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TECHNICAL NOTE

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Body Height Estimation Based on Dimensions of Sacral and Coccygeal Vertebrae*

ABSTRACT: This study is to evaluate whether it is possible to predict living stature from sacral and coccygeal vertebral dimensions. Individual vertebral body heights, sacral height (SH), and sacrococcygeal height (SCH) were recorded from the magnetic resonance images of 42 adult males. Sum of the heights of five sacral vertebrae (ΣS), the first four coccygeal vertebrae (ΣC), and the total height of the sacral and the first four coccygeal vertebrae together (ΣSC) were also recorded. Linear regression equations for stature estimation were produced using the above mentioned variables. The regression equations were constructed and tested by using jack-knife procedure. Statistical analyses indicated that the combined variables (SH, SCH, ΣS, ΣC, ΣSC) were more accurate predictors of stature than the heights of individual vertebrae. The results of the study pointed out that the equations derived from sacrococcygeal dimensions perform somewhat better than ones based on foot and head variables, but worse than those based on long-bone length. As a conclusion, the dimensions of sacral and coccygeal vertebrae could be used for stature estimation when long bones are not available.

KEYWORDS: forensic science, forensic anthropology, stature estimation, sacral vertebrae, coccygeal vertebrae

Victim identification is one of the most challenging aspects of forensic science. The four main attributes of biological identity that forensic investigators try to determine are sex, age, ethnic background and stature. Stature is positively correlated with long-bone length, and the most accurate estimates of body height are obtained when undamaged long bones of known sex and ethnic identity are available. As with dry bones, measurements of limb segments in living persons and in cadavers also yield accurate body height estimations. Several formulae have been derived for different populations, and even for individuals of certain age and sex groups (1,2). However, it is not always possible to obtain intact long bones, especially in mass disasters. In such cases, incomplete bones or bones other than long bones must be used for stature estimation. To date, measurements of the talus and calcaneus (3), metacarpal (4,5) and metatarsal bones (6), phalanges (7), scapulae (8), the vertebral column (9), and incomplete body parts such as the hand (10–12), foot (13,14), head (15) and dismembered lower limbs (16) have all been used to estimate body height. Still, none of these methods is as accurate as the method involving long bones.

The vertebral column is of special importance with respect to stature estimation. Tibbets (9), Terazawa et al. (17,18), and Jason and Taylor (19) calculated stature based on the lengths of the cervical, thoracic and lumbar segments of the spine or individual vertebrae. Lundy (20) investigated how sacralization affects estimation of living stature. However, no study to date has examined estimation of body height based on measurements of the sacral and coccygeal vertebrae. Our aim in this investigation was to establish new regression equations for stature prediction based on the dimensions of sacral and coccygeal vertebrae for forensic cases.

Subjects and Methods

All measurements were recorded from magnetic resonance imaging (MRI) scans of 42 male subjects who underwent endoluminal coil MRI for local staging of tumors after diagnosis with prostate or rectal carcinoma. The patients ranged in age from 45 to 81 years, and the mean age was 62.02 years (SD = 8.18). All imaging was done in an MRI unit with a 1.5-Tesla magnetic field. No intravenous paramagnetic contrast material was used in any of the scans. In addition to assessments of the prostate and rectum, sagittal T1-weighted images were used to measure the sacral and coccygeal vertebrae of each individual.

On the images, the length of each vertebral body (vertebral body height) was measured on the anterior side of the bone (Fig. 1). Sacral height (SH) and sacrococcygeal height (SCH) were also recorded for each case (Fig. 2). We defined SH as the linear distance from the anterior upper edge of the first sacral vertebral body to the anterior lower edge of the fifth sacral vertebral body. We defined SCH as the linear distance from the anterior upper edge of the first sacral vertebra to the anterior lower edge of the last coccygeal vertebra. All the measurements were made to the nearest 0.1 mm. The body

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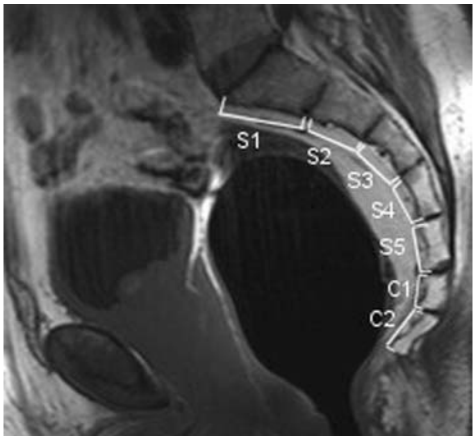

FIG. 1—*Measurements of sacral and coccygeal vertebral body heights.*

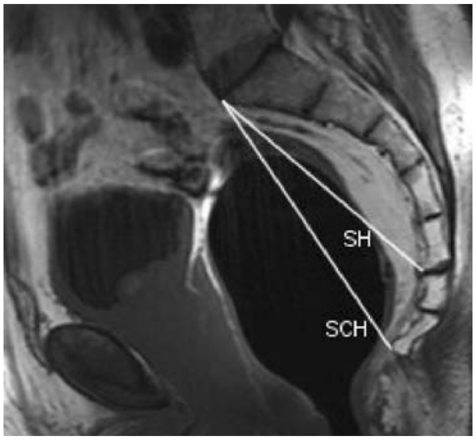

FIG. 2—*Measurements of sacral height (SH) and sacrococcygeal height (SCH).*

TABLE 1—*Technical errors of measurements ($n = 20$).*

	Intra-observer		Inter-observer	
Measurement	TEM*	R†	TEM	R
S1	0.813	0.928	0.672	0.948
S2	0.585	0.978	0.565	0.979
S3	0.769	0.941	0.798	0.936
S4	0.658	0.926	0.696	0.917
S5	0.688	0.824	0.681	0.815
C1	0.621	0.957	0.652	0.952
C2	0.661	0.896	0.669	0.893
C3	0.535	0.872	0.679	0.813
C4	0.604	0.735	0.602	0.749
SH	1.209	0.992	1.173	0.993
SHC	1.259	0.994	1.148	0.995

* TEM: Technical error of the measurements.
† R: Reliability.

height (measured to nearest 0.1 cm), age, birth date and birthplace of each subject were also noted.

In order to determine the intra- and inter-observer errors of the measurements, the vertebral body heights, SH, and SCH were re-measured on 20 MR images by one of the authors (E.K.) and by another radiologist who was not participated to the study (Table 1). The generous allowance for measurement error might be up to 0.9% of the observed inter-subject variance; this is equivalent to a reliability (R) value of 0.9 or more (21). For intra- and inter-observer error R-values are generally equal or above 0.9 except S5, C3, and C4.

None of the men in this study exhibited sacralization or lumbarization; in each case, the sacrum was composed of five vertebrae. Of the 42 subjects, 24 had 4, 15 had 5, 2 had 6, and 1 had 7 coccygeal vertebrae. In order to standardize the ΣC and ΣSC measurements, we used the sum of the heights of the first four coccygeal vertebrae.

Linear regression equations for stature estimation were derived using the SH, SCH, and the height of each sacral and coccygeal vertebrae. Some other formulae were also derived using the sum of the heights of five sacral vertebrae (ΣS), the first four coccygeal vertebrae (ΣC), and the total height of the sacral and the first four coccygeal vertebrae together (ΣSC). Later multiple regression equations were also constructed by using stepwise regression procedure.

The regression equations were constructed and tested by using jack-knife, or hold one out procedure. According to this method the first individual was removed and regression estimation was calculated depending on the remaining 41 subjects then the stature for the first individual was calculated. Later the second individual was removed and so on until all have been estimated. This prevents the estimated individual from biasing the results, yet allows the regression to be computed on N − 1 individuals.

The accuracy of the regression equations constructed in the study was evaluated by using the prediction sum of square (PRESS):

$$\underset{i=1}{\overset{n}{\mathrm{PRESS}}} = \sum (Y_i - \hat{Y}_{-i})^2$$

where Y_i is the measured stature of ith individual, $\hat{Y}_{-i}$ is the predicted stature of ith individual by the regression equation in which ith individual was excluded. The equations, which have the lowest PRESS values, were accepted as the most reliable ones.

All statistical calculations were performed using the statistical package SPSS for Windows version 11.0. The significance level was accepted as $P < 0.05$.

Results

The mean age, stature and anthropometric measurements of the sacral and coccygeal vertebrae of the subjects are presented in Table 2.

Table 3 shows the regression equations created for each variable. When stature was estimated using the equations that involved the dimensions of a single vertebra (sacral or coccygeal), the standard error was about 66–73 mm. In contrast, when the formulae that involved combinations of variables (ΣS, ΣC, ΣSC, SH, SCH) were used, the error was less than 66 mm. In most cases, the Pearson correlation coefficients (r) for these combined variables were higher than those for individual vertebrae (Table 3). As it is seen in the table $\sqrt{}$PRESS values for the equations based on single vertebral dimensions were higher than those of combined variables. In other words combined variables are more reliable. Among all sacral vertebral body heights S5 and all coccygeal vertebral body heights C2 gave the most accurate results. When combined variables were compared with each other ΣSC gives the most accurate results.

As expected multiple regression equations were more successful than equations derived from a single variable. The most reliable results were reached by multiple regression equations those consists four variables. The best two equations were presented in Table 4. Correlation coefficients of the multiple regression equations were higher when compared with those of regression equations based on a single variable, while standard errors of the estimates were lower.

TABLE 2—*Main characteristics and descriptive statistics of the sample ($n = 42$).*

	Mean	SD	Minimum	Maximum
Age (yrs)	62.02	8.18	45	81
Stature (mm)	1710.0	72.2	1540	1890
Sacral vertebrae (mm)				
S1	31.7	2.9	26.9	39.5
S2	26.0	3.3	18.6	32.0
S3	20.5	2.8	14.9	26.5
S4	18.1	2.6	10.2	23.1
S5	17.8	2.2	11.5	22.0
Coccygeal vertebrae (mm)				
C1	12.2	3.0	6.4	17.7
C2	7.4	2.2	4.0	13.1
C3	6.3	1.7	2.8	10.6
C4	5.1	1.3	2.2	8.4
Combined measurements (mm)				
ΣS	114.1	10.2	93.3	136.1
ΣC	31.0	6.0	18.9	47.0
ΣSC	145.1	12.7	120.9	174.2
SH	109.5	12.1	80.0	133.0
SCH	129.7	14.0	102.0	162.0

ΣS: S1 + S2 + S3 + S4 + S5.
ΣC: C1 + C2 + C3 + C4.
ΣSC: S1 + S2 + S3 + S4 + S5 + C1 + C2 + C3 + C4.
SH: Sacral height.
SCH: Sacrococcygeal height.

TABLE 3—*Regression equations for all variables for stature estimation (in mm).*

Variable	Regression Equations	r	SEE	$\sqrt{PRESS}$
S1	Stature = 1422.5 + 9.06 S1	0.367	68.0	448.7
S2	Stature = 1502.0 + 7.99 S2	0.362	68.1	451.1
S3	Stature = 1581.8 + 6.27 S3	0.243	70.9	467.6
S4	Stature = 1650.2 + 3.30 S4	0.121	72.5	482.4
S5	Stature = 1455.8 + 14.28 S5	0.435	65.8	449.0
C1	Stature = 1627.3 + 6.75 C1	0.277	70.2	470.9
C2	Stature = 1628.6 + 11.04 C2	0.341	68.7	455.7
C3	Stature = 1686.6 + 3.75 C3	0.088	72.8	481.5
C4	Stature = 1669.0 + 8.03 C4	0.147	72.3	480.7
ΣS	Stature = 1374.3 + 2.94 ΣS	0.414	66.5	440.5
ΣC	Stature = 1589.9 + 3.88 ΣC	0.321	69.2	463.6
ΣSC	Stature = 1313.0 + 2.74 ΣSC	0.482	64.0	425.1
SH	Stature = 1427.9 + 2.58 SH	0.432	65.9	434.7
SCH	Stature = 1429.1 + 2.17 SCH	0.421	66.3	439.3

SEE: Standard error of the estimate.
ΣS: S1 + S2 + S3 + S4 + S5.
ΣC: C1 + C2 + C3 + C4.
ΣSC: S1 + S2 + S3 + S4 + S5 + C1 + C2 + C3 + C4.
SH: Sacral height.
SCH: Sacrococcygeal height.

TABLE 4—*Multiple regression equations giving the most reliable results for stature estimation.*

Regression Equations	r	SEE	$\sqrt{PRESS}$
Stature = 1108.9 + 7.91 S1 − 9.35 S4 + 12.56 S5 + 1.82 SH + 3.09ΣC	0.676	56.8	399.7
Stature = 1114.1 + 8.42 S1 − 9.69 S4 + 14.31 S5 + 6.41 C1 + 1.56 SH	0.677	56.7	400.2

Discussion

Although there are some attempts for estimating stature from various parts of vertebral column (9,17–19) no such studies based on sacral dimensions have been reported. Due to its anatomical structure and its location in the human body it is thought to be available intact after mass disasters. Thus, measurements of the sacrum and coccygeal vertebrae are thought to be useful for estimating a victim's stature when the body has been severely burned or mutilated.

The analyses on technical errors of the measurements indicated that the reliability of individual vertebral measurements were generally above the 0.9% cutoff point both for intra- and inter-observer errors. However for S5, C3, and C4 the coefficients of reliability were below the 0.9% cutoff point. On the other hand, except S5, the correlation between individual vertebral heights and stature was relatively lower when compared with combined variables. Consequently, rather than individual vertebral dimensions, combined variables should be used to predict living stature.

Our assessment of $\sqrt{PRESS}$ and the standard errors of regression also pointed to the combined variables as the best vertebrae-related approaches to estimating stature. When we used data from all the subjects, the standard errors for the regression equations ranged from 64 to 73 mm (Table 3). When multiple regression equations were used standard errors of the estimate were decreased nearly 1 cm. In line with the above results, we also found that the standard errors for equations based on individual vertebrae were generally higher than those for equations based on combined variables. The errors for the calculations based on individual vertebrae ranged from 66 to 72.5 mm for sacral vertebrae, and from 69 to 73 mm for coccygeal vertebrae. For the combined variables standard error of the estimate varies between 64–69 mm.

A variety of studies on stature estimation have been published to date. Measurements of long bones, particularly those of the limbs, give the most accurate results. Currently, the stature-estimation formulae devised by Trotter and Gleser (22) are the ones most widely used in the fields of forensic science and anthropology. These equations are based on measurements of long bones in the limbs. With these formulae, the standard error of regression changes in relation to the particular bone that is used as independent variable. However, Trotter and Gleser showed that these formulae estimate living stature with standard error of approximately 3 to 5 cm.

Other researchers have reported similar figures for standard error of the estimation. For example, in a study on a German population, Breitinger (23) reported standard error of 4.7 to 5.4 cm. Similarly, Telkkä noted standard error of 4.4 to 5.2 cm in Finnish subjects, Černy and Komenda recorded 4.0 to 4.4 cm error in a Czech population, and Allbrook documented 3.5 to 4.4 cm error in British people (1). In a previous study in Turkey that investigated body-height estimation based on tibia length, the standard error was 3.94 cm (24).

Knee height in living subjects is another independent variable that is commonly used to estimate stature. This parameter is widely used to estimate body height in elderly people in order to determine nutritional needs. The formula devised by Chumlae et al. (25) is the one most frequently used for this purpose. With this equation, the authors reported estimation error of 3.80 cm in males and 3.96 cm in females. Donini et al. (26) proposed another equation for estimating stature from knee height in elderly people. The standard errors with this method were 3.10 cm in males and 2.74 cm in females. In another study, Prothro and Rosenbloom (27) used knee height to estimate body height with a different technique. In this case, the standard error of estimation was 4.98 cm.

Whereas most standard errors for regression formulae based on long-bone length and knee height are less than 5 cm, research has shown that height estimates based on dimensions of other bones and body parts are considerably less accurate. For example, the standard error reported for an equation based on foot dimensions was 8.6 cm (14). In addition, formulae developed by Holland (3) based on the dimensions of the talus and calcaneus gave standard errors of 4.09 to 6.11 cm. The metacarpal and metatarsal bones have also been used to predict body height. Reports indicate that the error with equations based on metacarpal dimensions is higher than that with equations based on other long bones. In work by Musgrave and Harneja (4) that focused on metacarpal bones, the standard error of regression was 5.5 to 8.1 cm. With an equation based on metatarsal dimensions, Byers et al. (6) reported a standard error of 4.0 to 7.6 cm. Interestingly, in a study by Shintaku and Furuya (7) that investigated formulae based on length of the proximal phalanges, the error was only 3.6 to 4.3 cm. A few investigators have also attempted to calculate stature from head dimensions. Based on head measurements from Japanese cadavers, Chiba and Terazawa (15) produced a regression equation with standard error of 6.6 to 8.0 cm.

Various segments of the vertebral column have also been used to estimate body height. Tibbets (9) reported an estimation error of 5.5 to 6.8 cm for equations based on heights of vertebral-bone groups in males. Terazawa et al. (17) tried to estimate stature based on the length of the vertebral column, and found an estimation error of 4.28 cm in men. In another study, Terazawa and co-workers (18) investigated the potential for approximating stature from the length of the lumbar part of the spine, and recorded an estimation error of 6.16 cm. Jason and Taylor (19) also estimated body height based on the lengths of cervical, thoracic, lumbar, thoraco-lumbar, and cervico-thoraco-lumbar segments of the spine, and noted a wider range of error than the latter study (2.60 to 7.11 cm).

As the above information conveys, authors have examined the potential of a variety of different variables as bases for stature estimation; however, ours is the first study to have investigated sacral and coccygeal vertebral dimensions. Our results suggest that these vertebrae are reliable indicators of stature. Comparison of our formulae based on combined sacral/coccygeal variables with the above-mentioned formulae based on other bones and body parts is revealing that the standard error for our combined-variable equations (approximately 6.5–7 cm) was significantly higher than only one grouping: the formulae based on long bone length.

In conclusion, this study shows that the dimensions of sacral and coccygeal vertebrae are of value for estimating stature in forensic practice. Since the present study was carried on living individuals the equations constructed here are useful for mutilated, but not decayed bodies, if necessary by radiographic examinations. These equations are not reliable for fully skeletalized remains. However, this study points out that sacral vertebral dimensions could be used for stature estimation. For the prediction of stature of fully skeletalized remains, new regression equations should be established based on proper material. It is clear that estimates based on sacrococcygeal dimensions are not as reliable as those based on length of long bones in the limbs, but these vertebral parameters are better predictors of stature than skull or foot dimensions.

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