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Methodological analysis of stature estimation from tibia osteometric data

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Abstract

Objectives: Stature is one of the characteristic elements of the biological profile, allowing the identification of human bone remains in a forensic context. Stature has a strong relationship of proportionality with the long bones of the lower limb. This study focuses on the biometric exploitation of the whole-bone tibia to estimate stature. The objective is to evaluate the performance of different stature estimation methods using various measurements. In addition, the use of age correction factors was studied in order to observe their influences.

Materials and Methods: The study was based on a sample of 91 tibias (43 males and 48 females) from the Belgian population for which 20 standard measurements were taken. A total of 28 regression equations from eight methods were used with or without the inclusion of two correction factors. The performance of the methods was evaluated by exploiting the estimation errors and the number of individuals included in the area of acceptability defined for the study.

Results: The tibia measurements were reproducible. The most effective for stature estimation were bone lengths. The whole-bone methods developed in the 21st century was the most efficient, and the application of correction factors allowed for the improvement of the equations.

Discussion and Conclusion: The best performing method is Nikita et al. 2017, and the correction age best emphasizing stature estimation was 30 years. Equations for females provided the majority of the best results, followed by those for undetermined sex.

Key words

Forensic Anthropology - Stature - Tibia - Biometry - Regression Equations

1. Introduction

When human remains in an advanced state of decomposition, fragmented or skeletonized, are discovered in a forensic context, the first goal is to gather as much information as possible about them and to establish the biological profile (age, sex, stature and biogeographical origin). At the same time, it is essential to document the place of discovery and its surroundings in order to maintain an overall view of the environment, which will help to orient and complete the interpretation of this discovery. The present study focuses on the estimation of one of the parameters of the biological profile: stature.

Stature [1] is a measurement projected in centimeters or millimeters, taken in the anatomical reference position (standing with the head placed in the Frankfurt horizontal plane from the vertex to the ground). This method of estimating stature applies to individuals who have completed their bone growth. Depending on the context of the acquisition, the stature can be taken in different positions. This biological parameter varies during the life of the individual, with a progressive increase in stature during growth [2-3] until it reaches a maximum level, varying according to the individual. It then gradually decreases during senescence, with the decrease in bone mineral content adding to this phenomenon [4-6]. The combination of these findings highlights the need for a correction factor related to the age of the individual to compensate for this loss of bone material [7-9]. In the interest of accuracy and reliability, it is recommended to associate the estimated maximum stature with the age-corrected stature.

This study focuses on the use of different stature estimation calculations through bone measurements. Moreover, there are different ways to estimate the stature of a skeleton [1], depending on the material available (complete or fragmented bones). In the present case, measurements were taken on a long bone (the tibia), and the measurements were integrated into simple or multiple regression equations based on a reference population panel using the same measurements [10-14]. The stature is said to be "reconstructed," because it results from mathematical methods established statistically. The equations proposed in these reference tables are accompanied by threshold values governed by notions of laterality, sex or biogeographic origin. However, the absence of this information can lead to biases in the correct application of the stature estimation method used. Finally, the estimation of stature is subject to different biases induced by the action of influencing factors, such as the secular trend, age, reference population used in the elaboration of the applied method or the modalities of the measurement.

This work concentrates on the exploitation of whole-bone tibia biometry to contribute to stature estimation. Indeed, there is a strong linear relationship between long bone length and stature, which is even more pronounced with the use of long bones of the lower limb [1] [15]. The tibia has often been used for metric examination, due to its good preservation in both forensic and archaeological contexts. In the literature, the use of the tibia is used to address different elements of the biological profile as a primary and/or supplemental specimen in the dry state. It can also be the subject of studies on the living, because it is easily palpable from one end to the other and different zones can be exploited.

The hypothesis of this study is the following: what are the issues surrounding the osteometric exploitation of the tibia in the definition of stature? The first objective is to carry out a comparative study of a panel of eight methods selected on a sample of tibias from a Belgian population in order to identify the best equations for the methods to be applied according to the bone elements of the tibias. The second objective is focused on the observation of the action of senescence on the bone and its impact on stature in order to conclude if the implementation of a correction factor related to age allows us to obtain better results.

2. Materials and Methods

2.1. Osteological Material

The entire sample was composed of tibias (right and left) from 93 individuals from the Belgian population. The acquisition of these tibias resulted from the Body Legacy Service of the Laboratory of Anatomy, Biomechanics and Organogenesis of the Université Libre de Bruxelles. They were collected after their respective dissections. These tibias were associated with information on the age, the sex and the stature at the time of death of the individuals. The stature was measured using an anthropometric measuring rod on the corpse in the dorsal decubitus position; the two rods of the measuring device were placed at the vertex and at the heel (the axis of the foot and the leg being 90°). The sample was composed of 44 males and 49 females. However, the absence of some data led to the creation of two subsamples in order to carry out the various analyses under study. First of all, the number of individuals retained for the comparative study of real and estimated stature was 91 because two statures were missing, one for each sex. The average stature for the sample was 161.6 cm and 169.4 cm for males and 154.6 cm for females. Then, in order to study the impact of the use of correction factors taking into account the age of the individual, a sub-sample of 70 individuals (36 females and 34 males) was selected, because 23 pieces of data were missing for age. The average age for the subsample was 81.4 years; it was 78.7 years for males and 84 years for females (Table 1). In addition, a summary of the numerical descriptive statistics for the tibia measurements used in the regression equations for the stature estimates is reported in Table 2 for the undifferentiated whole sample and for the female and male subsamples.

2.2. Selection of Stature Estimation Methods

This study brings together a panel of eight stature estimation methods, five are applicable to dry whole bone [16-20], two are applicable to percutaneous bone [21-22] and finally one method is applicable to fragmented bone [23]. These methods concerned samples of different biogeographic origin. On the other hand, among these methods there are four different ways to record the stature of the initial samples: a living stature, a reported stature, a cadaveric stature and a completed stature based on the combination of the two last mentioned. A total of 28 regression equations were established from these methods on different measurements, including the maximum, physiological and morphological bone lengths, followed by the measurements relating to the tibial plateau. The regression equations could be simple or multiple and sex or laterality dependent or non-dependent (Table 3). All these parameters were taken as criteria for the selection of the stature estimation methods. To this end, the origin of the samples and the collections to their elaboration, the proposal of generic equations or not and the criteria of applicability dependence of the equations, as well as the statistical elements proposed by the authors to their regression equations, were studied.

2.3. Measurements

First of all, whole measurements were taken using the osteometric board, the toise and the Seca tape measure in centimeters. The accuracy of this equipment is 0.1 cm. Measurements taken with the Vernier digital caliper (whose accuracy is 0.01 cm) were in millimeters.

The measurements selected for this study were part of the standard measurements taken on the tibia and are taken from Martin (1928) [24]. In order to improve the measurement, each tibia of the sample was previously marked with landmarks in the different areas of interest. For this study, 20 measurements per tibia were taken, including total length, lengths and widths of the upper articular surfaces of the medial and lateral condyles, maximum width of the upper and lower epiphysis, perimeters at the middle of the diaphysis, at the level of the nutrient foramen and the upper point of the fibular incisure. Finally, the sagittal and transverse diameters at the level of the tuberosity, the middle of the tibial diaphysis and the inferior epiphysis were recorded.

2.4. Study Approach

The study was carried out blindly, which means that the gender of the individual was not taken into consideration. The entire sample was initially considered to be of undetermined sex. This approach allowed us to evaluate which equation was the most efficient without taking into account the sex parameter, which is omnipresent in stature estimation formulas for each subsample. The same evaluation was conducted, but this time taking into account the sex of the individual.

The approach followed for the study of each individual in the sample was as follows:

- The first step focused on the collection of different metric data (20 measurements per tibia for the 93 individuals) without taking into account gender. This situation is often found in forensic or archaeological contexts;
- The second step included the calculation of the estimated stature with the different equations constituting the methods of estimation of the stature selected for each individual. This calculation was carried out, on the one hand, with the subsample of 91 individuals and, on the other hand, with the subsample of 70 individuals to which a correction factor related to age was applied in a second step;
- The third step consisted of distributing the individuals according to their sex in each analysis conducted and described in the second step;
- The fourth step was based on the comparative study of the different results obtained for the estimation of stature with the information associated with each individual (stature and age).

2.5. Statistical Analysis

For statistical processing and data editing, R studio software (macOS Mavericks 10.9.4 identifies itself as "Darwin Kernel Version 20.1.0: Sat Oct 31 00:07:11 PDT 2020") and Microsoft® Excel for Mac (version 16.43.1) were used.

Then, different statistical analyses were conducted for the analysis of the sample, with the calculations of the mean, standard deviation, quartiles (1st and 3rd), median and range (minimum and maximum) for quantitative variables.

The reproducibility of the measurements was investigated and evaluated by comparing the readings of two different observers on the same material (the first reading was taken in 2014 [25] and the second in 2020) using "Lin's concordance correlation coefficient" [26]. The result obtained will be interpreted following the interpretation of Partik et al. 2002 [27]. Repeatability could not be performed due to the health context that impacted the year 2020, preventing any further consultation of the sample.

The statistical analysis of the metric data began with the evaluation of the correlation that might exist between the different osteological measures and stature for the undifferentiated and sex-differentiated samples by exploiting the r Pearson's linear correlation coefficient (threshold $\alpha = 5\%$). This allows us to highlight the existence or not of a link between two quantitative variables.

The approach to study the results of the different stature estimation methods was based on the analysis of the difference between the actual and estimated stature (Real stature - Estimated stature), that is to say, the residual. Indeed, the smaller this residual is, the closer the estimated stature is to the real stature.

For each formula, a scatter plot illustrating the dispersion of residuals according to real stature was realized.

For the whole sample, the mean absolute error (MAE) was computed for each equation to assess its precision. The closer to 0 the value is, the closer the real stature is to the estimation. So, the exploitation of this indicator would allow us to evaluate the efficiency of the predictive model used.

In this graph, there were fixed different levels in order to establish reference points and to take note of the elements of comparison; the first one is located at 0 (red trace).

- An individual with a negative residual value will indicate an individual whose stature will be overestimated;
- Conversely, an individual with a positive residual value will be an individual whose stature will be underestimated.

Then, three other levels were added to our graph: black solid lines represent +/- 3 cm threshold, dotted blue lines represent +/- 6 cm and purple solid lines represent the MAE.

The results of these different analyses were studied with the following reading grid, which was established to quantify the performance of the equations. So, all the equations of the studied methods were classified according to the number of individuals present in the three zones defined by fixed levels.

These zones take into account the difference between the estimated and real stature.

- The first zone includes the estimation with an absolute value of residual inferior or equal to 3 cm. In that case, estimation was assumed to be precise.
- The second zone includes estimation with an absolute value of residual between 3.01 and 6 cm. In that case, estimation was assumed to be acceptable.
- The third zone includes the estimation with an absolute value of residual strictly superior to 6 cm. In that case, estimation was assumed to be poor.

In a nutshell, a method would be considered efficient if it allows to count a maximum of individuals included in an interval between -3 and 3 cm and a minimum of individuals with a residual strictly higher than 6 cm. In this case the equation from the method (X) will be considered as accurate.

On the contrary, a method would not be efficient if it allows to count a maximum of individuals with a residual strictly higher than 6 cm and to count a minimum of individuals included in an interval between -3 and 3 cm. In this case, the equation from the method (X) will be considered as poor.

The graph distinguishes the individuals with an overestimated or underestimated stature and allows to visualize their distribution in these three defined zones.

Subsequently, the implementation of a correction factor related to age was applied in order to observe its potential in producing better results on the estimation of stature by repeating the same study procedure. The latter was subtracted from the estimated stature. For this purpose, two correction factors with different correction ages and rates of stature average loss per year were selected and exploited (Table 4).

3. Results

3.1. Measurements

Lin's concordance correlation coefficient highlighted the reproducibility of the measurements. The best result was obtained for the maximum tibia length (M1a). The inter-observer reproducibility of the measurements was acceptable (Table 5).

For the study of the correlation of measurements with stature, the most correlated measurements were the four tibia lengths. Next, the measurements concerning the tibial plateau, then the distal end of the tibia and finally the perimeters concerning the mid-diaphysis and distal end. In general, we had good agreement with Lin's concordance correlation coefficients between 0.8 and 1. These results were consistent with the precision of the measurement equipment, which varies between 0.1 cm and 0.01 cm. This bias was therefore acceptable (Table 5).

3.2. The Methods

All the regression equations present in the eight selected methods were applied to the entire subsample of 91 individuals. The results concerning the study of the residuals are presented in Table 6.

Figure 1 allows us to observe the behavior of the equation of Nikita et al. 2017 [20] for female individuals with the M1b measure (i.e., tibia length), where an overestimation of stature for 10 males and 34 females was observed. Forty-seven individuals had an underestimated stature (33 males and 14 females). This equation allows us to count a total of 44% of the subsample (1)¹ within the defined accurate zone of ± 3 cm. That is to say, the majority of the individuals have a residual less than or equal to 3 cm in absolute value, so this estimation can be qualified as accurate. Afterwards, 29 individuals or 32% of the subsample (1) had an estimation considered acceptable, because the difference between the real and the estimated stature ranged to 3 to 6 cm in absolute value. Finally, 11 individuals (10 males and one female) had an underestimated stature of more than 6 cm, and 11 individuals (one male and 10 females) had an overestimated stature of more than 6 cm (i.e., a total of 22 individuals with a residual strictly superior at 6 cm, which represents 24% of the total population). Moreover, for this equation, we obtained the second smallest MAE (4.14 cm), which indicates that the prediction system used gives good results. This was the best performing equation for stature estimation.

The least performing equation is the one concerning the "total skeletal height" for females proposed by the method of Chibba et al. 2007 [23] (Figure 2). Indeed, an overestimation of stature was found for one woman, followed by 90 underestimations of stature (43 males and 47 females). Finally, 75 individuals (38 males and 37 females) had an underestimated stature of more than 6 cm (i.e., a total of 82% of the total number of individuals had a residual strictly superior than 6 cm). This equation tended to underestimate the stature of individuals regardless of their sex. Moreover, for this equation, we obtained the largest MAE (11.7 cm). In this case, the prediction system gave bad results.

In the second part of the study, the age of the individual was taken into account by applying a correction factor specific to age for the obtained result. A second set of data was obtained for each correction model analyzed in the same way as the abovementioned model with the subsample of 70 individuals. The results were better than those recorded in the generic study carried out previously. A decrease in the deviation indicators was observed, showing the effectiveness of the application of this correction factor (Table 7). For the correction factor of Trotter and Gleser [8], a better balance was obtained between the proportions of under- and overestimated individuals for 11 of the equations tested, compared to seven equations for the correction factor of Galloway [2]. Thus, this correction factor for the final stature estimate reduces the number of individuals not included in the acceptable limit zone.

¹ (1) : for the sample known stature sample n=91

4. Discussion

In the first instance, before proceeding to the methodological analysis of stature estimation, the different measurements were analyzed from the point of view of reproducibility. The collection of osteometric data from the tibia revealed the existence of a disparity between certain measurements. This finding highlighted the technical nature of certain handlings or reflects a poor understanding of the operator with respect to these measurements.

Then, the best correlation scores obtained between measurements and stature were held by those related to bone length, this result is consistent with data from the literature. This finding supported the important relationship of proportionality existing between long bones and stature [15]. Maximum (M1a) and total (M1) length should therefore be preferred, when possible, for the estimation of an individual's stature. However, if these measurements are not available, it is possible to use measurements of the tibial plateau (i.e., its width and the dimensions of its upper articular surfaces), as they also present the best correlation coefficients with stature. For this reason, these variables are used in simple and multiple stature estimation formulas developed for the exploitation of fragmented bones [23]. The lengths of the superior articular surface of the medial and lateral condyles (M4a and M4b) are the most significant along with the maximum width of the superior epiphysis (M3). Nevertheless, the presence of pathological elements, such as eburnation of the tibial plateau, can have the effect of modifying the dimension of the proximal end of the tibia. Finally, the results of measurements based on the tibial diaphysis are mixed. Indeed, measurements taken at the level of the nutrient foramen or the tuberosity of the tibia provide fewer good results, unlike those taken in the middle of the diaphysis or the fibular incisure. An element of answer can be brought by the fact that these anatomical regions are the place of development of pathologies in connection with senescence or repetitive activities, such as over ossification of the tibial tuberosity or the line of the soleus muscle. The presence of bony pathology can create an obstacle to accurate measurement and thus bias the final estimate.

The comparative study of the different methods of estimating stature was the subject of various analyses. First, the efficiency of the equations according to the sex of the individual was tested. These methods concerned samples of different construction in order to constitute a heterogeneous pool applicable to the largest number of individuals. In the context of an indeterminate sample, the equations for females produced the best estimates, as they obtained a smaller MAE, followed by the methods proposing equations for individuals of indeterminate sex. In general, for the male sample, the result was more heterogeneous. Thus, in this configuration, the equations for males worked better for three of the eight estimation methods dedicated to them; the second part is occupied by the equations originally intended for female or undetermined individuals. For the whole female sample, the equations for females were the most efficient, except for the equation proposed by Chibba et al. 2007 [23], where the equation for males was the most efficient. This first analysis showed that the MAE for female individuals was larger than that of males. This difference showed that the estimation of stature for these individuals was less accurate and reliable because it was subject to a larger margin of error. On the other hand, a constant had been observed with regard to the methods proposing equations using bone lengths as a variable for individuals of indeterminate sex, which proved to be a very good alternative because they produced very good results, especially since they are similar to those intended for the sex-specific equations. In light of these results, it appears that, in general, the stature of females is overestimated and that of males underestimated.

Then, the analysis of the methods performance was illustrated by the accounting of the largest number of individuals between the defined fixed steps. In this configuration, the equations defined by Nikita et al. 2017 [20] performed best. Indeed, this method holds the best scores of counting individuals in the accurate area (± 3 cm in absolute value); this is the case for seven out of nine of their equations. These equations also recorded the lowest percentage of individuals with an estimation error greater than 6 cm. This hybrid method based on the combination of anatomical and mathematical stature estimations therefore has relatively efficient equations. They provide "acceptable" results because the average error of each equation is between 3.99 cm and 5.18 cm, but this score can be considered quite low in a strict forensic context. However, the maximum difference of 5.18 cm on a real stature of 170 cm will

give an estimated stature of 175.18 cm; the typology of the subject will remain an individual of average height!

The third part of the study takes into account the age of the individual. To this end, the effects of the application of a correction factor were analyzed. The results showed that its influence was positive for the majority of the equations used in this study. Indeed, this correction factor contributed to an improvement of the results put in parallel and resulting from the three analyses carried out. This results in a decrease of the average error obtained for all the methods. This average error goes down to 5.5 cm for the Trotter and Gleser factor and 5.8 cm for the Galloway factor against 5.9 cm for the generic study (with a sample of 70 individuals) without correction factor.

In addition, the efficiency is also underlined by the fact that a larger number of individuals are counted between the defined fixed bearings of $\pm 0-3$ cm (i.e., in the area qualified as accurate). With the two correction factors, three equations allowed the inclusion of more than 50% of the individuals in this same zone against none in the study without correction factors. On the other hand, 13 equations contained between 40-49% of the sample well classified in this zone against five previously.

As a result, the rate of estimation of stature increases by increasing the performance of the methods exploited and in particular that of Olivier et al. 1978 [16], Cleuvenot et al. 1993 [17] and Albanese et al. 2017 [19], where the benefit was the most marked. Conversely, for some equations for female and indeterminate individuals, the intervention of this factor generated a moderate decrease in the number of individuals included in the acceptable margin. For example, this decrease was found with the equations of Nikita et al. 2017 [20] and Chibba et al. 2007 [23].

The effectiveness of the correction factors has been tested and attested in many studies that have compared different cut-off points in order to define the most effective one by using different cleavage ages: 20 years, 30 years, and 45 years. In accordance with the data in the literature and the results, the most effective correction factor was found to be the efficient one at the age of 30 years by Trotter and Gleser [5-6], [8-9]. The addition of a correction factor decreased the residual difference between the known true stature and the estimated stature. However, the effectiveness of this correction tool requires taking into account different factors, such as the profile and the trend of the decrease in stature, which is curvilinear and non-linear, gender or age, which progressively increased this loss of stature. This will result in overestimates of stature for young and old mature individuals. Nevertheless, the correct application of these correction factors requires knowledge of the exact age of the individual studied, which is rarely the case when human remains are discovered in a forensic context.

The analysis of the performance of the methods was re-evaluated following this study and several of them stand out. Firstly, it is two of the equations defined by Nikita et al. 2017 [20] that performed best. These equations give "acceptable" results, as the average error of each equation is between 3.91 cm and 5.05 cm. Then, there are two of the equations proposed by Olivier et al. 1978 [16], with an average error for each equation between 4.64 cm and 4.77 cm, respectively. After studying all the results, the equations defined by Nikita et al. 2017 [20], with the correction factor of Trotter and Gleser [8], performed the best.

5. Conclusion

To conclude, this study tested the effectiveness of a diverse panel of regression equations with a new sample. As a result of this analysis, it is the method of Nikita et al. 2017 [20] that was found to be the most effective. **On the other side, the use of this type of method leads to an underestimation of the stature, this could be corrected by the use of a correction factor.** The variables used in the equations are mostly those related to tibia lengths, as these are the measures most correlated with stature. However, a whole tibia is not always available. For this purpose, the exploitation of these extremities or the proportions of the tibial diaphysis are convincing alternatives that can be used in multiple regression equations. Although "sex-specific" equations are effective, those for indeterminate sex are equally effective. The development of the latter is therefore essential when constructing new estimation methods. Then, the complementary application of a correction factor taking into account age increases the efficiency of the chosen equations and reduces the errors in the estimation of stature, thus increasing the precision without changing the reliability. However, this question of the place of age in the estimation of stature is a current problem, because this parameter is not always accessible.

In addition, one of the biases in stature estimation is that all methods do not have generic equations that can be applied to indeterminate or "undeterminable" sex. Indeed, the sex of an individual in the skeletal state is not always available. It seems obvious to question the extent of the possibilities of the use of these measures to answer another element of the biological profile, here the sex. Therefore, a complementary study would allow to extend the use of the measures taken in order to test the possibility of distinguishing the individuals according to their sex.

Finally, one of the limitations of the study is the use of a European-type and elderly sample. Thus, to make this analysis more efficient, it would be appropriate to use a larger sample of heterogeneous age and bio-geographical origin. Furthermore, to expand this study, it would be interesting to add methods applicable to fragmented bone and to test the degree of correlation between non-standard measurements. In conjunction with this observation, it would be appropriate to develop, from this sample, a combination of simple and multiple regression equations applicable to individuals of differentiated and undifferentiated sex in order to increase the performance of stature estimation and to overcome the absence of intact bone material at hand. To conclude, this study could be oriented towards somatometry by collecting a panel of data from medical imaging and from the living subject in order to quantify the evolution of the loss of stature with age through the collection.

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7. Figures:

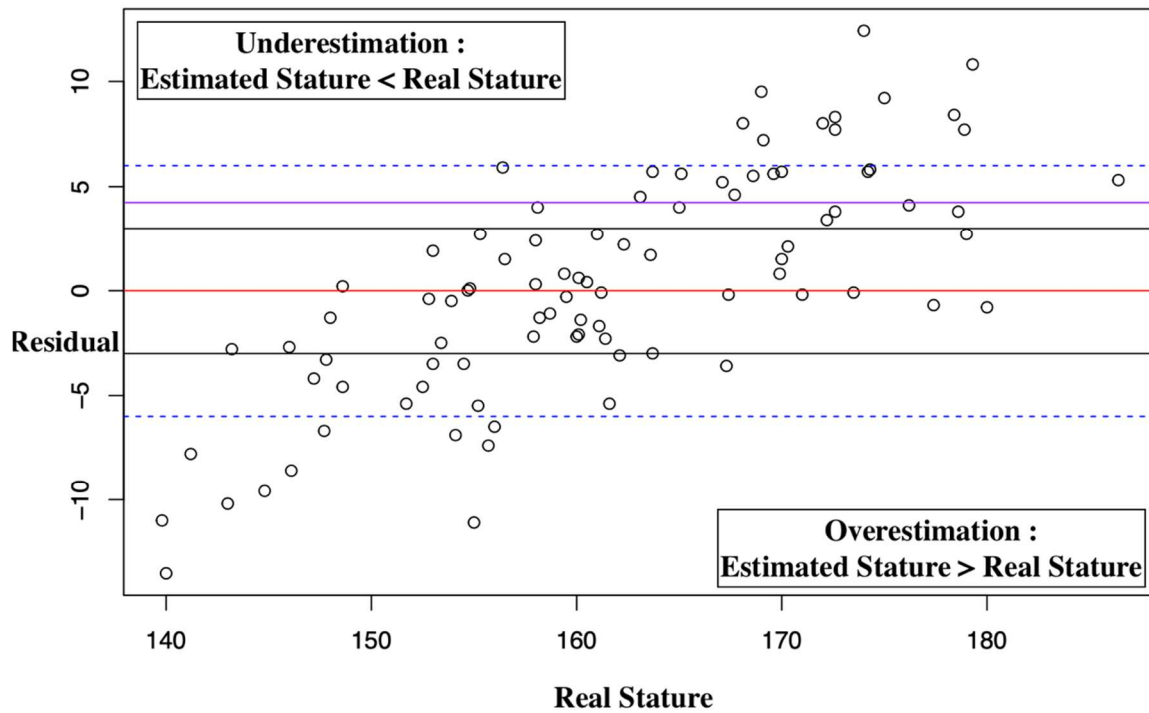


Figure 1: Scatterplot illustrating the dispersion of residuals according to the real stature for the equation of Nikita et al. 2017 for female individuals using the M1b measure. The black solid line represents the ± 3 cm thresholds, the dotted blue line the ± 6 cm thresholds, and the purple line represents the mean absolute error.

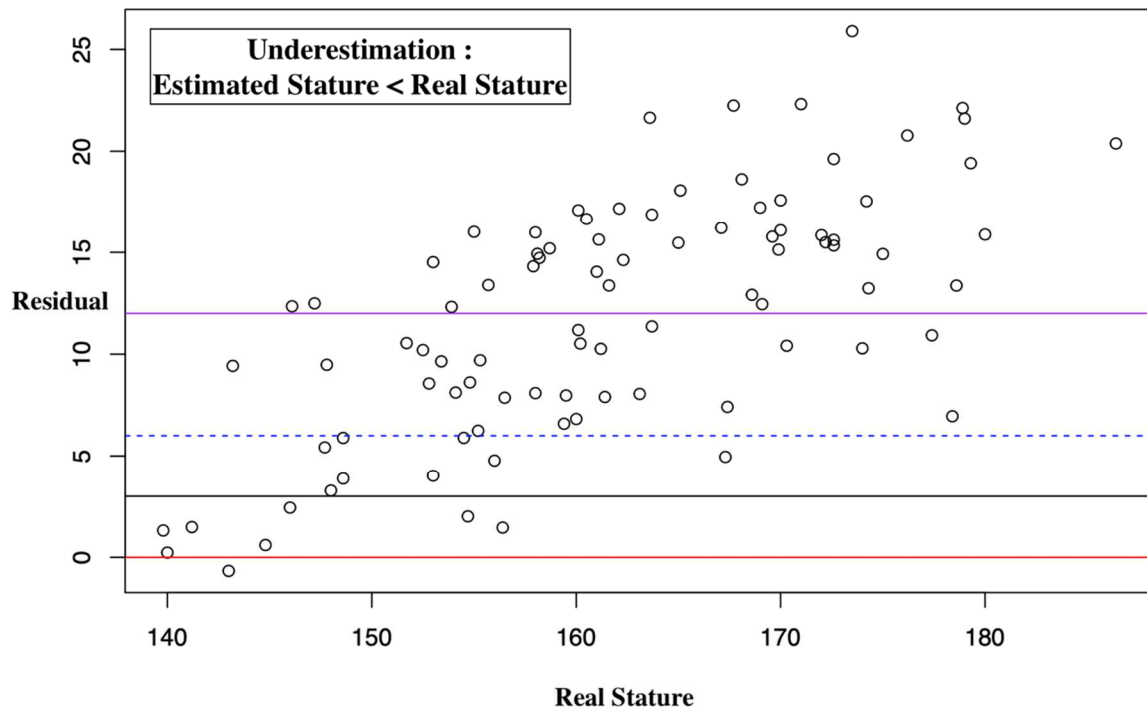


Figure 2: Scatterplot illustrating the dispersion of residuals according to the real stature for the equation Chibba et al. 2007 for female individuals (TSH). The black solid line represents the ± 3 cm thresholds, the dotted blue line the ± 6 cm thresholds, and the purple line represents the mean absolute error.

8. Tables :

Descriptive Statistics								
	Sample	Total of individuals	Average	Standard deviation	1st quartile	Median	3rd quartile	[Min ; Max]
Stature (cm)	Total sample (1)	91	161.6	10.58	154.6	161	169.95	[139.8 ; 186.4]
	Male	43	169.4	7.67	164.4	170	174.25	[153 ; 186.4]
	Female	48	154.6	7.51	148.45	155.1	160.12	[139.8 ; 173.5]
Stature (cm)	Total sample (2)	70	161.9	10.10	155.02	161.15	170	[139.8 ; 180]
	Male	34	169.2	7.07	165.6	170	173.65	[153 ; 180]
	Female	36	155.2	7.48	148.45	156.1	160.27	[139.8 ; 173,5]
Age (year)	Total sample (2)	70	81.4	10.16	75.25	83	88	[49 ; 98]
	Male	34	78.7	9.28	74.25	80	86	[49 ; 91]
	Female	36	84	10.41	77.5	87	91.25	[55 ; 98]

Table 1: Numerical summary of stature and age, (1) for the known stature sample (n = 91) and (2) for the known stature and age (n = 70)

Descriptive Statistics of Tibia Measures								
	Sample	Total of individuals	Average	Standard deviation	1st quartile	Median	3rd quartile	[Min ; Max]
M1: Total length (cm)	Total sample (1)	91	36.53	2.51	33.60	36.40	37.15	[31.4 ; 43.1]
	Male	43	38.05	2.22	36.60	37.90	39.40	[32.7 ; 43.1]
	Female	48	35.22	1.90	34.10	35.30	36.40	[31.4 ; 40.7]
M1a: Maximum length (cm)	Total sample (1)	91	37.08	2.53	32.60	36.90	35.95	[32.0 ; 43.7]
	Male	43	38.62	2.25	37.40	38.30	39.90	[33.3 ; 43.7]
	Female	48	35.69	1.91	34.40	35.80	36.90	[32.0 ; 41.3]
M1b: Tibia length (cm)	Total sample (1)	91	35.58	2.49	33.6	35.50	37.15	[30.5 ; 42.2]
	Male	43	37.06	2.29	35.75	36.80	38.15	[32.0 ; 42.2]
	Female	48	34.24	1.85	33.15	34.30	35.50	[30.5 ; 39.7]
M3: Maximum width of the upper epiphysis (cm)	Total sample (1)	91	7.39	0.58	6.96	7.40	7.08	[6.21 ; 9.23]
	Male	43	7.81	0.47	7.49	7.78	8.11	[6.99 ; 9.23]
	Female	48	7.01	0.40	6.78	7.02	7.30	[6.21 ; 7.91]
M3a: Width of the medial superior articular surface area (cm)	Total sample (1)	91	3.03	0.29	2.82	2.99	3.21	[2.51 ; 4.07]
	Male	43	3.24	0.23	3.11	3.18	3.33	[2.85 ; 4.07]
	Female	48	2.85	0.19	2.72	2.84	2.97	[2.51 ; 3.41]
M3b: Width of the lateral superior articular surface (cm)	Total sample (1)	91	3.28	0.31	3.05	3.28	3.46	[2.59 ; 4.13]
	Male	43	3.49	0.26	3.34	3.45	3.64	[2.99 ; 4.13]
	Female	48	3.09	0.22	2.97	3.09	3.25	[2.59 ; 3.49]
M4a: Length of the upper articular surface of the medial condyle (cm)	Total sample (1)	91	4.42	0.43	4.13	4.39	4.72	[3.12 ; 5.36]
	Male	43	4.71	0.34	4.50	4.71	4.88	[3.87 ; 5.36]
	Female	48	4.16	0.31	3.99	4.24	4.35	[3.12 ; 4.74]
M4b: Length of the upper articular surface of the lateral condyle (cm)	Total sample (1)	91	3.77	0.39	3.51	3.70	4.05	[2.81 ; 4.70]
	Male	43	4.02	0.35	3.75	4.01	4.29	[3.25 ; 4.70]
	Female	48	3.55	0.28	3.41	3.56	3.68	[2.81 ; 4.23]
M6: Maximum width of the lower epiphysis (cm)	Total sample (1)	91	4.31	0.35	4.05	4.30	4.53	[3.40 ; 5.17]
	Male	43	4.56	0.28	4.37	4.55	4.72	[3.98 ; 5.17]
	Female	48	4.09	0.24	3.94	4.09	4.28	[3.40 ; 4.52]

Table 2: Numerical summary of Tibia a measure used in the different regression equations, (1) for the known stature sample (n = 91)

Methods (Authors and date of publication)	Origin of the sample	Collection	Measures	Regression equations for stature estimation
Methods for a whole bone				
Olivier et al. 1978 [16]	France	French young population Olivier and Tissier Collection (1975a-1975b)	Total length of tibia (left or right side) (M1)	Male from left tibia: $72.06 + 2.5919 \times M1$ Male from right tibia: $71.32 + 2.6202 \times M1$ Female from left tibia: $80.4 + 2.3 \times M1$
Cleuvenot et al. 1993 [17]	United States of America	Trotter and Gleser (1952,1958)	Maximum length of tibia (M1a)	Male: $53.36 + 3.18 \times M1a$ Female: $42 + 3.44 \times M1a$ Undetermined sex: $51.77 + 3.19 \times M1a$
Wilson et al. 2010 [18]	United States of America	Database for Forensic Anthropology in United States: DFAUX Forensic Data Bank: FDB	Total length of tibia (M1)	Male: $62.953 + 2.891 \times M1$ Female: $80.108 + 2.351 \times M1$
Albanese et al. 2016 [19]	United States of America; Portugal	Terry Collection Lisbonne Collection Forensic Data Bank: FDB	Total length of tibia (M1)	Male: $78.999 + 2.44 \times M1$ Female: $73.985 + 2.44 \times M1$ Undetermined sex: $59.745 + 2.89 \times M1$
Nikita et al. 2017 [20]	Greece	Greek Collection	Total length of tibia (M1)	Male: $64.06 + 2.71 \times M1$ Female: $57.55 + 2.81 \times M1$ Undetermined sex: $46.4 + 3.16 \times M1$
			Physiological length or length of tibia (M1b)	Male: $72.26 + 2.6 \times M1b$ Female: $54.49 + 3 \times M1b$ Undetermined sex: $48.71 + 3.23 \times M1b$
			Morphological length or maximum length of tibia (M1a)	Male: $66.83 + 2.68 \times M1a$ Female: $54.28 + 2.94 \times M1a$ Undetermined sex: $46.21 + 3.22 \times M1a$
Percutaneous methods				
Gualdi-Russo et al. 2018 [21]	Italy	Living Italian young adults	Tibia length (M1b)	Male: $111.39 + 1.663 \times M1b$ Female: $94.45 + 1.899 \times M1b$ Undetermined sex: $80.01 + 2.366 \times M1b$
Saco-Ledo et al. 2019 [22]	Spain	Caucasus Spanish	Tibia length (M1b)	Undetermined sex: $48 + 3.29 \times M1b$

Methods for fragmented bone				
Chibba et al. 2007 [23]	Europe	Raymond A Dart Collection	Length of the upper articular surface of the medial condyle (M4a) Length of the upper articular surface of the lateral condyle (M4b) Maximum width of the upper epiphysis (M3) Width of the medial superior articular surface (M3a) Width of the lateral superior articular surface (M3b) Maximum width of the lower epiphysis (M6)	Male total skeletal height (TSH): $78.75 + (1.06 \times M3) - (0.25 \times M6)$ $+ (0.17 \times M4a)$ $- (0.23 \times M3a)$ $- (0.15 \times M3b)$ $+ (0.43 \times M4b)$ Female total skeletal height (TSH): $47.64 + (0.46 \times M3) + (0.86 \times M6)$ $+ (0.34 \times M4a)$ $- (0.35 \times M3a)$ $+ (0.81 \times M3b)$
				Male and female estimate of the living stature (ELS): Add 10 cm if TSH < 153.5 Add 10.5 cm if 153.6 < TSH < 165.4 Add 11.5 cm if TSH > 165.5

Table 3: Summary of eight methods and 28 regression equations used to estimate stature

Methods (Authors and date of publication)	Origin of the sample	Collection	Criteria of age correction factor	Age correction factor formula
Age correction factor				
Trotter et al. 1951 [8]	United States of America	Trotter and Gleser (1952, 1958) Terry Collection	Starting age for loss of stature: 30 years old Average loss rate: 0.06 cm	Correction factor = $0.06(\text{age} - 30)$ cm
Galloway 1988 [2]	United States of America	Living senior population residing in southern Arizona	Starting age for loss of stature: 45 years old Average loss rate: 0.16 cm	Correction factor = $0.16(\text{age} - 45)$ cm

Table 4: Summary of age correction factor methods

Measure		Reproducibility with Lin's concordance correlation coefficient	Pearson's linear correlation coefficient measure/stature ²
M1	Total length	0.987	0.883
M1a	Maximum length	0.994	0.887
M1b	Tibia length	0.99	0.877
M2	Condylo-astragalian length	0.992	0.858
M3	Maximum width of the upper epiphysis	0.902	0.765
M3a	Width of the medial superior articular surface area	0.828	0.597
M3b	Width of the lateral superior articular surface	0.897	0.706
M4	Maximum sagittal diameter of the tibia at the tuberosity of the tibia (TT)	0.804	0.712
M4a	Length of the upper articular surface of the medial condyle	0.648	0.776
M4b	Length of the upper articular surface of the lateral condyle	0.745	0.727
M5	Minimum transverse diameter at the TT	0.766	0.650
M6	Maximum width of the lower epiphysis	0.621	0.721
M7	Sagittal diameter of lower epiphysis	0.136	0.694
M8	Maximum transverse diameter in the middle of the diaphysis	0.748	0.626
M8a	Maximum transverse diameter at the level of the feeding foramen	0.766	0.605
M9	Maximum sagittal diameter in the middle of the diaphysis	0.966	0.714
M9a	Maximum sagittal diameter at the level of the foramen feeder	0.777	0.650
M10	Perimeter in the middle of the diaphysis	0.926	0.422
M10a	Perimeter at the level of the feeding foramen	0.895	0.672
M10b	Perimeter at the upper point of the fibular incision	Not evaluated ³	0.747

² All p-values associated with the Pearson linear correlation coefficient test were < 0.001.

³ The lack of data collected in 2014 for the M10b measure did not allow the calculation of reproducibility with Lin's concordance correlation coefficient.

Table 5: Summary table including assessment of reproducibility of measures and calculation of correlation of measures in relation to stature, known stature sample n = 91

Comparative study of stature estimation methods (sample n = 91)						
	MAE obtained for individuals according to their sex or not			Distribution of individuals		
	MAE			RESIDUAL ANALYSIS		
Equations	Undetermined sex n = 91	Males n = 43	Females n = 49	Accurate residual ≤ 3 cm	Acceptable 3 < residual ≤ 6 cm	Poor residual > 6 cm
Methods for a whole bone						
Olivier et al. 1978 [16]						
Male for left tibia	6.02	3.3	8.7	27.5%	27.5%	45%
Male for right tibia	6.2	3.4	8.9	27.5%	27.5%	45%
Female for left tibia	5.3	3.7	6.9	34%	32%	34%
Cleuvenot et al. 1993 [17]						
Male	9.5	6.8	12.3	11%	14%	75%
Female	7.9	5.6	10.2	15%	20%	65%
Undetermined sex	8.3	5.7	11.06	14%	19%	67%
Wilson et al. 2010 [18]						
Male	7.1	4.3	10.02	21%	22%	57%
Female	5.8	3.3	8.3	31%	25%	44%
Albanese et al. 2016 [19]						
Male	7.02	3.8	10.2	27%	21%	52%
Female	4.8	4.1	5.6	33%	32%	35%
Undetermined sex	5.03	3.1	6.9	33%	32%	35%
Nikita et al. 2017 [20]						
Male with M1	4.5	3.8	5.2	38%	31%	31%
Male with M1b	5.2	3.5	6.9	34%	34%	32%
Male with M1a	5.6	3.2	8.03	27%	29%	44%
Female with M1	4.4	5.6	3.6	38%	33%	29%
Female with M1b	4.1	4.7	3.9	44%	32%	24%
Female with M1a	4.3	3.5	5.1	43%	32%	25%
Undetermined sex with M1	3.9	4.1	4.1	43%	32%	25%
Undetermined sex with M1b	4.4	3.6	5.2	41%	36%	23%
Undetermined sex with M1a	5.04	3.3	6.8	31%	33%	36%
Percutaneous methods						
Saco-Ledo et al. 2019 [21]						
Undetermined sex	4.9	3.5	6.3	32%	35%	33%
Gualdi-Russo et al. 2018 [22]						
Male	9.2	4.6	13.7	23%	15%	62%
Female	5.5	5.7	5.5	32%	25%	43%
Undetermined sex	5.2	3.8	6.7	32%	34%	34%
Method for a fragmented bone						
Chibba et al. 2007 [23]						
Male/TSH	5.9	7.7	4.5	27%	30%	43%
Male/ELS	7.6	5.3	10.04	22%	25%	53%
Female /TSH	11.7	13.7	10.4	9%	9%	82%
Female/ELS	5.005	5.7	4.6	31%	35%	34%

Table 6: Evaluation and comparison of the accuracy of the different methods of stature estimation using the MAE, and the distribution of individuals in the three zones defined for the study, MAE (cm), residual (absolute value), and known stature sample n = 91

Comparative study of stature estimation methods (sample n=70)									
Equations	Distribution of individuals without addition of correction factor			Distribution of individuals with addition of the correction factor Trotter and Gleser (30 years)			Distribution of individuals with addition of the correction factor Galloway (45 years)		
	Accurate $ \text{residual} \leq 3 \text{ cm}$	Acceptable $3 < \text{residual} \leq 6 \text{ cm}$	Poor $ \text{residual} > 6 \text{ cm}$	Accurate $ \text{residual} \leq 3 \text{ cm}$	Acceptable $3 < \text{residual} \leq 6 \text{ cm}$	Poor $ \text{residual} > 6 \text{ cm}$	Accurate $ \text{residual} \leq 3 \text{ cm}$	Acceptable $3 < \text{residual} \leq 6 \text{ cm}$	Poor $ \text{residual} > 6 \text{ cm}$
RESIDUAL ANALYSIS									
Methods for a whole bone									
Olivier et al. 1978 [16]									
Male for left tibia	31%	26%	43%	40%	37%	23%	40%	34%	26%
Male for right tibia	31.5%	27%	41.5%	44.3%	31.4%	24.3%	43%	31%	26%
Female for left tibia	37%	34%	29%	43%	24%	33%	31%	26%	43%
Cleuvenot et al. 1993 [17]									
Male	13%	13%	74%	26%	24%	50%	44%	27%	29%
Female	16%	21%	63%	33%	30%	37%	52.8%	28.6%	18.6%
Undetermined sex	15.7%	18.6%	65.7%	31.4%	31.4%	37.2%	54%	20%	26%
Wilson et al. 2010 [18]									
Male	20%	27%	53%	40%	29%	31%	44%	37%	19%
Female	36%	21%	43%	32.8%	38.6%	28.6%	31%	39%	30%
Albanese et al. 2016 [19]									
Male	30%	23%	47%	41%	26%	33%	41%	36%	23%
Female	34.3%	34.3%	31.4%	34%	33%	33%	30%	19%	51%
Undetermined sex	36%	31%	33%	44%	36%	20%	30%	41%	29%
Nikita et al. 2017 [20]									
Male with M1	42.8%	28.6%	28.6%	40%	31%	29%	29%	20%	51%
Male with M1b	39%	34%	27%	43%	33%	24%	31%	29%	40%
Male with M1a	31%	29%	40%	40%	37%	23%	39%	40%	21%
Female with M1	37%	39%	24%	30%	23%	47%	16%	21%	63%
Female with M1b	44%	33%	23%	33%	27%	40%	16%	23%	61%
Female with M1a	48.6%	28.6%	22.8%	41%	33%	26%	27%	33%	40%
Undetermined sex with M1	44%	33%	23%	36%	31%	33%	21.4%	17.2%	61.4%
Undetermined sex with M1b	42.8%	38.6%	18.6%	51%	23%	26%	31%	36%	33%

Undetermined sex with M1a	33%	34%	33%	49%	36%	16%	40%	36%	24%
Percutaneous methods									
Saco-Ledo et al. 2019 [21]									
Undetermined sex	34%	36%	30%	44%	37%	19%	31.4%	41.4%	27.2%
Gualdi-Russo et al. 2018 [22]									
Male	24%	17%	59%	30%	23%	47%	37%	24%	39%
Female	34%	23%	43%	26%	29%	46%	27%	16%	57%
Undetermined sex	35.7%	35.7%	28.6%	37%	33%	30%	31.4%	24.3%	44.3%
Method for a fragmented bone									
Chibba et al. 2007 [23]									
Male/TSH	24%	29%	47%	24%	13%	63%	10%	20%	70%
Male/ELS	25.7%	28.6%	45.7%	44%	16%	40%	37%	33%	30%
Female /TSH	7%	10%	83%	0%	7%	93%	0%	0%	100%
Female/ELS	28.6%	35.7%	35.7%	21%	20%	59%	20%	11%	69%

Table 7: Summary table of the distribution of individuals in the zones defined for the study, residual (absolute value), known stature and age sample (n=70)