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SCIENTIFIC ARTICLE

Total body height estimation using sacrum height in Anatolian Caucasians: multidetector computed tomography-based virtual anthropometry

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Abstract

Objective Estimation of total body height is a major step when a subject has to be identified from his/her skeletal structures. In the presence of decomposed skeletons and missing bones, estimation is usually based on regression equation for intact long bones. If these bones are fragmented or missing, alternative structures must be used. In this study, the value of sacrum height (SH) in total body height (TBH) estimation was investigated in a contemporary population of adult Anatolian Caucasians.

Materials and Methods Sixty-six men (41.6±14.9 years) and 43 women (41.1±14.2 years) were scanned with 64-row multidetector computed tomography (MDCT) to obtain high-resolution anthropometric data. SH of midsagittal sections was electronically measured. The technique and methodology were validated on a standard skeletal model.

Results Sacrum height was 111.2±12.6 mm (77–138 mm) in men and 104.7±8.2 (89–125 mm) in women. The difference between the two sexes regarding SH was significant ($p<0.0001$). SH did not significantly correlate with age in men, whereas the correlation was significant in women ($p<0.03$). The correlation between SH and the stature was significant in men ($r=0.427$, $p<0.0001$) and was insignificant in women. For men the regression equation was $[\text{Stature} = (0.306 \times \text{SH}) + 137.9]$ ($r=0.54$, $\text{SEE}=56.9$, $p<0.0001$).

Conclusion Sacrum height is not susceptible to sex, or to age in men. In the presence of incomplete male skeletons, SH helps to determine the stature. This study is also one of the initial applications of MDCT in virtual anthropometric research.

Keywords Body height estimation · Multidetector computed tomography · Osteometric analysis · Sacrum height · Virtual anthropometry

Introduction

Antemortem profiling by estimating the sex, age, and the stature of the subject using his/her skeletal structures is a major field of forensic anthropology. In the presence of a complete set of bones, the procedure is relatively straightforward. In such cases, it is largely based on the determination of skeletal stature by measuring head height,

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vertebral column and lower extremity length, foot height, and applying a relevant equation to their sum [1]. If the skeleton is only partially available, mathematical methods that are based on regression coefficients of complete long bone lengths are used [2]. These methods were initially reported by Rollet in 1888 [3], and have been continually refined ever since [3, 4].

When calculating the stature, it is advisable to use more than one long bone [2]. However, natural disasters, violent crimes, terrorist attacks, plane crashes, and similar events result in the decomposition of victims. Extremities are often chewed by animals and are removed from the main cadaver if unattended corpses rest on the ground. There may, therefore, be certain cases where neither the skeleton, in toto, nor long bone measurements can be used. In those cases, alternative methods that depend on measurements of several other cranial or postcranial bones are used [5–9].

Stature estimation that depends on long bone measurements has additional disadvantages. Even when measurable, the appropriate equations are reliable only when the ethnicity and the sex of the victim are known [2]. The subject's age is another complicating factor when estimating the stature. The physical work leads to alterations of thoracic kyphosis and lumbar lordosis, also finally influence the body height of the subject [10]. Differential bowing of long bones in men and women, height loss in weight-bearing vertebrae as a result of aging, and similar additional factors may cause erroneous estimations if these variables are not carefully considered [11, 12].

Identification of a bone that would not be affected by at least age and sex, and would likely be preserved even in decomposed corpses, may therefore be valuable. The sacrum, a relatively dense bone that is well preserved between the iliac bones, is a potential candidate to be used in that context. The value of sacral measurements for the estimation of stature was recently investigated, but did not provide any results regarding the effects of sex and age [13].

The purpose of this study was thus to investigate the value of sacrum height (SH) for the estimation of stature, and to determine the effect of sex and age. Due to the limited availability of fresh bone collections, high-resolution radiological data, obtained with multidetector computed tomography, were used to construct virtual cadavers.

Materials and methods

The experimental protocol was approved by the ethics committee of the Turgut Ozal Medical Center, Medical Faculty at Inonu University. Informed consent was obtained from the research subjects.

Subjects

The radiological datasets were gathered from the digital archives of the multidetector computed tomography unit of the first author's institution. Most of the datasets were originally acquired from donor candidates for living donor liver transplantation under institutional guidelines and after obtaining informed consent. The rest belonged to patients who had undergone abdominal computed tomography scans for various reasons excluding orthopedic and metabolic bone disorders. These subjects consisted of 109 Caucasian adults living in Eastern Anatolia. There were 66 men (18–78 years, mean: 41.6±14.9 years) and 43 women (18–74 years, mean: 41.1±14.2 years). Their statures were measured in an erect position. When the measurement was not a whole number, the figure was rounded up or down.

Imaging protocol and measurement

Imaging was performed with a 64-row MDCT scanner (Aquilion 64, TSX101-A; Toshiba, Tokyo, Japan). The bony pelvis was scanned helically with the technical parameters shown in Table 1. Spatial resolution was 500 µm. Volumetric datasets were processed on a dedicated image analysis workstation (Vitrea 2; Vital Images, Minnetonka, MN, USA) to build 2D maximum intensity projection (MIP) anatomical images. Assessment of the images and measurements were performed by the fourth author, an experienced musculoskeletal radiologist and anatomy doctorate under the surveillance of the first author who had experience of the respected analysis hardware and software at tutorship level. Sacrum was visualized on thin-section images in the midsagittal plane. The plane of

Table 1 Scan parameters for human subjects and the pelvic model

	Representative pelvis[b]	Representative model[c]
Peak kilovoltage (kV)	120	120
Tube current (mA)	300	70
Slice thickness (mm)	0.5	0.5
Scan thickness (mm)	0.5×64	0.5×64
Range (mm)	250	250
Field of view (mm)	320	320
CTDIvol (mGy)[a]	2.4	–

[a] CTDI was calculated using the Scan Simulator tool of the scanner's software for Sure Exposure 3D dose reduction algorithm

[b] Representative pelvis: superoinferior diameter of 25 cm, anteroposterior diameter of 20 cm

[c] Representative model: A60 male genital pelvis (3B Scientific, Hamburg, Germany)

visualization was checked and corrected using axial and coronal images. The sacrum height, defined as the distance between the upper anterior end of the body of S1 (S) and the lower anterior end of the body of S5 (I), was measured by placing electronic cursors (Fig. 1a).

Validation on standard skeletal model

Before the analysis of actual datasets, the validity of the virtual measurement was tested on a male pelvic skeletal model (A60; 3B Scientific, Hamburg, Germany). The model had dimensions of $18\times28\times23$ cm, and weighed 0.8 kg. It consisted of a hip bone, a sacrum with coccyx, and two lumbar vertebrae, as well as a movable symphysis. The real distance between the upper anterior edge of S1 and the lower anterior edge of S5 was measured with a ruler. The model was scanned using similar scan parameters to the subjects (Table 1). The CT data of the model were analyzed on the Vitrea 2 image analysis workstation. SH of the pelvic model was identified on the midsagittal thin sections and the distance was measured using electronic cursors as described for the subjects. The electronically measured SH was equal to the SH that was measured with a ruler, both being 93 mm (Fig. 1b).

Statistical analyses

Measurements were taken to the nearest millimeter. Data were analyzed using Statistical Package for Social Sciences, version 15.0 (SPSS, Chicago, IL, USA). The mean, standard deviation, and the range of SH were calculated for each sex group. Independent samples *t* test was used to determine any statistical difference between the two sex groups regarding SH. The correlation between SH and age was evaluated using Pearson's moment correlation coefficients. Curve estimation was performed to choose a regression model, and a regression equation was constructed for the estimation of stature from sacrum length. A p value<0.05 was accepted as the level of significance.

Results

Mean body height of the study population was 167.5± 8.7 cm (range 148–190 cm). Sacrum height was 108.7± 11.5 mm (rang 77–138 mm). Descriptive statistics for mean body height and sacrum height for sex types are presented in Table 2.

There was a statistically significant difference between men and women regarding sacrum height for unequal variance *t* test ($p<0.002$). However, this significance was lower than the significance of the difference between the two sexes regarding total actual statures ($p<0.0001$). Sacrum height did not significantly correlate with age in men ($r=-0.057$, $p=0.647$). In women, however, the age and the sacrum height were slightly correlated ($r=-0.342$, $p<0.03$). Accordingly, the sacrum height decreased with age (Fig. 2).

There was a significant correlation between sacrum height and stature ($r=0.442$, $p<0.0001$) for all subjects. When subjects were grouped according to sex, the correlation between the sacrum height and the stature was significant in men ($r=0.427$, $p<0.0001$). However, in women, the correlation between sacrum height and stature was not found to be significant ($r=0.172$, $p=0.270$).

After the evaluation of the curve estimation process, linear regression that includes a constant in the equation (the intercept model) was preferred to build a regression model to estimate the stature of men from the sacrum beam length. The regression equation after the exclusion of two outliers was found to be [$\text{Stature} = (0.306 \times \text{SH}) + 137.9$] with a regression coefficient (r) of 0.54 and the standard error of the estimate was 56.9 mm ($p<0.0001$; Fig. 3).

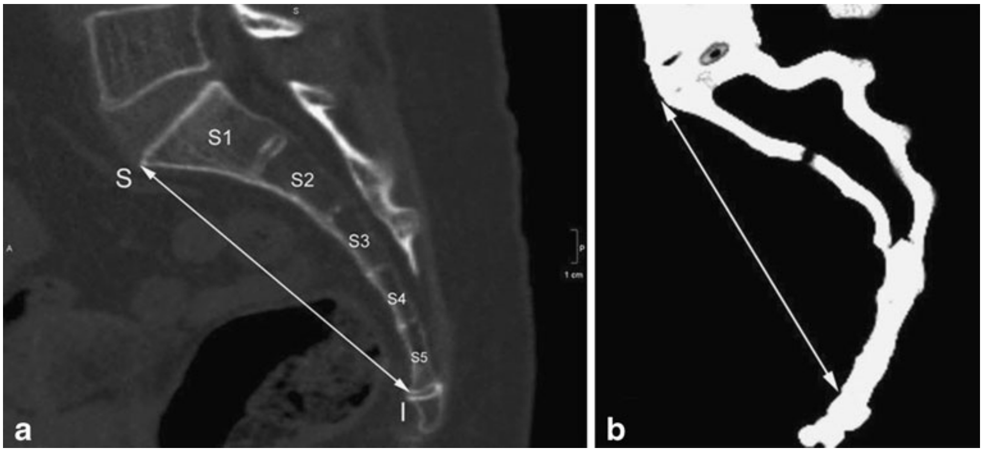

Fig. 1 **a** The measurement of sacrum height (SH) on sagittal maximum intensity projection images of the sacrum. **b** Midsagittal thin section image of the male pelvis model (A60) and the measurement of sacrum height

Table 2 Descriptive statistics on total body height and sacrum height

Parameter	Sex	Minimum	Maximum	Mean	SD
Stature (cm)	Male	160	190	172.3	6.8
	Female	148	170	160.1	5.4
	All	148	190	167.5	8.7
Sacrum height (mm)	Male	77	138	111.2	12.6
	Female	89	125	104.7	8.2
	All	77	138	108.7	11.5

Discussion

Stature can be estimated by anatomical or mathematical methods. The former has been shown to be reliable in the presence of a complete skeleton with intact bones [14]. However, it is time-consuming and tedious. Additionally, skeletons are rarely discovered as a whole, further complicating the use of anatomical methods. When skeletal parts are missing, long bone measurements and regression equations are used [2, 4, 14–17].

Population-specific regression equations for stature estimation have been derived from various bones. Skeletal collections had been used in most studies where measurements had been performed on dry bones. However, the practical application of existing equations on the measurements of a certain dry bone is limited when estimating the actual (living) stature. Stature data from samples that have been collected from historical graves is very doubtful. The data for relatively new skeletons, on the other hand, can be obtained from relatives of the victims or from their medical and/or administrative records (e.g., driving licences), but even these may be subject to considerable error. Even in fresh cadavers correct determination of the stature may sometimes be difficult and unreliable [15]. Our study employs the use of living persons in whom the stature and SH of the subjects were measured. This design reduces errors that originate from questionable stature data.

Measurement of bone lengths varies according to the methodology used. Dry bones are slightly (approximately 2 mm) shorter than their fresh counterparts and require the application of corrective measures for regression equations. The fact of shortening was previously described in long bones [2], but no data are available for the sacrum. Fresh bones are more reliable for precise measurements. However, these bones are difficult to obtain, and their availability for research studies is extremely limited. Even when available, the suboptimal dissection of soft tissues that overlie fresh bones causes the incorrect measurement of the bone length [15]. Finally, since stature considerably changes before, during and after rigor mortis, the stature measurements made on fresh cadavers may have variabilities [16].

Previous studies have shown that intact long bones had the lowest standard error of the estimates (SEE), which

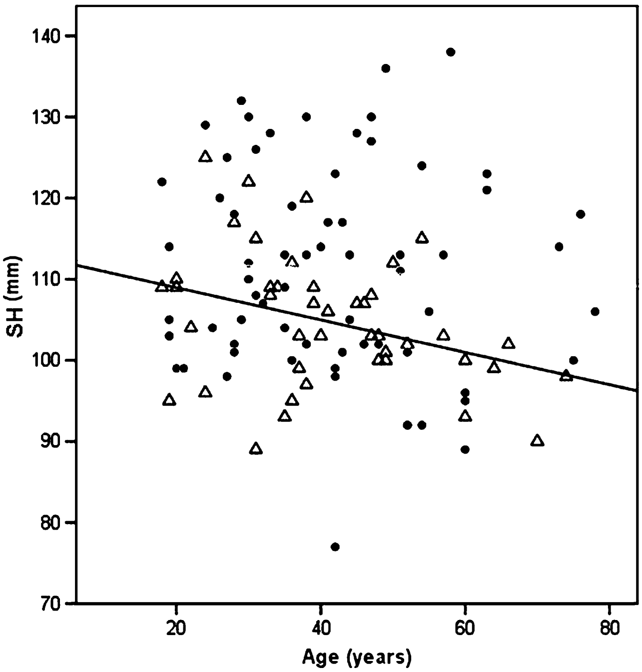

Fig. 2 Scatter plot showing the relation between SH and age. *Circles* represent male *subjects* and *triangles* represent female *subjects*. The *solid line* represents the fit line for female *subjects*

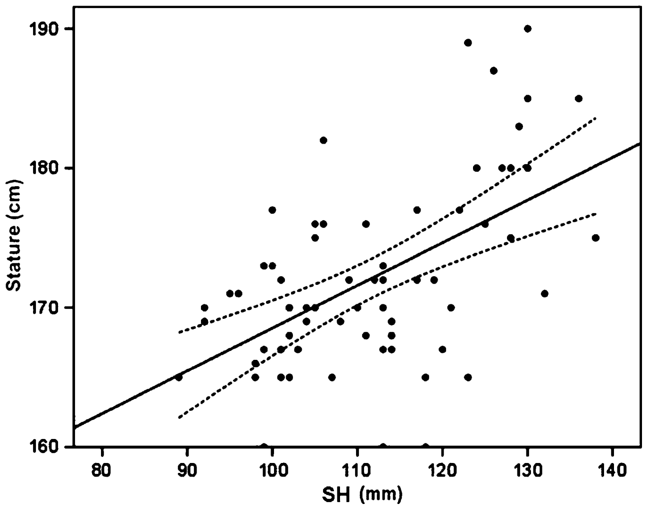

Fig. 3 Scatter plot showing the relation between SH and stature in male *subjects*. The *solid line* represents the fit line; *dotted curves* represent 95% confidence intervals for the mean

ranged between 18 and 55 (mm) compared with SEE that belonged to fragments of long bones. They therefore provide better estimates of stature [5, 9, 16–18]. Skull, vertebra, calcaneus, metacarpals and fragmented femora have relatively higher SEE values (40–72) and they are only used if long bones are missing [7, 8, 13, 17, 19]. When the sex of the victim was known, the present study had an SEE of 67, which had lower accuracy than the long bones, but was equal to other bones in estimating the stature.

Contrary to long bones, the sacrum has only recently been investigated as a measure of stature [5, 13]. Of note is the study that was conducted by Pelin et al. [13] on Anatolian Caucasians. That study was done with pelvic magnetic resonance images that were originally acquired for oncological disorders, and was conducted only on men. These researchers have measured sacral and coccygeal vertebral body heights, sacral height, and sacrococcygeal height. According to their findings, SH was equal to 109.5±12.1 (80–133.0) cm and they formulated the stature as $[(2.58 \times \mathrm{SH}) + 1427.9]$ with a regression coefficient (r) of 0.432 (Table 3) [13]. The SEE that they had found (SEE=65.9) was larger than the one that was found in the present study (SEE=56.9) . The difference between the two studies regarding SEE was probably caused by the technique in which anthropometric data were acquired. The lower SEE that was found in this study is probably due to finer spatial resolution (500 µm) of multidetector computed tomography data and the ability to manipulate the acquired volume in all planes to find the true midsagittal section of the sacrum. Although, the data that Pelin et al. [13] used had higher spatial resolution than ordinary magnetic resonance images (acquired with an endoluminal coil), the spatial resolution was still lower than that of computed tomography data. Spatial nonlinearity and an inability to postprocess anisotropic data to visualize true midsagittal sections pose additional problems, and magnetic resonance imaging is therefore not the method of choice in anthropometry.

Sex is known to be a contributing factor in stature estimation. Therefore, different charts are used for men and women. The only study on Anatolian Caucasians in which the sacrum height was investigated as an indirect measure of body height was conducted on men [13]. The findings were generalized to the population. Our study employed both sexes. Accordingly, in women the correlation between the sacrum height and the stature was not found to be significant, probably because of the effect of aging and parturition on the pelvis. This effect was extensively studied by Lazarevski [19]. He stated that the aging process provokes backward and downward displacement of the sacrum together with changes that enlarge the pelvic bone system caudally [19]. In that study, the sacral length was 9.74±0.18 cm in <35-year-old nulliparas, whereas it decreased to 9.72±0.17 cm in <30-year-old multiparas and to 9.18±0.22 cm in >60-year-old multiparas [19]. In agreement with Lazarevski [19], we also observed the effect of age in women on sacrum height, which decreases with age. Obstetrical trauma could represent a form of common overloading, which a female pelvis is often exposed to during her life. The weight of a gravid uterus, the delivery process, and holding and carrying the children all add their effects to those of the aging process. Childbearing, nursing, obesity, and heavy work are the other possible nonspecific overloading factors. Previous anthropological studies revealed that many women who have borne children displayed few or no bony changes and made the connection with complex interactions among hormonal levels, maternal birth canal diameter, fetal head circumference, amount of physical activity during pregnancy, obstetrical care, and age at time of death [20].

Table 3 Summary of previous studies on sacrum height (SH) and stature

Study	Method	Ethnicity	Sex	n	Age ± SD (years) (minimum to maximum)	Stature ± SD (cm)	SH ± SD (mm)	r	SEE (mm)
Mishra et al. [26]	Dry bones	India	Male	74	Unknown	Not studied	107.53±7.03 (92–122)	–	–
			Female	42			90.58±4.42 (64–100)	–	–
Pelin et al. [13]	Magnetic resonance imaging	Anatolian Caucasians	Male	42	62.02±8.18 (45–81)	171.0±7.2 (154–189)	109.5±12.1 (80–133)	0.43	65.9
Giroux and Wescott [5]	Dry bones	Whites	Male	92	43.5±15.4 (19–77)	176.8±7.73 (157–205)	109.7±12.1 (74–147)	0.39	71.7
			Female	60	36.4±18.0 (17–89)	163.5±7.7 (137–180)	108.1±11.1 (79–134)	0.13	77.3
		Blacks	Male	57	35.8±13.4 (18–73)	175.8±7.7 (155–193)	102.9±11.5 (76–142)	0.46	69.6
			Female	38	30.0±9.3 (17–65)	163.3±7.9 (142–182)	102.4±11.9 (80–121)	0.59	77.3
Present study	Multi-detector computed tomography	Anatolian Caucasians	Male	66	41.6±14.9 (18–78)	172.3±6.8 (160–190)	111.2±12.6 (77–138)	0.54	56.9
			Female	43	41.1±14.2 (18–74)	160.1±5.4 (148–170)	104.74±8.2 (89–125)	0.17*	54.6

*Not significant

Etiology of pelvic bone alterations can also be related to hereditary or constitutional factors, as well as endogenous factors such as osteoporosis and malnutrition, which facilitate the decrease in osseous resistance [19]. One may assume that the softening and microtrabecular fractures of the sacrum may induce shortening of the sacrum. The changing diameter of the pelvis due to these factors makes stature estimation impossible in subjects with unknown age and parturitional state. Unfortunately, we do not know the number of pregnancies and children born to the women of our study group. We propose further studies that focus on "possible bowing" of the sacrum with aging in women and it seems that it is only possible to achieve such studies in "virtual skeletons" of living persons.

Gender variances of the sacrum are less frequently investigated than other pelvic bones in the literature. Sacrum height and sacral index (=sacrum width × 100/ sacrum height) were found to be important parameters for determining gender in dry bones of the Agra region (India) [20]. In the study, sacrum height was found to be 107.53± 7.03 (92–122) in men (*n*=74) and 90.58±4.42 (64–100) in women (*n*=42), who are taller than in our population.

There are many factors affecting the morphology of the spinal column that influence body height. Both aging [12, 21, 22] and osteoporosis [23] are causes of vertebral osseous morphological alterations, in connection with human height. Low body weight and low body mass index can be seen as potentially significant risk factors for the development of vertebral deformities that are associated with shortened body height [24]. Nevertheless, the previous studies are mainly focused on the spinal column. The sacrum consists of the base of the spine and the upper and rear parts of the pelvic cavity, where it is inserted like a wedge between the two hip bones. Through the spinal column, the body load is shifted to the base of the sacrum and then through the pelvic girdle to the inferior extremities [19]. Despite its major static and dynamic role, the sacrum is one of the least studied bone structures.

Giroux and Wescott [5] have recently validated the value of SH in estimating stature using dry bones (Table 3). They calculated a higher SEE, and generally lower correlations with stature compared with SH measured from magnetic resonance images of men by Pelin et al. [13] as well as SH measured from MDCT images of our study. The presence of a higher SEE that was reported by Giroux and Wescott [5] was probably due to errors superimposed by the difficulty in preparing and measuring dry bones with precision, and perhaps due to the error in determining the actual stature, as discussed above. Contrary to dry bone studies, electronic measurement of finely calibrated tomographic data is an easy procedure.

Although the SH is shorter in blacks (6–7 cm shorter than in whites) [5], the stature does not differ between American blacks and whites. In other words, blacks have shorter sacrum and hips relative to their stature [5]. Anatolian Caucasians are 3.5–4.5 cm shorter than American whites,

Table 4 Summary of stature estimation studies in Turkish subjects

Study	Method	Sex	Mean stature (cm)	Structure	*n*	*r*	SEE
Iris and Celbis [31]	Fresh bone	Male	169.1	Humerus	51	0.79	44
		Female	156.5		29	0.79	37
Celbis and Agritmis [15]	Fresh bone	Male	169.9	Ulna	80	0.62	48
		Female	156.8		47	0.76	43
Celbis and Agritmis [15]	Fresh bone	Male	169.9	Radius	80	0.64	47
		Female	156.8		47	0.85	35
Karacam et al. [32]	Fresh bone	Male	167.7	Femur	53	0.87	34
		Female	157.3		42	0.91	28
Günay [33]	Fresh bone	Male	171.4	Tibia	49	0.72	48
		Female	158.1		31	0.63	40
Şam [34]	Fresh bone	Male	170.4	Fibula	51	0.76	44
		Female	157.6		31	0.64	38
Pelin et al. [13]	MRI	Male	Not indicated	Sacrum	42	0.43	66
				Sacrum-coccyx		0.42	66
				Sacrum-coccyx		0.48	64
				Coccyx		0.32	69
				Sacrum		0.41	67
Present study (2008)	Multi-slice CT	Male	172.3	Sacrum	66	0.17	54
		Female	160.1		43	0.43	62

but the average SH of the men in our study is 1.5 cm longer. The discrepancy may be explained by racial variance and points to the need for ethnicity-specific regression charts when estimating the stature. Since stature is also related to environmental factors, regression equations have to be periodically updated. Previous studies on stature estimation by the use of different bones in the Turkish population are summarized in Table 4. The mean stature that was found in this study was 160.1 cm in women and 172.3 in men. These figures were approximately 1.4 cm longer than that for the average man, and 2.3 cm longer than that for the average woman of the previous decade [13, 15, 25–27] (Table 4).

Sacrum measurement has some particular advantages when compared with long bones of the extremities. Anatomically, the sacrum is a midline compact bone; therefore, SH prevents discrepancies that might occur because of the asymmetry of the bones between the right and left sides of the body. Bowing and subsequent shortening of the long bones with aging and degenerative bony changes may result in erroneous measurements [11, 12, 28]. Therefore, stature estimates based on long bone measurements require a correction factor to compensate for stature decrease in older people [29]. SH is a constant parameter and unrelated to age of the subject, at least in men. Even if many parts of the skeleton are missing or fragmented, the sacrum is mostly protected and therefore it is a relatively reliable tool for estimating stature.

Traditionally, anthropometric measurements use bone remnants, but a limited number of skeletal remnants and the difficulties of obtaining these materials restrict researchers in many instances [11, 15]. Adequate cadaveric samples of contemporary populations are also rare in some countries, mainly for cultural and ethical reasons. This study has provided a sacral anthropometric feature of a contemporary Anatolian population by utilizing an alternative radiological method. Multidetector computed tomography offers three-dimensional representation of the human skeleton with excellent spatial resolution. With this technique, high quality imaging of the living subjects and subsequent skeletal observations has become possible. Radiography in general, and multidetector computed tomography in particular, enable us to perform measurements on virtual bones instead of fresh bones that are extremely limited and that need extensive preparation, including defleshing. On virtual skeletons, detailed anatomical observations and precise metric analyses can be performed at any time and in any place as long as the digital data are kept electronically. The electronically stored data may be reinterpreted at any time; subsequently, repeated measurements may reduce intra-observer variability, and data transfer between researchers increases the reliability of the estimations. Maceration of the bones is time-consuming and difficult. Additionally, for ethical and religious reasons, decomposition of the corpses is avoided in some societies. Recently, the advantages of virtual skeletons have led to their use becoming widespread in forensic medicine, anthropometry, and anthropology [25, 28–30].

We did not investigate inter- or intraobserver variations; a high-resolution CT protocol with an isotropic spatial resolution of 0.5 mm and an in-plane spatial resolution of 500 µm were used in the study to enable the precision of the measurement. The high resolution of the images allows for the visualization of even the smallest details of the skeleton (for example, cranial sutures, trabecular bone structure, texture of the symphyseal surface of the pubic bone, etc.) and this allows the use of MDCT in forensic medicine (virtopsy) [25, 28, 30].

In conclusion, sacrum height shows dimorphic gender variance; the morphological alteration of the sacrum is more complicated in women. Sacrum height can be used in the estimation of stature in the male gender. This study also demonstrates the use of multidetector computed tomography-based virtual anthropometry in forensic medicine for collecting data on living subjects.

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Conflict of interest None.

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