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Forensic anthropology population data

Estimating adult stature from radiographically determined metatarsal length in a Spanish population

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ABSTRACT

The ability to determine height in adult life can be crucial in the identification of skeletal remains. Very often, the small bones found among such remains are not only the most numerous, but also the best preserved, a fact which calls for more research into developing methods to estimate height from metatarsals. The aim of this paper is to verify the use of the dimensions of the metatarsals as estimators of adult height in a Spanish population using radiologically determined metatarsal lengths and to propose regression equations and test the formulae for determining adult stature. The present research is based on a study of 228 healthy Caucasoid adults from Galicia (NW Spain). The first and second metatarsals of the left foot were measured by a dorso-plantar X-ray using a digital medical image viewer. The best correlation obtained was with the maximum length of the 1st metatarsal for males. The corresponding regression equation is as follows: $S = 819.88 + 12.79$ M1. A comparison of our statistical results with those of neighbouring population groups indicates that ours is more accurate. This must be due to the so-called specificity of regression equations in relation to the series on the base from which they were developed.

The ability to determine height in adult life can be crucial in the identification of skeletal remains. It is an aspect of forensic science which has not yet been completely resolved, mainly due to the need for an appropriate methodology to enable estimation from diverse bones and also to have recourse to a well studied data base of the reference population. In order to obtain reliable results, it is important to have comparative data obtained from the same population group as the skeletal remains. Given that a skeleton maintains certain proportional relationships between different bones, it is agreed that these estimates are more accurate when long bones are available [1–7]. This need to estimate height is also present in situations where, although no bones are available, other evidence such as footprints of a suspect or victim are present [8–10].

Previous publications have used regression studies to link the dimensions of the feet, hands and footprints with height [11–19], as well as indicating possible relationships between various measures of soft tissue and height [20]. Skeletal development is influenced by many factors with the result that the proportions between the various bones differ not only between different races, but also between different geographical areas [5]. It is well known that issues such as sex, weight and place of origin have a direct impact on the regression formulas for estimating height [8–15,21] and the possible influence of asymmetry of the limbs in this estimation has also been considered [22]. Evidently, any of these circumstances can modify the estimation, a fact which is reflected in the abundant and necessary scientific literature on this subject [15,17,22–24].

While it is accepted that long bones such as the femur, tibia, fibula, humerus, ulna and radius are those which provide a more accurate estimate of height [4,5,7], in practice one is far more likely to be confronted with bone fragments, thus making the forensic task of estimation even more difficult [25]. However, it is also a fact that small bones are the best preserved and easier to find among skeletal remains, and for this reason it is requisite to develop methods for estimating height from such bones, including those of the foot. For the reasons discussed above, accurate studies of different bones of the hand and foot [11–13,26–32] and metatarsals [24,33] for different populations and regions have

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been published. Although the formulas developed by Byers have been routinely used in the forensic area more than 20 years, it is clear that it is the reference population from which they were obtained which gives them some specificity. Thus, for greater accuracy, it necessary to obtain appropriate formulae for each population area [7,8,34–36]. This need has been demonstrated by the differences that have arisen when used with other populations [24].

To verify the use of the dimensions of the metatarsals as estimators of adult height in our population, we have developed a method for estimating the stature of Spanish adults using radiologically determined metatarsal lengths.

1. Materials and methods

The present research is based on a study of 228 healthy Caucasoid adult volunteers (118 females and 110 males) from Galicia (NW of Spain). All individuals were within the age range of 19–82, and of Galician descent. All persons with skeletal deformities, pathologies or fractures which could preclude accurate measurements were excluded from the study. The volunteers were recruited from the towns and surrounding vicinities of Monforte de Lemos and Santiago de Compostela.

Height was determined using a standard hospital measuring rod, with the volunteer barefoot standing in an erect military position and looking upwards with the back against a graduated ruler. The back was stretched and arms held to the sides. The head, buttocks and heels were in contact with the vertical plane of the instrument. For horizontal reference the Frankfurt horizontal plane was used (an imaginary line from the inferior orbital rim on the same horizontal plane as the external auditory canal). The upper end of the instrument was lowered gently, flattening the hair and making contact with the vertex of the skull. The measurement was recorded twice and registered to the nearest millimetres. The mean was used to obtain the regression formula.

The first and second metatarsals of the left foot of the 228 volunteers were measured by a dorso-plantar X-ray using a digital medical image viewer with an RAIM (Radiological Archive and Image Management) application 1607 JAVA from UDIAT, commonly used in hospitals. Although digital measurement is calibrated by the system itself, in order to minimise errors a metallic ruler was used to confirmed the precision (Fig. 1). All measurements were carried out three times and registered in millimetres.

Fig. 1. Dorso-plantar projection of left foot, showing M1 and M2, with a metallic ruler on the right.

1.1. Description of the measurements, according to [24]

M1 – Maximum length of 1st metatarsal – the distance between the tip of the tuberosity and the most distal point of the head.

M2 – Maximum length of 2nd metatarsal – the distance between the proximal tip and the most distal point of the head.

The measurements obtained were statistically analysed using the *R* environment within which statistical techniques are implemented and can be extended via packages (www.r-project.org). The statistical techniques included means, standard deviations and Linear Regression. Additive Models (AM, which are widely used as an extension of traditional linear models (LMs) especially when continuous covariates are present, were obtained via an additional package (http://cran.es.r-project.org/web/packages/mgcv/index.html). The existence of standard software in *R*, such as mgcv package, makes it easy to fit models of this type in practice. In order to calculate a non-biased prediction error, one should not use the same data as that used to obtain predictive formulas. To do this we calculated n models, removing from each of these a predictable observation without letting it partake in the estimation. This method is usually called Cross Validation (CV) and is a standard means to establish the predictive ability of a non-biased model.

2. Results

The average age of men ($n = 110$) was 45.21 years, whereas for women ($n = 118$) was 51.14 years. Descriptive statistics of all measurements for each group are shown in Table 1.

The coefficients of correlation between the metatarsal lengths and the true stature were always positive and statistically significant. The correlation value was higher for the male and for the female sample, where the coefficients were higher than 0.7. The correlation value was slightly lower for the entire sample, labelled as "unknown sex" (Tables 2–4).

The highest correlation with stature was M1 for males (maximum length of 1st metatarsal). The corresponding regression equation is as follows: $S = 819.88 + 12.79$ M1, $R = 0.783$.

To test whether this formula performed better than others, we applied it to both single and double measurements, and no significant differences in the correlation coefficients were detected. However, *R* figures do not increase when a multiple regression is used.

Additive Models have also been used in the field of forensic pathology to estimate time of death [37], where it demonstrated its high predictive power [38]. With this model, for example, to estimate the height of an "unknown sex" from M1, we obtain the formula $S = f(\vec{x}) + \varepsilon = a + \sum_{j=1}^{p} f_j(x_j) + \varepsilon$. Calculation of the estimate requires a computer with an appropriate statistical package, which complicates its use, but gains in accuracy. The precision in this case would increase from a value of $R = 0.645$ with the linear model of Table 4 to $R = 0.710$ with the AM (Table 5).

To validate the model in an objective and measurable manner, we estimated the height of our entire population sample used the formulae proposed in this present paper as well as those published

Table 1
Descriptive statistics of all measurements (mm) for each group.

	Female ($n = 118$)				Male ($n = 110$)			
	Minimum	Maximum	Mean	S.D.	Minimum	Maximum	Mean	S.D.
Stature	1390	1723	1581	67.46	1501	1890	1707	81.31
M1	52	88	67.79	6.43	54	82	69.53	5.07
M2	53	88	71.31	6.31	59	83	72.26	4.21

Table 2
Regression formulae for males (in mm).[a]

Formula	R	Adj R^2	SE
$S = 819.88 + 12.79$ M1	0.783	0.613	51.02
$S = 687.69 + 14.20$ M2	0.705	0.498	59.78

[a] Stature (S), maximum length of 1st metatarsal (M1), maximum length of 2nd metatarsal (M2), in mm. SE: standard error; R: correlation coefficient; Adj R^2: adjusted determination coefficient.

Table 3
Regression formulae from females (in mm).[a]

Formula	R	Adj R^2	SE
$S = 1062.852 + 7.606$ M1	0.731	0.534	45.43
$S = 1051.211 + 7.507$ M2	0.711	0.505	46.66

[a] Stature (S), maximum length of 1st metatarsal (M1), maximum length of 2nd metatarsal (M2), in mm. SE: standard error; R: correlation coefficient; Adj R^2: adjusted determination coefficient.

by Cordeiro et al. for the Portuguese population [24]. The results were compared with the actual heights by calculating the mean-squared errors for each model and the results are shown in Table 6. The errors in estimating stature are much less when our formulae are used. A mean square error of 10,185.63 was obtained with the Portuguese M1 formulae compared to a mean square error of 5692.857 with our M1 formulae.

3. Discussion

In estimating height, several factors must be borne in mind, one of them being age, which should be more than 19, when fusion of the epiphyses occurs [4]. All participants in our study were adults and our formulae cannot therefore be used with under 19 year olds.

The fact that the estimate of height from M1 has the highest value of R may be considered an advantage given that the 1st metatarsal tends to be better preserved than the 2nd.

The values of R are similar to those obtained in other published work from other population groups (South Africa, Portugal and USA), but with different regression formulae [16,24,33]. Byers et al. [33] reported moderate relationships with correlation coefficients that ranged between 0.59 and 0.89, while Bidmos reported slightly lower values with correlation coefficients ranging between 0.44 and 0.73 [16]. A similar value to ours, which ranged between 0.56 and 0.78, was obtained by Cordeiro et al., with a range between 0.64 and 0.79 [24]. The correlations found here and the validation

Table 4
Regression formulae for unknown sex (in mm).[a]

Formula	N	R	Adj R^2	SE
$S = 886.797 + 11.016$ M1	228	0.645	0.416	75.81
$S = 914.09 + 10.15$ M2	228	0.567	0.322	80.61

[a] Stature (S), maximum length of 1st metatarsal (M1), maximum length of 2nd metatarsal (M2), in mm. SE: standard error; R: correlation coefficient; Adj R^2: adjusted determination coefficient.

Table 5
Linear Regression Model versus Additive model R figures.[a]

Sample	LM-M1	AM-M1	LM-M2	AM-M2
Unknown sex	0.645	0.710	0.567	0.583
Females	0.731	0.732	0.711	0.719
Males	0.783	0.817	0.705	0.705

[a] R figures of Stature estimation by maximum length of 1st metatarsal (M1) and 2nd (M2) formula; LM-M1: with Linear Regression Model (LM); with Additive Models (AM).

Table 6
Mean square error Spanish versus Portuguese [24] and Spanish validation for the total sample.[a]

	Mean square error	Cross Validation error
Cordeiro et al. M1 formulae	10,185.63	
Our M1 formulae	5692.857	5822.006
Cordeiro et al. M2 formulae	6692.185	
Our M2 formulae	6427.904	6575.789

[a] Stature estimation by maximum length of 1st metatarsal (M1) formulae, and stature estimation by maximum length of 2nd metatarsal (M2) formulae.

test is significant and therefore the analysis proceeded with confidence.

When our formulae are applied to the previous population groups it is seen that for a male M1 of 69 mm the estimated male stature given by our formula is 1702.3 mm, for Cordeiro et al. (Portuguese) 1714.7 mm, for Byers et al. (Euro-American males) 1813.8 mm, and for Bidmos (Indigenous South Africans males) 1589 mm. Estimation from a female M2 of 71 mm using our formulae gives a stature of 1583.7 mm, with that of Byers et al., 1608.4 mm and 1422.2 mm with that of Bidmos. The formulae proposed by Cordeiro et al. and Byers et al. give higher values than ours (in the example we used the mean values of M1 and M2 in our sample), whereas those of Bidmos give lower values than ours. This situation is explained by the fact that because the reference population is different, so also is the regression formulae.

The precision of estimation obtained with these models has been validated with a CV. To complete the validation we carried out a CV of the total sample and the mean-squared error was estimated (Table 6). As can be deduced from the data shown, the formulas proposed in this paper to estimate height from the measurements obtained from M1 and M2 are more accurate than those proposed by Cordeiro et al. since these latter were obtained from a Portuguese population. This validation is compared with the formulae proposed by Cordeiro et al. due to the geographical and temporal proximity of their reference population with ours. Despite the fact that Additive Models (AM) could offer more flexibility and precision than the Linear Regression Model (LM) we chose the latter because of its widespread use, ease of understanding and speed of calculation.

The correlation figures shown in Tables 2–4 are approximately the same magnitude as for living stature from anthropometric soft tissue measurements [20], or stature estimated from fragmentary long bones [39–41], or from foot dimensions [8,26,42]. It is also reported that the dimensions of feet and hands can be used in forensic work to provide a satisfactory estimate of stature. The length of the foot has similar R values to those proposed in this present study, but for other populations [14], and with certain limitations dependent on body weight [21] which were not taken into consideration in this present study.

4. Conclusion

The metatarsals are often the most complete and well preserved bones in cases of forensic anthropology. The data they supply has proved to be a valuable contribution in assessing the biological profile and made it possible to construct anthropometric regression equations for stature estimation. Although it is possible to obtain more accurate, albeit more complex, estimations of stature with AM models, the use of LM to predict stature from metatarsal measurements has proved to be the quickest and most useful mathematical model [24].

Obviously, recent studies on estimation of stature are far more accurate than those previously published simply because they have benefited from access to reference population formulae subjected to the same regional, social and ethnic variations as the skeletal remains under investigation [16,24,26,43].

When the results from Cordeiro's equations [24] were compared to ours, statistical results indicate that ours were more accurate. This must be due to the so-called specificity of regression equations in relation to the series on the base from which they were developed. In fact, our formulae were obtained from a reference population of contemporary individuals with known in life stature.

Although our formulae seem more appropriate to estimate stature, other formulae should not be rejected because they could still be useful when specific formulae for a specific population are unknown or not available.

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