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Estimating Stature from Tibia Length: A Comparison of Methods*

ABSTRACT: Most forensic and biological anthropological studies use the stature-estimation formulae developed by Trotter and Gleser (1). In recent decades, studies of morphological differences between populations have indicated that population-specific formulae are necessary to obtain accurate estimates. A number of equations have been devised for the Turkish population. Previously, we introduced a "general formula" and three "stature-group-specific formulae" based on tibial length. The purpose of the present study was to determine whether formulae in the literature are suitable for estimating height in the Turkish population. To make this assessment, we compared the accuracy of formulae designed for Turkish people to the accuracy of formulae devised for other populations. We also evaluated the accuracy in short, medium, and tall height groupings. The formulae were tested on 110 healthy Turkish male adults, with estimated height compared to true height in each case. Analysis showed that the Trotter-Gleser formula for Mongoloids was most accurate for estimating stature in the study group as a whole. The formulae of Sağır (9) for the Turkish population and our previously published (6) "general formula" were the next most accurate methods, respectively. When the 110 subjects were categorized as short (1652 mm and below), medium (1653 to 1840 mm), and tall (1841 and above), the stature-group-specific formulae calculated in the present study were more accurate than all other equations for subjects at the height extremes. The results of this study indicate that stature-group-specific formulae are more reliable for forensic cases.

KEYWORDS: forensic science, forensic anthropology, stature estimation, tibia length, anthropometry, Turkish population

Reconstruction of stature from human skeletal remains continues to be an important aspect of forensic science. Although a variety of bones have been used to estimate stature, the most reliable results are based on long bone lengths and particularly the bones of the lower limbs. Several authors have developed limb bone-based regression formulae for different populations. Those devised by Trotter and Gleser in the United States (1) and by Manouvrier in Europe have been widely used in forensic and anthropological work (2). Researchers such as Brothwell (3), Krogman and İşcan (4), and Ubelaker (5) have recommended the Trotter-Gleser equations as the most useful set of formulae.

In Turkey, the Trotter-Gleser formulae for whites and the Pearson formula have been the most popular methods for estimating stature in forensic and anthropological investigations. However, to date, there has been no detailed examination of the reliability of these formulae. One purpose of this study was to evaluate the accuracy of equations reported in the literature in the stature estimations for the Turkish population.

In a recent report, we presented a new method for estimating stature from tibia length (6). This system includes three different regression formulae for groups defined as "short," "medium," and "tall." Compared to findings with our "general formula," the height estimates from these stature-group-specific calculations were more accurate for individuals at the extremes (short and tall subjects).

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In the present study, we used a Turkish sample group to compare the accuracy of the above-mentioned general and stature-group-specific formulae to the accuracy of other tibia length-based regression formulae that have been published.

Material and Methods

In a previous investigation, we constructed a general formula and stature-group-specific formulae for the Turkish population based on the anthropometric measurements taken from 121 volunteer male subjects (6). Body height of 1652 mm and below was defined as short, height between 1653 and 1840 mm was defined as medium, and height 1841 mm and above was defined as tall. These regression formulae are as follows:

General formula ($n = 121$):

$$\text{stature} = 678.68 + 2.738 \times \text{tibia length}$$

Group-specific formulae:

short subjects ($n = 18$): stature $= 951.94 + 1.890 \times$ tibia length
medium subjects ($n = 86$): stature $= 944.82 + 2.057 \times$ tibia length
tall subjects ($n = 17$): stature $= 1224.15 + 1.530 \times$ tibia length

For the present study, we applied the same formulae to a group of 110 Turkish male adults whose anthropometric measurements were known. These anthropometric measurements are listed in Table 1. Body height was measured using the methods described by Cameron et al. (7). For tibia length, the technique by Martin et al. (8) was used; the distance between the proximal end of the medial border and the tip of the medial malleolus was measured. The shaft of the anthropometer was maintained parallel to the long axis of the tibia.

As mentioned, the literature contains a range of stature-estimation formulae that have been created for populations around the world. We applied 24 of these (Table 2) to the study group and compared the accuracy of each to the accuracy with our previously published formulae.

The investigation was carried out in two stages. In the first stage, the height of each subject was estimated using our previously published general formula and the 24 other regression formulae. All estimates were compared to the subject's true height, and the differences were recorded. The formulae were then ranked in order of the smallest estimation error. In the second stage, the 110 subjects were assigned to short, medium, and tall stature groups, as detailed above. The height of each subject in each group was estimated using the appropriate stature-group-specific formula and the 24 other formulae. Again, the estimates were compared to the true heights, and the formulae were ranked for each height grouping, as described above.

We used the Statistical Package for Social Sciences for Windows, Version 8.0, for all statistical analyses. The paired *t*-test was used to assess the differences between the estimated and true heights. *P* values <0.05 were considered significant.

Results

The findings for the first stage of the study (accuracy of the general regression formula versus the other formulae) are shown in Table 2. The Trotter-Gleser formula for Mongoloids yielded the most accurate results. The Sağır formula and our general equation, both devised for the Turkish population, yielded the next most accurate results, respectively. The mean difference between true height and the stature estimated by these three formulae was 0.1 cm or less. After these three equations, the next most accurate estimates were yielded by the formulae of Dupertuis-Hadden for American blacks, Telkkä for Finns, and Muñoz et al. for Spanish people, respectively. With these methods, the mean difference between true and estimated height was less than 1 cm.

TABLE 1—*Age, height, and tibia length in the study group (n = 110).*

	Mean	SD	Min-Max
Age, years	21.7	2.58	18.0–30.1
Stature, mm	1746.7	88.30	1523–1950
Tibia length, mm	390.4	28.14	326–467

The results from the second stage of the investigation (estimates made with the stature-group-specific formulae versus the other formulae) are summarized in Tables 3, 4, and 5. For the short group, the Genovés formula for Mesoamericans was most accurate, followed by the formulae by Shitai for South Chinese and by Allbrook for the Nilo-Hamit population, and then our short-group equation (Table 3). For these four formulae, the estimation error was about 1 cm or less. In contrast, when the equation by Lundy for South Africans was applied to the short subjects, the estimation error was greater than 14 cm.

For the medium-stature group, the Sağır formula for the Turkish population and the Trotter-Gleser formula for Mongoloids yielded the best results. In both these cases, the estimates were extremely close to true height. The next most accurate was our medium-group formula. With this method, the mean difference between true and estimated stature was 0.18 cm. At the other extreme, estimates using the formulae of Lundy for South Africans, Allbrook for Bantu, and Allbrook for the Nilotic population were far off the true heights, erring by means of −18.88, −12.00, and −8.83 cm, respectively (Table 4).

For the tall group, Stevenson's formula for the North Chinese yielded the smallest estimation error. Our group-specific formula and the formula of Trotter-Gleser for whites also yielded good

TABLE 2—*Differences between estimated and true height, comparing our previously introduced general formula to others in the literature (n = 110).*

Author	Population	Mean Difference*	SD	*t*	Sig.
Trotter-Gleser (1)	Mongoloids	−0.01	3.88	−0.03	0.975
Sağır (9)	Turkish	−0.06	3.91	−0.16	0.876
This study (general formula)	Turkish	0.10	3.63	0.28	0.778
Dupertuis-Hadden (4)	American blacks	−0.65	3.68	−1.84	0.068
Telkkä (4)	Finnish	0.70	4.20	1.75	0.083
Muñoz et al. (10)	Spanish	0.73	3.84	2.00	0.048
Allbrook (4)	British	−1.09	3.95	−2.90	0.005
Breitenger (11)	Germans	−1.46	4.37	−3.51	0.001
Trotter-Gleser (1)	Mexicans	−2.06	3.82	−5.64	0.000
Choi et al. (12)	Koreans	−2.12	3.73	−5.97	0.000
Stevenson (4)	North Chinese	2.71	3.64	7.80	0.000
Shitai (4)	South Chinese	−3.02	3.64	−8.71	0.000
Pearson (4)	French	−3.09	3.86	−8.38	0.000
Trotter-Gleser (1)	Whites	3.14	3.77	8.72	0.000
Dupertuis-Hadden (4)	American whites	3.21	4.09	8.23	0.000
Trotter-Gleser (1)	Blacks	−3.74	4.09	−9.57	0.000
Trotter-Gleser (1)	Puerto Ricans	−3.97	4.43	−9.38	0.000
Neumann (4)	North American Indians	−4.80	5.29	−9.51	0.000
Allbrook (4)	Nilo-Hamit	−5.39	4.36	−12.99	0.000
Mohanty (13)	Oriya (India)	−5.43	4.39	−12.95	0.000
Genovés (5)	Mesoamericans	−6.89	4.42	−16.36	0.000
Günay et al. (14)	Turkish	−8.09	4.52	−18.78	0.000
Allbrook (4)	Nilotic	−8.89	4.42	−21.09	0.000
Allbrook (4)	Bantu	−12.06	3.76	−33.68	0.000
Lundy (4)	South Africans	−18.94	3.82	−52.06	0.000

* Negative values indicate underestimates, and positive values indicate overestimates.

TABLE 3—*Differences between estimated and true height, comparing our previously introduced stature-group-specific formula to others in the literature for the short stature group (n = 15).*

Author	Population	Mean Difference*	SD	*t*	Sig.
Genovés (5)	Mesoamericans	−0.41	3.17	−0.49	0.629
Shitai (4)	South Chinese	−0.68	3.56	−0.74	0.472
Allbrook (4)	Nilo-Hamit	0.94	3.18	1.14	0.273
This study	Turkish	1.08	3.16	1.32	0.207
Günay et al. (14)	Turkish	−1.36	3.17	−1.67	0.118
Pearson (4)	French	1.74	3.27	2.06	0.058
Trotter-Gleser (1)	Blacks	1.88	3.22	2.27	0.040
Choi et al. (12)	Koreans	2.08	3.33	2.42	0.030
Allbrook (4)	Nilotic	−2.40	3.17	−2.93	0.011
Trotter-Gleser (1)	Puerto Ricans	2.56	3.17	3.13	0.007
Trotter-Gleser (1)	Mexicans	2.62	3.29	3.08	0.008
Dupertuis-Hadden (4)	American blacks	3.27	3.36	3.77	0.002
Neumann (4)	North American Indians	3.55	3.16	4.35	0.001
Allbrook (4)	British	4.05	3.25	4.83	0.000
Breitinger (11)	Germans	4.92	3.18	5.99	0.000
Trotter-Gleser (1)	Mongoloids	4.92	3.27	5.83	0.000
Sağır (9)	Turkish	4.94	3.26	5.87	0.000
Stevenson (4)	North Chinese	4.99	3.57	5.42	0.000
Muñoz et al. (10)	Spanish	5.48	3.28	6.48	0.000
Mohanty (13)	Oriya (India)	−6.01	4.05	−5.74	0.000
Telkkä (4)	Finnish	6.64	3.20	8.04	0.000
Trotter-Gleser (1)	Whites	7.57	3.31	8.86	0.000
Allbrook (4)	Bantu	−7.71	3.32	−9.00	0.000
Dupertuis-Hadden (4)	American whites	8.83	3.22	10.64	0.000
Lundy (4)	South Africans	−14.30	3.29	−16.84	0.000

* Negative values indicate underestimates, and positive values indicate overestimates.

TABLE 4—*Differences between estimated and true height, comparing our previously introduced stature-group-specific formula to others in the literature for the medium stature group (n = 79).*

Author	Population	Mean Difference*	SD	*t*	Sig.
Sağır (9)	Turkish	−0.00	2.81	−0.00	1.000
Trotter-Gleser (1)	Mongoloids	0.07	2.81	0.22	0.826
This study	Turkish	0.18	2.80	0.57	0.572
Dupertuis-Hadden (4)	American blacks	−0.59	2.93	−1.78	0.079
Neumann (4)	North American Indians	−0.75	3.14	−13.46	0.000
Telkkä (4)	Finnish	0.76	2.80	2.41	0.019
Muñoz et al. (10)	Spanish	0.79	2.83	2.49	0.015
Allbrook (4)	British	−1.03	2.80	−3.28	0.002
Breitinger (11)	Germans	−1.41	2.82	−4.44	0.000
Trotter-Gleser (1)	Mexicans	−2.00	2.83	−6.27	0.000
Choi et al. (12)	Koreans	−2.06	2.89	−6.34	0.000
Stevenson (4)	North Chinese	2.78	3.29	7.50	0.000
Shitai (4)	South Chinese	−2.96	3.27	−8.02	0.000
Pearson (4)	French	−3.03	2.82	−9.55	0.000
Trotter-Gleser (1)	Whites	3.20	2.86	9.94	0.000
Dupertuis-Hadden (4)	American whites	3.27	2.79	10.42	0.000
Trotter-Gleser (1)	Blacks	−3.68	2.79	−11.72	0.000
Trotter-Gleser (1)	Puerto Ricans	−3.91	2.83	−12.28	0.000
Allbrook (4)	Nilo-Hamit	−5.34	2.82	−16.86	0.000
Mohanty (13)	Oriya (India)	−5.35	4.28	−11.12	0.000
Genovés (5)	Mesoamericans	−6.84	2.83	−21.50	0.000
Günay et al. (14)	Turkish	−8.03	2.85	−25.06	0.000
Allbrook (4)	Nilotic	−8.83	2.83	−27.76	0.000
Allbrook (4)	Bantu	−12.00	2.87	−37.22	0.000
Lundy (4)	South Africans	−18.88	2.84	−59.14	0.000

* Negative values indicate underestimates, and positive values indicate overestimates.

TABLE 5—*Differences between estimated and true height, comparing our previously introduced stature-group-specific formula to others in the literature for the tall stature group (n = 16).*

Author	Population	Mean Difference	SD	t	Sig.
Stevenson (4)	North Chinese	0.25	4.08	0.25	0.806
This study	Turkish	−0.44	2.01	−0.87	0.396
Trotter-Gleser (1)	Whites	−1.31	3.15	−1.67	0.116
Dupertuis-Hadden (4)	American whites	−2.33	2.70	−3.46	0.003
Muñoz et al. (10)	Spanish	−4.01	3.02	−5.30	0.000
Dupertuis-Hadden (4)	American blacks	−4.62	3.36	−5.50	0.000
Trotter-Gleser (1)	Mongoloids	−4.88	2.96	−6.59	0.000
Sağır (9)	Turkish	−5.03	2.93	−6.87	0.000
Telkkä (4)	Finnish	−5.14	2.59	−7.95	0.000
Mohanty (13)	Oriya (India)	−5.24	5.41	−3.87	0.002
Shitai (4)	South Chinese	−5.54	4.05	−5.47	0.000
Allbrook (4)	British	−6.20	2.87	−8.64	0.000
Chioi et al. (12)	Koreans	−6.35	3.25	−7.83	0.000
Trotter-Gleser (1)	Mexicans	−6.73	3.06	−8.81	0.000
Breitinger (11)	Germans	−7.71	2.44	−12.64	0.000
Pearson (4)	French	−7.90	2.99	−10.56	0.000
Trotter-Gleser (1)	Blacks	−9.28	2.70	−13.77	0.000
Trotter-Gleser (1)	Puerto Ricans	−10.35	2.39	−17.30	0.000
Allbrook (4)	Nilo-Hamit	−11.60	2.46	−18.90	0.000
Neumann (4)	North American Indians	−12.87	1.99	−25.92	0.000
Genovés (5)	Mesoamericans	−13.24	2.41	−22.02	0.000
Günay et al. (14)	Turkish	−14.66	2.34	−25.11	0.000
Allbrook (4)	Nilotic	−15.24	2.41	−25.33	0.000
Allbrook (4)	Bantu	−16.44	3.18	−20.67	0.000
Lundy (4)	South Africans	−23.57	3.07	−30.70	0.000

results for the tall subjects. The mean difference between true stature and estimated height with the Stevenson formula was 0.25 cm, whereas the mean difference with our tall-group formula was −0.44 cm and the Trotter-Gleser formula for whites was −1.31 cm. The largest differences between true and estimated height were observed with the formulae of Lundy for South Africans, Allbrook for Bantu, and Allbrook for the Nilotic population. In these latter three cases, the mean estimation error was greater than 15 cm (Table 5).

Discussion

Only three studies have presented regression formulae specific for the Turkish population that estimate stature from long bone length (6,9,14). In two cases, the estimation was based solely on tibia length (6,14). In the other, height was estimated from radiograms of six limb bones (9). To date, most biological and forensic anthropological studies that have been done in Turkey have used the equation of Trotter-Gleser for whites to estimate stature. A formula devised by Pearson, which is based on Rollet's data from French cadavers (4), has also been popular. However, no one has yet assessed whether these formulae are accurate for the Turkish population.

The main aim of the present study was to determine whether the height-estimation formulae published in the literature are accurate for the Turkish population. Since the Trotter-Gleser formula for whites and the Pearson formula are the ones that have been most commonly used in Turkey to date, we were primarily interested in the reliability of these two equations. Contrary to what we expected, the Trotter-Gleser formula for whites did not yield accurate height estimates in the Turkish males we studied. Stature was overestimated when this formula was applied to the sample group as a whole, and the mean estimation error was 3.14 cm. When the Pearson formula was used, stature was underestimated by a mean of 3.09 cm. Both these formulae yielded estimation errors greater than 3 cm. Interestingly, estimates made with the Trotter-Gleser formula for Mongoloids were more accurate than either of the above equations. In this case, the mean difference between true and estimated height was only 0.01 cm ($p = 0.975$). These findings suggest that the formulae based on tibia length devised for white populations are not suitable for the Turkish population.

We also found that stature-estimation methods created for black populations, especially sub-Saharan Africans, yielded significantly higher errors in our sample. For example, the equations for South Africans and Bantu produced mean errors greater than 10 cm. It is well known that the tibia-to-height ratio is significantly higher in black people compared to other populations (15), and this would explain such large errors. It is likely that formulae for Mongoloid populations yield more accurate results in the Turkish population because of similarities in body proportions.

Another aim of this study was to assess whether stature-group-specific formulae generate more accurate height estimates than other formulae. Researchers have already established that equations for estimating stature from long bones produce greater error in individuals at the height extremes (15,16). This was also confirmed by our findings. For example, the Trotter-Gleser formula for Mongoloids and the Sağır formula for the Turkish population yielded minor estimation errors in our sample group as a whole (mean error of less than 0.1 cm). However, for individuals at the extremes (the short and tall groups), these equations produced significantly higher mean estimation errors (approximately 5 cm for both). This emphasizes the need for stature-group-specific formulae. When we applied our group-specific formulae, the mean error was 1.08 cm for short subjects and 0.44 for tall individuals.

The study results showed that the Sağır formula and our formulae, all of which were devised for the Turkish population, yielded more accurate height estimates than the other equations we tested. One might expect that any formula created for a specific population would be more reliable than one that is not geared towards that particular group. However, the results generated with the regression formula of Günay et al., which was created for the Turkish population, were not accurate. This inaccuracy may be a factor of the small sample size that was used to develop the formula.

In addition to the general finding of better overall accuracy (all height groups together) with formulae for Turkish population, the stature-group-specific equations gave more accurate results, especially for subjects at the height extremes. These estimates were even more accurate than those of our general formula, which was specific for the sample population. In conclusion, we suggest that stature-group-specific formulae provide more reliable results and that it is especially important to use these equations in forensic investigations.

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