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Sex Estimation Using Cephalometric Data in a Turkish Population: A Logistic and ROC-Based Analysis

Estimación del Sexo Mediante Datos Cefalométricos en una Población Turca: Un Análisis Logístico y Basado en la Curva ROC

Yarenkür Alkan[1]

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SUMMARY: Sex estimation is a fundamental task in biological anthropology; however, most previous studies rely on skeletal collections or radiological data. This study is distinctive in its use of cephalometric measurements collected from living individuals to develop a population-specific sex estimation model based solely on head dimensions in a contemporary Turkish cohort. This approach offers a soft-tissue-based, population-specific model that may be useful in certain forensic screenings or clinical anthropological applications where skeletal data or imaging are not available. Although advanced imaging technologies such as CT and 3D scanning have become increasingly popular for metric analysis, they are often inaccessible in many contexts. Fourteen standardized cephalometric measurements were taken from a total of 244 adult individuals (128 males, 116 females). Both univariate and multivariate logistic regression models were constructed to evaluate sex estimation accuracy, while Receiver Operating Characteristic (ROC) analysis was used to assess model performance and identify optimal classification thresholds. The final multivariate model, which included maximum head breadth, total facial height, maximum head length, head circumference, nasal aperture breadth, and bigonial breadth, achieved an overall classification accuracy of 89.8 %, with a sensitivity of 89.84 %, specificity of 93.10 %, and an AUC of 0.965. These results demonstrate the strong discriminative power of the model and highlight the effectiveness of integrating cephalometric data with logistic regression and ROC analysis. By establishing population-specific threshold values, this study offers a robust and replicable framework for sex estimation applicable in both forensic and archaeological contexts. The findings also emphasize the value of accessible and cost-effective methods, particularly for use in resource-limited environments. Further research with larger and more diverse samples is encouraged to validate and broaden the applicability of these standards.

KEY WORDS: Sex estimation; Cephalometric measurements; Turkish population; ROC analysis; Logistic regression; Anthropometry.

INTRODUCTION

Understanding cranial morphometric variation across human populations remains a key focus in biological anthropology. Various methods are employed for sex estimation in paleoanthropological research. In cases where the postcranial skeleton is incomplete or absent—such as in forensic or archaeological remains—the skull often serves as the primary anatomical basis for biological profiling. Morphological assessments involve the visual evaluation of sexually dimorphic traits of the skull. Although subjective, these methods are widely used due to their simplicity and ease of application. Metric approaches are commonly employed to quantify these differences using statistical models that offer more objective means of sex classification (Gonzalez *et al*., 2011). These methods utilize caliper-based measurements along with statistical analyses to classify individuals based on patterns of sexual dimorphism. However, these metric approaches are not without limitations. For instance, population diversity can reduce measurement accuracy, while conservation-related issues can further complicate reliability in paleoanthropological contexts. Considering these limitations, cephalometric measurements should be applied cautiously and preferably in conjunction with advanced statistical techniques for sex estimation. This study aims to address this practical challenge by developing population-specific standards for sex estimation based on cephalometric measurements from a contemporary Turkish sample. It investigates whether reliable sex estimation can be achieved using only

[1] Kırsehir Ahi Evran University, Faculty of Arts and Sciences, Department of Anthropology, Kirsehir, Turkey.

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cephalometric measurements, particularly in cases involving skeletal remains where postcranial elements are missing. By applying logistic regression and Receiver Operating Characteristic (ROC) analysis to 14 cephalic dimensions, this study evaluates the discriminative power of both individual and combined variables, and establishes robust cut-off thresholds. The results contribute to the development of accessible and statistically sound tools for sex estimation in bioarchaeology and forensic anthropology, particularly in resource-constrained or fragmentary contexts.

Receiver Operating Characteristic (ROC) analysis has emerged as a powerful statistical tool for evaluating the performance of classification models in sex estimation studies. It offers a comprehensive measure of diagnostic accuracy by analyzing the trade-off between sensitivity and specificity (Metz, 1978). This method enhances reliability in forensic and bioarchaeological applications by enabling researchers to determine optimal classification thresholds. When integrated with logistic regression, ROC analysis contributes to improved prediction accuracy and enhances the generalizability of classification models across different populations.

The aim of this study was to statistically analyze cephalometric measurements obtained from living individuals and to develop sex estimation standards that reflect cephalic morphological variation. Fourteen cephalometric variables were included in the analysis. The study also aimed to assess the effectiveness of ROC analysis for sex estimation using these variables and to compare different statistical models in determining optimal classification thresholds. In addition to developing a predictive model based on a comprehensive set of cephalometric variables, the present study also aims to explore whether a minimal set of skeletal-representative measurements can be used to construct an alternative model that may offer applicability in osteological contexts. By analyzing variables least influenced by soft tissue, such as maximum head length, maximum head breadth, bigonial breadth and bizygomatic breadth, this study provides a preliminary assessment of their utility in dry skull-based sex estimation. The findings are expected to contribute to forensic science and paleoanthropological research by improving methodological precision in sex estimation practices. This study also lays the groundwork for future research on cranial morphometric variation and the development of population-specific paleoanthropological standards.

This study employs cephalometric measurements to establish population-specific standards for Turkish individuals. This methodological shift is particularly relevant in contexts where imaging resources are limited and direct physical measurement remains the only feasible alternative. By generating robust, accessible, and replicable standards, this research addresses a critical gap in both forensic and bioarchaeological practice and provides a practical alternative to imaging-based approaches.

MATERIAL AND METHOD

This study utilized a dataset consisting of craniofacial measurements collected from a sample of individuals with varying ages and sexes. Measurements were conducted on students and staff from various regions of Turkey who were studying or working at Kırs¸ehir Ahi Evran University at the time of data collection. A total of 244 individuals participated in the study, including 128 males and 116 females. Ethical approval was obtained from Ahi Evran University Ethics Committee in accordance with the principles of the Declaration of Helsinki (2023-14/91). The dataset included biometric measurements such as maximum head length (MCL), maximum head breadth (MCB), bigonial breadth (BGB), bizygomatic breadth (BZB), minimum frontal breadth (MFB), total facial height (TFH), upper facial height (UFH), nasal aperture height (NAH), nasal aperture breadth (NAB), and head circumference (HC). All measurements were recorded in millimeters (mm) using standard anthropometric instruments. Derived indices—including the cephalic index, total facial index, and nasal aperture index—were calculated from the primary measurements to facilitate comparative analysis. All measurements were collected in accordance with established anthropometric protocols to ensure measurement accuracy and consistency. Definitions of the measurements used are presented in Table I. Craniofacial anthropometric data were obtained using validated techniques and high-precision instruments, including a digital sliding caliper and a spreading caliper, both calibrated to 0.01 mm (Mitutoyo Corp., Japan).

The participants were between 18 and 45 years of age. All data were anonymized, and ethical procedures were followed in compliance with institutional guidelines for research involving human subjects. Statistical analyses were performed to examine the distribution and interrelationships among the collected anthropometric parameters (Fig. 1).

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, version 23.0; IBM Corp., Armonk, NY, USA). The normality of data distribution for each variable was assessed both visually—using histograms and Q-Q plots—and analytically via the Kolmogorov-Smirnov test. Descriptive statistics, including

Table I. Cephalometic measurements and indices: definitions and calculations.

Measurements	**Distance**
Max. Head Lenght (MCL)	Distance between glabella to opisthocranion (g-op)
Max. Head Breadth (MCB)	Distance between euryon to euryon (eu-eu)
Bigonial Breadth (BGB)	Distance between gonion to gonion (go-go)
Bizygomatic Breadth (BZB)	Distance between zygion to zygion (zy-zy)
Min. Frontal Breadth (MFB)	Distance between frontotemporale to frontotemporale (ft-ft)
Total Facial Height (TFH)	Distance between gnathion to nasion (gn-n)
Upper Facial Height (UFH)	Distance between prosthion to nasion (pr-n)
Nasal Aperture Breadth (NAB)	Distance between alare to alare (al-al)
Nasal Aperture Height (NAH)	Distance between nasion to nasospinale (n-ns)
Head Circumference (HC)	Distance between glabella to glabella via opisthocranion
Cephalic Index (CI)	(head breadth ÷ head length) X 100
Total Facial Index (TFI)	(total facial height ÷ bizygomatic breadth) X 100
Nasal Aperture Index (NAI)	(nasal aperture breadth ÷ nasal aperture height) X 100

Fig. 1. Distribution of cephalometric measurements used in binary logistic regression analysis.

means and standard deviations, were computed for all variables. To explore sex-related differences in cephalometric dimensions, independent samples t-tests were used for normally distributed variables, while the Mann-Whitney U test was applied for non-normally distributed variables. These univariate comparisons were conducted for descriptive purposes only and were not used for variable selection, in order to avoid an inflated Type I error risk due to multiple comparisons. Binary logistic regression analysis was used to evaluate the association between cephalometric measurements and sex classification, with sex coded as the dependent variable. Each variable was initially modeled individually; subsequently, a forward stepwise approach was applied to construct a multivariate logistic regression model. At each step, variable inclusion was determined based on the Wald test, and statistically significant predictors were added sequentially. The classification accuracy of the model was evaluated and recorded at each stage of model development. To assess the relative quality of each regression model, Akaike Information Criterion (AIC) values were calculated and used as an additional model selection criterion. Receiver Operating Characteristic (ROC) analysis was applied to assess the discriminative performance of cephalic variables and the logistic regression models in sex estimation. The Area Under the ROC Curve (AUC) was calculated to quantify model performance. AUC values were interpreted as follows: 0.90-1.00 = excellent, 0.80-0.90 = good, 0.70-0.80 = fair, 0.60-0.70 = poor, and 0.50-0.60 = failure (Dirican, 2001). Optimal cut-off probabilities for each logistic regressionmodel were determined using the Youden Index, which maximizes the combined value of sensitivity and specificity. For each model iteration, sensitivity, specificity, AUC values, and 95 % confidence intervals were reported.

RESULTS

Primary Model Based on Full Cephalometric Dataset

Logistic regression models for maximum head length, maximum head breadth, bigonial breadth, bizygomatic breadth, minimum frontal breadth, total facial height, upper facial height, nasal aperture height, nasal aperture breadth, head circumference, cephalic index, and nasal aperture index revealed p-values less than 0.0001 for sex-based differences. Descriptive statistics for each parameter by sex, along with p-values, indicating their significance in the model, are presented in Table II. Male measurements were consistently higher than female measurements across almost all variables, reflecting expected sexual dimorphism in cephalic morphology. Total facial index and cephalic index are not found significant in the model (p>0,05) and exluded from further evaluation.

As sex is a binary variable, logistic regression analysis was used to model its relationship with cephalic parameters. Initially, each measurement was modeled individually; then, a stepwise approach was used to develop multivariate regression models. When these 14 measurements were evaluated using forward logistic regression, the model incorporating six cephalometric variables was identified as the most effective. Table III presents the variables added at each step along with the corresponding sex classification accuracies.

The model that included maximum head breadth, total facial height, maximum head length, head circumference, nasal aperture breadth, and bigonial breadth achieved the highest classification accuracy, with an overall accuracy of 89.8 %—88.8 % for females and 90.6 % for males. These findings suggest that the multiple logistic regression model improves sex prediction accuracy compared to univariate models. Model selection was based not only on classification accuracy and ROC performance but also on AIC values, which penalize model complexity. AIC values decreased progressively with each additional variable, with the lowest value (AIC = 137) observed at Step 6 (Table III), indicating optimal model parsimony. Therefore, Step 6 was selected as the final model, as it demonstrated the best balance between explanatory power and complexity while also yielding the highest overall classification performance.

Table III. Sex classification accuracy and Akaike Information Criterion (AIC) values for each logistic regression step.

	Female	Male	Overall Percentage	AIC
Step 1. Maximum Head Breadth	78.4 %	85.2 %	82 %	218
Step 2. Maximum Head Breadth Total Facial Height	83.6 %	84.4 %	84 %	174
Step 3. Maximum Head Breadth Total Facial Height Maximum Head Lenght	84.4 %	89.8 %	87.3 %	162
Step 4. Maximum Head Breadth Total Facial Height Maximum Head Lenght Head Circumference	88.8 %	89.1 %	88.9 %	153
Step 5. Maximum Head Breadth Total Facial Height Maximum Head Lenght Head Circumference Nasal Aperture Breadth	88.8 %	90.6 %	89.8 %	140
Step 6. Maximum Head Breadth Total Facial Height Maximum Head Lenght Head Circumference Nasal Aperture Breadth Bigonial Breadth	88.8 %	90.6 %	89.8 %	137

Table II. Descriptive statistics (mean, standard deviation) and p-values for cephalometric measurements by sex.

	Female		Male		
	Mean	**Std**	**Mean**	**Std**	**P values**
Max. Head Lenght	183.67	7.05	192.49	7.50	0.001
Max. Head Breadth	152.04	5.22	160.67	5.86	0.001
Bigonial Breadth	104.81	4.95	114.05	7.14	0.001
Bizygomatic Breadth	134.96	4.93	144.10	6.75	0.001
Min. Frontal Breadth	110.85	4.98	115.04	7.32	0.001
Total Facial Height	116.34	6.17	124.01	7.35	0.001
Upper Facial Height	65.20	4.93	69.33	4.98	0.001
Nasal Aperture Height	50.96	5.11	52.79	3.88	0.001
Nasal Aperture Breadth	25.39	2.74	28.63	2.85	0.001
Head Circumference	544.56	15.08	568.85	16.44	0.001
Cephalic Index	82.89	4.03	83.59	4.32	0.218
Total Facial Index	86.35	6.22	86.20	5.76	0.093
Nasal Aperture Index	50.28	7.38	54.63	7.56	0.008

Table IV. ROC analysis results including AUC, confidence intervals, sensitivity, specificity, and significance for each model.

	AUROC (%)	%95 confidence interval		Sensitivity (%)	Specificity (%)	P
		Lower limit	**Upper limit**			
Step 1	0,881	0,839	0,923	66,41	87,93	,000
Step 2	0,934	0,904	0,963	83,59	88,79	,000
Step 3	0,947	0,921	0,972	87,50	88,79	,000
Step 4	0,952	0,928	0,976	89,06	90,52	,000
Step 5	0,962	0,941	0,983	89,84	91,38	,000
Step 6	0,965	0,945	0,985	89,84	93,10	,000

The performance of each logistic regression model was further assessed using ROC analysis. This analysis yielded sensitivity, specificity, and optimal cut-off probabilities for each model (Table IV). Among all models, Step 6 demonstrated the highest AUC value (0.965) and the best overall classification performance. This model also achieved the highest sensitivity (89.84 %) and specificity (93.10 %), indicating a strong capacity to accurately classify both male and female individuals. The narrow confidence interval observed for this model (0.945-0.985) underscores the robustness and statistical reliability of its predictive performance.

These ROC results highlight the model's strong diagnostic capability and confirm the advantage of combining multiple cephalometric variables to enhance classification accuracy. ROC curves for each model iteration are shown in Figure 2. The curve corresponding to

Step 6 exhibited the largest area under the curve and emerged as the most discriminative model. The final model achieved an overall classification accuracy of 89.8 %, with 89.84 % sensitivity and 93.10 % specificity. The area under the ROC curve (AUC) was 0.965, indicating excellent discriminative ability (Fig. 2).

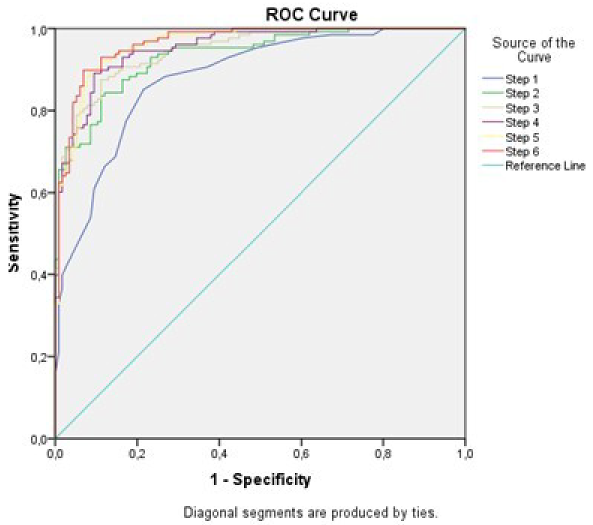

Fig. 2. Receiver Operating Characteristic (ROC) curve of the binary logistic regression model for sex estimation.

Auxiliary Model Using Skeletally Representative Measurements

To evaluate the discriminative power of cephalometric variables least affected by soft tissue, a secondary logistic regression model was constructed using maximum head breadth, maximum head length, and bigonial breadth. These three variables were selected based on their minimal susceptibility to soft tissue distortion.

Initially, four cranial measurements—maximum head breadth, maximum head length, bigonial breadth, and bizygomatic breadth—were considered for inclusion in the model due to their proximity to bony landmarks. However, during the regression analysis, bizygomatic breadth was excluded from the final model as its Wald statistic did not reach statistical significance.

The classification accuracy of the secondary model across three logistic regression steps is presented in Table V. At Step 1, maximum head breadth alone yielded an overall classification accuracy of 82 %, with an AIC of 214. The inclusion of maximum head length in Step 2 increased the accuracy to 82.4 %, and reduced the AIC to 177. In Step 3, the addition of bigonial breadth resulted in the highest classification accuracy for this model (84.8 %) and the lowest AIC value (169), indicating improved model performance.

Table V. Sex classification accuracy and Akaike Information Criterion (AIC) values for the skeletal-variable model.

	Female	Male	Overall Percentage	AIC
Step 1. Maximum Head Breadth	78.4 %	85.2 %	82 %	214
Step 2. Maximum Head Breadth Maximum Head Lenght	78.4 %	85.9 %	82.4 %	177
Step 3. Maximum Head Breadth Maximum Head Lenght Bigonial Breadth	83.6 %	85.9 %	84.8 %	169

Receiver Operating Characteristic (ROC) analysis was performed to assess the diagnostic capability of the skeletal-variable model. The AUC values, confidence intervals, sensitivity, and specificity for each step are provided in Table VI. The highest AUC (0.931) was observed in Step 3, with corresponding sensitivity and specificity values of 83.59 % and 89.65 %, respectively. The ROC curve for this model, depicted in Figure 3, illustrates a consistent increase in diagnostic accuracy across the model steps, confirming the enhanced discriminative performance with the inclusion of all three variables.

Table VI. ROC analysis results for the skeletal-variable model, including AUC, confidence intervals, sensitivity, specificity, and significance.

	AUROC (%)	%95 confidence interval		Sensitivity (%)	Specificity (%)	P
		Lower limit	Upper limit			
Step 1	0,881	0,839	0,923	85.15	78.44	,000
Step 2	0,919	0,887	0,952	92.96	75	,000
Step 3	0,931	0,902	0,961	83.59	89.65	,000

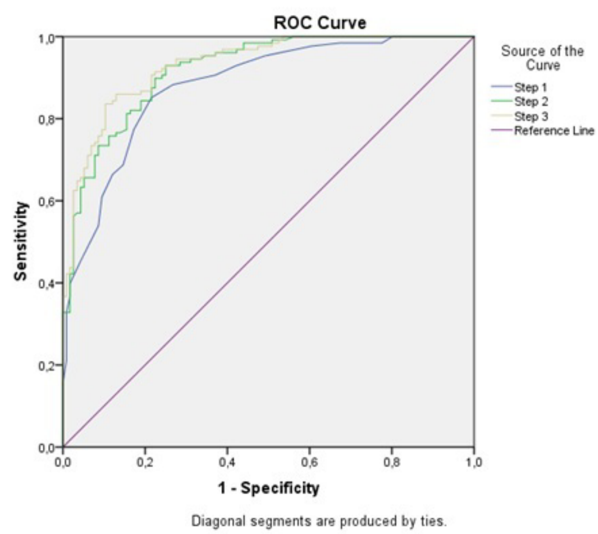

Fig. 3. Receiver Operating Characteristic (ROC) curve of the skeletal-representative binary logistic regression model.

DISCUSSION

Sex estimation is a fundamental component of forensic anthropology, paleoanthropology, and bioarchaeology, playing a critical role in the identification of skeletal remains. In this study, logistic regression and ROC analysis were applied to assess the effectiveness of various cephalometric measurements in distinguishing male and female individuals in a Turkish sample. By integrating logistic regression with ROC analysis, this study provides a reference framework for sex estimation, particularly in archaeological populations where standardized osteometric data are limited. Logistic regression analysis identified maximum head breadth, total facial height, maximum head length, head circumference, nasal aperture breadth, and bigonial breadth as highly significant discriminative parameters. The final multivariate model achieved an overall classification accuracy of 89.8 %, sensitivity of 89.84 %, specificity of 93.10 %, and an AUC of 0.965, demonstrating robust discriminative power and statistical reliability. The univariate logistic regression models confirmed statistically significant sex differences (p<0.001) for nearly all cephalic variables, with the exception of the cephalic index and total facial index. Male individuals consistently exhibited larger measurements, reflecting known patterns of sexual dimorphism. When cephalometric measurements were entered into logistic regression stepwise, classification accuracy increased from 82 % in the first step (using only maximum head breadth) to 89.8 % by incorporating six measurements. Additionally, a secondary model based on three skeletal-representative variables—maximum head breadth, maximum head length, and bigonial breadth—achieved an accuracy of 84.8 % and an AUC of 0.931, supporting its potential applicability in osteological contexts. These findings reinforce the value of multiple approaches in improving sex estimation accuracy. In conclusion, probabilistic modeling approaches appear to offer greater reliability and contextual robustness than univariate thresholds in both forensic and bioarchaeological applications. These findings emphasize the necessity of developing population-specific standards for sex estimation, particularly in forensic applications where reference data must accurately reflect the biological variation of the target population.

Several recent studies have highlighted the potential of cephalic dimensions for sex estimation in forensic contexts. A comparable study by Ekizoglu *et al*. (2016), used CT-based cranial measurements in a modern Turkish population and achieved classification accuracies of 87.5 % for females and 87.0 % for males with an AUC of 0.953 using four variables. In contrast, the present study attained a slightly higher accuracy (89.8 %) and AUC (0.965) using six cephalometric variables obtained from living individuals. These differences may stem from the nature of the measurements: CT-based skeletal data in Ekizoglu *et al*., versus soft tissue-inclusive surface data in the current study. Furthermore, the use of ROC-AUC and AIC in the present analysis may have enhanced model performance. Although both studies utilize logistic regression frameworks on similar populations, the disparity in measurement techniques likely contributes to the observed differences. Therefore, while direct validation using CT-based datasets like Ekizoglu *et al*.'s would strengthen generalizability, the methodological divergence currently limits such comparisons. Another comparable study by Cekdemir *et al*. (2021), utilized cranial CT scans of 616 Turkish individuals to assess sex estimation based on morphometric parameters. Their most discriminative variables were bizygomatic breadth, maximum cranial length, and bimastoid diameter, with a triple-variable model achieving an AUC of 0.942. Notably, while Cekdemir *et al*. (2021) measurements were derived from high-resolution postmortem CT scans, the current study used surface-level data from living individuals, which may account for differences in accuracy due to soft tissue influence. These methodological distinctions highlight the potential value of accessible, population-specific protocols developed from direct anthropometry, especially in settings where advanced imaging or dry skeletal data are unavailable. Kranioti *et al*. (2008), developed a sex estimation model based on 16 cranial measurements from a contemporary Cretan population. Their stepwise discriminant function analysis achieved a maximum classification accuracy of 88.2 % using five cranial dimensions, with bizygomatic breadth being the most predictive single variable (accuracy: 82 %). Franklin *et al*. (2013), examined cranial sexual dimorphism in a contemporary Western Australian population using 3D volume-rendered multi-slice CT data. They assessed 18 linear cranial measurements and reported the highest classification accuracy (90.0 %) with a stepwise discriminant function including glabello-occipital length, bizygomatic breadth, and mastoid height, achieving an AUC of 1.000 and a minimal sex bias (±2.2 %). Abdel Fatah *et al*. (2014), employed an advanced three-dimensional morphometric approach to examine cranial sexual dimorphism using CT-derived models from 222 modern U.S. Whites. By constructing a statistical bone atlas and using automated landmarking, they achieved high classification accuracies of 97.3 % with 11 variables and 95.5 % with only eight, primarily including bizygomatic breadth, cranial base length, and mastoid height. Swift *et al*. (2022), developed cranial sex estimation standards for the contemporary Australian population based on CT-derived three-dimensional cranial measurements from 771 individuals. Their most accurate multivariate model, employing 11 variables in a stepwise discriminant function analysis, achieved a classification accuracy of 90.3 % with an AUC of 0.835. Absalan *et al*. (2023), examined cranial sexual dimorphism in a southwestern Iranian population using cephalometric MRI data from 163 individuals across two ethnic groups (Lur and Arab). Although significant sex-based differences were reported for nearly all cranial dimensions, the only variable that maintained predictive value in logistic regression was the euryon-euryon (eu-eu) distance, which also exhibited a low diagnostic power (AUC = 0.5977). Furthermore, Absalan *et al*. (2023) focused more on ethnic differentiation than on robust sex estimation. Although imaging-based studies offer high precision, they require sophisticated equipment and trained personnel, which may not be available in all forensic or archaeological settings.

Unlike most contemporary studies that use radiological or 3D imaging to derive cranial metrics, this study provides a rare contribution by offering population-specific standards based on measurements from living individuals. As demonstrated in this study, anthropometric methods enable accurate sex estimation using portable and cost-effective tools, thereby enhancing the method's applicability in diverse practical settings. While the method provides a useful approximation of cephalic dimorphism in living individuals, its applicability to forensic cases involving skeletal remains is limited due to the influence of soft tissue. However, some researchers have proposed correction factors to adjust for soft tissue depth, recent studies suggest that cranial dimensions are poor predictors of soft tissue thickness, and such corrections may introduce further error instead of eliminating it (Simpson & Henneberg, 2002; Hona & Stephan, 2025). Since no dry cranial data were available for the sampled individuals, and given the questionable validity of generalized correction factors, no such adjustments were applied in this study. Instead, to address this limitation, a secondary model was constructed using cephalometric variables that most closely reflect cranial morphology, enabling cautious application in osteological contexts where soft tissue is absent but bony contours are preserved. Despite its strengths, this study has several limitations that should be acknowledged. The sample size and demographic variability may influence the robustness of the established classification thresholds. Future studies could address these limitations and further enhance classification accuracy. Moreover, integrating comprehensive cephalometric datasets with advanced modeling techniques holds significant potential for establishing reliable, population-specific protocols, thereby increasing the evidentiary strength of sex estimation in forensic practice.

CONCLUSION

This pilot study demonstrates the effectiveness of cephalometric measurements for sex estimation in a contemporary Turkish population. Through logistic regression and ROC analysis of data collected from living individuals, six key cephalometric variables were identified which, when combined, yielded high classification accuracy. The final model attained 89.8 % classification accuracy with an AUC of 0.965, confirming its strong discriminative capacity and statistical reliability. This study reveals population-specific cephalometric measurements based model that may improve forensic and anthropological investigations in Turkey.

Comparison with previous research confirms the consistency of the present findings with established studies and underscores the need for population-specific standards. The results further emphasize the importance of developing population-specific standards for forensic and anthropological applications, especially in contexts where direct cranial measurements from living individuals are available—such as in clinical anthropology or preliminary forensic screenings involving intact cadavers. Moreover, the cephalometric-based model enhances the practical applicability of these findings for sex estimation in both bioarchaeological and forensic contexts involving Turkish individuals.

In conclusion, the use of logistic regression combined with ROC analysis has proven to be a valuable methodological approach in advancing more precise and objective techniques for forensic anthropological sex estimation. As emphasized in prior research, integrating comprehensive cephalometric datasets with advanced modeling techniques holds considerable potential for establishing reliable, population-specific protocols, thereby enhancing the evidentiary value of sex estimation in forensic settings.

While this study offers valuable insights, it also underscores the need for expanded research across diverse population groups to enhance the universality and practical applicability of cephalometric-based sex estimation. Future studies incorporating larger and more heterogeneous samples, along with refined methodologies, may build upon these foundational findings to further improve the accuracy of osteometric sex estimation. In addition, a secondary model incorporating three cranial measurements minimally affected by soft tissue was developed to offer a more osteologically applicable alternative, achieving 84.8 % accuracy and an AUC of 0.931. This skull-based, population-specific approach addresses a critical need in osteological analysis where postcranial elements or advanced imaging are absent.

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RESUMEN: La estimación del sexo es una tarea fundamental en la antropología biológica; sin embargo, la mayoría de los estudios previos se basan en colecciones esqueléticas o datos radiológicos. Este estudio se distingue por el uso de mediciones cefalométricas obtenidas de individuos vivos para desarrollar un modelo de estimación del sexo específico para la población, basado únicamente en las dimensiones de la cabeza en una cohorte turca contemporánea. Este enfoque ofrece un modelo poblacional basado en tejidos blandos que puede ser útil en ciertas pruebas forenses o aplicaciones antropológicas clínicas donde no se dispone de datos esqueléticos o imágenes. Si bien las tecnologías de imagen avanzadas, como la tomografía computarizada y el escaneo 3D, se han vuelto cada vez más populares para el análisis métrico, a menudo son inaccesibles en muchos contextos. Se tomaron catorce mediciones cefalométricas estandarizadas de un total de 244 individuos adultos (128 hombres, 116 mujeres). Se construyeron modelos de regresión logística univariados y multivariados para evaluar la precisión de la estimación del sexo, mientras que el análisis de la Característica Operativa del Receptor (ROC) se utilizó para evaluar el rendimiento del modelo e identificar los umbrales de clasificación óptimos. El modelo multivariado final, que incluyó la anchura máxima de la cabeza, la altura facial total, la longitud máxima de la cabeza, el perímetro cefálico, la anchura de la abertura nasal y la anchura bigonial, alcanzó una precisión de clasificación general del 89,8 %, con una sensibilidad del 89,84 %, una especificidad del 93,10 % y un AUC de 0,965. Estos resultados demuestran el elevado poder discriminatorio del modelo y resaltan la eficacia de la integración de datos cefalométricos con la regresión logística y el análisis ROC. Al establecer valores umbral específicos para cada población, este estudio ofrece un marco robusto y replicable para la estimación del sexo, aplicable tanto en contextos forenses como arqueológicos. Los hallazgos también enfatizan el valor de los métodos accesibles y rentables, especialmente para su uso en entornos con recursos limitados. Se recomienda realizar investigaciones con muestras más amplias y diversas para validar y ampliar la aplicabilidad de estos estándares.

PALABRAS CLAVE: Estimación del sexo; Mediciones cefalométricas; Población turca; Análisis ROC; Regresión logística; Antropometría.

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Corresponding author:
Yarenkür Alkan
Kırsehir Ahi Evran University
Faculty of Arts and Sciences
Department of Anthropology
Kirsehir
TURKEY

E-mail: alkanyaren@gmail.com