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Derya Atamturk,[1] Ph.D. and Izzet Duyar,[2] Ph.D.

Age-Related Factors in the Relationship Between Foot Measurements and Living Stature and Body Weight

ABSTRACT: The measurements of feet and footprints are especially important in forensic identification, as they have been used to predict the body height and weight of victims or suspects. It can be observed that the subjects of forensic-oriented studies are generally young adults. That is to say, researchers rarely take into consideration the body's proportional changes with age. Hence, the aim of this study is to generate equations which take age and sex into consideration, when stature and body weight are estimated from foot and footprints dimensions. With this aim in mind, we measured the stature, body weight, foot length and breadth, heel breadth, footprint length and breadth, and footprint heel breadth of 516 volunteers (253 males and 263 females) aged between 17.6 and 82.9 years using standard measurement techniques. The sample population was divided randomly into two groups. Group 1, the study group, consisted of 80% of the sample (*n* = 406); the remaining 20% were assigned to the cross-validation group or Group 2 (*n* = 110). In the first stage of the study, we produced equations for estimating stature and weight using a stepwise regression technique. Then, their reliability was tested on Group 2 members. Statistical analyses showed that the ratios of foot dimensions to stature and body weight change considerably with age and sex. Consequently, the regression equations which include these variables yielded more reliable results. Our results indicated that age and sex should be taken into consideration when predicting human body height and weight for forensic purposes.

KEYWORDS: forensic science, forensic anthropology, forensic identification, stature estimation, body weight estimation, body proportions

It has long been established that apart from bone material, isolated body parts and body imprints can also be used in forensic identification. The foot, in particular, has proven itself to be a much more significant organ than other parts of the body due to the fact that footprints and upper and lower limb fragments are more likely to be obtained in crime or incident scene investigations, as in some airplane crashes (1,2). Accordingly, the number of studies on foot measurements and footprints has been observed to increase dramatically in the anthropological literature of recent years (3–9). One of the typical characteristics of these studies is that the whole or a large part of the samples examined in them seems to be made up of young adults. Yet, these studies carried out on young adults have two limitations: the first one is that the formulas developed concomitantly do not come close to reflecting the whole variability in a given population, as a result of the fact that middle-aged and the aged individuals are rarely included in the samplings. The second limitation is that the regression equations in such studies are formed by taking into consideration the body proportions of only young individuals. However, there are a number of studies on adults attesting to the fact that the proportions of their body parts do not remain fixed; in fact, they change throughout adulthood (10,11). This implies a higher rate of error in estimations used in cases where the regression equations meant for young individuals are relentlessly used for middle-aged and aged individuals, too. In light of such shortcomings, this study aims primarily to develop age-sensitive body height and body weight estimation regression equations based on foot and footprint measurements.

Department of [1]Archaeology and [2]Sociology, University of Gaziantep, Sehitkamil, Gaziantep 27310, Turkey.

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In addition, sex is considered to be a significant factor in forensic studies in which body heights are estimated via foot or footprint measurements. Gordon and Buikstra (5) have been among the first researchers to consider sex as an independent variable among regression models. Studies on the morphological characteristics of the foot and its proportion to the general body size attested the importance of the sex factor as well (12–14). In a detailed review of differences in foot dimensions between the sexes by Fessler et al. (15), it has been concluded that the ratio of foot length (FL) to stature is smaller in women than it is in men. These findings suggest that consideration of the sex factor is very likely to yield much more dependable and reliable results in calculations of body heights and weights from foot and footprint measurements. The second purpose of this study, thus, is to generate a more precise formula in forensic estimations by taking into consideration both the age and sex factors.

The number of the studies on estimating body weight from foot and footprint measurements is quite limited; in fact, the literature review done in this study points to a single study carried out to that end (16). It was posited in this study that body weight can be estimated from FL. Robbins (16) was observed to have taken into consideration the sex factor, but to have omitted the age factor altogether in his estimations of body weights. It is already known that average body weight of adults may fluctuate over time, and forensic studies necessitate samplings with wider age-spans. The third purpose of this study, then, is to develop a more reliable formula in forensic estimations by simultaneously taking into consideration both age and sex.

Materials and Methods

The research was conducted on 516 volunteer individuals (263 females and 253 males) living in Ankara, Turkey, with the age range of 17.6–82.9 years. The ages of the women ranged between 17.7 and 82.9 (mean 43.33, SD = 14.86 years), while those of the male volunteers ranged between 17.6 and 82.5 (mean 40.51, SD = 13.39 years). These individuals were categorized in five subgroups according to their age ranges: 18–29, 30–39, 40–49, 50–59, and 60 and over. Table 1 displays the number of individuals in each group.

The individuals constituting the sampling are reflective of the population in general, as they were selected randomly from a variety of socioeconomic and occupational groups on a voluntary basis.

The eight anthropometric measurements taken from the individuals are as follows: body weight, height (stature), FL, foot breadth (FB), heel breadth, footprint length (FPL), footprint breadth (FPB), and footprint heel breadth (FPHB). Body weight and height were taken in accordance with the techniques proposed in *Anthropometric Standardization of Reference Manual* (17). Foot measurements (as described in the following sentences) were taken via a sliding caliper from the bare left feet of the individuals while they were standing.

Foot Length

Foot length is taken as the distance between the *pternion* (extreme point of the heel) and the *akropodion* (extreme point of longest toe) (18).

Foot Breadth

Foot breadth is the distance between the surface of the first and fifth metatarsal bone heads (18,19).

Foot Heel Breadth

Foot heel breadth (FHB) is taken as the distance between the extreme points on the lateral protrusions of the heel.

Footprints were taken on B4 size tracing paper. The individuals were asked to wet their soles totally in buckets of water and then to step on the tracing paper, so as to facilitate measurements. This method was observed to facilitate the successful obtainment of footprints. In most of the samples, the footprints were taken successfully, only 13 individuals (2.52%) were asked for a second trial. Footprint measurements on the tracing paper were taken by a transparent ruler in the following manner:

Footprint Length

Footprint length is measured as the direct maximum distance from the most posterior point of the heel to tip of longest toe.

Footprint Breadth

Footprint breadth is the largest distance between the extreme point of the fifth metatarsal bone to the lateral and the extreme point of the first metatarsal bone to the medial.

TABLE 1—*Age characteristics and distribution of the sample.*

Age Groups (Years)	Males		Females		Total	
	n	Mean Age	*n*	Mean Age	*n*	Mean Age
18–29	65	24.64	58	24.49	123	24.57
30–39	67	35.67	63	35.63	130	35.65
40–49	60	44.12	62	45.80	122	44.97
50–59	41	54.84	50	55.63	91	55.27
60+	20	68.03	30	70.32	50	69.40
Total	253	40.51	263	43.33	516	41.94

Footprint Heel Breadth

Footprint heel breadth is the distance between the extreme lateral and medial points on the paper (20).

All the foot and footprint measurements were taken and registered in millimeters by one of the authors (DA).

The total sample was divided into two groups (the study group and the cross-validation group) by using the random selection function of the Statistical Package for the Social Sciences (SPSS; SPSS Inc., Chicago, IL). Eighty percent of the individuals were evaluated as the study group, while the remaining 20% constituted the cross-validation group. While the study group was made up of 406 individuals (199 males and 207 females), the cross-validation group included 110 individuals (54 males and 56 females). Body height and weight formulas were obtained from the study group and their accuracy and validation were checked on the cross-validation group. All the variables measured were subjected to linear regression analysis via the stepwise technique and four or five of them were selected to yield best equations. The reliability of the equations was evaluated through the pure error formula (PE):

$$PE = \sqrt{\sum (y - y_i)^2 / n}$$

where y and y_i are the observed and predicted values for an individual and n is the number in the sample.

All the calculations and statistical tests were performed using the statistical package program of SPSS Version 13.0. The association between foot measurements and body height and weight was examined through Pearson correlation analysis. The age-related changes in the ratio of foot dimensions to general body dimensions (according to age and sex groups) were tested via a one-way analysis of variance (ANOVA).

Results

The descriptive statistics of all females ($n = 263$) and males ($n = 253$) are presented comparatively in Table 2. As expected, all the measurements pertaining to the male participants are greater than those of the female ones. The sex differences are statistically significant ($p < 0.001$). The most conspicuous difference is in males' and females' body heights and FLs; there are also minor differences in their weights and FPHBs.

Whether or not the general body size (weight and height), foot dimension (FL), and the ratio of the FL to stature change according to age group was examined; and all the variables were observed to display statistically significant change according to age (Table 3). For example, the body weights continuously increase up to ages 50–59, and decline thereafter. The body heights and FLs are also observed to continuously decrease with age. Yet, since the decrease in body height is greater than that of the FL, the FL/stature ratio increases steadily. These findings reveal that age is a considerably significant factor in figuring regression formulas.

The correlation coefficients between the foot and footprint measurements, and body height and weight are statistically significant ($p < 0.01$) (Table 4). The highest correlation established with stature in the male group are found in FPL ($r = 0.734$) and FL ($r = 0.713$). Although the same pattern can be observed in the female group, the correlation coefficients belonging to women are lower than those of the men ($r = 0.663$, $r = 0.678$ respectively). The most conspicuous variable reflecting body weight pertains to the FB ($r_{male} = 0.555$ and $r_{female} = 0.545$), which is followed by heel breadth.

Of the regression equations formed by the stepwise technique (Table 5), the equation which is inclusive of five variables (FL,

TABLE 2—*General anthropometric characteristics of males, females, and total sample.*

	Males (n = 253)		Females (n = 263)		Total (n = 516)		
Variable	Mean	SD	Mean	SD	Mean	SD	F
Body weight (W, kg)	74.42	10.75	66.51	12.26	70.39	12.19	60.61*
Stature (S, cm)	172.37	7.33	157.39	6.53	164.74	10.21	602.09*
Foot length (FL, cm)	25.84	1.26	23.45	1.07	24.62	1.67	544.64*
Foot breadth (FB, cm)	9.95	0.48	9.05	0.54	9.49	0.68	406.95*
Foot heel breadth (FHB, cm)	7.18	0.44	6.54	0.47	6.85	0.56	257.87*
Footprint length (FPL, cm)	24.93	1.18	22.68	1.18	23.79	1.63	469.71*
Footprint breadth (FPB, cm)	9.95	0.64	9.16	0.65	9.55	0.79	194.61*
Footprint heel breadth (FPHB, cm)	6.17	0.53	5.75	0.60	5.96	0.60	69.71*

*$p < 0.001$.

TABLE 3—*The differences in anthropometric dimensions according to age.*

	Age Groups					
	18–29 (n = 123)	30–39 (n = 130)	40–49 (n = 122)	50–59 (n = 91)	60+ (n = 50)	F
Body weight (W, kg)	64.63	70.87	72.45	74.51	70.74	11.199**
Stature (S, cm)	168.07	166.33	164.13	161.78	159.27	10.374**
Foot length (FL, cm)	24.93	24.82	24.56	24.36	23.96	4.140*
Foot length/stature (%)	14.83	14.92	14.97	15.07	15.06	8.910**

*$p < 0.05$ and **$p < 0.001$.

TABLE 4—*Pearson's correlation coefficients of stature and body weight, and foot and footprint measurements.*

	Stature			Body Weight		
	Males (n = 253)	Females (n = 263)	Total (n = 516)	Males (n = 253)	Females (n = 263)	Total (n = 516)
Foot length (FL)	0.713*	0.678*	0.857*	0.343*	0.314*	0.447*
Foot breadth (FB)	0.408*	0.254*	0.654*	0.555*	0.545*	0.604*
Foot heel breadth (FHB)	0.278*	0.167*	0.547*	0.523*	0.535*	0.597*
Footprint length (FPL)	0.734*	0.663*	0.850*	0.299*	0.300*	0.429*
Footprint breadth (FPB)	0.360*	0.258*	0.564*	0.335*	0.412*	0.473*
Footprint heel breadth (FPHB)	0.285*	0.177*	0.399*	0.186*	0.433*	0.407*

*$p < 0.01$.

FPL, FPB, sex, and age) was observed to be the best model in estimation of the body height. These variables explain 81% of the total variance in body height. Nevertheless, the error in the equations formed for body weight appears to be even higher, as can be observed both in the coefficient of determination (R^2) and the standard error of the estimate configurations. The most accurate model for body weight estimation seems to be the one which includes four independent variables (FB, heel breadth, age, and sex). The variables in this model explain 42% of the total variance in body weight.

The formulas developed for body height and weight on the study group were tested on the control group (n = 110) (Tables 6 and 7); and the model with the smallest PE value was selected as the best model. Accordingly, the best model for the body height is the fourth one, which includes FL, FPL, sex, and age. Of these four models generated for prediction of body weight, the fourth one

TABLE 5—*Stepwise regression equations for the estimation of body weight and stature in the study group* (n = 406).

Model	Equation*	Adjusted R^2	SEE (cm)
Stature (cm)			
1	S = 5.295 × FL + 38.903	0.737	5.142
2	S = (4.211 × FL) + (4.981 × Sex) + 62.208	0.768	4.835
3	S = (3.957 × FL) + (5.070 × Sex) + (−0.111 × Age) + 72.862	0.792	4.580
4	S = (1.847 × FL) + (2.423 × FPL) + (4.165 × Sex) − (0.111 × Age) + 64.279	0.804	4.456
5	S = (1.794 × FL) + (2.286 × FPL) + (0.888 × FPB) + (3.896 × Sex) − (0.116 × Age) + 60.688	0.807	4.430
Body weight (kg)			
1	W = 12.716 × FHB − 16.752	0.336	9.538
2	W = (5.440 × FB) + (7.733 × FHB − 34.319	0.382	9.216
3	W = (5.525 × FB) + (7.501 × FHB) + (0.146 × Age) − 39.671	0.414	8.982
4	W = (6.712 × FB) + (8.147 × FHB) + (0.128 × Age) − (3.127 × Sex) − 53.044	0.423	8.923

*All foot and footprint measurements in cm, body weight in kg, and age in years.
FL, foot length; FB, foot breadth; FHB, foot heel breadth; FPL, footprint length; FPB: footprint breadth.
For sex; female = 0 and male = 1.

TABLE 6—*The comparison of measured and estimated stature in the cross-validation group (n = 110).*

Model	Actual Stature (mean, cm)	Estimated Stature (mean, cm)	Mean Difference (cm)	Pure Error (PE, cm)
1	165.24	165.75	−0.52	6.17
2	165.24	165.53	−0.30	5.45
3	165.24	165.53	−0.29	5.44
4	165.24	165.43	−0.20	5.14
5	165.24	165.41	−0.17	5.19

TABLE 7—*The comparison of measured and estimated body weight in the cross-validation group (n = 110).*

Model	Actual Body Weight (mean, kg)	Estimated Body Weight (mean, kg)	Mean Difference (kg)	Pure Error (PE, kg)
1	71.05	70.94	−0.10	10.69
2	71.05	70.63	−0.42	9.87
3	71.05	70.56	−0.49	9.50
4	71.05	70.62	−0.43	9.29

proved to be the most functional one. It was also observed that while the FL is the best means for predicting body height, heel breadth is the most helpful variable in predicting body weight.

Discussion

Whereas the relationships between foot dimensions and stature have long interested researchers (21), similar studies carried out for the purposes of forensic identification started only at the beginning of the 20th century, right after the development of the regression technique (22). Furthermore, the employment of the regression technique in forensic identification became widespread only as of the mid-1980s. A considerable number of recent studies make use of foot measurements (4–6,8,23), while a few of them consider shoe dimensions (5,23) and footprint measurements (4,20).

One of the starting points of this study was the observation that the ratio of the foot measurements to body height and weight does not remain fixed, but rather, changes throughout adult life. The analyses carried out in this study explicitly reflect that (Table 2). Such findings strongly suggest that the contribution of the age factor is very likely to render regression equations much more reliable. As a matter of fact, the involvement of the age factor in the equations will enable forensic researchers to attain more accurate (less erroneous) results in their calculations of body height. For example, while the R^2 value was 0.737 in the model with one variable (FPL), the same value reached up to 0.792–0.807 via multiple regressions involving the age factor (Table 5). Furthermore, with the involvement of the age factor, the error range was observed to become 0.73–1.03 cm lower in the cross-validation group.

In most forensic cases, the ages of the individuals cannot be determined via bodily traces (foot and footprint measurements) found in the place of the incidents. Such cases necessitate recourse to equations that do not involve the age factor. But, in cases where additional data can be gathered through witnesses or other clues, the age-inclusive models (3–5) proposed in Table 5 can be implemented to attain better results.

The degree of the most helpful variables with the best predictive quality is a matter of discussion, since general body characteristics (height and weight) must be figured through regression analyses.

The prediction of body weight via foot measurements appears to have drawn less attention throughout history. Robbins (16) seems to be the first person to have researched and proposed that body weight can be predicted on the basis of the foot measurements (FB). The same author posited that 73.4% of FB would be suggestive of body weight. This study, in turn, proposes four different models for the prediction of body weight. Even though these models are less successful in predicting of body weight than are the models developed for the prediction of body height, it must be noted that the smallest clues can sometimes be very helpful in the identification of suspects in some criminal cases (which might necessitate the determination of body weights from foot measurements). As a matter of fact, and contrary to expectation, our findings reveal that it is not the FB, but rather, the heel breadth that works as a better variable in the prediction of actual body weight. It is also understood that the four different body weight estimation models formed by the stepwise method point to the significance of age and sex, too.

The characteristics of the sample are extremely important in studies focused on determining identity from foot and footprint measurements. As mentioned, such studies are generally conducted on groups of young individuals from a given occupation, such as soldiers. One of the largest scale research projects, carried out by Giles and Vallandigham (4), was conducted on 6682 male and 1330 female soldiers. The average ages of the male and female soldiers in that study were 22.2 and 23.1 years, respectively. Gordon and Buikstra (5) also studied a similar sample (taken from a U.S. Army database) featuring almost the same age groups. Such samples, which include only young individuals, are not very helpful for applications in the field of forensic science, because middle-aged and elderly individuals can also be involved in crimes. Therefore, the formulas to be formed must be developed from individuals selected from all the age groups in a given population. Clearly, our study meets this condition satisfactorily, since it selected the same number of individuals from a number of age groups categorized by 10-year intervals, thus preventing the sampling from being reflective of only a given specific age group. Additionally, selecting a sampling from amongst a given occupation is not preferable, because any such group (e.g., soldiers) may not be reflective of the general population, as is also stated by Giles and Vallandigham (4). This is due to the fact that military organizations are likely to summon individuals with given body measurements, and thus to exclude some others from this occupation. Our study, which drew from a number of socioeconomic and occupational groups, avoided this dilemma.

In conclusion, our findings point to two significant problems in forensic investigations: the first is that to be more successful in estimations of body height and weight, it is necessary to take as many measurements as possible from the foot and/or footprints. And the second is that the predictions of body height and weight from foot and footprint measurements in similar investigations would yield more successful results with the inclusion of age and sex factors.

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Additional information and reprint requests:
Derya Atamturk, Ph.D.
Department of Archaeology, University of Gaziantep
Sehitkamil, Gaziantep 27310
Turkey
E-mail: derya_atm@yahoo.com