Article

Stepwise Multiple Regression Formulae for Estimating the Total Skeletal Height Using Patellar Measures

***Thom Kaledzera* [1, 2]**
***Amanda Alblas* [1]**
***Nadine Rampf* [1]**

Abstract: The patella is often available for biological profile estimation. However, there is a lack of information supporting the use of the patella in total skeletal height estimation. This study was thus conducted to evaluate the applicability of patellar measures in estimating total skeletal height. Fifty-two complete skeletons of known age-at-death and sex were sampled. The revised Fully's anatomical method was used to establish total skeletal height for each sampled skeleton. Additionally, six patellar measurements (maximal height, maximum breadth, maximum thickness, height of the articular facet, lateral articular facet width, and medial articular facet width) were measured using a sliding digital calliper. Pearson correlation and simple linear regression was used to evaluate the relationship between each patellar measure and total skeletal height. Stepwise multiple linear regression objectively selected combinations of patellar measures for accurate total skeletal height estimation. Each patellar measure showed a significant positive linear correlation with total skeletal height ($p < 0.001$). Maximum thickness showed the highest correlation for the right ($r = 0.814$) and left patella ($r = 0.772$). Stepwise multiple regression selected maximum thickness and maximum height as total skeletal height predictor variables for the left patella (SEE = 55.478 mm), whereas maximum thickness and height of the articular facet were chosen for the right (SEE = 50.478 mm). These results show that patellar measurements can be used to accurately estimate the total skeletal height. This information could be helpful to forensic anthropologists, especially when estimating the living stature in the absence of a complete skeleton..

1 Division of Clinical Anatomy, Department of Biomedical Sciences, Faculty of Medicine & Health Services, Stellenbosch Univ., Cape Town, South Africa

2 Department of Rehabilitation Sciences, School of Life Sciences & Allied Health Professionals, Kamuzu University of Health Sciences, Blantyre, Malawi

Introduction

The estimation of living stature is essential when developing a biological profile of unidentified human skeletal remains [1, 2]. Living stature, along with other biological profile components such as sex, age-at-death, and population affinity, is used to identify unknown human remains in forensic cases [1, 3, 4]. To establish the living stature of the deceased, knowledge of total skeletal height is crucial [5, 6, 7]. In general, an individual's living stature is estimated based on their known total skeletal height. To a large extent, this is accomplished by adding various soft tissue and age adjustment factors to the known total skeletal height [5, 6, 7]. If not known, the total skeletal height of the deceased can be estimated using either the mathematical method [2, 8] or the anatomical method [6, 7, 9, 10, 11].

The anatomical method was first introduced by Dwight in 1894, later modified by Fully in 1956, and more recently by Raxter *et al.,* in 2006 [5, 6, 12]. This method determines the total skeletal height of human remains by summing the measurements from all skeletal components that provide a substantial contribution to an individual's living stature. The measurements include the cranial height, the maximum vertebral height of C2 - S1, the physiological length of the femur, the physiological length of the tibia, and the talus to calcaneal height [5, 6]. To estimate living stature from the calculated total skeletal height, Fully (1956) and Raxter *et al.,* (2006) recommended soft tissue correction factors [5, 6]. However, the universal applicability of the soft tissue correction factors presented by Fully (1956) and Raxter *et al.,* (2006) has been questioned by some authors [5, 6]. For example, Bidmos and Manger (2012), Brits *et al.,* (2017) and Loubser *et al.,* (2022) all observed that the soft tissue correction factors recommended by Fully (1956) and Raxter *et al.,* (2006) underestimated living stature when applied to a South African population [9, 10, 11]. To address this challenge, Bidmos and Manger (2012), Brits *et al.,* (2017), and Loubser *et al.,* (2022) presented new soft tissue correction factors for use in a South African population.

The anatomical method is widely regarded as being tedious and complicated, as it requires the availability of a nearly complete skeleton [5]. In comparison to this method, the mathematical method uses linear regression formulae to determine the deceased's total skeletal height from measurements of the available skeletal components. The mathematical method is simpler to use and does not require a whole skeleton to be present [8, 13, 14]. However, the use of mathematical methods is limited to the population, age, and sex groups from which the regression formulae were derived [15]. In the absence of a complete skeleton, regression formulae derived from measurements of long bones are often preferred [2, 14].

The most recommended metrics when attempting to calculate the total skeletal height using the mathematical method include physiological lengths of the femur and tibia [8, 14, 16, 17, 18]. This is due to the significant influence that femur and tibia lengths have on the individual's total skeletal height. Regression functions developed from femur and tibia measures are generally considered to have a lower standard error of estimate (SEE), implying accuracy in total skeletal height estimation [2]. For example, Dayal *et al*., (2008) reported a SEE of 2.64 cm when using the physiological length of the femur to estimate the total skeletal height in a South African population [2].

Although long bones are often favoured when estimating the total skeletal height of an individual, they may not always be available for analysis in some forensic cases. Human skeletal components may be lost or show a range of post-mortem changes that make them unsuitable for anthropological analysis [1, 4, 19]. This may pose challenges. To address the challenge, previous reports have recommended using regression formulae developed from fragmented components of long bones [18]. However, the SEE obtained from these regression formulae is considered to be high [18]. For example, Chibba and Bidmos (2007) reported a SEE of 6.52 - 6.71 cm in males and 5.20 - 5.94 cm in females while using tibia fragments to estimate total skeletal height in a South African population [18]. Other alternative formulae considered when estimating total skeletal height, include regression equations derived from short and sesamoid bones such as the metatarsal length [20], metacarpal length [21, 22], vertebral height [2], calcaneal measures [23, 24], and talus measurements [24]. Likewise, the SEE attained by these skeletal components is considerably higher than those reported for long bones.

Compared to long bones, short and sesamoid bones are said to be more susceptible to being lost or overlooked at a forensic scene. However, other evidence also suggests that short and sesamoid bones are more resilient to post-mortem changes and more likely to be found intact in forensic cases [23, 25, 26]. The patella is one such sesamoid bone in the human body, renowned for its high resistance to post-mortem changes [25, 26, 27]. Although the patella has previously been used to estimate components of a biological profile, most notably sex [28] and age-at-death [29, 30], not much is known regarding the use of patellar measurements in estimating the total skeletal height. This information may be helpful to forensic practitioners, especially when dealing with cases where an extremely limited number of human skeletal components have been recovered for anthropological analysis. Thus, this study was conducted to assess the usefulness of patellar measurements in the estimation of the total skeletal height. Additionally, the current study endeavoured to develop patellar linear regression formulae that may be considered when estimating the total skeletal height in the absence of a complete skeleton.

Materials and Methods

Study setting and sample composition

Fifty-two complete skeletons of known age-at-death and sex were sampled from the skeletal collection housed in the Division of Clinical Anatomy at Stellenbosch University in South Africa. The minimum sample size calculated using G-power version 3.1.9.4, was 55 complete skeletons. However, only 52 complete skeletons met the inclusion and exclusion criteria for this study. All skeletons with missing, fragmented, or commingled components as well as those displaying signs of pathology or taphonomy were excluded from the study. Male skeletons constituted 63.5% of the sample, while females made up the remaining 36.5%. The age-at-death of skeletons in this sample varied from 22 - 86 years, presenting with a mean age-at-death of 52.06±18.166 years.

Total skeletal height of sampled skeletons

The database of the skeletal collection in which this study was conducted does not contain information on the living stature or the total skeletal height of curated skeletons. As a result, the revised Fully's anatomical method [5] was used to establish the total skeletal height of each sampled skeleton. From each sampled skeleton, the cranial height, maximum vertebral height (C2-S1), physiological length of the femur, physiological length of the tibia, as well as the height of talus and calcaneus were measured following the guidelines described by Raxter *et al.*, in 2006 [5] and shown in Table 1. These measurements were then summed to establish the total skeletal height for each skeleton in the sample. In keeping with Fully's original method, the average value of the left and right measurements was used for all paired skeletal components (i.e., femur, tibia, talus, and calcaneus).

Measure	Description
Maximum cranial height	The height of the cranium as measured from the bregma to the basion using a spreading calliper.
C2 maximum vertebral height	Maximum height as measured from the most superior point of the odontoid process (dens) to the most inferior point on the anteroinferior rim of the vertebral body using a sliding digital calliper.
C3 - C7 maximum vertebral height	Maximum height of each cervical vertebra (C3 - C7) as measured in the anterior third of each vertebral body using a sliding digital calliper.
T1 - T12 maximum vertebral height	Maximum height of each thoracic vertebra as measured anterior to the rib articular facet using a sliding digital calliper.
L1 - L5 maximum vertebral height	Maximum height of each lumbar vertebrae as measured anterior to the pedicles using a sliding digital calliper.
S1 maximum vertebral height	Maximum height of the first sacral vertebra (S1) as measured with a sliding digital calliper from the anterior-superior rim of the S1 body to the point of S1 and S2 articulation.
Physiological length of femur	Maximum distance, as measured with an osteometric board, between the horizontal line passing through the most superior point of the femur's head and the horizontal line connecting its two condyles.
Physiological length of tibia	Maximum measurement made with an osteometric board between the medial malleolus's most inferior point and the lateral condyle of the tibia's most superior point (excluding the intercondylar eminence).
Height of talus and calcaneus	Maximum distance between the most superior point of the talus and the most inferior point of the calcaneus, measured on an osteometric board whilst the two bones are articulated.

Table 1

Measurement protocol for total skeletal height estimation, as described by Raxter et al., (2006) [5]

Patellar measurements

Six measurements, namely: maximum height (MAXH), maximum breadth (MAXB), maximum thickness (MAXT), height of the articular facet (HAF), lateral articular facet width (LAFW), and medial articular facet width (MAFW) were measured from each patella using a sliding digital calliper as outlined in Table 2 and Figure 1. The patellar measurement protocol used in this study was first described by Knussmann and Martin in 1988 [31] and later revised by Dayal and Bidmos in 2005 [27].

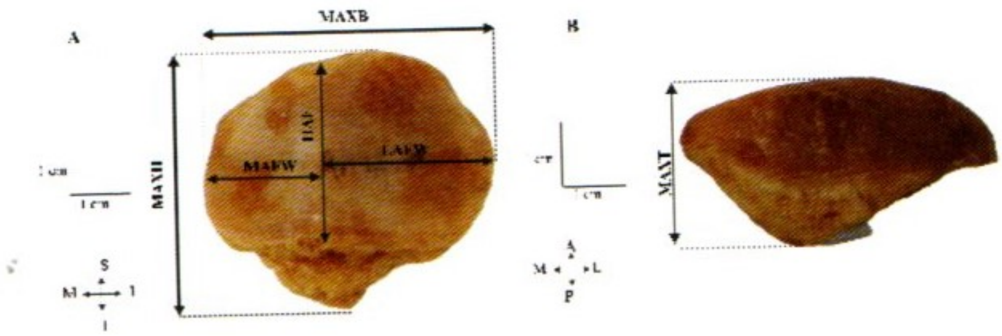

Figure 1

Locations for measuring attributes of the patellar bone.

Patellar Measure	Description
Maximum height	Maximum vertical distance between the patella bone's most superior point at its base and its most inferior point at the apex
Maximum breadth	Maximum horizontal distance measured between the most medial and lateral projecting points of the patella bone
Maximum thickness	Maximum measurement obtained between the most anterior and posterior points of the patella bone
Height of the articular facet	Maximum height measurement obtained at the median ridge of the patella bone
Medial articular facet width	Maximum horizontal distance of medial articular facet, measured between the mid-point of the median ridge and the corresponding point on the medial edge of the patella bone
Lateral articular facet width	Maximum horizontal distance of the lateral articular facet, measured between the mid-point of the median ridge and the corresponding point on the lateral edge of the patella bone

Table 2

A patellar measurement protocol as described by Dayal and Bidmos (2005) [27]

Intra-observer and inter-observer reliabilities

To assess the repeatability of all measurements used in this study, 12% of the sample was randomly selected and remeasured by the principal investigator and an independent researcher. An intraclass correlation coefficient was used to evaluate the level of agreement between these independent measurements. In addition, a paired student T-test was used to compare independent measurements and assess for statistically significant differences. Intraclass correlation coefficients were interpreted based on reporting guidelines recommended by Koo and Li in 2016 [32]. Koo and Li (2016) described an intraclass correlation coefficient of less than 0.5 as demonstrating poor reliability, 0.5 – 0.75 as moderate reliability, 0.75 – 0.9 as good reliability and a coefficient greater than 0.9 as demonstrating an excellent level of reliability.

Data analysis

Statistical Package for Social Sciences software (SPSS version 28) was used to analyse the data. A p-value of less than 5% was considered statistically significant. The relationship between each patellar measurement and total skeletal height was assessed using the Pearson correlation test. A simple linear regression analysis was used to describe the linear relationship between each patellar measurement and total skeletal height. From the simple linear regression analysis, stepwise multiple regression analysis was conducted. A forward stepwise selection was used as an objective screening procedure for deciding which patellar measurements to include in the final multiple regression model. In this type of analysis, variables were sequentially chosen to be included in the final prediction model based on the SEE attained at each step. The lowest SEE, in this case, indicates a high accuracy of prediction. A p-value of 0.05 was set as a stopping rule. Thus, the procedure was stopped when there were no remaining variables with a p-value of less than 0.05. The stepwise multiple regression analysis in this study was conducted based on the following assumptions: 1) linear relationship between each patellar measure and total skeletal height, and 2) normality in the distribution of the outcome variable (i.e., total skeletal height). The normal distribution of total skeletal height was assessed using a Shapiro-Wilk test (normal distribution, $p > 0.05$).

Results

Total skeletal height of sampled skeletons

Independent measurements from the cranium, vertebrae (C2 – S1), femur, tibia, talus and calcaneus were compared to assess their repeatability (Tables 3 and 4). There was no statistically significant difference (T-test, $p > 0.05$) between the measurements obtained from the initial observation and those made by the primary researcher during the second observation. Similarly, no statistically significant difference was observed between measurements taken by the primary researcher and those made by an independent researcher (T-test, $p > 0.05$). In addition, all independent measurements made during the initial and second observations displayed intra-observer and inter-observer reliability that varied from a moderate level of measurement agreement to an excellent level of agreement. Table 3 displays the descriptive statistics for the measurements of cranial height, cervical vertebral height, and thoracic vertebral height. Table 4 displays the descriptive statistics for the measurements of lumbar vertebrae, S1, femur, tibia, talus, and calcaneus.

Measurement	Mean ± SD (cm)	Range (cm)	Intra-observer reliability (ICC)	Inter-observer reliability (ICC)
Cranial height	13.61±0.62	12.1 – 15.4	0.996	0.948
C2 maximum height	3.75±0.34	2.97 – 4.34	0.961	0.954
C3 maximum height	1.34±0.15	1.02 – 1.60	0.902	0.981
C4 maximum height	1.32±0.16	1.02 – 1.69	0.927	0.946
C5 maximum height	1.26±0.15	0.99 – 1.62	0.691	0.920
C6 maximum height	1.29±0.15	0.94 – 1.64	0.823	0.873
C7 maximum height	1.43±0.14	1.16 – 1.71	0.963	0.955
T1 maximum height	1.61±0.13	1.35 – 1.91	0.904	0.912
T2 maximum height	1.77±0.15	1.45 – 2.08	0.856	0.839
T3 maximum height	1.78±0.16	1.31 – 2.10	0.868	0.952
T4 maximum height	1.82±0.16	1.37 – 2.21	0.702	0.887
T5 maximum height	1.86±0.17	1.46 – 2.21	0.781	0.804
T6 maximum height	1.92±0.16	1.59 – 2.24	0.729	0.690
T7 maximum height	1.96±0.17	1.67 – 2.31	0.624	0.570
T8 maximum height	1.99±0.17	1.64 – 2.37	0.646	0.620
T9 maximum height	2.05±0.19	1.55 – 2.51	0.852	0.840
T10 maximum height	2.16±0.18	1.81 – 2.55	0.752	0.749
T11 maximum height	2.26±0.18	1.91 – 2.64	0.698	0.709
T12 maximum height	2.39±0.20	2.03 – 2.78	0.750	0.933

Table 3

Descriptive statistics for the measurements of cranial height, cervical vertebral height, and thoracic vertebral height. ICC: Intraclass Correlation Coefficient

Measurement	Mean ± SD (cm)	Range (cm)	Intra-observer reliability (ICC)	Inter-observer reliability (ICC)
L1 maximum height	2.55±0.19	2.12 – 2.94	0.707	0.914
L2 maximum height	2.65±0.20	2.28 – 3.18	0.699	0.852
L3 maximum height	2.73±0.23	2.35 – 3.32	0.894	0.941
L4 maximum height	2.75±0.22	2.31 – 3.17	0.775	0.945
L5 maximum height	2.78±0.24	2.13 – 3.25	0.696	0.636
S1 maximum height	3.07±0.29	2.39 – 3.67	0.697	0.616
Femur physiological length	43.90±2.86	37.3 – 51.35	0.973	0.937
Tibia physiological length	36.85±2.62	31.25 – 42.35	0.960	0.969
Height of talus and calcaneus	6.62±0.65	5.3 – 8.1	0.924	0.640

Table 4

Descriptive statistics for the measurements of lumbar vertebrae, S1, femur, tibia, talus and calcaneus.ICC; Intraclass Correlation Coefficient

Cranial height in this sample, varied from 12.1 cm – 15.4 cm, with a mean value of 13.61±1.02 cm (Table 3). Among all the vertebrae measured (C2 – S1), S1 displayed the greatest mean value (3.07±0.29 cm) followed by L5 vertebral height (2.78±0.24 cm) (Table 3 and Table 4, respectively). The lowest vertebral height measurement was observed at C5, which demonstrated a mean value of 1.26±0.15 cm (Table 3). Measurements of the physiological length of the femur ranged from 37.3 cm – 51.35 cm (mean = 43.80±2.86 cm) whereas the tibia's physiological length varied from 31.25 cm – 42.35 cm (mean = 36.85±2.62 cm) (Table 4). The height of the talus and calcaneus was measured to range between 5.3 cm and 8.1 cm, with a mean value of 6.62±0.65 cm (Table 4).

After summing measurements obtained from the cranium, vertebrae (C2 – S1), femur, tibia, talus and calcaneus, the total skeletal height for the sample as a whole ranged from 129.17 cm - 173.37 cm (mean =151.51±9.26 cm). The total skeletal height was normally distributed (Shapiro-Wilk test, $p = 0.727$). In males, total skeletal height varied between 144.37 cm - 173.37 cm (mean = 155.55±7.23 cm) as shown in Figure 2. In females, however, the total skeletal height ranged from 129.17 cm - 157.56 cm (mean =144.62±8.34 cm). The mean difference between total skeletal height in males and females was statistically significant (T-test, $p < 0.001$). In addition, a weak, positive linear correlation was observed between age-at-death and total skeletal height as shown in Figure 3 ($r = 0.224$). However, the correlation was not statistically significant ($p = 0.138$).

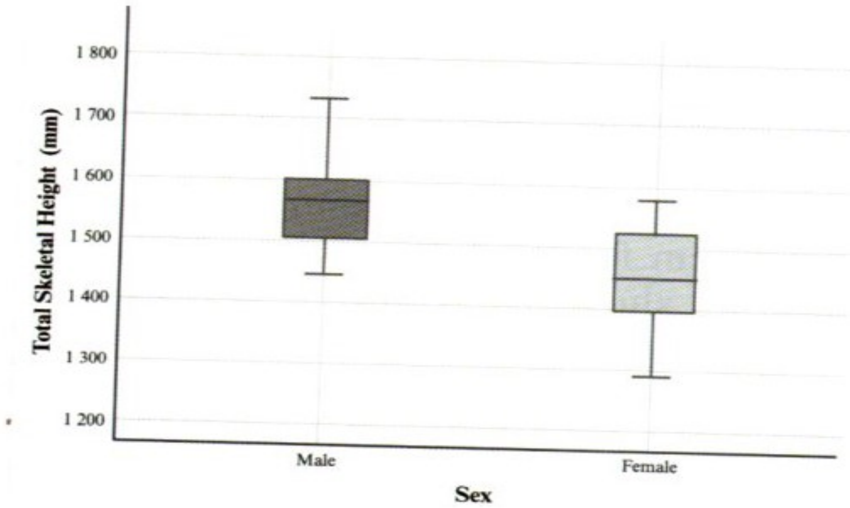

Figure 2

A diagram showing the distribution of total skeletal height in males and females.

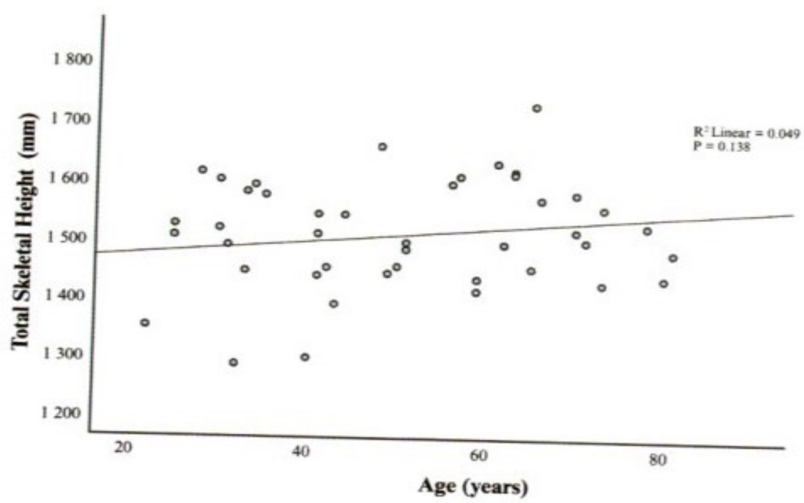

Figure 3

A scatter plot illustrating a weak, positive linear correlation between age-at-death and total skeletal height.

Descriptive statistics of patellar measurements

No statistically significant difference was observed between patellar measurements from the initial observation and those made by the primary investigator during the second observation (T-test, $p > 0.05$). Likewise, no statistically significant difference was observed between the measurements taken by the primary researcher and an independent investigator (T-test, $p > 0.005$). Additionally, the patellar measurements showed intra-observer and inter-observer reliabilities that varied from a good level of measurement agreement to an excellent level of agreement (ICC = 0.573 – 0.980).

All six patellar measurements from both sides were normally distributed (Shapiro-Wilk test, $p > 0.05$) and showed an equal variance between males and females (Levene's test, $p > 0.05$). MAXB showed the highest measurement values, with a mean value of 4.19±0.45 cm for the left patella and 4.20±0.46 cm for the right patella as shown in Table 5. However, MAXT was the lowest, presenting with a mean value of 2.03±0.25 cm for the left patella and 2.00±0.26 cm for the right patella. All six patellar measurements from both sides showed a positive linear correlation with total skeletal height as shown in Figure 4. The correlation in each case was statistically significant ($p < 0.001$). For the left patella, MAXT ($r = 0.772$, $p < 0.001$) and MAXB ($r = 0.772$, $p < 0.001$) displayed the highest level of correlation, whereas HAF ($r = 0.621$, $p < 0.001$) showed the lowest. Similarly, for the right patella, the highest correlation was observed in MAXT ($r = 0.814$, $p < 0.001$) and MAXB ($r = 0.800$, $p < 0.001$) and the lowest for HAF ($r = 0.667$, $p < 0.001$).

Measure	Left patella bone		Right patella bone	
	Mean ± SD	**Range (cm)**	**Mean ± SD**	**Range (cm)**
MAXH	4.06±0.51	2.73 – 5.02	3.99±0.53	2.75 – 5.08
MAXB	4.19±0.45	3.19 – 5.06	4.20±0.46	3.13 – 5.06
MAXT	2.03±0.25	1.48 – 2.60	2.00±0.26	1.43 – 2.53
HAF	2.96±0.34	2.07 – 3.96	2.93±0.33	2.19 – 3.76
LAFW	2.50±0.25	1.85 – 3.02	2.50±0.23	1.94 – 3.03
MAFW	2.08±0.25	1.37 – 2.56	2.05±0.24	1.56 – 2.53

Table 5

Descriptive statistics of the left and right patellar measures. MAXH: maximum height; MAXB: maximum breadth; MAXT: maximum thickness; HAF: height of the articular facet; LAFW: lateral articular facet width; MAFW: medial articular facet

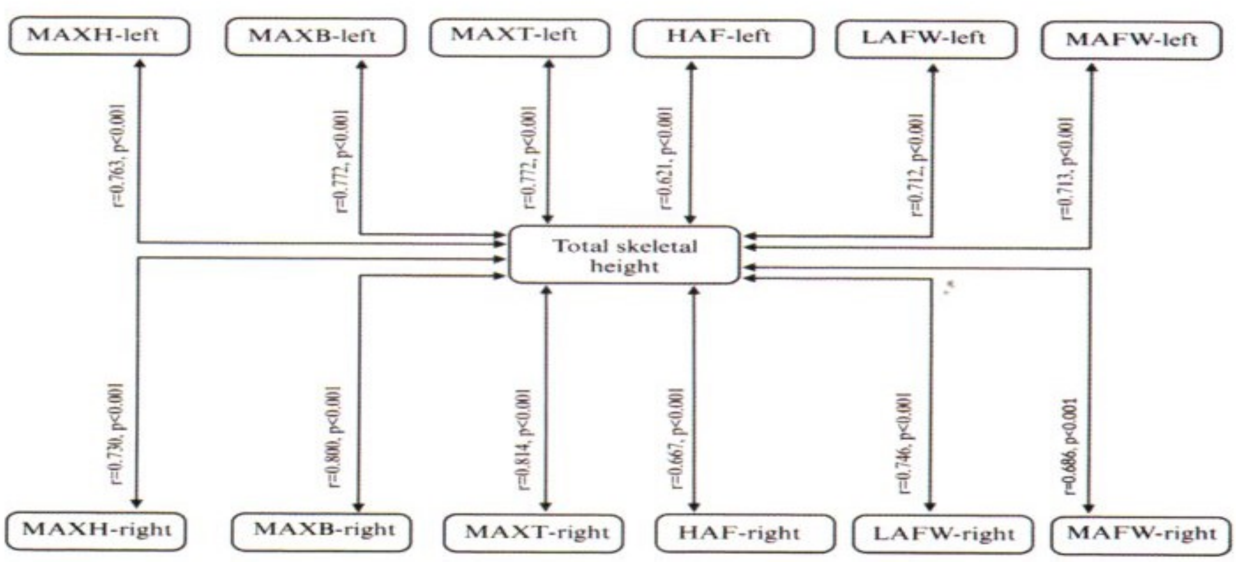

Figure 4

Image illustrating the correlation between total skeletal height and patellar measures. MAXH: maximum height; MAXB: maximum breadth; MAXT: maximum thickness; HAF: height of the articular facet; LAFW: lateral articular facet width; MAFW:

medial articular facet (Created with Biorender.com).

Linear regression analysis of patellar measures and total skeletal height

A simple linear regression analysis was applied between each of the six patellar measures from both sides and total skeletal height. Results are shown in Table 6 (left patellar) and Table 7 (right patellar). All univariate functions derived following the simple linear regression analysis were statistically significant ($p < 0.001$). Among all the univariate functions derived, MAXT displayed the lowest SEE, both for the left (SEE = 5.95 cm, R^2 = 0.595) and the right patella (SEE = 5.51 cm, R^2 = 0.662). On the other hand, HAF showed the highest SEE for both the left (SEE = 7.34 cm, R^2 = 0.372) and the right patella (SEE=7.06 cm, R^2=0.445). In the stepwise multiple regression analysis, MAXT and MAXH were selected as total skeletal height predictor variables for the left patella (SEE = 5.55 cm, R^2 = 0.657), whereas MAXT and HAF were selected for the right patella (SEE = 5.09 cm, R^2 = 0.718). All the remaining variables failed to satisfy the set selection criteria, as they demonstrated a p-value > 0.05 in step 3 of the stepwise analysis as shown in Table 6 and Table 7.

Table 6 (Next Page)

Stepwise regression analysis between left patellar measures and total skeletal height. †: selected in step 1; ‡: selected in step 2; cm: centimeters; SEE; Standard Error of Estimate

Steps	Models	R-Square	SEE (cm)	Unstandardized Coefficients	t-value	p-value
Step 1	1. Constant	0.583	6.05	95.13	13.130	<0.001
	MAXH			13.88	7.842	<0.001
	2. Constant	0.595	5.96	85.69	10.412	<0.001
	MAXB			15.72	8.044	<0.001
	3. Constant	0.595	***5.95*†**	93.64	12.924	<0.001
	MAXT			28.47	***8.047*†**	<0.001
	4. Constant	0.372	7.34	101.00	10.444	<0.001
	HAF			17.05	5.256	<0.001
	5. Constant	0.507	6.57	85.04	8.564	<0.001
	LAFW			26.55	6.726	<0.001
	6. Constant	0.508	6.57	96.80	11.840	<0.001
	MAFW			26.34	6.740	<0.001
Step 2	7. Constant	0.657	***5.55*‡**	87.82	12.423	<0.001
	MAXT			16.52	3.042	0.004
	MAXH			7.41	***2.773*‡**	0.008
	8. Constant	0.644	5.65	84.57	10.819	<0.001
	MAXT			15.43	2.440	0.019
	MAXB			8.50	2.434	0.019
	9. Constant	0.619	5.84	87.04	10.657	<0.001
	MAXT			23.55	5.138	<0.001
	HAF			5.60	1.642	0.108
	10. Constant	0.613	5.89	86.29	9.686	<0.001
	MAXT			21.33	3.429	0.001
	LAFW			8.73	1.389	0.172
	11. Constant	0.616	5.87	89.77	11.844	<0.001
	MAXT			20.99	3.479	0.001
	MAFW			9.18	1.519	0.136
Step 3	12. Constant	0.680	5.42	82.43	10.890	<0.001
	MAXT			9.48	1.422	0.162
	MAXH			5.93	2.158	0.037
	MAXB			6.14	1.742	0.089
	13. Constant	0.658	5.61	86.80	11.074	<0.001
	MAXT			16.30	2.948	0.005
	MAXH			6.88	2.167	0.036
	HAF			1.22	0.317	0.753
	14. Constant	0.666	5.54	82.80	9.761	<0.001
	MAXT			12.01	1.747	0.088
	MAXH			6.97	2.582	0.013
	LAFW			6.38	1.067	0.292
	15. Constant	0.663	5.57	86.19	11.743	<0.001
	MAXB			13.43	2.058	0.046
	MAXH			6.74	2.411	0.020
	MAFW			5.12	0.858	0.396

Steps	Models	R-Square	SEE (cm)	Unstandardized Coefficients	t-value	p-value
Step 1	1. Constant	0.533	6.47	100.41	13.634	<0.001
	MAXH			12.80	7.000	<0.001
	2. Constant	0.641	5.68	82.60	10.438	<0.001
	MAXB			16.42	8.757	<0.001
	3. Constant	0.662	***5.51*†**	92.15	14.129	<0.001
	MAXT			29.65	***9.175*†**	<0.001
	4. Constant	0.445	7.06	96.45	10.216	<0.001
	HAF			18.80	5.869	<0.001
	5. Constant	0.556	6.31	87.47	9.972	<0.001
	LAFW			25.61	7.344	<0.001
	6. Constant	0.470	6.89	97.05	10.940	<0.001
	MAFW			26.58	6.180	<0.001
Step 2	7. Constant	0.686	5.37	88.82	13.424	<0.001
	MAXT			22.64	4.537	<0.001
	MAXH			4.346	1.810	0.077
	8. Constant	0.704	5.21	82.73	11.390	<0.001
	MAXT			17.49	3.008	0.004
	MAXB			8.04	2.458	0.018
	9. Constant	0.718	***5.09*‡**	80.44	11.094	<0.001
	MAXT			23.45	6.387	<0.001
	HAF			8.24	***2.901*‡**	0.006
	10. Constant	0.683	5.39	85.47	11.375	<0.001
	MAXT			22.23	4.103	<0.001
	LAFW			8.61	1.686	0.099
	11. Constant	0.684	5.39	86.43	11.970	<0.001
	MAXT			24.13	5.319	<0.001
	MAFW			8.18	1.695	0.097
Step 3	12. Constant	0.718	5.15	80.49	10.836	<0.001
	MAXT			23.31	4.860	<0.001
	HAF			8.13	2.158	0.037
	MAXH			0.14	0.046	0.964
	13. Constant	0.733	5.01	76.95	10.256	<0.001
	MAXT			16.97	3.032	0.004
	HAF			6.41	2.107	0.041
	MAXB			5.20	1.517	0.137
	14. Constant	0.731	5.03	76.03	9.708	<0.001
	MAXT			18.07	3.421	0.001
	HAF			7.67	2.702	0.010
	LAFW			6.74	1.400	0.169
	15. Constant	0.730	5.04	77.11	10.134	<0.001
	MAXB			19.83	4.367	<0.001
	HAF			7.58	2.655	0.011
	MAFW			6.09	1.330	0.191

Table 7

Stepwise regression analysis between right patellar measures and total skeletal height. †: selected in step 1; ‡: selected in step 2; cm: centimeters; SEE; Standard Error of Estimate

Discussion

The primary aim of this study was to evaluate the applicability of patellar measurements in estimating the total skeletal height of an individual. All patellar measurements from both sides displayed a strong, positive linear correlation with total skeletal height. The correlation in each case was statistically significant, suggesting that patellar measures substantially change with an increase in total skeletal height. This observation led to the development of linear regression formulae that may be considered when estimating the total skeletal height of unidentified human remains, especially in cases where a complete skeleton is not available for analysis.

The epiphyseal plate, commonly referred to as a "growth plate," is an important anatomical feature that ensures the continued longitudinal development of juvenile skeletal components [33]. An open epiphyseal plate in children enables a continued lengthening of skeletal components which further facilitates an age-related increase in the total skeletal height of a child [33 – 36]. In adults, however, epiphyseal plates ossify, suggesting the attainment of skeletal maturity [33 – 35]. Given this, it can be argued that the total skeletal height of an adult does not significantly change with ageing. However, limited data exist to support or dispute this claim.

While assessing the relationship between age-at-death and total skeletal height in adults, the current study noted a weak, positive linear correlation ($r = 0.222$) between total skeletal height and age-at-death, which was not statistically significant ($p = 0.062$). From a statistical point of view, this finding suggests that the total skeletal height of an adult does not change with ageing. The observation is not surprising considering that epiphyseal plates in adults are closed. However, some authors have argued that while an adult's total skeletal height does not change with age, their living stature does significantly decline with age [6, 37, 38]. Age-related loss of intervertebral disc height, mainly in the lumbar spine, is one of the variables that have been linked to this decline [39, 40, 41]. These arguments in general, serve as a foundation for applying age correction factors to the total skeletal height when determining an individual's living stature.

Long bones, in particular the femur and tibia, provide substantial contributions to the total skeletal height of an individual. As a result, they are expected to display a stronger correlation with total skeletal height in comparison to smaller skeletal components, such as the patella [2, 42, 43, 44]. Dayal *et al.,* (2008) studied the relationship between measures of long bones (i.e., femur, tibia, fibula, radius, ulna and humerus) and total skeletal height using a sample of skeletons from South Africa [2]. A strong, positive linear correlation was reported (r= 0.83 – 0.93), with femur and tibia lengths showing the highest correlations. Similarly, in the current study, all patellar measurements from both sides showed a strong, positive linear correlation with total skeletal height. The level of correlation ranged from 0.621 – 0.772 for the left patella and 0.667 – 0.814 for the right patella. In comparison to previous reports on long bone measures, a lower level of correlation was observed in the current study [2, 14, 16]. This observation is not surprising, considering the relatively small contribution that patellar measures make toward an individual's total skeletal height. However, the correlations noted in the current study are higher than that previously reported on measurements of the lumbar spine [2] and calcaneus [23, 45]. In general, these findings establish a direct relationship between patellar measurements and total skeletal height. Essentially, the findings provide a solid foundation for developing linear regression formulae that may assist with total skeletal height estimation from patellar measurements.

When establishing a biological profile of unknown human remains for forensic application, accuracy and reliability are crucial factors to consider. For linear regression functions, the level of accuracy is mostly explained by the SEE provided [23]. In essence, the lower the SEE provided, the higher the accuracy of the regression function being used. Linear regression functions derived from measurements of long bones are widely considered as being more accurate at estimating total skeletal height due to their low SEE [2, 14, 43, 44, 46]. This is not surprising given the strong correlation that exists between measures of long bones and the total skeletal height. As a result, when accessible, long bones are frequently preferred for determining the total skeletal height of an individual. In the current study, the stepwise multiple regression analysis of patellar measures and total skeletal height provided a SEE of 5.09 cm for the right patella and 5.55 cm for the left patella. In comparison to other regression functions derived from measures of long bones [27], the current study's SEE is higher. However, the SEE noted in the current study is similar to those reported from measurements of the metatarsal [20], metacarpal [21, 22], calcaneus [23, 45], talus [24], lumbar spine [2], and fragmented femur [47]. This finding supports the conclusion that patellar measurements can be used to accurately estimate the total skeletal height of unidentified human remains for forensic purposes.

Previous reports on different skeletal components have shown that combining multiple measurements improves the level of accuracy when estimating an individual's total skeletal height [2, 23, 45]. For example, Dayal *et al.*, (2008) reported a SEE of 1.75 – 2.49 cm for multivariate regression functions and 2.40 – 5.21 cm for univariate regression functions [2]. Based on these observations, multivariate linear regression functions are preferred for total skeletal height estimation over univariate functions. The current study observed that the SEE attained from univariate regression functions (SEE = 5.95 - 6.57 cm left patella, SEE = 5.51 - 7.06 cm right patella) was higher than what the stepwise multiple regression functions showed (SEE = 5.55 cm left patella, SEE = 5.09 cm right patella). This finding agrees with reports from authors who studied measures of the other skeletal components [2, 23, 45]. It is therefore advised to use a combination of patellar measurements for determining the total skeletal height (MAXT and MAXH for the left patella, MAXT and HAF for the right patella) as it yields a higher accuracy of the estimate.

It is well-known that the total skeletal height largely assists with the determination of living stature in forensic cases. To establish the living stature of an individual, soft tissue correction factors are applied to the known total skeletal height [5, 6]. However, these soft tissue correction factors are widely considered to be sex and population-specific [9, 10, 11]. Bidmos and Manger (2012), Brits *et al.,* (2017), and Loubser *et al.,* (2022) have presented updated soft tissue correction factors and recommended their use in a South African population [9, 10, 11]. These updated soft tissue correction factors are thus, of great value to the application of findings from this study. By applying these soft tissue correction factors, total skeletal height determined from the patellar measurements may be converted into an individual's living stature. This makes it possible to use the patella to help identify unknown human remains.

Study limitations

The findings of this study have to be interpreted based on the following limitations. For ethical reasons, the sample used in this study was limited to skeletons derived from individuals who had donated their bodies and given consent for their use in research. This limitation affected the sample size of this study.

Additionally, considering that most of the donated cadavers were obtained from individuals residing in the Western Cape, the results of the study cannot be generalized to an entire South African population. Furthermore, this study does not establish a direct correlation between living stature and patella measurements because living stature data were not available for this study. Thus, future studies should assess the direct relationship between patella measures and living stature using population groups where living stature is known.

Conclusion

Findings from this study have established the direct relationship between patellar measurements and total skeletal height. Additionally, the results have also shown that patellar measurements may estimate total skeletal height with a similar level of accuracy when compared to linear regression functions derived from measurements of the calcaneus, talus, metatarsal, lumbar spine, and metacarpal. Forensic anthropologists may find this information useful, in particular when attempting to estimate the total skeletal height in a context where an extremely limited number of human skeletal components have been recovered for analysis. The results, however, should be interpreted with caution, due to the limited sample that was used.

Ethics approval and consent to participate in the study

All the skeletal specimens used in this study were obtained from individuals who willingly donated their bodies to the Division of Clinical Anatomy at Stellenbosch University and also consented to their use in research. The study was conducted in accordance with the code of ethics from the World Medical Association Declaration of Helsinki [48] and the South African Human Tissue Act [49]. Ethics clearance was obtained from the Health Research Ethics Committee at Stellenbosch University (ethics clearance number: S22/04/64). Additional approval to conduct this study was obtained from the Division of Clinical Anatomy at Stellenbosch University.

Availability of data and materials

Datasets used and analyzed during the current study are available from the corresponding author upon reasonable request. The use of this data for prospective future research projects must