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Modeling the Entire Length of the Fragmentary Dry Femur Using Population-Specific Morphometric Characteristics

Modelado de la Longitud Total del Fémur Seco Fragmentario Mediante Características Morfométricas Específicas de la Población

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SUMMARY: This study aims to develop a model for estimating the entire length of the femur (FEL) from dry femur specimens using measurements from its proximal and distal parts, contributing to the process of stature estimation in biological profile analysis. The study was conducted on 40 dry femurs (22 right, 18 left) of unknown age and sex from the bone collection of the Anatomy Department at Bolu Abant Izzet Baysal University Faculty of Medicine. Measurements were taken using a digital caliper with a precision of 0.01 mm. A significant linear relationship was observed between all measurements and the FEL (A-K). The highest linear correlations were found with the E-K, B-K, and G-K measurements, while the lowest correlation was observed with the Axl measurement. As no significant difference was found between the right and left femurs, analyses were performed using the average values. In the first stage, multiple linear regression analysis was applied. Using the backward variable selection method, 7 out of 19 measurements (B-K, F-K, B-H, B-G, A-E, Lnt, H-K) were included in the model. The final multiple linear regression model yielded a determination coefficient of 94.4 %. In the MARS model, 5 out of the 19 independent variables were included in the formula. The MARS model had a determination coefficient of 97.1 %. The measurements with the highest importance values in the model were, in order: E-K, B-K, A-H, F-K, and B-H. It is expected that the modeling of the FEL using measurements from the proximal and distal parts of the dry femur will have a high success rate in predicting femur length, and that the results will contribute to researchers working on stature estimation from femurs and biological profile analysis in the next phase.

KEY WORDS: Femur morphometry; Stature prediction; Height; Individual identification; Forensic anthropology; Turkish population.

INTRODUCTION

Forensic anthropology is an important scientific discipline that identifies individuals using human skeletal fragments (Kira *et al*., 2023). Age, sex, ethnicity, and stature are fundamental factors in determining the biological profile (Thompson & Black 2006; Srivastava *et al*., 2012). Stature estimation is a critical component of identification studies, and bones with proven reliability are preferred in this process (Duyar *et al*., 2003). The intact presence of bones in the examination area facilitates accurate analyses. However, due to environmental factors, it is not always possible to access the entire skeleton or ensure that the bones remain undamaged (Delannoy *et al*., 2016). Despite mutilation or taphonomic changes, fragments of long bones in the limbs provide high accuracy in stature estimation (Nanayakkara *et al*., 2020). Various methods are applied for biological profile analysis in cases of incomplete or damaged bones (Ahmed, 2013). Anatomical methods require the complete or a substantial portion of bones contributing to stature (Zhang *et al*., 2021). When bones are missing, mathematical methods involving proportional calculations or regression formulas are used (Abu Bakar *et al*., 2017; Yerli *et al.*, 2021).

The anatomical structure of the femur varies based on ethnicity, age, and sex. Even among individuals of the same ethnic group, distinguishing features may arise due to geographical differences (Irdesel & Ari, 2006; Cho *et al*., 2015; Kang *et al*., 2016; Biswas & Bhattacharya, 2017). An intact femur is recognized as having the highest correlation with stature (Nanayakkara *et al*., 2020).

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Population-specific prediction equations have been developed based on femoral measurements. When the entire femur is unavailable, modeling the relationship between its proximal and distal parts allows for estimating the entire length of the femur (FEL) (Babacan & Deniz, 2022).

This study aims to develop a model for estimating the FEL from dry femur specimens using measurements from its proximal and distal parts.

MATERIAL AND METHOD

The present study was conducted on 40 dry femurs (22 right, 18 left) of unknown sex and age from the bone collection of the Anatomy Department at Bolu Abant Izzet Baysal University Faculty of Medicine. Measurements were taken using a digital caliper with a precision of 0.01 mm.

A total of 20 measurements were taken for predicting the FEL, including 3 measurements from the distal part and 7 measurements from the proximal part of the dry femur. Morphometric measurements made on the dry femur are listed below. Ethical approval was received from Bolu Abant Izzet Baysal University, Clinical Researches Ethics Committee Approval for the present study with decision number: 2023/179.

Femoral measurement parameters (Figs. 1 and 2).

A. Highest point of the femoral head
B. Highest point of the greater trochanter
C. Medial point of the femoral head
D. Lateral point of the greater trochanter
E. Lower edge point of the femoral head
F. Lower edge point of the greater trochanter
G. Lower edge point of the lesser trochanter
H. Upper edge point of the lateral epicondyle
I. Upper edge point of the medial epicondyle
J. Lateral point of the lateral epicondyle
K. Lower edge point of the medial condyle

Distances between the transverse axes passing through the femoral markers. (Figs. 1 and 2).

P1:A-K (FEL), **P2**:E-K, **P3**:B-K, **P4**:F-K, **P5**:G-K, **P6**:A-H, **P7**:E-H, **P8**:B-H, **P9**:F-H, **P10**:G-H, **P11**:A-G, **P12**:B-G, **P13**:D-C, **P14**:A-E, **P15**:H-K, **P16**:J-I, **P17**:Femoral head diameter (Fhd), **P18**:Length of linea intertrochanterica (Lnt), **P19**:Femoral neck axis length (Axl), **P20**: Anteroposterior length of distal femur (Apl).

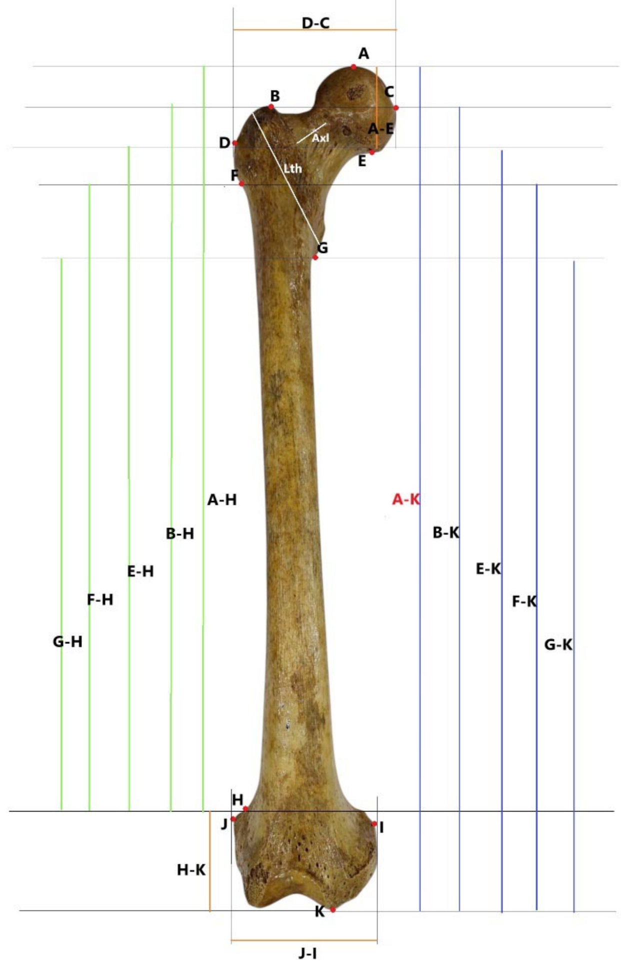

Fig. 1. Illustration of femoral measurements on dry femur.

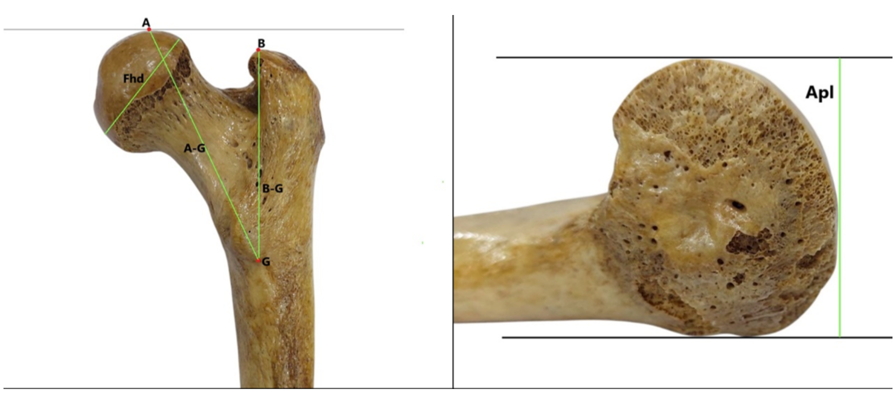

Fig. 2. Illustration of proximal and distal femoral measurements on dry femur.

Statistical Analysis. Descriptive statistics of the measurements were calculated as mean, standard deviation (SD), median, 25th and 75th percentiles, count, and percentage frequencies. The normality of the numerical properties obtained from the measurements was tested using the Shapiro-Wilks test, and it was determined that the data followed a normal distribution. A total of 20 measurements, including 19 from the distal and proximal parts of the dry femur and the FEL, were taken and used to develop a formula for predicting the FEL. First, the relationships between the FEL and the other 19 measurements were compared with the Simple Pearson Correlation analysis. Measurements from the right and left bone sections were compared using the Independent Samples t-test. Since no significant difference was found, the right and left measurements were combined for the modeling process. Afterward, two different models were used to determine the measurements related to FEL.The first model was a multiple linear regression model with backward variable selection. The second model was a nonparametric and nonlinear model, known as multivariate adaptive regression splines (MARS). Both models were compared in terms of complexity, determination coefficient, and model error. A significance level of $p <= 0.05$ was considered statistically significant. The calculations were performed using SPSS (version 23) and the R (version 4.4.2) software, utilizing the "earth" package.

RESULTS

The study included 40 measurements in total, with 22 from the right side and 18 from the left side. Descriptive statistics for the measurements from the right and left sides are presented in Table I. Comparison of the measurements between the right and left sides revealed no significant differences. Consequently, all 40 measurements were analyzed together without distinguishing between right and left sides in the modeling process.

Before starting the modeling process, the simple correlations between A-K (FEL), considered the dependent variable, and the other measurements were examined, and the results are presented in Table II. As shown in Table II, a significant linear relationship was observed between FEL and all measurements. Among these, E-K, B-K, and G-K showed a very high linear correlation, while the lowest correlation was found with the Axl measurement.

Multiple Linear Regression Model with Backward Variable Selection Method. Since all simple linear correlations between dry femur length and the other 19 measurements were found to be significant, the modeling process initially employed multiple linear regression analysis. When the backward method was applied during model construction, the final model results were obtained as shown in Table III. As shown in Table III, 7 out of 19 measurements were included in the model using the backward variable selection method, while some measurements were excluded due to multicollinearity issues (VIF > 10). The resulting model was referred to as the final multiple linear regression model. The determination coefficient of this final model was calculated as 94.4 %, with a root mean square error (RMSE) of 0.646. These results indicate that the model provides highly accurate predictions (Fig. 3).

Table I. Descriptive values of femur measurements from the right and left sides.

	Right (n=22)		Left (n=18)		
	Mean	SD	Mean	SD	P
A-K (FEL)	44.805	3.2256	43.772	1.8880	0.216
E-K	39.991	3.0119	39.150	1.8545	0.308
B-K	42.223	3.2399	41.922	1.8587	0.729
F-K	37.486	3.3663	37.850	1.7922	0.665
G-K	35.109	2.6219	34.733	1.7047	0.604
A-H	38.886	3.2775	38.544	2.5317	0.719
E-H	34.345	3.0486	34.194	2.5972	0.869
B-H	36.923	3.0659	36.667	1.8563	0.758
F-H	32.932	2.9424	32.578	2.0627	0.669
G-H	30.695	2.8463	29.256	1.7827	0.070
A-G	9.4436	0.88902	9.2333	0.85802	0.454
B-G	7.6127	0.74443	7.6417	0.60868	0.895
D-C	9.1932	0.63311	9.2044	0.65271	0.956
A-E	4.1223	0.40419	4.0233	0.37677	0.432
Fhd	4.5618	0.38402	4.5411	0.28313	0.850
Lnt	5.9491	0.82847	5.7378	0.46184	0.341
Axl	2.7750	0.36829	2.9167	0.43408	0.271
H-K	5.4109	0.53794	5.4383	0.32208	0.843
J-I	7.7227	0.71633	7.5522	0.56757	0.417
Apl	5.9118	0.48123	5.8189	0.55148	0.573

Table II. Simple correlations between entire length of the femur measurements and other parameters.

n=40		r	P
A-K (FEL)	**E-K**	0.954	**<0.001**
	B-K	0.944	**<0.001**
	F-K	0.826	**<0.001**
	G-K	0.922	**<0.001**
	A-H	0.848	**<0.001**
	E-H	0.838	**<0.001**
	B-H	0.856	**<0.001**
	F-H	0.850	**<0.001**
	G-H	0.845	**<0.001**
	A-G	0.728	**<0.001**
	B-G	0.596	**<0.001**
	D-C	0.708	**<0.001**
	A-E	0.653	**<0.001**
	Fhd	0.682	**<0.001**
	Lnt	0.621	**<0.001**
	Axl	0.370	**0.019**
	H-K	0.410	**0.009**
	J-I	0.538	**<0.001**
	Apl	0.474	**0.002**

Table III. Measurements significantly correlated with entire length of the femur.

	B	SE	P*
(Constant)	4.897	1.749	**0.009**
B-K	1.162	0.108	**0.000**
F-K	-0.414	0.111	**0.001**
B-H	0.302	0.109	**0.009**
B-G	-1.197	0.284	**0.000**
A-E	1.171	0.402	**0.006**
Lnt	0.626	0.256	**0.020**
H-K	-0.789	0.296	**0.012**

*: Multiple linear regression model with Backward variable selection method.

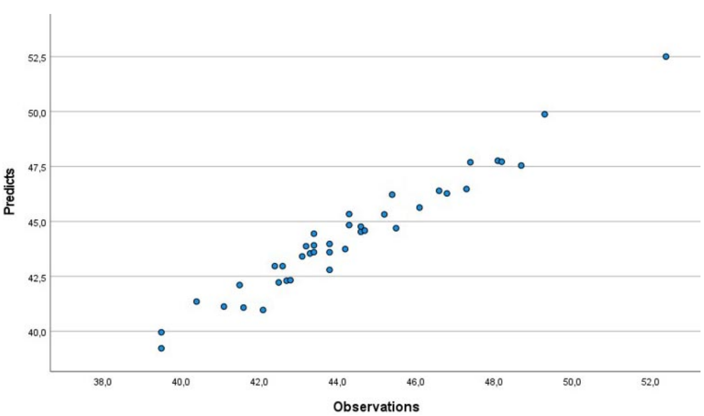

Fig. 3. Comparison of observed and predicted values in the multiple linear regression model.

MARS model. Using the MARS model, the same variables were reintroduced to create a new model, and the results are presented in Table IV. The basis functions (BFs) listed in the table represent the terms significantly associated with the FEL. An analysis of the model revealed that five out of the 19 independent variables were included, with two of these showing interaction effects. The interactions occurred when the B-K measurement exceeded 42.1, specifically in relation to F-K and B-H. In Table IV, the constant term of the model is noted as 44.5.

To obtain the predicted values from the model, when the condition defined in the "Condition" column are checked. When a condition is met, the calculation in the last column of the table is applied to compute the corresponding BF value. The BF values are then summed to estimate the A-K (FEL) value.

The functioning of the model presented in Table IV is explained by using the measurements from example number 2 in the data set, and the predicted values are obtained as shown in Table V.

Table IV. MARS model for entire length of the femur estimation.

Final Model: *Predicted Entire Length of the Femur* = Constant + BF1+BF2+ BF3+ BF4+ BF5+BF6+BF7

Basis Functions	Conditions	Predicted femur length = + 44.5 (Constant)
BF1	If "**E-K < 39.6**"	- 0.953* (39.6 – EK)
BF2	If "**E-K > 39.6**"	+ 0.893* (EK-39.6)
BF3	If "**B-K > 42.1**"	+ 5.35 * (BK- 42.1)
BF4	If "**B-K > 42.1**"	- 0.334 * (BK-42.1) * FK
BF5	If "**B-K > 42.1**"	+ 0.219* (BK-42.1) * BH
BF6	If "**A-H > 37.4**"	- 0.544 * (AH - 37.4)
BF7	If "**A-H > 39.8**"	+ 0.909* (AH - 39.8)

BF: Basis Functions in the Model

Table V. Estimation of FEL value for the sample using the MARS model.

Independent variables in final MARS model	Values of the ID=2 in data set	Model and prediction of FEL
E-K	46.7	
B-K	49.8	**Predicted FEL** = 44.5 + 0.893*(46.7-39.6) + 5.35*(49.8-42.1) -
A-H	47.4	0.334*(49.8-42.1)*45.1 + 0.219*(49.8-42.1)*44.3 - 0.544*(47.4-37.4) +
F-K	45.1	0.909*(47.4-39.8) = **52.2**
B-H	44.3	

The obtained MARS model uses five variables for prediction, whereas the linear regression model incorporates seven variables. Additionally, the presence of two interaction terms in the MARS model demonstrates the contribution of interaction effects within the model. The determination coefficient of this model is 97.1 %, which is 2.7 % more successful than the linear regression model. When evaluating the models based on goodness-of-fit criteria, the MARS model's root mean square error (RMSE) was found to be 0.458, which is smaller compared to the linear regression model. The Corrected Akaike's Information Criterion (CAIC) was calculated as -41.868, indicating a smaller value. The model's internal validation was assessed using cross-validation, with a generalized cross-validation (GCV) value of 0.725. These results demonstrate that the model makes highly accurate predictions. When evaluating the measurements contributing to the model, the most influential measurement, with the highest importance value, was found to be E-K. It was followed by B-K, A-H, F-K, and B-H. The graph showing the model's predicted values against the observed values is presented in Figure 4.

DISCUSSION

Due to its role as a component of the biological profile, stature estimation is one of the fundamental factors in identification studies (Thompson & Black 2006; Srivastava *et al*., 2012). This method uses bones that have been proven reliable (Duyar *et al*., 2003). It is easier to perform analysis when bones are found intact in the examination area; however, there is also the possibility that they may be damaged due to environmental factors (Delannoy *et al*., 2016). Specifically, the femur, as a long bone of the lower limb, helps fill the gap in the identification process when skeletal parts are not available or are missing (Rattanachet, 2022). For such cases, regression formulas have been developed in different populations to estimate the FEL from its proximal and distal components (Babacan & Deniz, 2022). This study aimed to predict the FEL by formulating the relationship between measurements taken from the proximal and distal parts of the dry femur.The results showed a significant linear relationship between all measurements and FEL. Upon examining the degree of correlation, it was found that E-

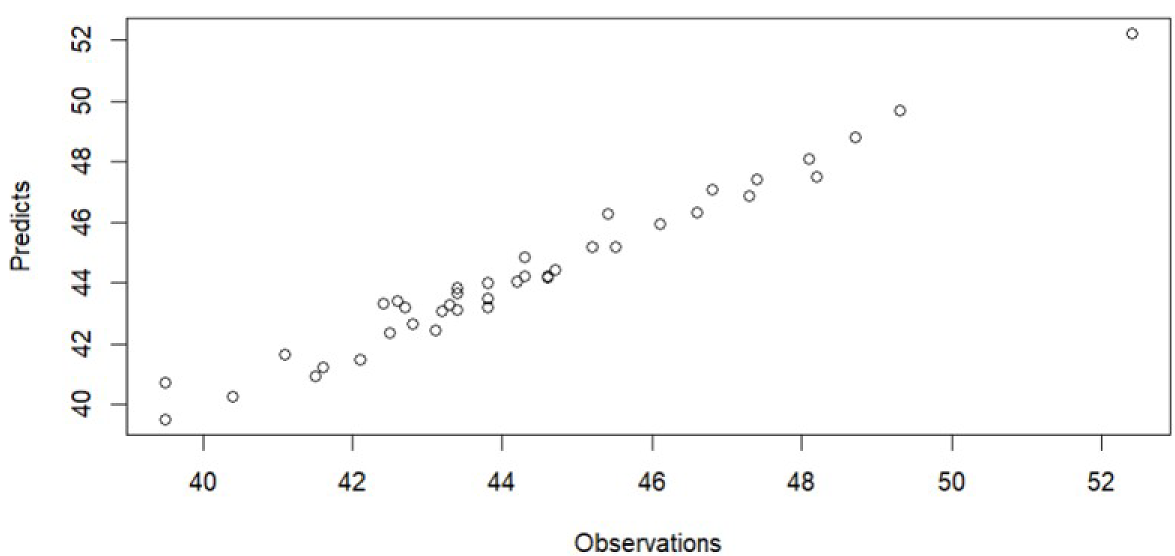

Fig. 4. Comparison of observed and predicted values in the MARS model.

K, B-K, and G-K exhibited very high linear correlations, while the lowest correlation was observed with the AxL measurement. Since no significant difference was found between the measurements from the right and left sides, the statistical relationships were evaluated using the average values from both sides. Given that all simple linear correlations between the FEL and the other 19 measurements were found to be significant, multiple linear regression analysis was used in the first stage of the modeling process. Using the backward variable selection method, 7 out of 19 measurements (B-K, F-K, B-H, B-G, A-E, Lnt, H-K) were included in the model. The determination coefficient of the final multiple linear regression model was found to be 94.4 %. These results demonstrate that the model provides highly accurate predictions. The MARS model, is a flexible regression approach that accounts for nonlinear structures and interactions between variables. Using only five variables (E-K, B-K, A-H, F-K, and B-H), the MARS model achieved a notably high coefficient of determination at 97.1 %. Additionally, the model included two interaction terms: multiplicative effects involving F-K and B-H when the condition B-K > 42.1 was met. In this respect, the MARS model outperformed the linear model by using fewer variables and achieving a lower error rate (RMSE = 0.458). Notably, the E-K variable had the highest importance value, clearly indicating its critical role in stature estimation. It was followed in importance by B-K, A-H, F-K, and B-H. In the literature, there are studies aimed at estimating stature from different sections of the femur using various methods. Rattanachet (2022) emphasized that the proximal femur is valuable in biological profile estimation and that reliable predictions can be made when the femoral head, neck, greater trochanter, and lesser trochanter are preserved. In our study, the vertical measurements taken from these regions of the proximal femur (A-H, E-H, B-H) also demonstrated high correlations (>85 %), supporting this finding. They also pointed out that a regression formula needs to be developed for each population (Rattanachet, 2022). Irdesel & Ari (2006) identified a strong positive correlation between proximal femoral morphometry and body mass index in their study using radiographic images of Turkish women. In our study, the relationship between the proximal femur and body mass index demonstrates that the MARS modeling, which achieved high accuracy (97.1 %) in stature estimation from femoral measurements, will significantly contribute to the next phase of biological profile creation. This strong relationship highlights the potential to enhance the accuracy and reliability of biological profile predictions. Similar estimations based on femoral fragments have been conducted in different populations in the literature. For instance, in the study by Kaur *et al*. (2024), regression models were developed using 12 measurements from the distal end of 200 dry femur and the highest correlation was reported with the height of the lateral condyle. In the present study, the measurements representing these regions also demonstrated high correlation values (e.g., G-K: r = 0.922), suggesting that similar biomechanical influences are applicable to the Turkish sample as well (Kaur *et al*., 2024). Rattanachet *et al*. (2023) in their study, aimed to estimate stature from the proximal part of the dry femur using machine learning algorithms. Similar to our study, they found a positive correlation between the femoral head diameter and the femoral neck axis length with the FEL. However, with the method they used, they predicted stature with an error of 4.68 cm (Rattanachet *et al*., 2023). In our study, when analyzing the example data set in Table V, it was found that the measured length of femur sample number 2 was 52.4 cm, while the regression formula estimated it as 52.2 cm, indicating that the model provided a high prediction accuracy with an error of only 0.2 cm. Zhang *et al*. (2021) developed regression formulas for estimating stature based on measurements of the femur, tibia, and fibula from the lower limbs, conducting a comparative study. They found that the most accurate result came from the formula based on femur measurements (Zhang *et al*., 2021). Babacan & Deniz (2022) in their study analyzing femoral morphometry in terms of biomechanical functionality, developed successful regression models for estimating femur length using measurements from both the proximal and distal ends. Notably, measurements such as A-E and H-K were included in both their models and ours, which strengthens the validity of the model (Babacan & Deniz, 2022). The use of the femur for biological profile estimation cannot ignore the anatomical differences between populations; this issue can be addressed by developing population-specific methods that account for the variability in skeletal sizes across different ethnic backgrounds or by establishing regional standards (Koteˇrová *et al*., 2017). Therefore, stature estimation formulas involving the femur have been developed using various methods in different ethnic groups and populations (Bidmos, 2008; Hasegawa *et al*., 2009; Mahakkanukrauh *et al*., 2011; Jeong & Jantz, 2016; Saco-Ledo *et al*., 2019; Simon *et al*., 2023).

CONCLUSION

The findings of this study indicate that the developed model lays a reliable foundation for advancing stature estimation and biological profile analysis, with the potential to yield results that closely align with an individual’s actual height measurement, as evidenced by existing literature. This significant step promises to enhance the accuracy and reliability of future anthropometric assessments.

Ethical approval. Ethical approval was received from Bolu Abant Izzet Baysal University Clinical Research Ethics Committee Approval for the present study with decision number 2023/179. The study was conducted in accordance with ethical guidelines.

SERTEL MEYVACI, S.; ANKARALI, H. & CELIK, B. Modelado de la longitud total del fémur seco fragmentario mediante características morfométricas específicas de la población. *Int. J. Morphol., 43(5)*:1635-1642, 2025.

RESUMEN: Este estudio tuvo como objetivo desarrollar un modelo para estimar la longitud total del fémur (FEL), a partir de especímenes de fémur seco, mediante mediciones de sus partes proximal y distal, contribuyendo así al proceso de estimación de la estatura en el análisis del perfil biológico. El estudio se realizó en 40 fémures secos (22 derechos, 18 izquierdos) de edad y sexo desconocidos, procedentes de la colección ósea del Departamento de Anatomía de la Facultad de Medicina de la Universidad Bolu Abant Izzet Baysal. Las mediciones se realizaron con un calibrador digital con una precisión de 0,01 mm. Se observó una relación lineal significativa entre todas las mediciones y la FEL (A-K). Las correlaciones lineales más altas se encontraron con las mediciones E-K, B-K y G-K, mientras que la correlación más baja se observó con la medición Axl. Como no se encontró diferencia significativa entre los fémures derecho e izquierdo, se realizaron análisis utilizando los valores promedio. En la primera etapa, se aplicó el análisis de regresión lineal múltiple. Utilizando el método de selección de variables hacia atrás, se incluyeron en el modelo 7 de 19 mediciones (B-K, F-K, B-H, B-G, A-E, Lnt, H-K). El modelo de regresión lineal múltiple final arrojó un coeficiente de determinación del 94,4 %. En el modelo MARS, se incluyeron en la fórmula 5 de las 19 variables independientes. El modelo MARS tuvo un coeficiente de determinación del 97,1 %. Las mediciones con los valores de importancia más altos en el modelo fueron, en orden: E-K, B-K, A-H, F-K y B-H. Se espera que el modelado de la FEL mediante mediciones de las partes proximal y distal del fémur seco tenga una alta tasa de éxito en la predicción de la longitud del fémur, y que los resultados contribuyan a los investigadores que trabajan en la estimación de la estatura a partir de fémures y el análisis del perfil biológico en la siguiente fase.

PALABRAS CLAVE: Morfometría del fémur; Predicción de la estatura; Altura; Identificación individual; Antropología forense; Población turca.

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