



Piecewise regression equations for estimating stature: an anthropometric study in Spanish females

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Abstract

In forensic anthropology, generic equations are generally preferred for estimation of stature. However, recent studies have demonstrated that regression equations specific to stature groups yield more accurate predictions. Almost all previous studies have been conducted on male subjects, and it is not currently known how well such equations work for females. Therefore, this study aims to test whether regression equations specific to stature groups work for females as well. To this end, a cross-sectional study was conducted to estimate stature on a sample of 351 Spanish adult females. The participants were randomized into a calibration group ($n = 185$) and a validation group ($n = 166$). Equations for stature estimation based on tibial length were developed in the calibration group, which was categorized according to stature (short, medium, and tall) using the 15th and 85th percentiles as cut-off points. The standard errors of the estimations (SEEs) for the group-specific regression equations ($SEE = 2.35\text{--}2.66$ cm) were lower than for the general formula derived for all participants of the calibration group ($SEE = 3.46$ cm). The specific equations resulted in smaller differences between estimated and recorded statures than the generic equation when we tested the equations with the validation group. Additionally, the SEE values of the stature-specific equations are lower compared to generic equations applied to other human populations. In conclusion, the group-specific equations from tibial length have high accuracy compared with previously derived equations for Spanish females and other populations. This procedure for estimating stature thereby improves the tools available to forensic scientists.

Keywords Forensic anthropology · Human identification · Stature estimation · Anthropometry · Tibia

Introduction

In forensic anthropology, living stature is a crucial component in the process of human identification, and various bones and

body parts have been examined for their utility in stature estimation [1–13]. The principal purpose of estimating living stature is to narrow the potential list of presumptive identifications, especially in natural or man-made disasters, wars, and crimes [14–16]. Equations for estimating stature are usually based on univariate or multivariate regression models in which one or several bone dimensions have been used to build equations with the highest accuracy. In this context, researchers have analysed general and specific equations in different populations [17–19]. Generic equations refer to a single formula that can be applied to all individuals, regardless of differences such as sex, age, and ancestry. In contrast, group-specific equations do not treat multiple subgroups as a single entity but are based instead on the use of different equations for subgroups of the population. The accuracy rates of generic formulae versus specific equations have resulted in contradictory findings. In some studies, generic equations obtained higher accuracy than specific ones [20, 21], whereas others yielded higher estimation accuracy using specific equations [22–27].

One of the suggested ways to estimate living stature with minimal error is to use regression equations specific to stature

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groups, using different equations for short, medium, and tall people. This method was first introduced using tibial length in a modern Turkish sample and was shown to be more accurate than nonspecific equations, especially for tall and short individuals [22, 23]. In a later study, Duyar et al. [24] analysed the tibia and ulna, both individually and in combination, and demonstrated that stature-specific equations lead to more accurate stature estimations. This was further assessed by Sargin et al. [25] who tested this procedure on a relatively small group of male and female cadavers and reported that it provides less erroneous estimates than generic equations. Recently, Sacolledo et al. [28] tested the stature-group regression equations on modern Spaniards and found lower estimation errors than for nonspecific equations. However, because all of the aforementioned studies, except one, were performed on males, the accuracy of this new stature estimation procedure in females is unknown. Considering this limitation, the aim of the present study is to develop stature-specific equations for estimating living stature based on tibial length in a large female sample.

Materials and methods

Study design

This cross-sectional study was conducted on a sample of Spanish females. The participants were randomised into two groups: a calibration group and a validation group. Three stature sub-groups (Group ST1, stature ≤ 158.9 cm; Group ST2, stature between 159.0 and 171.1 cm; Group ST3, stature ≥ 171.2 cm) were also designated using the 15th and 85th percentiles as cut-off points in both groups [22, 28]. In the Gaussian distribution, the area below the curve between the ± 1 standard deviation (SD) mark constitutes approximately 68.27% of the total area, which we accepted as 70%. We have placed the body height values between -1 SD and $+1$ SD into the “medium”, the values below -1 SD (i.e. 15th percentile) into the “short”, and those above $+1$ SD (i.e. 85th percentile) into the “tall” stature categories. The use of the 15th and 85th percentiles as cut-off points is common in studies focusing on aspects of public health (e.g. National Health and Nutrition Examination Survey, NHANES, in the USA), particularly those focusing on body weight [29–32].

The study consists of two phases. In the first phase, the stature-group-specific equations for three sub-groups were developed using data from the calibration group. In the second phase, the tibial length values of individuals in the validation group were tested using regression equations derived from the calibration group.

The project followed the recommendations of the Declaration of Helsinki on Human Rights [33] and was approved by the Clinical Research Ethics Committee of the Sports Administration of Catalonia (12/2015/CEICEGC).

Participants

The sample consisted of 351 Spanish adult female living participants who were randomized into two groups (the calibration group with 185 participants and the validation group with 166 participants) using the Statistical Package for Social Sciences (SPSS). The calibration group was categorized according to stature into three sub-groups, short, stature ≤ 158.9 cm ($n = 27$); medium, stature between 159.0 and 171.1 cm ($n = 130$); and tall, stature ≥ 171.2 cm ($n = 28$). The validation group was also divided into three groups according to the same stature categories as the calibration group in order to test the equations and included $n = 18$, $n = 127$, and $n = 21$ participants in the short, medium, and tall stature groups, respectively. The inclusion criteria for study participants included being between 18 and 55 years of age and being of Spanish nationality.

Anthropometric measurements

Two authors of this paper (GSL, JP), who are anthropometrists certified by the International Society for the Advancement of Kinanthropometry (ISAK), performed the anthropometric measurements. Stature and tibial length were measured following the protocol of a previous study on Spanish males [28]. The tibial length of the right side was measured as the distance between tibiale mediale and sphyrion tibiale, and stature was measured as the distance between the vertex and the bottoms of the feet. The technical error of measurement (TEM) was acceptable (TEM $\leq 1.0\%$, intra-observer; TEM $\leq 1.5\%$, inter-observer) based on 20 individuals. Stature and tibial length were measured using a Harpenden Anthropometer (Holtain Model 601) and a Harpenden Stadiometer (Holtain Model 603) in the laboratory. Other anthropometric instruments, such as an anthropometric bench, a square with an attached level, and a segmometer (UWA), were used in the evaluations in the fieldwork.

Statistical analysis

Descriptive statistics were calculated to permit comparisons between stature groups. Normality of the data and the homogeneity of variance between groups were tested using the Kolmogorov–Smirnov test or the Shapiro–Wilk test and Levene’s test. Group comparisons were performed with parametric or nonparametric tests. For group comparisons, we employed the *t* test for independent samples and the Mann–Whitney *U* (Table 1), and Kruskal–Wallis and Scheffe (Table 2) tests for nonparametric and parametric comparisons. Using known stature and tibial length, we verified the association between these two variables and developed multiple equations for stature estimation. We analysed correlations,

Table 1 Descriptive statistics of the study group and the validation group

Variable	Calibration group (<i>n</i> = 185)		Validation group (<i>n</i> = 166)		<i>p</i> value
	$\bar{x} \pm SD$	(Min.–Max.)	$\bar{x} \pm SD$	(Min.–Max.)	
Age (years)	29.5 ± 9.3	(18.1–51.7)	29.7 ± 9.7	(18.3–54.7)	0.803
Stature (cm)	164.7 ± 6.1	(146.0–183.8)	164.6 ± 5.3	(149.4–179.3)	0.894
Tibial length (cm)	37.1 ± 2.3	(31.3–43.6)	37.0 ± 1.8	(33.2–41.4)	0.408
TLR	22.5 ± 0.8	(20.7–25.1)	22.5 ± 0.8	(19.9–24.7)	0.386

Min., minimum; *Max.*, maximum; \bar{x} , arithmetic mean; *SD*, standard deviation; *TLR*, tibial relative length (tibial length × 100/stature); *cm*, centimetres

regression equations, coefficients of determination (R^2 and $AdjR^2$) and standard errors of estimation (SEE). Normality and homoscedasticity of the residual were also verified. All statistical analyses were performed with SPSS software (IBM Corp. released 2011, IBM SPSS Statistics for Windows, Version 20.0, Armonk, NY). The figures were produced using the SigmaPlot software (Version 12.0, Systat Software Inc., San Jose, CA, USA). The level of significance was established at $p < 0.05$.

Results

Anthropometric variables

The general characteristics of the study sample are shown in Tables 1 and 2. We did not find significant differences ($p > 0.05$) between the calibration and the validation groups (Table 1). Statistical analysis supported the assumption of normality of the anthropometric variables ($p > 0.05$) in both groups. The variance within groups was homogeneous for age, stature, and relative tibial length, but not for absolute tibial length.

The scatterplots (Figs. 1 and 2) show significant high correlations ($p < 0.001$) between stature and tibial length in both

the calibration and validation groups—the dotted lines indicate the 95% prediction intervals for the calibration group (Fig. 1) and the validation group (Fig. 2). These figures clearly demonstrate the close relationship between tibial length and stature, and by extension, the value of tibial length for estimating stature.

Table 2 reports significant differences ($p \leq 0.001$) between the stature sub-groups for almost all of the anthropometric variables, except between the medium and tall stature groups for relative tibial length. The anthropometric variables showed a normal distribution for tibial length and relative tibial length ($p \geq 0.05$) but not for stature groups or ages ($p < 0.05$). The variance was homogeneous across groups for the different variables ($p \geq 0.05$). Tibial length and relative tibial length have higher values in the tall and medium stature groups than in the short stature group. Therefore, the results indicate that a piecewise regression technique could be an innovative approach for estimating stature, since relative tibial length increases as stature increases in Spanish adult females.

Regression equations

The ordinary least square (OLS) regression formulae were generated for each stature group (short, medium, and tall) using the measurements of the calibration group (Table 3).

Table 2 Descriptive statistics of the study group based on stature groups

Variable	< 159.0 cm (<i>n</i> = 27)	159.0–171.1 cm (<i>n</i> = 130)	> 171.1 cm (<i>n</i> = 28)	<i>p</i> value ^a
	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	
Age (years)	30.4 ± 9.8	29.1 ± 9.2	30.7 ± 9.7	0.612
Stature (cm)	155.0 ± 3.0	164.6 ± 3.2	174.3 ± 3.0	0.000
Tibial length (cm)	33.9 ± 1.3	37.2 ± 1.7	39.9 ± 1.5	0.000
TRL	21.9 ± 0.7	22.6 ± 0.8 ^d	22.9 ± 0.7	0.000

\bar{x} , arithmetic mean; *SD*, standard deviation; *TRL*, tibial relative length (tibial length × 100/stature); *cm*, centimetres

^a Statistical significance (between groups)

^d No significant differences between medium and tall stature groups in tibial relative length

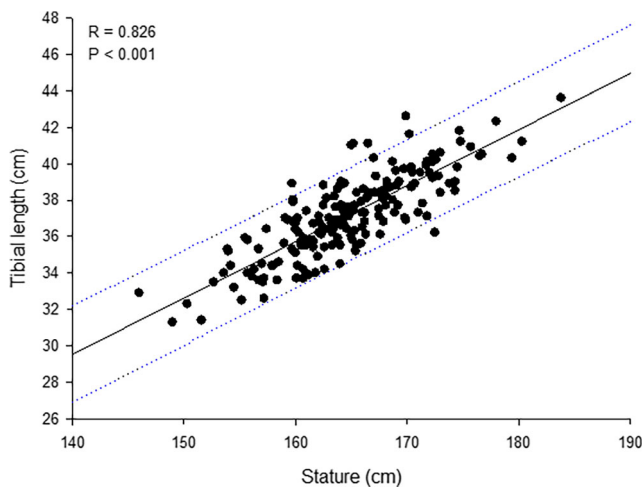


Fig. 1 Scatterplot with 95% prediction intervals (dotted lines) based on tibial length and stature in the calibration group

Both SEE and R^2 values for the equations of all stature groups were lower than those of the general formula. Although the low R^2 values of the equations for the stature-specific groups are considered a negative result, the low SEE values indicate that these equations provide more accurate estimations of stature. The main factor underlying the lower R^2 values in the group-specific regression equations is the smaller number of participants in those groups.

Differences between stature estimates using the equations of the calibration group in the validation group

Table 4 shows the difference between statures estimated by the general equation and the group-specific regression equations using data from the validation group. Overall, the equations specific to stature groups yield more accurate stature

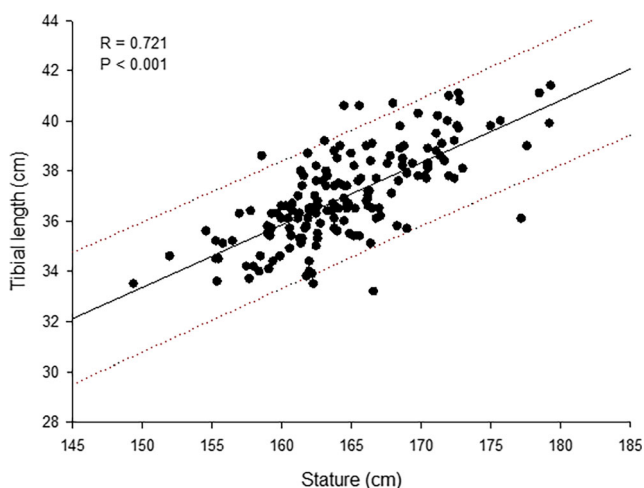


Fig. 2 Scatterplot with 95% prediction intervals (dotted lines) based on tibial length and stature in the validation group

estimates. The most significant difference between the two calculation methods (i.e. general or group-specific equation) was observed in the short and tall stature groups. The equations for short and tall groups produce underestimates (mean 0.34 cm), while the equation for the medium group yields overestimates (mean 0.18 cm) when applied to the short and tall stature groups. However, in the medium-stature group, little difference was found between the two estimation procedures.

Discussion

The findings of this study clearly demonstrate that, as stature increases, the ratio of tibial length to stature does not remain constant but instead increases. While the average tibial length-to-stature ratio is 21.9 in the short sub-group, it rises to 22.6 in the medium group, and 22.9 in the tall group, an increase that is statistically significant between the short and tall stature groups. Relative tibial length has also been shown in previous studies to be larger in taller males [23, 28]. Therefore, the results presented here demonstrate that relative tibial length increases steadily, in a positively allometric fashion, as stature increases in both females and males. The proportional allometric increase is approximately equivalent in both sexes. These findings suggest that separate regression equations should be created for short, medium, and tall people when calculating stature from tibial length.

Group-specific (sex, age, population, or ancestry) formulae are often used in anthropological studies and forensics to estimate stature. In recent years, however, some studies have claimed that generic formulae yield less erroneous estimates than group-specific ones [20, 21]. These studies have recommended using general equations for estimating stature, because these equations can estimate the stature regardless of age, sex, ancestry, or population. However, the SEE values of these generalized equations are remarkably higher than we found in our study, suggesting that calculations specific to stature groups yield more accurate estimates than generic equations. The findings of other studies also support these results [22, 24–28]. Furthermore, while another study in Spanish individuals reported low SEE for stature group regression equations based on multiple long bone lengths [8], our stature-group-specific equations have even lower SEE. Thus, the simple and multiple regression equations of previous work [8] still show a higher SEE than the simple regression stature-group-specific equations of this study, emphasizing the utility of our equations and the use of tibial length to estimate stature. In this context, the specific equations based on stature groups obtained higher accuracy than has been reported in other studies that developed equations for estimating stature in Spanish females [5, 8, 34].

Table 3 Regression equations by stature groups in the calibration group

Stature group	<i>n</i>	Calibration group						
		Equation	<i>R</i>	<i>R</i> ²	Adj <i>R</i> ²	SEE	<i>F</i>	<i>p</i> value
≤ 158.9 cm	27	$S = (1.18 \times TL) + 114.9$	0.50	0.25	0.22	2.66	8.40	0.008
159.0–171.1 cm	130	$S = (1.16 \times TL) + 121.3$	0.60	0.37	0.36	2.57	75.2	0.000
≥ 171.2 cm	28	$S = (1.31 \times TL) + 121.9$	0.65	0.42	0.40	2.35	19.3	0.000
All participants	185	$S = (2.21 \times TL) + 82.4$	0.82	0.68	0.68	3.46	393.5	0.000

S, stature; *SEE*, standard error of estimation; *TL*, tibial length; *R*, correlation; *R*², coefficient of determination; *AdjR*², adjusted coefficient of determination; *cm*, centimetres

While stature estimation equations specific to stature groups have previously been developed from a sample of Spanish males [28], the present study is one of the first to investigate stature estimation in females using this method. A previous study conducted by Sargin et al. [25] on the cadavers of 62 females and 78 males from Antalya, Turkey, estimated female stature based on stature-group-specific regression equations. The equations specific to the stature groups yielded more accurate cadaver height estimations, but these findings had not previously been tested in a larger sample, or in living populations. The conclusions of the present study on Spanish females for estimating living stature support the results of the previous investigation on cadavers [25].

As this is only the second study investigating stature estimation in females with stature-group-specific regression equations, when formulating this study, we wondered about the differences in SEE for equations based on tibial length between Spanish females and males. In males [28], the stature-group-specific equations were found to produce accurate estimates (SEE = 2.12–2.66 cm), similar to the analogous equations in Spanish females (SEE = 2.35–2.66 cm). However, we found some differences when the equations were applied to the validation group. The results reveal differences primarily in the medium stature groups—the equations of all Spanish females and the medium stature-group obtained similar accuracy when we used the data of the validation group; but the equation with all Spanish male participants obtained much

lower accuracy than the specific equation for medium stature when the data of the validation group were used.

Since the tibia is one of the long bones that is most highly correlated with stature, it has been used frequently in studies aimed at reconstructing living stature in forensic, archaeological, and paleontological contexts. Thus, the tibia has been the subject of numerous studies across various populations from different geographical regions [1–4, 7, 9, 13, 19, 35–46]. Some of these studies were based on percutaneous measurements of the tibia of living people, while some were based on radiographic images and others on the measurements of cadavers or dry bones [2–4]. We collated the SEE values calculated from females of these studies, listed from lowest to highest (Table 5). Studies which were conducted on dry bones, and stature estimations based on anatomical reconstructive techniques, are not included. In almost all cases, the SEE values reported are considerably higher than those we report here. This indicates that we have reached a relatively low SEE value compared to the range of these previous studies. Furthermore, for short (2.66 cm), medium (2.57 cm), and tall (2.35 cm) individuals, we found even lower values than all previously reported SEE values. These findings clearly demonstrate that formulae specific to stature groups return more accurate estimates than generic equations.

In forensic anthropological contexts, recovered remains may include the entire skeleton, or may be limited to isolated bones or dismembered body parts. Cases where only isolated

Table 4 Differences between measured and estimated stature in the validation group

Stature group	<i>n</i>	Equation of all participants ^a		Stature-group-specific equations ^b	
		Mean difference (cm)	SD (cm)	Mean difference (cm)	SD (cm)
≤ 158.9 cm	18	−3.52	2.94	−0.34	2.32
159.0–171.1 cm	127	0.35	3.11	0.18	2.66
≥ 171.2 cm	21	4.32	3.74	−0.34	3.04
All controls	166	0.43	3.70	–	–

^a Differences between stature estimates using the equation developed from the calibration group on the validation group

^b Differences between stature estimates using stature-group-specific equations developed from the calibration group on the validation group

Table 5 Standard errors of estimate (SEE) in estimating stature based on different tibial length measurement techniques in females from different geographical regions

Author(s)/reference	Country/population	Sample size (<i>n</i>)	Age ranges (years)	Measurement technique	SEE (cm)
Hasegawa et al. [35]	Japan	342	18–59	Radiography	2.87
Chay et al. [19]	Mexico (Maya)	63	21–25	Percutaneous	2.94
Ahmed [37]	Sudan (Arab)	80	25–30	Percutaneous	3.15
Mohanty [38]	India (Oriya)	500	20–80	Percutaneous	3.44
Genoves [39]	Mexico (Mesoamerican)	59	–	Osteometry	3.51
Bridge et al. [40]	Australia	60	18–59	Percutaneous	3.80
Zhang et al. [41]	China (Han)	171	11–79	Radiography	3.81
Bach [4]	Germany	500	18.5–60	Percutaneous	3.90
Hishmat et al. [9]	Japan	109	20–97	Radiography	4.39
Gualdi-Russo et al. [12]	Italy	140	19.9–28.9	Percutaneous	4.62
Trivedi et al. [42]	India (Gwalior)	270	18–21	Percutaneous	4.69
Lee et al. [43]	South Korea	50	42–95	Osteometry	4.80
Kieffer [44]	USA	83	19–88	Radiography	4.83
Petroveckí et al. [45]	Croatia	19	35–82	Radiography	4.91
Mahakkanukrauh [7]	Thailand (Thai)	68	26–93	Osteometry	5.79
Garmendia et al. [13]	Mexico	30	19–91	Percutaneous	5.89
Ramezani et al. [46]	Iran	74	20–40	Radiography	6.30
Saiyed et al. [36]	India (Gujarat)	84	17–30	Percutaneous	6.76

SEE, standard error of estimation; *n*, number of participants; *cm*, centimetres

bones or dismembered body parts are present pose a potential hurdle for determining which stature-group-specific equation to use. However, it is possible to overcome this issue. It is well known that there is a strong correlation between the main long bones of the limbs and the body height [1–4, 22, 28]. This is further shown in the present study, where the correlation between stature and tibia length was found to be high for the whole sample ($r = 0.785$, $p < 0.001$). This strong correlation supports the use of the length of the tibia as an indicator of stature, which permits placement of the individual into a stature group. Thus, mirroring our stature groupings, we categorized tibiae as short (length < 34.5 cm), medium (length between 34.6 and 39.5 cm), and long (length > 39.6 cm), using the 15th and 85th percentiles as cut-off points. Based on these values, the forensic practitioner is able to estimate stature using the most appropriate stature-specific formula even in cases where they are limited to working with an isolated tibia.

We have considered several limitations of the present study, including the fact that our short and tall stature groups have few participants, and we do not yet have enough data available for large-scale comparisons, especially for females. On the other hand, it is important to emphasize the considerable strengths of this study, in that we have produced stature estimation equations for different stature groups based on tibial length and have therefore made available highly accurate stature-specific equations for use in forensic anthropology.

Conclusions

The regression equations specific to stature groups led to more accurate estimates than generic formulae. These findings suggest that this calculation procedure yields similar standard error of estimation in Spanish males and females, and that generating regression equations specific to stature groups appears to be an effective technique for estimating living stature. Thus, this procedure, piecewise regression, could be used in osteological, archaeological, and forensic cases, where isolated bones or body part(s) can be evaluated in order to decide which stature-specific equation is best applied. In future research, we recommend the analysis of stature-group-specific equations for estimating stature in other human populations.

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 Drafting of the manuscript: Gonzalo Saco-Ledo, Izzet Duyar
 Statistical analysis: Gonzalo Saco-Ledo
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 Derya Atamtürk, Izzet Duyar

Compliance with ethical standards

The project followed the recommendations of the Declaration of Helsinki on Human Rights, and was approved by the Clinical Research Ethics Committee (12/2015/CEICEGC).

Competing interest The authors declare that they have no conflict of interest.

References

- Breitinger E (1937) Zur Berechnung der Körperhöhe aus den langen Gliedmassenknochen. *Anthropol Anz* 14:249–274
- Trotter M, Gleser G (1952) Estimation of stature from long bones of American whites and negroes. *Am J Phys Anthropol* 10:463–514
- Trotter M, Gleser G (1958) A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. *Am J Phys Anthropol* 16:79–123
- Bach H (1965) Zur Berechnung der Körperhöhe aus den langen Gliedmassenknochen in weiblicher Skelette. *Anthropol Anz* 29:12–21
- Macaluso PJ Jr, Lucena J (2014) Stature estimation from radiographic sternum length in a contemporary Spanish population. *Int J Legal Med* 128(5):845–851
- Cordeiro C, Muñoz-Barús JI, Wasterlain S, Cunha E, Vieira DN (2009) Predicting adult stature from metatarsal length in a Portuguese population. *Forensic Sci Int* 193(1–3):131.e1–131.e4
- Mahakkanukrauh P, Khanpetch P, Prasitwattanseree S, Vichairat K, Troy CD (2011) Stature estimation from long bone lengths in a Thai population. *Forensic Sci Int* 210(1–3):279.e1–279.e7
- Muñoz JI, Liñares-Iglesias M, Suárez-Peñaranda JM, Mayo M, Miguéns X, Rodríguez-Calvo MS, Concheiro L (2001) Stature estimation from radiographically determined long bone length in a Spanish population sample. *J Forensic Sci* 46(2):363–366
- Hishmat AM, Michiue T, Sogawa N, Oritani S, Ishikawa T, Fawzy IA, Hashem MA, Maeda H (2015) Virtual CT morphometry of lower limb long bones for estimation of the sex and stature using postmortem Japanese adult data in forensic identification. *Int J Legal Med* 129(5):1173–1182
- González-Colmenares G, Medina CS, Báez LC (2016) Estimation of stature by cephalometric facial dimensions in skeletonized bodies: study from a sample modern Colombians skeletal remains. *Forensic Sci Int* 258:101.e1–101.e6
- Kyllonen KM, Simmons-Ehrhardt T, Monson KL (2017) Stature estimation using measurements of the cranium for populations in the United States. *Forensic Sci Int* 281:184.e1–184.e9
- Gualdi-Russo E, Bramanti B, Rinaldo N (2018) Stature estimation from tibia percutaneous length: new equations derived from a Mediterranean population. *Sci Justice* 58(6):441–446
- Menéndez Garmendía A, Sánchez-Mejorada G, Gómez-Valdés JA (2018) Stature estimation formulae for Mexican contemporary population: a sample based study of long bones. *J Forensic Legal Med* 54:87–90
- Krishan K, Kanchan T, Menezes RG, Ghosh A (2012) Forensic anthropology casework-essential methodological considerations in stature estimation. *J Forensic Nurs* 8(1):45–50
- Kim W (2019) A comparative study on the statistical modelling for the estimation of stature in Korean adults using hand measurements. *Anthropol Anz* 76(1):57–67
- Kimmerle EH, Jantz RL, Konigsberg LW, Baraybar JP (2008) Skeletal estimation and identification in American and East European populations. *J Forensic Sci* 53(3):524–532
- Bidmos MA (2008) Stature reconstruction using fragmentary femora in South Africans of European descent. *J Forensic Sci* 53(5):1044–1048
- Klein A, Nagel K, Gührs J, Poodendaen C, Püschel K, Morlock MM, Huber G (2015) On the relationship between stature and anthropometric measurements of lumbar vertebrae. *Sci Justice* 55(6):383–387
- Chay S, Batún J, Vázquez-Gómez A, Tiesler V, Dickinson F (2018) New linear regression equations to calculate stature from tibial length in modern Maya populations. *Homo*. 69(6):340–346
- Albanese J, Osley SE, Tuck A (2016) Do group-specific equations provide the best estimates of stature? *Forensic Sci Int* 261:154–158
- Albanese J, Tuck A, Gomes J, Cardoso HF (2016) An alternative approach for estimating stature from long bones that is not population- or group-specific. *Forensic Sci Int* 259:59–68
- Duyar I, Pelin C (2003) Stature estimation based on tibia length in different stature groups. *Am J Phys Anthropol* 122(1):23–27
- Pelin C, Duyar I (2003) Estimating stature from tibia length: a comparison of methods. *J Forensic Sci* 48(4):708–712
- Duyar I, Pelin C, Zagyapan R (2006) A new method of stature estimation for forensic anthropological application. *Anthropol Sci* 114(1):23–27
- Sargin OÖ, Duyar İ, Demirçin S (2012) Estimation of stature from the lengths of ulna and tibia: a cadaveric study based on group-specific regression equations. *Eurasian J Anthropol* 3(1):1–9
- Duyar I, Pelin C, Zagyapan R (2003) A comparison of methods for body height estimation based on ulna length. *Forensic Sci Int* 136:180
- Duyar I, Pelin C (2010) Estimating body height from ulna length: need of a population-specific formula. *Eurasian J Anthropol* 1(1):11–17
- Saco-Ledo G, Porta J, Duyar I, Mateos A (2019) Stature estimation based on tibial length in different stature groups of Spanish males. *Forensic Sci Int* 304:109973
- Must A, Dallal GE, Dietz WH (1991) Reference data for obesity: 85th and 95th percentiles of body mass index (wt/ht²) and triceps skinfold thickness. *Am J Clin Nutr* 53:839–846
- Ortega FB, Sui X, Lavie CJ, Blair SN (2016) Body mass index, the most widely used but also widely criticized index: would a criterion standard measure of total body fat be a better predictor of cardiovascular disease mortality? *Mayo Clin Proc* 91(4):443–455
- Ljungvall A, Zimmerman FJ (2012) Bigger bodies: long-term trends and disparities in obesity and body-mass index among US adults, 1960–2008. *Soc Sci Med* 75(1):109–119
- Lytle LA (2012) Dealing with the childhood obesity epidemic: a public health approach. *Abdom Imaging* 37(5):719–724
- World Medical Association (2013) World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. *JAMA*. 310(20):2191–2194
- Rodríguez S, Miguéns X, Rodríguez-Calvo MS, Febrero-Bande M, Muñoz-Barús JI (2013) Estimating adult stature from radiographically determined metatarsal length in a Spanish population. *Forensic Sci Int* 226(1–3):297.e1–297.e4
- Hasegawa I, Uenishi K, Fukunaga T, Kimura R, Osawa M (2009) Stature estimation formulae from radiographically determined limb bone length in a modern Japanese population. *Legal Med* 11:260–266

36. Saiyed MZ, Patel PR (2016) Relation of stature and percutaneous tibial length. *Indian J Forensic Med Toxicol* 10(2):143–147
37. Ahmed AA (2013) Estimation of stature using lower limb measurements in Sudanese Arabs. *J Forensic Legal Med* 20:483–488
38. Mohanty NK (1998) Prediction of height from percutaneous tibial length amongst Oriya population. *Forensic Sci Int* 98(3):137–141
39. Genovés S (1967) Proportionality of the long bones and their relation to stature among Mesoamericans. *Am J Phys Anthropol* 26(1):67–77
40. Bridge A, L, Oxenham MF, Miskiewicz JJ (2020) Estimating stature using human forearm and leg anthropometric data in an Australian female sample. *Aust J Forensic Sci* 52(1):83–95
41. Zhang K, Zhan M-j, Cui J-h, Luo Y-z, Qiu L-r, Deng L-p, Li Z-l, Chen X-g, Deng Z-H (2019) Estimation of stature from radiographically determined lower limb bone length in modern Chinese. *J Forensic Legal Med*. <https://doi.org/10.1016/j.jflm.2019.02.012>
42. Trivedi A, Saxena S, Morya R, Jehan M, Bhadkaria V (2014) Stature estimation using per-cutaneous tibial length in people of Gwalior region. *IOSR-JDMS Sci* 13(5):65–70
43. Lee J-H, Kim YS, Lee U-Y, Park D-K, Jeong Y-K, Lee NS, Han S-Y, Han S-H (2014) Stature estimation from partial measurements and maximum length of lower limb bones in Koreans. *Aust J Forensic Sci* 46(3):330–338
44. Kieffer CL (2010) Tibia and fibula stature formulae for modern female populations based on digital radiographic measurements. *J Forensic Sci* 55(3):695–700
45. Petrovecki V, Mayer D, Slaus M, Strinovic D, Skavic J (2007) Prediction of stature based on radiographic measurements of cadaver long bones: a study of the Croatian population. *J Forensic Sci* 52(3):547–552
46. Ramezani M, Shokri V, Ghanbari A, Salehi Z, Niknami KA (2019) Stature estimation in Iranian population from x-ray measurements of femur and tibia bones. *J Forensic Radiol Imaging* 19:100343

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