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Original Article

Sex Estimation Using Patellar Morphometry: Evidence from a Late Roman Population in Anatolia

Patellar Morfometri Kullanarak Cinsiyet Tahmini: Anadolu'daki Geç Roma Dönemi Nüfusundan Kanıtlar

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ABSTRACT

Objective: Accurate sex estimation is a cornerstone in forensic and bioarchaeological investigations. While the pelvis and skull are traditionally used for this purpose, their absence due to taphonomic damage necessitates the use of alternative skeletal elements such as the patellar. This study evaluates the diagnostic potential of patellar morphometry for sex estimation in a Late Roman population.

Methods: The study analyzed 146 adult patellar (70 males, 76 females) recovered from the Karlığın Tepesi Necropolis 3rd-6th centuries AD in Malatya, Türkiye. Standard osteological methods were used to determine sex. Three patellar dimensions/length (PL), patellar width (PW), and patellar thickness (PT)-were measured. Intraobserver reliability was assessed via technical error of measurement (TEM), relative TEM (rTEM), and the reliability coefficient (R). Stepwise logistic regression and receiver operating characteristic analyses were conducted to identify the best predictors of sex. Area under the receiver operating characteristic (AUROC) values, cut-off thresholds, and effect sizes were reported.

Results: Statistically significant differences were found between males and females in PL (p=0.001), PW (p<0.001), and PT (p=0.003). The stepwise logistic regression model using PL and PT produced AUROC values of 0.906 in Step 1 and 0.920 in Step 2, with sensitivity and specificity ranging from 82.85% to 94.73%. All intraobserver reliability metrics (TEM, rTEM, R) indicated excellent measurement precision (R=1.000).

Conclusions: Patellar morphometry demonstrates high diagnostic accuracy for sex estimation, particularly when multivariate models are applied. Despite the moderate discriminative power of patella thickness alone, its combination with other parameters enhances overall performance. The study provides the first population-specific discriminant model for sex estimation using the patella in an Anatolian archaeological sample. However, the skewed sex distribution and the possibility of post-depositional changes in ancient skeletal remains should be considered when interpreting results. Additionally, the population-specific nature of the archaeological sample and the lack of external validation on independent datasets limit the generalizability of the model to other contexts.

Keywords: Patellae, sex determination by skeleton, receiver operating characteristic, logistic regression models, sexual dimorphism

ÖZ

Amaç: Cinsiyet tayini, adli tıp ve biyoarkeolojik araştırmalarda temel bir adımdır. Pelvis ve kafatası geleneksel olarak bu amaçla kullanılsa da bu kemiklerin yokluğu ya da tahrip olması durumunda alternatif kemik elemanlarına, örneğin patellaya başvurulması gerekebilir. Bu çalışma, Geç Roma Dönemi'ne ait bir Anadolu topluluğunda patella morfometrisinin cinsiyet tahminindeki tanısal değerini değerlendirmeyi amaçlamaktadır.

Yöntemler: Araştırma kapsamında, Türkiye'nin Malatya ilindeki Karlığın Tepesi nekropolünden çıkarılan 146 yetişkin patella (70 erkek, 76 kadın) incelenmiştir. Cinsiyet tayini standard osteolojik yöntemlerle gerçekleştirilmiştir. Patellanın uzunluk (PL), genişlik (PW) ve kalınlık (PT) ölçümleri alınmıştır. Tekrarlı ölçümlerin güvenilirliği teknik hata (TEM), göreli TEM (rTEM) ve güvenilirlik katsayısı (R) ile değerlendirilmiştir. Cinsiyet tahmini için aşamalı lojistik regresyon ve alıcı işletim karakteristiği eğrisi analizleri uygulanmıştır. Alıcıişletim karakteristiği eğrisi altında kalan (AUROC) değerleri, eşik noktaları ve etki büyüklükleri raporlanmıştır.

Bulgular: Erkek ve kadınlar arasında tüm patella ölçümlerinde anlamlı farklar bulunmuştur: PL (p=0,001), PW (p<0,001), PT (p=0,003). PL ve PT'yi içeren lojistik regresyon modeli Step 1'de AUROC =0.906, Step 2'de AUROC =0,920 elde etmiş, duyarlılık ve özgüllük %82,85 ila %94,73 arasında değişmiştir. Ölçüm güvenilirliği tüm parametrelerde mükemmel düzeydedir (R=1,000).

Sonuçlar: Patella morfometrisi özellikle çok değişkenli modellerle birleştirildiğinde, cinsiyet tahmini için yüksek tanısal doğruluk sağlamaktadır. Kalınlık ölçümünün tek başına ayırt edici gücü sınırlı olsa da diğer değişkenlerle birlikte kullanıldığında modelin performansını artırmaktadır. Bu çalışma Anadolu arkeolojik örnekleminde patella kullanılarak yapılmış ilk nüfus-özgül cinsiyet tahmin modeli olması açısından literatüre önemli katkı sunmaktadır. Ancak örneklemdeki cinsiyet dengesizliği ve iskelet kalıntılarında zamanla oluşabilecek bozulmalar dikkate alınmalıdır. Ayrıca arkeolojik örneklemin popülasyona özgü niteliği ve modelin bağımsız veri setlerinde test edilmemiş olması, sonuçların diğer bağlamlara genellenebilirliğini sınırlamaktadır.

Anahtar kelimeler: Patella, iskelet ile cinsiyet tahmini, ROC eğrisi, lojistik regresyon modelleri, cinsel dimorfizm

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INTRODUCTION

Sex determination of skeletal remains plays a vital role in the disciplines of forensic medicine, archaeology, anthropology, and anatomical education[1-3]. The human skeleton serves as a reliable source for determining sex. While the skull and pelvic bone are most commonly used for this purpose, their absence or fragmentation can necessitate the use of alternative skeletal elements, such as the patella[4]. In forensic contexts, accurate sex estimation can eliminate half of the possibilities in missing persons cases[5]. Although osteometric analyses have been shown to be effective in sex estimation, their results are population-specific and should be evaluated accordingly[6].

The patella, the largest sesamoid bone in the human body, has recently attracted significant attention due to its morphological differences between males and females. It is anatomically located within the quadriceps femoris tendon and articulates with the patellar surface of the femur[7,8]. Functionally, the patella enhances knee joint stability and quadriceps leverage during movement, and its cartilage covering helps reduce friction between articular surfaces[9,10]. Given its compact shape and frequent preservation in skeletal remains, the patella presents itself as a valuable alternative for sex estimation.

Recent forensic and anthropological studies have applied discriminant function analysis, logistic regression, and even artificial intelligence models to assess patellar dimensions such as length, width, and thickness for sex determination[11]. Although the accuracy of using the patella alone is generally lower than that of the more sexually dimorphic bones such as the pelvis or skull, combining patellar measurements with other skeletal metrics can significantly improve reliability[12].

Despite the growing body of research on patellar morphometry, there remains a significant gap in population-specific standards for sex estimation using the patella, particularly in archaeological populations from Anatolia. Most existing studies have focused on modern or clinical samples, which may not accurately reflect the morphological features of ancient populations. Our study addresses this gap by analyzing 144 adult patellae (44 males, 100 females) from the Late Roman necropolis of Karlığın Tepesi in Malatya, Türkiye. By applying logistic regression and receiver operating characteristic (ROC)-based modeling, this research aims to develop robust, population-specific discriminant values for sex estimation and to evaluate the diagnostic potential of the patella in cases where more traditional indicators, such as the pelvis or skull, are unavailable.

Therefore, this study aims to investigate the sexual dimorphism of the patella, evaluate its morphological differences between males and females, and determine the reliability and applicability of these differences in sex estimation within a bioarchaeological context.

MATERIALS and METHODS

This study has been approved by the Ordu University Non-Entrepreneurial Scientific Research Ethics Committee (approval no: 2025/181, date: 16.05.2025). The dry bones were obtained from the rescue excavations carried out by the Malatya Archaeological Museum in the Karlığın Tepesi Necropolis, in the Battalgazi district of the Malatya province, in 2020. According to the archaeological findings, there are underground rock grave chambers and boat-type graves carved into the rock in the necropolis dated to the 3rd to the 6th centuries *Anno Domini* (AD). During these excavations, 259 individuals were identified in 17 graves[13]. Our study was carried out on 146 adult dry patella bones of known sex (70 males, 76 females). The sex of the individuals was estimated based on morphologically dimorphic skeletal regions, particularly the pelvis and the cranium. In this process, the standard criteria described by Brothwell[14], Bass[15], İşcan and Steyn[16] and Olivier[17] were applied. Key pelvic traits, such as the morphology of the pubic symphysis, greater sciatic notch, and sacrum, as well as cranial features including glabellar prominence, mastoid process, mental eminence, and nuchal crest, were evaluated in accordance with established anthropological protocols. For each individual, multiple skeletal regions were assessed to ensure consistency and reliability in sex estimation[18-20]. Only those adult individuals whose sex could be confidently determined using these criteria were included in the patella analysis. Since our study was performed on dry bones, patient consent was not required. Patellae with any fracture deformity and paediatric patellae were not included in the study.

In our study, patellar length (PL), patellar width (PW), and patellar thickness (PT) were measured. Three morphological locations related to the patella were measured. Digital callipers with an accuracy of 0.01 millimetre (mm) were used for anthropometric measurements (Figure 1). Intraobserver reliability was assessed using technical error of measurement (TEM), relative TEM (rTEM), and the reliability coefficient (R), following Ulijaszek and Kerr[21] and applied in similar anthropometric research. To evaluate intraobserver reliability, a subset of patellae (n=30 for each sex) was re-measured by the same observer at a two-week interval. TEM, rTEM, and the R were calculated for length, width, and thickness of the patella. Among male individuals,

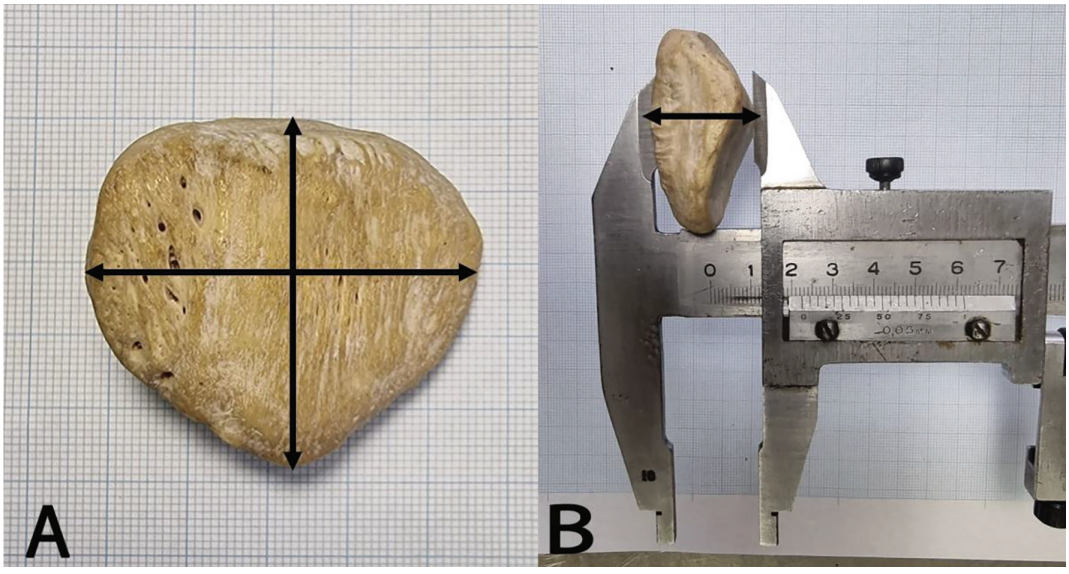

Figure 1. Morphometric landmarks and measurement directions of the patella: (A) length and width; (B) thickness.

TEM values ranged from 0.030 to 0.034 mm, rTEM values were below 0.24%, and the R were 1.000 for all measurements. Similarly, for female individuals, TEM values were consistently low, rTEM values ranged from 0.087% to 0.235%, and all R values were also 1.000. These results indicate excellent intraobserver precision and confirm the consistency of the anthropometric measurements used in this study.

Statistical Analysis

The fit of data to the normal distribution was assessed by histograms, q-q plots, and Shapiro-Wilk tests. The homogeneity of variance was examined by Levene's test. In binary comparisons, the independent two-sample t-test and Mann-Whitney U test were used for quantitative variables. To evaluate the predictive power of patellar dimensions on sex estimation, logistic regression analysis was performed using a stepwise (forward and backward) selection method to identify the most significant variables contributing to the model. This allowed for the construction of the most parsimonious model with optimal classification accuracy. ROC analysis was also conducted to determine cut-off values for sex estimation, and corresponding sensitivity and specificity values were calculated. Effect sizes (Cohen's d) were calculated for key comparisons to assess the magnitude of observed differences. Confidence intervals (95%) were provided for area under the receiver operating characteristic (AUROC) values and regression coefficients. No missing data were present in the analyzed dataset; all measurements were complete and suitable for statistical analysis. All statistical analyses were performed using R software version 3.2.2[1]. A p-value of <0.05 was considered statistically significant.

RESULTS

Descriptive statistics for PL, PW, and PT by sex are presented in Table 1. Males exhibited higher mean values across all dimensions. The mean PL was 39.9 mm [standard deviation (SD)=3.83] in males and 33.0 mm (SD=4.15) in females. PW averaged 41.7 mm (SD=3.75) in males and 36.2 mm (SD=4.53) in females. For patella thickness, the mean was 18.4 mm (SD=3.39) in males and 15.4 mm (SD=4.29) in females. All variables showed statistically significant differences between sexes: PL (p=0.001), PW (p<0.001), and PT (p=0.003).

Logistic regression analysis was conducted to assess the utility of patellar dimensions in sex estimation. In Step 1, using PL alone, the model achieved an AUROC of 0.906, yielding a sensitivity of 82.85% and specificity of 94.73% (p<0.001). In Step 2, the model included both PL and thickness, resulting in a higher AUROC of 0.920, sensitivity of 87.14%, and specificity of 86.84% (p<0.001), as shown in Table 2. Although PW was initially considered in the regression model, it was not statistically significant (p=0.266) and therefore excluded from the final equation. The multivariate model retained PL (p<0.001) and thickness (p<0.001) as the only significant predictors of sex.

According to the classification accuracy rates (Table 3), Step 1 achieved an overall classification accuracy of 84.9%

using PL, with 84.2% accuracy for females and 85.7% for males. Step 2, which incorporated both length and thickness, yielded an improved overall accuracy of 86.3%, with 85.5% for females and 87.1% for males. These results indicate that patellar morphometric measurements can provide high diagnostic accuracy for sex estimation in archaeological samples.

DISCUSSION

The patella (kneecap bone) is an important bone that plays a crucial role in knee joint function and stability[22]. The morphometry of the patella has been the subject of numerous studies. Significant differences in morphometric comparisons between the sexes have emerged[23,24].

In addition to its diagnostic value, the patella's compact morphology and central location within the extensor mechanism, make it less susceptible to postmortem fragmentation compared to long bones or cranial elements. This preservation advantage is particularly beneficial in archaeological contexts where taphonomic damage often limits the availability of complete skeletal elements. According to Tomaszewska et al. [4] the patella was among the most frequently preserved skeletal components in medieval burials in Poland, supporting its utility in sex estimation when more sexually dimorphic bones are missing or damaged. Similarly, in our sample, patellae were well-preserved, allowing for consistent measurements and reliable statistical modeling, which strengthens the forensic applicability of our findings. Only intact, fully measurable patellae were included in the analysis, and fragmented or heavily weathered bones were excluded. Moreover, all measurements were conducted shortly after excavation, minimizing the likelihood of postmortem alterations. Therefore, taphonomic processes are unlikely to have significantly impacted our results.

Moreover, the integration of patellar morphometry into sex estimation protocols holds promise in multidisciplinary contexts. In forensic casework, combining patellar data with available postcranial elements can improve identification rates in commingled or fragmentary remains. Recent advances in artificial intelligence and image-based modeling have further expanded the potential of morphometric data[25]. Future studies may consider employing three-dimensional imaging or machine learning algorithms to refine the discriminatory thresholds derived from patellar metrics. Additionally, comparing our findings with modern populations could help trace morphometric changes over time, which may reveal the influence of

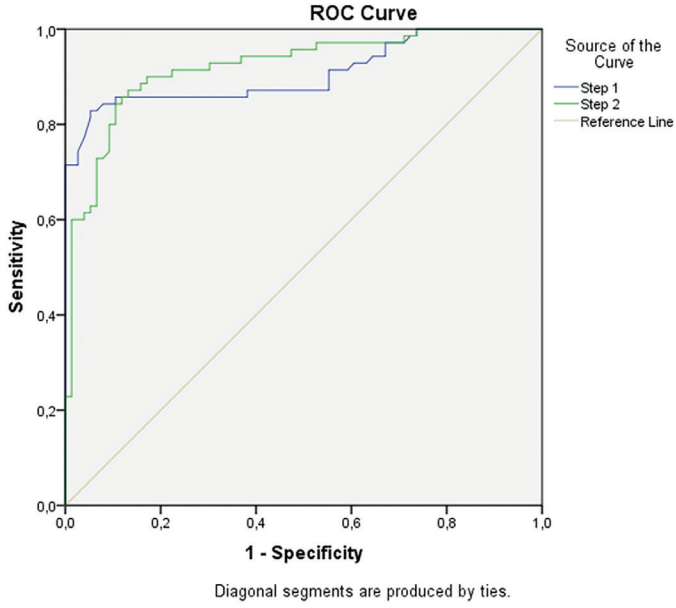

Figure 2. ROC curves showing the classification performance of Step 1 and Step 2 logistic regression models for sex estimation based on patellar measurements.

ROC: Receiver operating characteristic

Table 1. The measurements of patella.

	Sex	N	Mean	95% Confidence interval	SD	Cohen's d	Min	Max
PL	M	70	39.9	39-40.8	3.83	1.71	30	46.9
	F	76	33	32.1-34	4.15		22.7	38.8
PW	M	70	41.7	40.8-42.6	3.75	1.32	32.5	48
	F	76	36.2	35.1-37.2	4.53		26	45
PT	M	70	18.4	17.6-19.2	3.39	0.78	10.6	23
	F	76	15.4	14.4-16.4	4.29		6.7	21.9

Mean ±, minimum and maximum values (mm)

SD: Standard deviation, PL: Patella length, PW: Patella width, PK: Patella thickness, Min: Minimum, Max: Maximum

Table 2. ROC analysis results including AUC, cut-off probabilities, sensitivity, specificity, and significance for each model.

	AUROC (%)	Sensitivity (%)	Specificity (%)	p
Step 1	0.906	82.85	94.73	0.000
Step 2	0.920	87.14	86.84	0.000

ROC: Receiver operating characteristic, AUC: Area under the curve, AUROC: Area under the receiver operating characteristic

Table 3. Sex classification accuracy rates for each logistic regression step

	Female	Male	Overall percentage
Step 1. Patella length	84.2%	85.7%	84.9%
Step 2. Patella length patella thickness	85.5%	87.1%	86.3%

evolutionary, nutritional, or lifestyle-related factors on skeletal dimorphism[26].

In our study, all three patellar dimensions, length, width, and thickness showed statistically significant differences between males and females. The mean PL was measured as 39.9 mm in males and 33.0 mm in females, while the width was 41.7 mm in males and 36.2 mm in females. Similarly, patella thickness was 18.2 mm in males and 15.4 mm in females. Furthermore, the stepwise logistic regression model yielded an AUROC of 0.906 in Step 1 and 0.920 in Step 2, demonstrating excellent overall classification performance. These results indicate that the patella, especially when its dimensions are combined in a multivariate model, serves as a reliable skeletal element for sex estimation in bioarchaeological and forensic contexts. Although there was a slight imbalance in sex distribution (70 males vs. 76 females), this did not appear to affect the classification accuracy. However, the absence of age-at-death estimations and age stratification within the adult sample limits our ability to evaluate potential age-related effects on patellar morphology. Age estimation was not performed from the patella in this study, as the element is not a reliable indicator of chronological age. Our primary aim was to assess sexual dimorphism, and sex estimation was derived from pelvic and cranial morphology.

Although PW showed significant differences between sexes ($p<0.001$), it was not statistically significant as an independent predictor in the logistic regression analysis ($p=0.266$) and was thus excluded from the final model. In addition to statistical significance, effect size values (Cohen's d) indicated that PL and width differences between sexes were of very large magnitude ($d=1.71$ and $d=1.32$, respectively), while thickness differences were of a moderate-to-large magnitude ($d=0.78$). These values highlight the substantial practical relevance of patellar morphometry for sex estimation, particularly for length and width, which show strong discriminatory power beyond mere statistical significance. This indicates that multivariate analyses, through interactions among measurements, can yield different outcomes from univariate analyses. A possible reason for the diminished significance of PW in the regression model might be its high correlation with PL and thickness. Therefore, it is crucial to evaluate the independent contribution of each variable when developing multivariate models. Although intraobserver reliability was excellent, interobserver reliability was not assessed in this study. Nonetheless, standardized measurement protocols and consistent technique by a single trained observer ensured high precision. Future studies involving multiple observers could further assess reproducibility under broader research conditions.

The morphometry of the patella has been the subject of numerous studies, and significant differences in morphometric comparisons between the sexes have emerged. Studies generally show that male patellae are longer and wider than female patellae[27]. These values are broadly consistent with those reported by Kedia and Kadian[28], who found a mean PL of 42.21 mm in men and 36.07 mm in women, and a thickness of 19.3 mm in men and 17.7 mm in women. Koyuncu et al.[29] 2011 reported that the PL and thickness in men were greater than those in women, but there was no statistically significant difference, and anatomical variations may not always be associated with clinical implications. In our study, there was a significant difference in the mean length, width, and thickness of the patella between genders.

Sex-related morphometric differences in the patella have implications not only for forensic anthropology but also for understanding anatomical variation in historical populations. Previous studies have reported varying levels of accuracy for sex estimation using patellar measurements. For instance, Indra et al.[6] reported accuracy levels ranging from 62.8% to 83.8%, while Maio et al.[30] achieved up to 96% accuracy in a Portuguese sample. These values demonstrate the diagnostic potential of the patella, although differences in population, methodology, and sample size can affect comparability. Our study supports these findings, with an AUROC value of 0.920

in the multivariate model, indicating high diagnostic performance in a well-preserved archaeological sample from Late Roman Anatolia.

In forensic anthropology, diagnostic metrics such as accuracy, sensitivity, and specificity have direct implications for casework outcomes. False positive or false negative classifications in sex estimation can significantly affect the identification process in medico-legal investigations. In a bioarchaeological context, such misclassifications may alter demographic reconstructions and interpretations of past populations. Therefore, alongside reporting high diagnostic performance, it is essential to consider the potential consequences of classification errors in both forensic and archaeological applications.

Study Limitations

The sample consisted of 146 patellae from individuals excavated in a specific archaeological context in Malatya, Türkiye, dating to the 3rd-6th centuries AD. This limited geographical and temporal scope may reduce the generalizability of the results to other populations or modern individuals. Morphometric differences influenced by genetic, environmental, or cultural factors could affect the applicability of the established cut-off values. While the overall sample size was sufficient, a slight imbalance in sex distribution (70 males and 76 females) and the absence of age-group stratification, may have restricted the assessment of age-related variation in patellar morphology. External validity testing was not performed on an independent sample, and future studies should explore the reproducibility of the model across different populations. That the model was tested only on the present archaeological sample, represents a limitation regarding its applicability to different populations. Future studies should test the model's performance on independent datasets obtained from different geographical and chronological contexts, which will be critical for verifying its generalizability.

Although interobserver reliability was not assessed, intraobserver consistency was excellent, and measurements were conducted by a single trained observer using standardized protocols. As such, we consider the potential for measurement bias to be minimal. In addition, only well-preserved, intact patellae were included, and all bones were analyzed shortly after excavation, reducing the likelihood of postmortem alteration. Nevertheless, a systematic documentation of taphonomic changes could further strengthen data integrity in future research.

As this study focused exclusively on bone morphology, it does not consider the influence of surrounding soft tissues that might affect bone shape during life. This limits the applicability of the findings in living populations or in clinical contexts.

CONCLUSION

This study demonstrated that patellar dimensions, particularly length and thickness, are effective in sex estimation with high diagnostic accuracy when combined in a logistic regression model. Although patella width showed strong discriminatory power in univariate analysis, it was not statistically significant in multivariate modeling and was thus excluded. The model achieved an AUROC of 0.920 with high sensitivity and specificity, highlighting its utility in forensic anthropology and bioarchaeological investigations. These findings contribute valuable data from an ancient Anatolian sample, supporting the development of region-specific standards for osteometric sex estimation. However, limitations such as sample size imbalance and the lack of soft tissue evaluation should be considered in interpreting the results and designing future research.

Acknowledgement

Permission has been obtained from the Turkish Ministry of Culture and Tourism for the use of bone samples in this study.

Ethics

Ethics Committee Approval: This study has been approved by the Ordu University Non-Entrepreneurial Scientific Research Ethics Committee (approval no: 2025/181, date: 16.05.2025).

Footnotes

Author Contributions

Surgical and Medical Practices: Y.A., A.T., Concept: A.T., Design: Y.A., A.T., Data Collection and/or Processing: Y.A., Analysis and/or Interpretation: A.T., Literature Search: Y.A., A.T, Writing: Y.A., A.T.

Conflict of Interest: No conflict of interest was declared by the authors.

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