are scarce in the literature. This study helps bridge that gap by establishing normative data that can serve both forensic anthropologists and radiologists working in Turkey. By applying QDA to a demographically balanced and well-controlled sample, we demonstrate that conventional linear measurements remain robust and informative in sex estimation, especially in settings with limited access to advanced tools.

However, this study has certain limitations. Although the sample size is comparable to or larger than those in similar studies, its single-center design may limit the generalizability of the findings. In addition, the artificially balanced distribution of sex and age groups—while statistically beneficial for model development—may not accurately reflect the demographic heterogeneity of real-world populations. Considering the substantial ethnic and geographic diversity across different regions of Turkey, population-specific variations in cranial morphology are likely and should be explored in future research. Another methodological limitation is the absence of internal validation techniques, such as k-fold cross-validation or bootstrapping, which are important for assessing the robustness and generalizability of classification models. Although QDA was selected based on the unequal covariance structure detected via Box's M test, future studies with larger and more diverse datasets are encouraged to incorporate additional models—such as logistic regression or machine learning-based classifiers—and to apply internal validation procedures to improve model reliability and external applicability.

CONCLUSION

In conclusion, this study demonstrated that craniometric parameters obtained from CT images—particularly bizygomatic width, maximum cranial length, and cranial base length—are effective in sex estimation, achieving an overall classification accuracy of 86%. The findings support the use of CT-based craniometric analysis as a reliable and non-invasive tool in forensic anthropology. By providing population-specific reference data, this study contributes to the establishment of national standards in sex estimation. Future multicenter studies using diverse populations and advanced modeling techniques are recommended to further enhance generalizability.

Declarationsr

Conflict of interest

None declared.

Ethics approval and consent to participate

Ethical approval was obtained from the Clinical Research Ethics Committee of Gaziantep University Faculty of Medicine between 09/03/2022 and 04/01/2023 (Approval No: 2022/35).

Clinical trial

Not applicable

Data Availability

Data are available with a reasonable request to the corresponding authors.

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