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ORIGINAL ARTICLE

Medicine Science International Medical Journal

Medicine Science 2024;13(3):583-9

# Estimating body weight from foot measurements in the Eastern Turkish Population using linear methods and artificial neural networks

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Received 07 May 2024; Accepted 17 June 2024
Available online 15 August 2024 with doi: 10.5455/medscience.2024.05.040



**Abstract**

In forensic and archaeological contexts, accurately determining an individual's age, sex, height, and weight is essential for the identification of unidentified bodies and dismembered remains. This study assesses the effectiveness of linear regression analysis and artificial neural networks (ANNs) in estimating body weight using foot measurements within the Eastern Turkish population. The research was conducted with medical students, including 149 volunteers—76 males and 73 females. Participants' height and weight were recorded using a stadiometer. Foot measurements were taken with a Vernier caliper and an osteometric board. The data were assessed utilizing SPSS 26.0, and ANN models were developed using the Keras library within the Google Colab platform. In terms of height, weight, and foot size, all these values were significantly higher in males than in females. Linear regression methods resulted in a root mean squared error (RMSE) of 11.83 kg for males, 6.23 kg for females, and 9.56 kg for the entire sample. With ANNs, these error values were reduced to 10.13 kg for males, 5.10 kg for females, and 8.07 kg for the entire sample. The analysis shows that ANNs are more adept at handling complex data, leading to improved prediction accuracy.

**Keywords:** Weight estimation, anthropometry, forensic anthropology, linear regression, artificial neural networks

## Introduction

In forensic investigations and archaeological research, determining the age, sex, stature, and weight of an individual is crucial for identifying unidentified bodies and dismembered remains. Using anthropological methods to match individuals significantly reduces the number of people that need to be considered, thereby saving resources, time, and money [1].

The degree of preservation of remains can significantly impact the evaluation of any parameter within a biological profile. Often, only the skull and long bones are found, while in cases of mass disasters, explosions, or terrorist attacks, only a few bone fragments may be preserved [2]. In such cases, forensic identifications may need to be conducted on isolated body parts apart from bone material. In disaster scenarios, lower extremities tend to withstand taphonomic changes better than upper extremities, making them more enduring. Particularly, the foot has proven to be a much more significant organ compared to other body parts. This is because footprints and fragments of lower and upper limbs are more commonly retrieved at crime or incident scenes [3]. Feet, often preserved within shoes, remain intact and thus serve as valuable sources for forensic analysis [4]. These characteristics have made anthropometric measurements of the foot a focus of many forensic anthropology studies [5-9]. In Türkiye, Özaslan et al. explored how measurements from the lower extremities correlate with stature, and Ozden et al. applied both foot and shoe measurements to estimate stature and determine sex [1,10]. Additionally, Krishan's study focused on stature estimation from footprints in the Indian Gujjar population, while Awais et al. analyzed sex determination from footprints in the Punjab population of Pakistan [5,11].

**CITATION**
Turan O, Parlak ME, Ozkul BB, et al. Estimating body weight from foot measurements in the Eastern Turkish Population using linear methods and artificial neural networks. Med Science. 2024;13(3):583-9.



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DOI: 10.5455/medscience.2024.05.040

Despite numerous studies on sex and stature estimation using measurements of the foot and foot bones, research focusing on estimating body weight from these measurements remains notably limited [12-15]. The results from such research are often specific to particular populations, highlighting the importance of establishing population-specific standards in the development of biological profiles. Changes and diversity within a society over time necessitate the continuous research and updating of biological profiling standards to reflect and account for the biology of the population on a regional and temporal level [2]. Although studies on weight estimation based on foot anthropometry have been conducted in the Turkish population, no such study exists for Turks living in the eastern regions.

Linear regression analysis is frequently utilized for developing body weight estimation models [3,13,16,17]. Although this method is cost-effective and straightforward, it demands certain conditions like linear relationships and normally distributed data. On the other hand, Artificial Neural Networks (ANNs) excel in managing non-linear relationships, offering enhanced capabilities for complex problem-solving [18,19]. ANNs provide a robust alternative to traditional statistical models, particularly effective in accurately predicting outcomes from non-linear data [20].

The purpose of this study is to estimate body weight using foot measurements in the Eastern Turkish population through Linear Regression Analyses. In addition to linear analyses, the data have also been evaluated using Artificial Neural Networks.

## Material and Methods

Ethical approval for our study was obtained from the İnönü University Faculty of Medicine, Health Sciences Non-Interventional Clinical Research Ethics Committee, under approval number 2023/4992 dated September 20, 2023. Following the receipt of ethical clearance, measurements were conducted on students from our faculty. We included 149 volunteers in the study, consisting of 76 males and 73 females, all of whom provided informed consent. The study excluded individuals with physical abnormalities, trauma, or surgeries that might have impeded proper stature or lower limb measurement. This included conditions such as deformities of the spine or limbs, disorders affecting the long bones or spine, or individuals who had undergone surgical interventions on these bones. Pregnancy and being under 18 were also considered exclusion criteria. Data on the age, sex, and weight of the participants were recorded. All participants were from Malatya and its neighboring areas in Eastern Türkiye.

### Measurement of Stature and Body Weight

The assessment of stature and weight was conducted as depicted in Figure 1. Participants were positioned in an erect posture with their heads aligned in the Frankfurt Horizontal Plane, eyes oriented directly forward, backs flush against a vertical surface, and feet positioned flat on the measuring surface. The vertical distance from the surface under the feet to the vertex of the head was meticulously measured using a stadiometer with a precision of 0.1 centimeters [21]. In preparation for weight measurement, participants were instructed to remove heavy outer garments (such as jackets, coats, trousers, skirts, etc.) and footwear. Those participants who declined to remove trousers or skirts were asked to empty their pockets; this adjustment was duly noted and recorded in the data collection form [22].

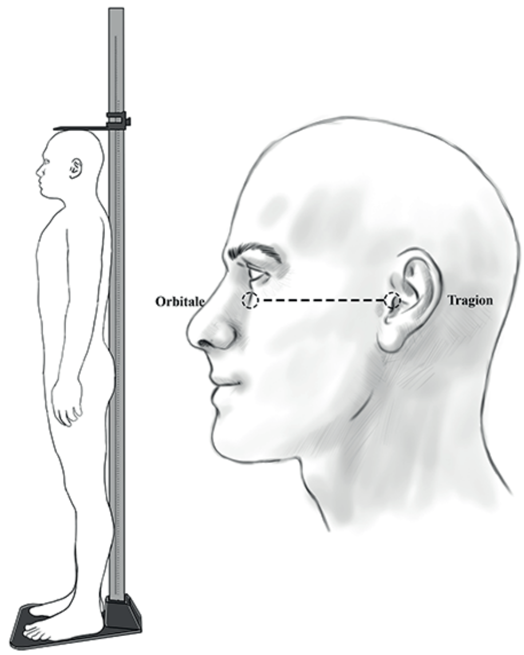


**Figure 1.** Stature and weight assessment using a stadiometer, with individuals positioned in the Frankfurt Horizontal Plane. (Drawings by MEP)

### Assessment of Measurement Error

The fifth author provided initial technical training to all individuals who conducted the measurements. Following this training, the other two authors carried out the measurements for each foot separately. To verify the intraobserver and interobserver reliability, measurements were conducted again on a random sample of 20 participants.

The technical error of measurements (TEM), the relative technical error of measurements (rTEM), and the coefficient of reliability (R-value) were calculated for both intra and inter observer error. For beginner anthropometrists, acceptable intraobserver rTEM values are below 1.5%, and for interobserver, below 2.0% is considered adequate [23]. When the reliability coefficient (R) surpasses 0.95, it indicates that measurement-induced errors are negligible, affirming the method's high level of accuracy [24].

### Measurement of Foot Dimensions

Foot height (FH) is measured from the lateral malleolus to the heel, and this measurement is taken while the foot rests on an osteometric board with the lower extremity in a relaxed position. Foot length (FL) is determined from the acropodion,

DOI: 10.5455/medscience.2024.05.040

the most anterior point, to the pternion at the heel's posterior. Measurements are conducted with the subject seated and the foot suspended to avoid any distortion from body weight, utilizing a standard Vernier sliding caliper measured to the nearest 1/100 of a millimeter. Foot breadth (FB), defined as the distance between the surfaces of the first and fifth metatarsal bone heads, is measured with the same technique used for foot length, ensuring accuracy and consistency in the data collected. The measurement points of all foot dimensions are shown in Figure 2.

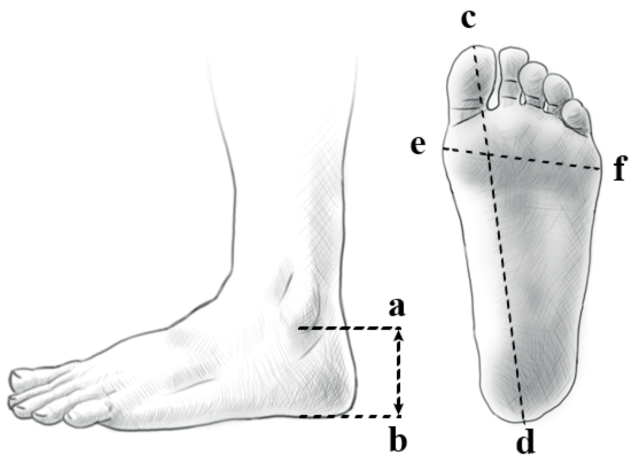


**Figure 2.** Foot dimensions; » Foot Height (FH) (a-b), » Foot Length (FL) (c-d), » Foot Breadth (FB) (e-f). (Drawings by MEP)

### Statistics and Data Analysis

Descriptive statistics for the study sample presented quantitative data as median (minimum-maximum) and mean ± standard deviation, while qualitative data were expressed as percentages. All obtained values were analyzed, and comparisons were made between both sexes. The distribution of the data was evaluated using normality tests. Depending on the data distribution, we applied t-tests and linear regression for normally distributed measurements, and the Mann-Whitney U Test for those not normally distributed. We calculated unstandardized coefficients, beta values, mean absolute error (MAE), and root mean squared error (RMSE) for the regression models. Statistical significance was established at $p<0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0.

In addition to linear methods, ANNs were also employed for predicting body weight in our research. ANNs, an artificial intelligence method capable of making decisions by mimicking the operational principles of the human brain, utilize neurons and synapses rather than formulas, as in the brain. The most effective model is achieved by adjusting synaptic weights using the backpropagation technique, which allows the finalized ANN to effectively make predictive decisions [25-27].

ANNs were developed and evaluated using the Keras framework within the Google Colab coding environment. Google Colab was chosen for its support of various Python versions and different runtime environments, which ensures reproducibility in scientific analyses. The model architecture was defined with Keras as a Sequential structure, incorporating a dense layer with 100 neurons using the ReLU activation function and a linear activation function in the output layer due to the regression problem. Model architectures were compiled using the mean squared error as the loss function, trained over 200 epochs, and optimized with an Adam optimizer with a learning rate of 0.2.

Linear Regression and Artificial Neural Network (ANN) models were developed independently for each sex and both feet. To evaluate the efficacy of these models, we employed a k-fold cross-validation technique, where the technique was applied with 10 folds. In this approach, the dataset is randomly partitioned into k nearly equal-sized segments. For each iteration of the cross-validation, k-1 segments are used for training the model, and the performance is then tested on the remaining segment. This cycle is repeated k times, with each segment serving once as a test set, thereby guaranteeing that every part of the dataset is used effectively for validation [28,29].

## Results

Intra and interobserver rTEM values were below 1.5% and 2.5%, respectively, indicating precise measurements. Reliability coefficients for both exceeded 95%, underscoring the methods' consistency and reliability. Results are detailed in Table 1.

**Table 1.** Measurement error values

| | Intraobserver | | | Interobserver | | |
|---|---|---|---|---|---|---|
| **Variables** | **TEM** | **rTEM** | **R** | **TEM** | **rTEM** | **R** |
| **Right side** | | | | | | |
| **FH** | 0.061 | 1.28% | 0.989 | 0.089 | 1.86% | 0.976 |
| **FL** | 0.082 | 0.32% | 0.997 | 0.166 | 0.65% | 0.987 |
| **FB** | 0.095 | 1.01% | 0.981 | 0.097 | 1.04% | 0.980 |
| **Left side** | | | | | | |
| **FH** | 0.065 | 1.28% | 0.989 | 0.065 | 1.28% | 0.989 |
| **FL** | 0.069 | 0.27% | 0.998 | 0.135 | 0.53% | 0.992 |
| **FB** | 0.050 | 0.53% | 0.995 | 0.092 | 0.99% | 0.982 |

TEM: technical error of measurement, rTEM: relative technical error of measurement, R: reliability coefficient, FH: foot height, FL: foot length, FB: foot breadth

Descriptive statistics and t-tests comparing male and female groups are detailed in Table 2. Measurements across all parameters were higher in males compared to females, with mean values significantly greater in the male group. No significant age difference was observed between the male and female groups.

**Table 2.** Descriptive statistics of stature (cm), body weight (kg) ages (years) and all foot measurements (cm) for males and females

| | Male (n=76) | | | | | Female (n=73) | | | | | p values |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | Median | S.D. | Min | Max | Mean | Median | S.D. | |
| **Weight** | 57.00 | 118.00 | 78.42 | 9.11 | 13.39 | 43.00 | 84.00 | 56.18 | 55.00 | 8.08 | **0.000**[a] |
| **Stature** | 162.80 | 193.80 | 176.52 | 25.60 | 6.10 | 150.40 | 177.70 | 162.30 | 162.00 | 6.40 | **0.000**[a] |
| **Age** | 20.00 | 30.00 | 22.63 | 4.90 | 1.94 | 19.00 | 30.00 | 21.99 | 22.00 | 1.90 | **0.063**[b] |
| **Foot dimensions** | | | | | | | | | | | |
| **Right side** | | | | | | | | | | | |
| **FH** | 4.01 | 5.87 | 4.77 | 22.00 | 0.49 | 2.49 | 5.40 | 3.76 | 3.74 | 0.57 | **0.000**[a] |
| **FL** | 23.10 | 28.40 | 25.65 | 176.90 | 1.17 | 20.55 | 25.70 | 23.06 | 23.00 | 1.11 | **0.000**[a] |
| **FB** | 7.87 | 10.44 | 9.11 | 75.50 | 0.55 | 6.70 | 9.00 | 7.92 | 7.90 | 0.47 | **0.000**[a] |
| **Left side** | | | | | | | | | | | |
| **FH** | 3.50 | 6.10 | 4.87 | 4.77 | 0.62 | 2.73 | 5.20 | 3.81 | 3.79 | 0.54 | **0.000**[a] |
| **FL** | 23.10 | 28.70 | 25.63 | 25.60 | 1.19 | 20.90 | 25.40 | 22.97 | 22.90 | 1.12 | **0.000**[a] |
| **FB** | 7.89 | 10.48 | 9.13 | 9.04 | 0.55 | 6.90 | 9.20 | 7.94 | 7.90 | 0.48 | **0.000**[a] |

FH: foot height, FL: foot length, FB: foot breadth, a: Independent Samples t Test, b: Mann Whitney U Test

Right foot length was significantly longer in females ($p<0.05$). No significant differences were noted in foot breadth between the two feet for both sexes. However, foot height was significantly greater on the left side in males ($p < 0.05$). These findings from the paired samples t-tests are presented in Table 3.

**Table 3.** Analysis of differences between measured right and left foot dimensions via Paired Samples t-Test

| | Foot dimensions | Mean | S.D. | p value |
|---|---|---|---|---|
| **Female (n=73)** | **Right FH-Left FH** | -0.05017 | 0.23 | 0.063 |
| | **Right FL-Left FL** | 0.08435 | 0.29 | **0.015** |
| | **Right FB-Left FB** | -0.02192 | 0.20 | 0.351 |
| **Male (n=76)** | **Right FH-Left FH** | -0.10125 | 0.35 | **0.014** |
| | **Right FL-Left FL** | 0.01974 | 0.32 | 0.592 |
| | **Right FB-Left FB** | -0.02524 | 0.24 | 0.368 |

FH: foot height, FL: foot length, FB: foot breadth

The coefficients from the Linear Regression analysis are detailed in Table 4. Following cross-validation, the linear regression models for males showed $R^2$ values of 0.185 for the right foot and 0.208 for the left foot, while for females, these values were 0.397 for the right foot and 0.369 for the left foot, as summarized in Table 5. The formulas for estimating body weight, derived from multiple regression analysis based on foot measurements, are outlined below:

- ***Weight (Male) =***

  [-73.690 + 1.358 (Right foot height) + 4.052 (Right foot length) + 4.580 (Right foot breadth)];

  [-80.706 + 0.228 (Left foot height) + 3.776 (Left foot length) + 6.706 (Left foot breadth)]

- ***Weight (Female) =***

  [-62.173 + 4.375 (Right foot height) + 3.205 (Right foot length) + 3.539 (Right foot breadth)];

  [-57.194 + 4.185 (Left foot height) + 3.013 (Left foot length) + 3.555 (Left foot breadth)]

For males, established ANNs underwent 10-fold cross-validation, resulting in post-validation $R^2$ values of 0.420 for right foot measurements and 0.414 for left foot measurements. For females, the ANNs similarly underwent 10-fold cross-validation, yielding $R^2$ values of 0.595 for right foot measurements and 0.537 for left foot measurements. Detailed results are compiled in Table 5, and visual representations of the ANNs utilized for predicting stature are depicted in Figure 3.

DOI: 10.5455/medscience.2024.05.040

**Table 4.** Multiple Linear Regression coefficients utilized in regression equations to calculate body weight

| | Variables | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Right side | | | | Left side | | | |
| | **Constant** | **FH** | **FL** | **FB** | **Constant** | **FH** | **FL** | **FB** |
| **Male** | -73.690 | 1.358 | 4.052 | 4.580 | -80.706 | 0.228 | 3.776 | 6.706 |
| **Beta** | | 0.050 | 0.354 | 0.187 | | 0.011 | 0.334 | 0.275 |
| **Female** | -62.173 | 4.375 | 3.205 | 3.539 | -57.194 | 4.185 | 3.013 | 3.555 |
| **Beta** | | 0.307 | 0.439 | 0.204 | | 0.281 | 0.416 | 0.213 |

FH: foot height, FL: foot length, FB: foot breadth

**Table 5.** Linear Regression analysis and ANN model results

| | Cross-validated results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Results obtained from right foot measurements | | | | | Results obtained from left foot measurements | | | | |
| | **R** | **$R^2$** | **Adj. $R^2$** | **MAE (kg)** | **RMSE (kg)** | **R** | **$R^2$** | **Adj. $R^2$** | **MAE (kg)** | **RMSE (kg)** |
| **Linear Regression** | | | | | | | | | | |
| **Male** | 0.431 | 0.185 | 0.151 | 9.01 | 12.00 | 0.456 | 0.208 | 0.175 | 9.02 | 11.83 |
| **Female** | 0.630 | 0.397 | 0.370 | 5.15 | 6.23 | 0.607 | 0.369 | 0.341 | 5.20 | 6.37 |
| **Total** | 0.789 | 0.623 | 0.607 | 7.12 | 9.62 | 0.792 | 0.628 | 0.612 | 7.15 | 9.56 |
| **ANNs** | | | | | | | | | | |
| **Male** | 0.648 | 0.420 | 0.396 | 7.68 | 10.13 | 0.644 | 0.414 | 0.390 | 8.19 | 10.18 |
| **Female** | 0.772 | 0.595 | 0.578 | 4.16 | 5.10 | 0.733 | 0.537 | 0.517 | 4.19 | 5.46 |
| **Total** | 0.857 | 0.735 | 0.724 | 5.96 | 8.07 | 0.852 | 0.725 | 0.714 | 6.23 | 8.21 |

ANNs: Artificial neral networks, R: Pearson's correlation coefficient, R2: Coefficient of determination, Adj. R2: Adjusted coefficient of determination, MAE: Mean Absolute Error, RMSE: Root Mean Squared Error

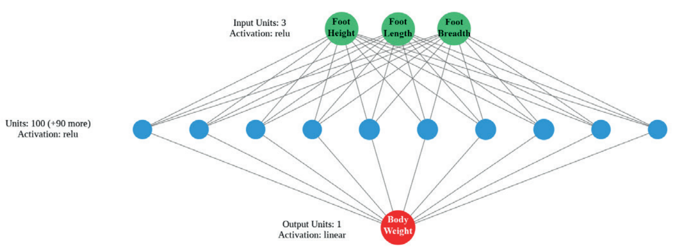


**Figure 3.** Structure of the developed ANNs for body weight estimation based on foot measurements

## Discussion

In studies predicting stature and age, sex is considered a crucial factor. The literature demonstrates the necessity of treating sex as an independent variable in regression models [3,6]. For instance, studies conducted by Moorthy and Khan in Malaysia have shown that omitting the sex factor in regression equations for weight estimation from footprints resulted in higher error margins [17,30]. Therefore, in our study, we developed separate models for each sex to enhance the accuracy of our predictions, thereby aiming to achieve more reliable and precise results.

The age range of 18 to 65 years was selected for this study. According to Roche (1972), the stature of an 18-year-old is generally considered adult, although it is noted that slight increases in stature may occur beyond this age. It has been documented that the median age at which stature stabilization occurs in males is 21.2 years, with continued growth observed in 10% of males until the age of 23.5 [31]. Additionally, this age range was chosen because it corresponds to the age range of medical students at our center.

A review of the literature reveals that foot anthropometry has always been of interest to anthropologists, leading to diverse studies on the subject. Lower extremity dimensions hold significant value in forensic sciences, especially for estimating stature. Prior studies have shown that bones from the lower extremities offer more reliable data for estimating stature than those from the upper extremities [32]. Furthermore, measurements of extremity breadth have been shown to provide better sex differentiation than length measurements [33,34]. In this context, the use of parameters such as foot and footprint anthropometry and shoe sizes allows for stature estimation with up to 2 cm of error and over 95% accuracy in sex prediction, and their importance in creating a biological profile has been demonstrated in various studies [1,4,6-8]. However, data are more limited when considering foot anthropometry and body weight. Fawzy and Kamal (2010) conducted a study on stature and weight estimation based on footprint measurements among Egyptian male university students, achieving weight estimations with errors ranging from 4.05 to 5.28 kg using regression equations [14]. Moorthy and Khan (2016) in their study evaluating footprints in the Iban community of Malaysia, obtained weight estimation regression equations with errors of 4.232 kg for males and 4.022 kg for females [17]. In a similar study by Moorthy and Khan (2016) conducted on the Melanau community, they estimated weight with errors of 7.881 kg for males and 6.998 kg for females [30]. Krishan (2008) created regression formulas with an average error of 3.08 kg using footprint measurements in India [16].

When examining similar studies conducted in Türkiye; Altuntaş and Uzun (2022) have developed regression equations using metatarsal measurements from foot X-Ray images. They achieved weight estimations with errors of 11.505 kg for males and 8.772 kg for females [13]. Atamturk and Duyar (2008) conducted a study in the Turkish population on foot and footprint measurements related to stature and body weight, achieving an average error of 9.29 kg in weight estimation [3]. When comparing the results of studies conducted in Türkiye with our findings, there is a parallelism in average body weight values and regression equation error values. Our analysis resulted in regression equations with an error value of 11.83 kg for males, 6.23 kg for females, and 9.56 kg for the entire sample (RMSE). These values are consistent with the errors reported by Altuntaş and Uzun (2022) [13], suggesting that the community and regional characteristics are similar and that their study, conducted at a time quite close to ours, may reflect the current characteristics of the Turkish population. However, methodological differences should be taken into consideration.

While similar results are observed within the Turkish population, studies conducted in other countries have yielded quite different estimation values. Particularly, studies in genetically more homogeneous communities have found significantly lower error values [16]. Estimation errors can vary due to differences in average weights and standard deviations among sample populations, as well as environmental influences on growth including diet, physical activity, and climate. Additionally, ethnic and regional distinctions within the study communities also contribute to these variations [17,30].

ANNs are seen as a promising method for Forensic Anthropology, often achieving higher accuracy compared to linear methods [7,27,35]. In this study, it has been observed that ANNs produce better weight estimation results (9.25-8.07 kg RMSE) than linear regression analysis. The classical linear regression analysis is subject to certain limitations due to its need for linear relationships and normal distribution. Particularly, missing, incorrect, or unusually variable data are known disadvantages that negatively affect the performance of linear regression analyses, while for ANNs, such data can enhance variation and turn into an advantage. It is noted that ANNs provide more effective results in situations where the prediction process of independent parameters is non-linear [20]. In our study, the importance of 10-fold cross-validation techniques is significant in ensuring reliable evaluation of model accuracy. Cross-validation allows for training and testing the model on different data subsets, objectively measuring the model's generalization ability. This technique reduces the risk of overfitting to a specific part of the dataset and more realistically evaluates the performance of the model across the entire sample [36].

This study provides critical data on body weight estimation through foot measurements within a predominantly university student population from Eastern Türkiye. However, our focus on a relatively uniform age group may limit the generalizability of these results, potentially not capturing the full spectrum of demographic and lifestyle diversity found throughout the broader Eastern Turkish population. Atamturk and Duyar (2008) incorporated the age factor into regression equations used for estimating stature and weight, based on their observation that foot measurements and body weight do not remain constant throughout life, to achieve more accurate results [3]. Nevertheless, it should not be overlooked that in forensic cases, the ages of individuals often cannot be determined from bodily traces (such as foot and footprint measurements) found at the scene. Such circumstances necessitate the use of equations that do not include the age factor.

## Conclusion

In our study, regression analyses using linear methods for weight estimation from foot measurements resulted in a total error of 9.56 kg, which was reduced to 8.07 kg with the use of ANNs. These results suggest that ANNs may provide a more effective approach for handling this type of data. However, one of the limitations of the study could be the difference between subcutaneous soft tissue thickness and direct bone measurements. Future research should evaluate the consistency and accuracy of variations in soft tissue measurements compared to direct or radiological bone measurements. Additionally, it is recommended to conduct studies on a more diverse sample that includes different age groups and demographic characteristics to better represent the Turkish population. This will enhance the generalizability of the model, offering more accurate and reliable predictions for applications in forensic sciences.

**Conflict of Interests**
*The authors declare that there is no conflict of interest in the study.*

**Financial Disclosure**
*The authors declare that they have received no financial support for the study.*

**Ethical Approval**
*İnönü University Medical Faculty's Deanship Ethics Board for Non-Interventional Clinical Research approved the study's ethical protocol under the approval number 2023/4992, dated September 20, 2023. This research was conducted in accordance with the principles of the Helsinki Declaration. Informed written consent was obtained from participants prior to data collection.*

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