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Machine learning-based estimation of Calcaneus volume using plain radiographic morphometry

Ali Utkan[1, 2], Emre Doğan[3], Bülent Özkurt[2], Aysun Uz[4]

[1]*Ankara University, Graduate School of Health Sciences (Clinical Anatomy), Ankara, Turkiye*
[2]*University of Health Sciences, Ankara Bilkent City Hospital, Department of Orthopedics and Traumatology, Ankara, Turkiye*
[3]*Middle East Technical University, Faculty of Economics and Administrative Sciences, Ankara, Turkiye*
[4]*Ankara University, Faculty of Medicine, Department of Anatomy, Ankara, Turkiye*

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Background: *Few studies have examined calcaneal volume because of the difficulty of calculating it. The aim of this study was to generate a formula that can provide an approximate calcaneal volume through simple mathematical calculations based on measurements taken from plain radiographs.*

Materials and methods: *The study was carried out on 216 dry calcanei from the adult population of Anatolia. The volumes were calculated using Archimedes' water displacement method aided by a new technique for temporarily coating dry bones. On lateral radiographs, the following were measured: maximum anteroposterior length (max AP l), maximum body length (max body l), body height (body h), minimum body height (min body h), facies articularis cuboidaea height, Böhler's angle, and angle of Gissane; on axial radiographs, maximum posterior transverse width (max post w) and minimum posterior transverse width (min post w) were measured. The formula was derived using Python 3.12, which is commonly used in machine learning.*

Results: *The mean volume was 55.8 mL, with a standard deviation of 11.7. After evaluation using machine learning techniques, multiple linear regression was determined to be the most effective model, and the formula was identified as follows: Volume (mL) = 0.96 × max AP l (mm) + 0.40 × max body l (mm) – – 0.29 × body h (mm) + 0.76 × min body h (mm) + 0.14 × max post w (mm) + + 0.48 × min post w (mm) – 7.49.*

Conclusions: *The proposed formula can serve as an index for future studies on calcaneal volume, and the methods we used may be helpful for similar studies, particularly on dry bones.* (Folia Morphol 2026; 85: e01726073)

Keywords: calcaneus; coating dry bones; machine learning; party balloon coating technique; radiographic measurements; volume estimation; water displacement volumetry

Address for correspondence: Ali Utkan, University of Health Sciences, Ankara Bilkent City Hospital, Department of Orthopedics and Traumatology, Universiteler Mahallesi Bilkent Cad. No: 9 Cankaya, 06800 Ankara, Turkiye; tel. +90 533 3370111, e-mail: utkana@yahoo.com

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INTRODUCTION

Many studies on the morphological analysis of the calcaneus have been reported in the fields of anatomy, orthopedics, and sports medicine. Changes in its size and shape may cause various foot, knee, and hip disorders [21]. It is known that differences in calcaneal morphology may provide athletes with advantages in some disciplines and disadvantages in others [20]. High-intensity training may also alter calcaneal volume [7, 9]. Additionally, it is one of the bones commonly used in anthropology and forensic medicine research, as foot bones are often well preserved by shoes and the calcaneus is frequently found intact in corpses. For example, it is possible to make predictions about the age and sex of unidentified remains using morphometric values of the calcaneus [4, 6, 10, 17].

Several morphometric measurements of the calcaneus have been defined on radiological images for the purpose of diagnosing and monitoring calcaneal diseases and of planning or evaluating surgeries [6, 13, 14, 18, 27]. However, because of the difficulty of calculating volume, very few studies in the literature have addressed calcaneal volume [2, 10, 17].

If an irregular geometric shape can be represented as a combination of regular shapes, its total volume can be found by summing the volumes of each part. Since the calcaneus cannot be divided into regular geometric shapes, its volume can be calculated only by using either the Cavalieri method or Archimedes' water displacement method [2]. Archimedes' method has been used to determine the volume of many organs and tissues in forensic autopsies [1, 24]. Volume can also be estimated by taking slices of the object and summing the volumes of those slices. According to Cavalieri's principle, if slices obtained from two solid objects have the same surface area, their volumes are equal. This principle is applicable to volume estimation using thin-slice computed tomography (CT). Although computer software assists with this process, manual outlining of bone borders in each section is often required, making it time-consuming and resource-dependent. Besides, its availability depends on the specific resources, funding, and capabilities of forensic and anatomy laboratories.

Among medical diagnostic imaging methods, direct radiography is the most frequently used method in bone imaging because of its accessibility and low cost. The aim of this study was to obtain a simple formula that can estimate calcaneal volume using only measurements obtained from plain radiographic images. We believe this formula can be developed using machine learning with a heuristic approach, which is a problem-solving technique in which a near-optimal solution is sought in the fastest and easiest way, regardless of whether the result is definitive or provable by an algorithm. Although the formula may not provide the exact volume, we anticipate that it could serve as an index for future studies.

MATERIALS AND METHODS

A total of 216 dry unpaired adult calcanei of unknown sex, intact and undamaged, belonging to the Department of Anatomy, Ankara University Faculty of Medicine, were used for this study. The study was approved by the Ankara University Human Research Ethics Committee (date: 28.03.2024, approval decision No. I03-238-24). Once the bones had been numbered, their volumes were calculated using Archimedes' water displacement method.

Diffusion of water into bones is an important limitation of this procedure that has not been solved to date. We used a novel method to overcome this problem, which we called the 'party balloon coating' technique. In this technique, after the bone was placed in a 10-inch party balloon (Fig. 1A), the air inside the balloon was sucked out using a 50-mL syringe (Fig. 1B). Subsequently, a piece of thread was wrapped around the body-neck transition and knotted to prevent air from flowing in. The balloon was cut right above the knot, and the excess part of the balloon was discarded. Thus, all bone surfaces became covered with a thin layer of latex (Fig. 1C).

These bones were completely immersed in water inside a graduated cylinder by applying pressure with thin Kirschner wires (Fig. 1D). The amount of displaced water corresponding to the bone volume was calculated [26]. The reliability of this technique was validated in a preliminary study conducted by the authors on 14 dry calcanei. In that study, volumes measured using the Archimedes method were compared with those obtained through three-dimensional reconstruction of 1-mm-thick CT slices using the Aquarius iNtuition Volume Rendering program. The two sets of measurements were found to be statistically comparable [15].

Then, the bones were placed in groups on X-ray film cassettes in order to obtain radiographs. During lateral radiography, the bones were laid on their

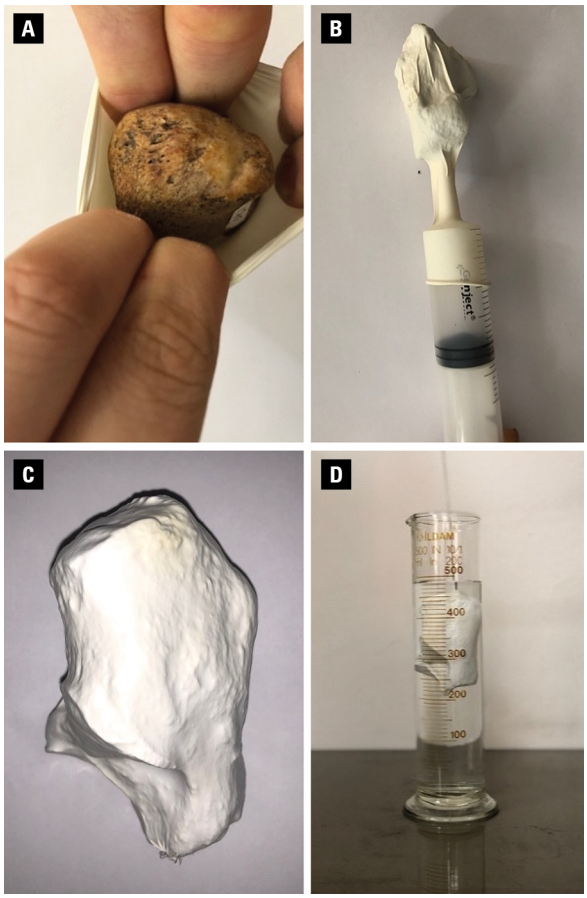

Figure 1. A. Dry bones are placed inside the balloon; **B.** Air is sucked out of the balloon using a 50 mL syringe; **C.** A piece of thread is wrapped around the neck of the balloon and knotted to prevent air from inflowing. The excess part is removed; **D.** Using Archimedes' water displacement method. By pressing with Kirschner wires, the bone is completely submerged in water.

lateral surfaces, and during axial radiography, they were laid on their plantar surfaces. When needed, the bones were supported with pieces of cotton to prevent them from tipping over. A vernier caliper with its external jaws opened to 10 cm was also placed on the cassettes to be used later for calibration.

The X-ray images were obtained with the IMD Basic 100 mobile X-ray device from a perpendicular distance of 1 m to the cassettes. Film negatives were scanned using an Epson Expression 1200XL model A3 graphic scanner (Epson, Suwa, Japan) with an A3 Transparency unit (Fig. 2A, B). Each radiograph was digitally loaded onto a computer, and the image colors were inverted to facilitate measurement (Fig. 2C, D).

These images were displayed on the computer screen, and measurements were taken using a screen ruler program after calibration according to the caliper jaw.

Although many morphometric measurements of the calcaneus have been described, only the following were used in this study, as they can be easily obtained from plain radiographs (Fig. 3).

On the lateral radiographs:

1. Maximum anteroposterior length (max AP l): The length of the line drawn from the most posterior point of the tuber calcanei to the most anterior point of the proc. anterior superior calcanei.
2. Maximum body length (max body l): The length of the line drawn from the most plantar end of the proc. medialis tuberis calcanei to the most anterior point of the proc. anterior calcanei.
3. Body height (body h): The length of the line drawn from the most plantar end of the proc. medialis tuberis calcanei to the most dorsal and superior point of the tuber calcanei.
4. Minimum body height (min body h): The length of the shortest line that can be drawn between the plantar surface and the superior surface at the posterior part of the calcaneus.
5. Facies articularis cuboidaea height (FA cuboidea): The length of the line drawn from the most superior point of the proc. anterior calcanei to the most inferior point of the facies articularis cuboidea.
6. Böhler's angle (Böhler angle): The angle between the line drawn from the highest point of the proc. anterior calcanei to the highest point of the facies articularis talaris posterior and the line drawn from the highest point of the facies articularis talaris posterior to the most superior point of the tuber calcanei.
7. Gissane's angle (Gissane angle): The angle between the line drawn tangential to the facies articularis talaris anterior and the line drawn tangential to the facies articularis talaris posterior.

On the axial radiographs:

1. Maximum posterior transverse width (max post w): The maximum length of the line that can be drawn perpendicularly between the medial and lateral surfaces of the calcaneus.
2. Minimum posterior transverse width (min post w): The minimum length of the line that can be drawn perpendicularly between the medial and lateral surfaces of the calcaneus.

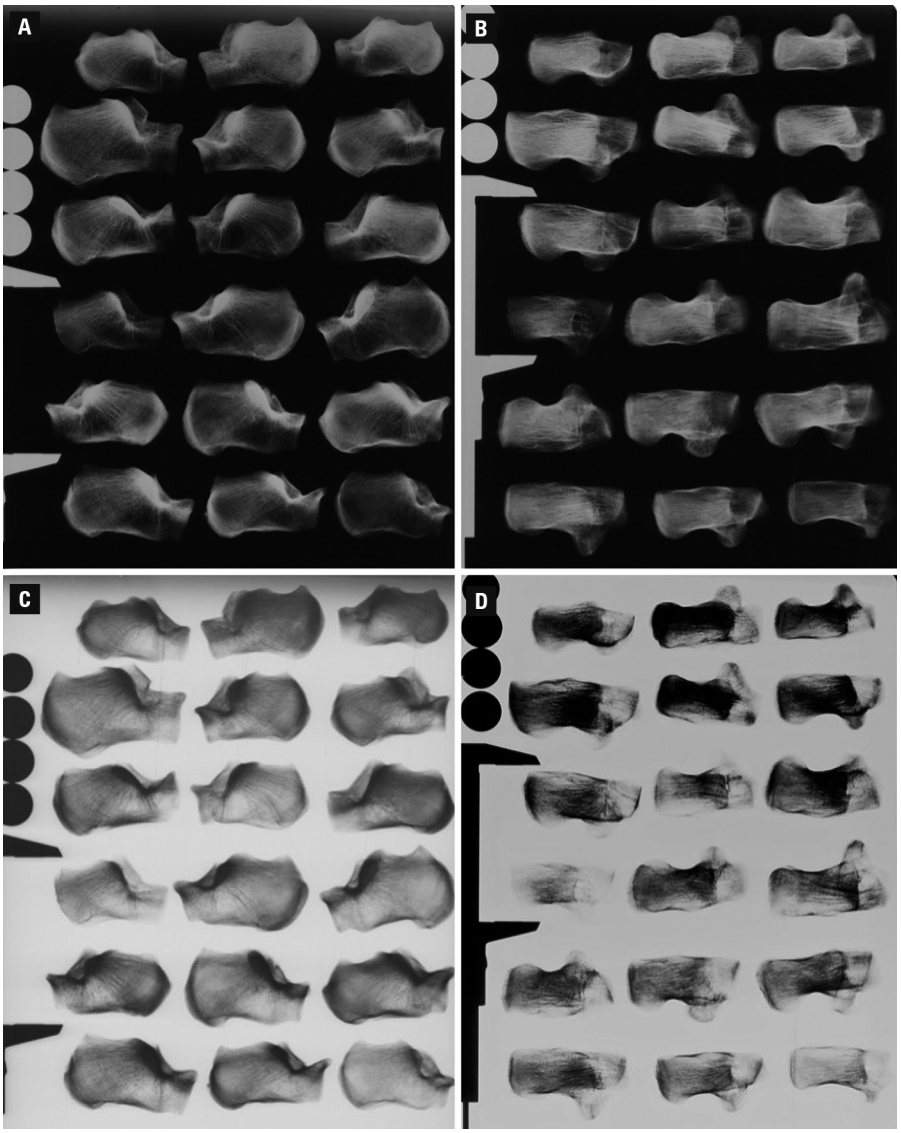

Figure 2. A. Lateral radiographs (calcanei 162–179); **B.** Axial radiographs (calcanei 162–179); **C.** Lateral radiographs with inverted colors (calcanei 162–179); **D.** Axial radiographs with inverted colors (calcanei 162–179).

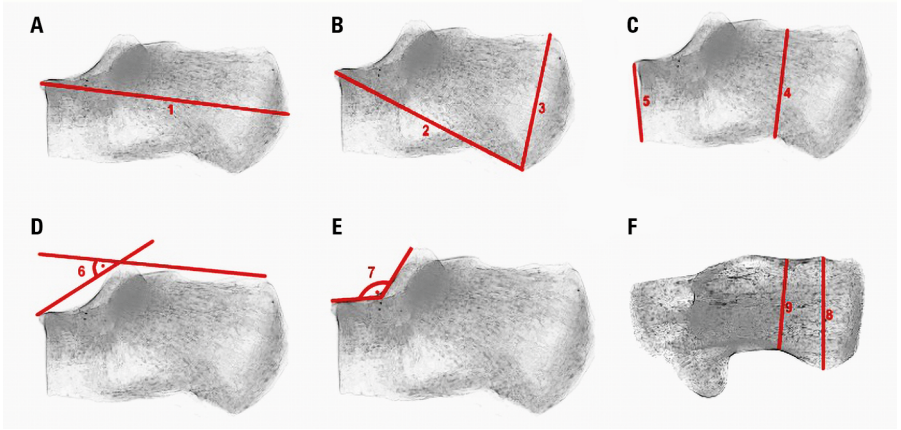

Figure 3. Radiographic measurements; **A.** 1: Maximum anteroposterior length; **B.** 2: Maximum body length, 3: Body height; **C.** 4: Minimum body height, 5: Facies articularis cuboidaea height; **D.** 6: Böhler's angle; **E.** 7: Angle of Gissane; **F.** 8: Maximum posterior transverse width; 9: Minimum posterior transverse width.

Statistics and data analysis

Statistical analyses were performed using IBM® SPSS® version 24.0 (IBM Corp, Armonk, NY, USA, 2017) software. Since the obtained values did not follow a normal distribution, nonparametric tests were used. Descriptive values were calculated as mean, standard deviation, median, minimum, and maximum. The values of the right and left bones were compared with the Mann–Whitney *U* test. Correlations between volume and other variables were assessed with Spearman's correlation test. The strength of the correlation between the variables was calculated using the rho coefficient. A p value less than 0.05 was considered statistically significant.

For data analysis and modeling, Python version 3.12 was used with the pandas and NumPy libraries to process data and explore relationships between variables. The seaborn and matplotlib libraries were used for visualization, while SciPy and statsmodels were used to perform statistical computations.

RESULTS

Out of the 216 calcanei measured in total, 116 were right and 100 were left calcanei. Maximum anteroposterior length, maximum body length, body height, minimum body height, Böhler's angle, angle of Gissane, facies articularis height, maximum posterior transverse width, minimum posterior transverse width, and volume values were compared between the right and left calcanei, and no significant difference was found in any of the measurements (Tab. 1).

Since the data distribution was not normal, the Spearman test was used to define the direction and degree of the relationship between the variables, and the results are given in Table 2. There was a significant positive correlation between volume and max AP l ($r = 0.709$, $p < 0.01$); between volume and max body l ($r = = 0.563$, $p < 0.01$); between volume and body h ($r = 0.494$, $p < 0.01$); between volume and min body h ($r = = 0.534$, $p < 0.01$); between volume and FA cuboidea ($r = 0.392$, $p < 0.01$); between volume and max post w ($r = 0.499$, $p < 0.01$); and between volume and min post w ($r = 0.432$, $p < 0.01$). However, no significant correlation was found between volume and either Böhler angle or Gissane angle ($p > 0.05$).

Data analyses with Python

Volume data exhibited a mean of 55.8 mL (SD = = 11.7). Using the rule of three standard deviations, only one outlier was detected (Fig. 4). The volume data was not normally distributed, as confirmed by the Shapiro–Wilk test for normality (W-statistic = 0.96, $p = 0.000014$). It is expected that with larger sample sizes, the data distribution may approach normality.

For both the right and left calcanei, the mean volumes were found to be 56.3 mL (SD = 12.9) and 55.4 mL (SD = 10.2), respectively. The Mann–Whitney *U* test was conducted to assess the significance of the side variable, yielding a U-statistic of 5953.0 with a p value of 0.64, indicating no significant difference between the right and left calcanei.

Modeling analysis

After performing preliminary analyses in Python, three models were tested to estimate calcaneal volume: multiple linear regression, polynomial regression,

Table 1. Comparison of radiographic measurements and volume values in the right and the left calcanei.

	Right Mean ± SD (median; min–max)	Left Mean ± SD (median; min–max)	p value
Max AP l	77.4 ± 5.5 (77.0; 63–92)	77.4 ± 5.0 (77.0; 67–89)	0.921
Max body l	62.7 ± 4.7 (63.0; 53–76)	63.0 ± 4.7 (62.5; 53–77)	0.824
Body h	43.6 ± 7.0 (43.0; 32–104)	43.1 ± 4.4 (43.0; 35–66)	0.817
Min body h	37.0 ± 3.7 (37.0; 30–47)	37.0 ± 3.0 (37.0; 30–45)	0.767
FA cuboidea	24.0 ± 3.0 (24.0; 17–30)	24.0 ± 2.9 (24.0; 17–32)	0.860
Böhler angle	34.0 ± 7.7 (34.0; 17–61)	34.5 ± 7.9 (33.0; 16–56)	0.949
Gissane angle	128.0 ± 8.6 (128.0; 98–149)	126.4 ± 8.9 (126.0; 98–147)	0.232
Max post w	33.0 ± 3.8 (33.0; 27–47)	34.1 ± 4.0 (34.0; 27–46)	0.413
Min post w	27.5 ± 3.0 (27.5; 20–36)	27.8 ± 2.9 (28.0; 21–37)	0.381
Volume	56.3 ± 12.9 (54.0; 34–112)	55.4 ± 10.2 (53.5; 37–83)	0.727

body h — body height; FA cuboidea — facies articularis cuboidaea height; max AP l — maximum anteroposterior length; max body l — maximum body length; max post w — maximum posterior transverse width; min body h — minimum body height; min post w — minimum posterior transverse width; SD — standard deviation.

Table 2. Correlation analysis of radiographic measurements and volume values.

		Volume	Max AP l	Max body l	Body h	Min body h	FA cuboidea	Böhler angle	Gissane angle	Max post w
Max AP l	Correlation	**0.709**								
	Significance	0.000								
Max body l	Correlation	**0.563**	**0.725**							
	Significance	0.000	0.000							
Body h	Correlation	**0.494**	**0.607**	**0.298**						
	Significance	0.000	0.000	0.000						
Min body h	Correlation	**0.534**	**0.608**	**0.358**	**0.751**					
	Significance	0.000	0.000	0.000	0.000					
FA cuboidea	Correlation	**0.392**	**0.495**	**0.435**	**0.368**	**0.399**				
	Significance	0.000	0.000	0.000	0.000	0.000				
Böhler angle	Correlation	0.015	–0.013	0.035	–0.075	–0.019	0.008			
	Significance	0.831	0.846	0.610	0.271	0.780	0.909			
Gissane angle	Correlation	0.110	0.093	0.093	0.097	0.024	0.046	**0.196**		
	Significance	0.106	0.174	0.174	0.156	0.721	0.503	0.004		
Max post w	Correlation	**0.499**	**0.612**	**0.506**	**0.433**	**0.456**	**0.522**	0.129	0.098	
	Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.058	0.149	
Min post w	Correlation	**0.432**	**0.455**	**0.308**	**0.462**	**0.540**	**0.339**	0.119	0.060	**0.611**
	Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.377	0.000

body h — body height; FA cuboidea — facies articularis cuboidaea height; max AP l — maximum anteroposterior length; max body l — maximum body length; max post w — maximum posterior transverse width; min body h — minimum body height; min post w — minimum posterior transverse width.

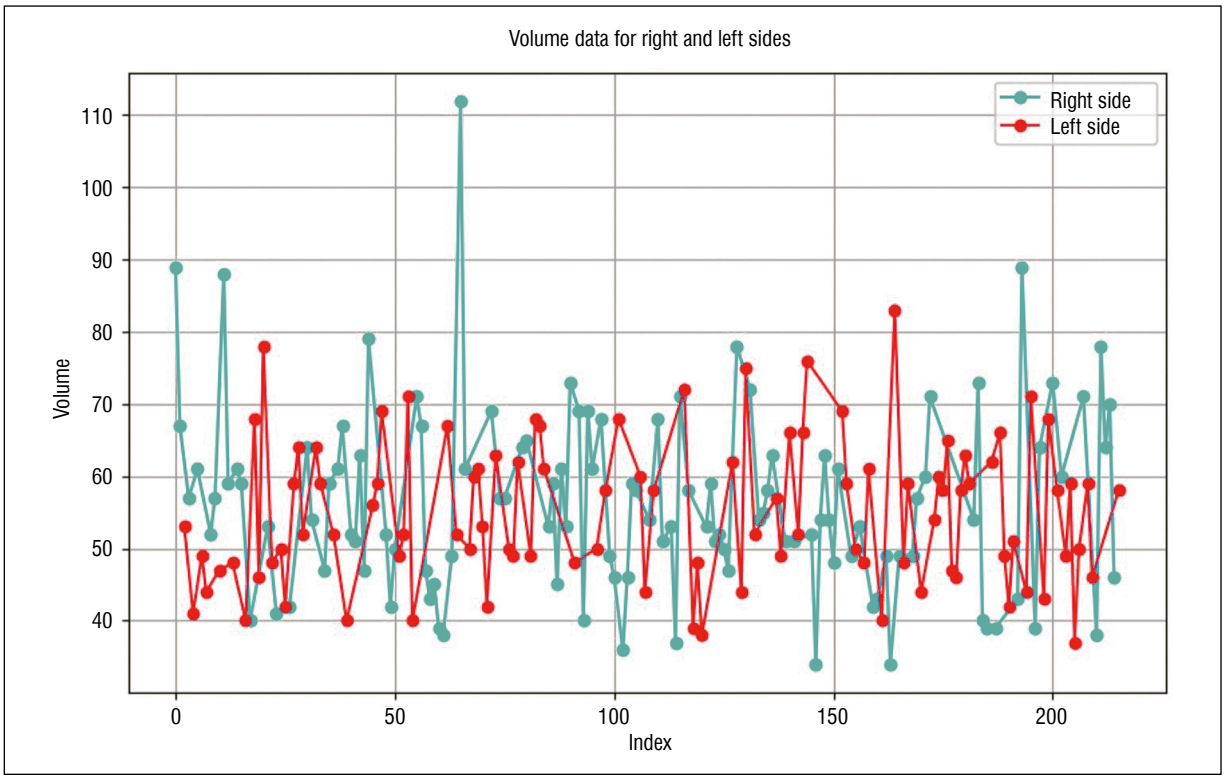

Figure 4. Plot of volume values.

and a LightGBM-based decision tree. The multiple linear regression model was selected as the most appropriate because of its superior performance.

Several polynomial regression models were constructed to explore potential nonlinear relationships. The model with the highest goodness of fit was: Volume = β0 + β1 × Böhler angle + β2 × Böhler angle^2 + + β3 × max AP l × min body h + β4 × Böhler angle × × min post w + β5 × max post w × min body h, which yielded an adjusted R-squared value of 0.475. This model did not show a significant improvement in goodness of fit compared with the multiple linear regression model. The model also yielded a mean squared error (MSE) of 70.24, a root mean squared error (RMSE) of 8.38, and a mean absolute error (MAE) of 6.005.

In the machine learning evaluation, the LightGBM decision tree algorithm was used. Similar to the multiple linear regression model, Böhler's angle, Gissane's angle, and FA cuboidea were excluded because of insignificance. A standard 80–20 train-test split was employed (meaning 80% of the dataset was used for training and 20% for testing), with the random state set to 42 for reproducibility. Since there were no discontinuities or problematic values in the dataset, no transformation was required before model training. Only a reference dataset was created for validation.

Gradient Boosting Decision Trees were set as the boosting type with the objective of predicting continuous values (regression). sklearn.model_selection was used to fine-tune the parameters of the model. At the end of the parameter fine-tuning process, the following parameters were selected as appropriate. The number of leaves (complexity of the tree model) was set to 31, the learning rate (step size for weight updates) was set to 0.05 to prevent overfitting, the feature fraction was set to 0.9 (meaning the algorithm randomly selected 90% of the features per iteration to reduce the risk of overfitting), and the number of boosting rounds was set to 100.

After training with the 80% training dataset, the algorithm made predictions on the target values in the test set. sklearn.metrics was used to evaluate the performance of the model. The MSE and R-squared values obtained were 93.98 and 0.22, respectively, meaning that no significant improvement in goodness of fit was achieved compared with the best multiple linear regression model.

Multiple linear regression model

The final multiple linear regression model was formulated as Volume = β0 + β1 × max AP l + β2 × × max body l + β3 × body h + β4 × min body h + + β5 × max post w + β6 × min post w. Böhler angle and Gissane angle, which were found to be insignificant variables, and FA cuboidea, with a correlation coefficient of 0.39, were removed from the multiple linear regression model, and the remaining variables yielded the results shown in Figure 5.

OLS Regression Results

Dep. Variable:	Volume	R-squared:	0.543
Model:	OLS	Adj. R-squared:	0.530
Method:	Least Squares	F-statistic:	41.36
Date:	Mon, 10 Jun 2024	Prob (F-statistic):	5.04e-33
Time:	19:14:31	Log-Likelihood:	-753.31
No. Observations:	216	AIC:	1521.
Df Residuals:	209	BIC:	1544.
Df Model:	6		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	-77.4862	8.727	-8.879	0.000	-94.690	-60.283
max AP l	0.9629	0.191	5.049	0.000	0.587	1.339
max body l	0.3959	0.170	2.324	0.021	0.060	0.732
body h	-0.2857	0.119	-2.397	0.017	-0.521	-0.051
min body h	0.7622	0.250	3.046	0.003	0.269	1.255
max post w	0.1447	0.197	0.734	0.464	-0.244	0.533
min post w	0.4777	0.245	1.948	0.053	-0.006	0.961

Omnibus:	59.930	Durbin-Watson:	1.879
Prob(Omnibus):	0.000	Jarque-Bera (JB):	222.487
Skew:	1.072	Prob(JB):	4.87e-49
Kurtosis:	7.486	Cond. No.	1.96e+03

Figure 5. Ordinary least squared (OLS) regression results.

The regression results yielded an R-squared value of 0.543, indicating that approximately 54.3% of the variance in calcaneal volume can be explained by the model. The regression equation was: Volume = = 0.96 × max AP l + 0.40 × max body l – 0.29 × × body h + 0.76 × min body h + 0.14 × max post w + + 0.48 × min post w – 7.49.

To assess multicollinearity, variance inflation factor (VIF) values were calculated, and no significant multicollinearity was observed. The Durbin–Watson statistic was 1.879, indicating no significant autocorrelation. The adjusted R-squared value of 0.530, coupled with an MSE of 62.62, an RMSE of 7.91, and an MAE of 5.68, suggests that while the selected variables are necessary, more research is required to identify other potential influencing factors.

DISCUSSION

The calcaneus has acquired a unique shape in accordance with the human need to walk and move upright during the evolutionary process [12]. Many osteometric parameters associated with the calcaneus have been described in the literature. However, very few studies on calcaneal volume have been reported because of its irregular geometric shape [6, 13, 14, 18, 27]. In this study, we aimed to obtain a simple formula that can estimate calcaneal volume using measurements obtained from plain radiographs of the calcaneus, and a novel formula was generated. Using this formula, it will be possible to estimate calcaneal volume with a heuristic approach.

The landmarks, lines, and angles used in our study have been described in various previous studies. Nozaki et al. [18] analyzed sex- and age-related differences in the calcaneus with a quantitative approach using 37 landmark coordinates defined in three-dimensional geometric models. They found differences not only in the size but also in the shape of the calcaneus by sex. They also found that the shape of the calcaneus changes with aging, possibly due to remodeling caused by mechanical stress. Ekizoğlu et al. [6] defined measurements on three-dimensional models obtained from CT sections of the foot in 208 contemporary Turkish patients and reported that sex prediction could be made based on these measurements. Amuti et al. [3] and Koshy et al. [13] reported from South India that a person's height can be estimated using measurements defined on the calcaneus with certain equations. Among the landmarks mentioned above, those that were easy to identify on direct radiographs were selected for use in our study.

In the study conducted by Acer et al. [2], dry calcanei were immersed in a graduated cylinder filled with water to measure their volume using Archimedes' method. Before the development of more advanced techniques, fluids were commonly used to penetrate bone in order to determine the volume of cancellous bone [29]. Pietak et al. [19] also reported that the volume values obtained using Archimedes' method were lower than those measured using the Cavalieri method. The amount of water penetrating the bones differed in each trial, and they were unable to establish a reproducible method to eliminate this issue. Similarly, in our preliminary experiments, we observed variability in repeated measurements of the same bone. To avoid making permanent changes to the bones housed in the anatomy laboratories of Ankara University Faculty of Medicine and to prevent damage, we tested various approaches and found the party balloon coating technique to be the most suitable. Although water adhesion to the balloon surface may be considered a potential source of error, the volume was recorded while the bone was fully submerged. Therefore, any water adhering to the balloon after removal does not affect the displaced water measurement and is unlikely to compromise the accuracy of the results.

Volume measurement using CT is also not easy and presents many challenges. Commean et al. [5] investigated volume changes due to osteolysis in the metatarsal and tarsal bones of neuropathic patients using volumetric quantitative CT. In their study, in addition to the need for thin-section tomography, since the computer program they developed could not determine the bone boundaries completely and accurately, independent researchers were required to do so. They explained that these researchers needed 10 hours of training at the beginning.

Stereology is defined as the estimation of three--dimensional space from a two-dimensional plane [28]. Examination with computerized video systems to measure the volume of products with irregular shapes based on three-dimensional reconstruction is a known method in stereology [22, 23]. However, no method has been reported in the literature to calculate bone volume with the help of a formula using only plain radiographs of any bone. By using machine learning, in theory, it is possible to find such a formula

with a heuristic approach. Machine learning is a subfield of artificial intelligence focused on learning from data and making predictions without fixed permanent code. Three main tools are used in machine learning decision-making: logic, statistics, and heuristic methods. Each is suited to a particular type of problem. Although machine learning has been used in some studies in the field of anatomy, the method we used is novel.

Python is a programming language that is used extensively, especially in the field of data science, and is available in source or binary form for all major platforms. It has numerous open-source libraries and frameworks that make it easy to implement machine learning algorithms, is available free of charge, and can be freely distributed. Since Python is easy to learn, it is used as an introductory programming language in schools, but it is also used by professional software developers in high-level institutions such as NASA.

For simple analyses and direct data visualization, SPSS® may be sufficient, but for text analysis or more complex analyses involving large datasets, Python's libraries offer more advanced features. Both SPSS® and Python were used in our study.

In our study, based on analysis of nine distinct measurements and volume values, no statistical difference was detected between the right and left calcanei. Similarly, Misselyn et al. [16] could not find a statistically significant difference between the right and left calcanei, which they explored using three-dimensional CT reconstructions of 46 healthy individuals.

In our study, a statistically significant positive correlation was found between volume and max AP l, max body l, body h, min body h, FA cuboidea, max post w, and min post w. The relationship between volume and Böhler angle or Gissane angle was not statistically significant. Similarly, Acer et al. [2] used maximum length, body height, and minimum width measurements and found a positive correlation between these measurements and volume. Krmek et al. [14] reported that the anterior part of the calcaneus did not affect its volume greatly, but the measurements they defined as length and posterior length had a positive correlation with volume.

Determining sex from skeletal remains is the most important step required for biological identification, and many scientists have conducted studies on sex determination using morphometric features of the calcaneus with data obtained from their own populations. Lee et al. [15] calculated the volumes and surface areas of the calcaneus and some other bones of 110 known Korean cadavers using CT images and examined differences according to sex using discriminant analysis. Kim et al. [11] reported that maximum calcaneal length gave an 85% accurate result in determining sex, but a much more reliable result was achieved when all morphometric measurements were used together.

Inamori-Kawamoto et al. [10] reported that they were able to make predictions about the sex, age, and height of the corpse using morphometric data obtained from CT of the calcaneus and talus. In their study, they used 179 postmortem autopsy cases from the Japanese population at a forensic medicine institution. Gürlek and Akman [8] assessed the area and volume of the tarsal bones and analyzed the classification of the talus and calcaneus according to sex using foot CT images from 90 healthy Turkish individuals. In our study, the variables were obtained from bilateral plain calcaneal radiographs. Plain radiography is a more easily accessible and more commonly used method.

This study has several limitations. Although Picture Archiving and Communication Systems (PACS) and Digital Imaging and Communications in Medicine (DICOM) are used almost routinely nowadays, and it is easier to make measurements with these programs, the radiographs used in our study were originally film-based and had to be digitized manually because of limited resources. Measurements were then performed using a separate program.

While more accurate systems, such as those using overflow collection with sensitive weighing scales, have been described in the literature, such equipment was not available to us. Additionally, potential inaccuracies due to the small added volume from the knot and Kirschner wires were not fully eliminated. These factors may have introduced minor errors into the volume calculations.

Another limitation is the lack of formal reliability testing, such as intraclass correlation coefficient (ICC) analysis, and the absence of standardized observer training. These issues should be addressed in future validations of the method.

Finally, a key limitation of this study is the lack of demographic information, such as age, sex, and ethnicity, for the calcanei used. These characteristics are known to influence bone morphology and may have improved the model's predictive accuracy.

Future studies using well-documented samples and larger, more diverse populations are recommended to validate and refine the proposed model.

Although more accurate volume estimation may require larger datasets or the inclusion of additional three-dimensional shape parameters derived from CT or CBCT, the formula proposed in this study can serve as a practical and accessible index. When combined with patient data such as age, sex, height, body mass, and standard radiographic measurements, it may contribute significantly to fields such as anthropology, forensic medicine, and orthopedics. Expanding the study across multiple populations and comparing it with more advanced imaging techniques would enhance generalizability and clinical relevance. Multicenter validation of the findings is required before the method can be put into practical use.

CONCLUSIONS

The proposed formula for estimating calcaneal volume from plain radiographs offers a cost-effective and accessible tool for both clinical and research applications, particularly in resource-limited settings. The volume of the calcaneus can be estimated using six key measurements: maximum anteroposterior length, maximum body length, body height, and minimum body height from lateral radiographs, and maximum and minimum posterior transverse width from axial radiographs.

Additionally, the latex balloon coating technique presented in this study provides a simple and effective method to prevent water infiltration during volume measurement using Archimedes' water displacement method. This approach may prove valuable in similar research involving dry bones.

ARTICLE INFORMATION AND DECLARATIONS

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics statement

The study was approved by the Ankara University Human Research Ethics Committee (date: 28.03.2024, approval decision No. I03-238-24).

Author contributions

Utkan A: Protocol/project development, data collection, manuscript writing/editing. Doğan E: Data analysis (machine learning). Özkurt B: Manuscript editing. Uz A: Supervision and mentorship, manuscript editing.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Supplementary material

None.

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