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Original Article

Development of a Sacrum-Based Stature Estimation Model for Koreans Using 3D Reconstruction of Postmortem CT Images

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Abstract : The purpose of this study was to investigate the correlation between sacral measurements and sex and stature by reconstructing postmortem computed tomography (PMCT) data in 3D, thereby proposing a regression model that can predict stature. This study has the potential to be applied in various fields, such as forensic medicine and morphology. This study utilized PMCT images from a total of 67 subjects (34 males, 33 females) derived from the Korean population, taken at the National Forensic Service between January and December 2022. The 2D PMCT images were reconstructed into 3D images using the Mimics program, and the measurement of sacral morphology was also performed using this program. We established four bony landmarks on the sacrum and measured the distance connecting each landmark: SW (Sacral width), SL (Sacral length), LOL (Left oblique length), and ROL (Right oblique length). The SW/SL/LOL/ROL ratio was calculated by dividing these measurements by the cadaver's stature to explore their proportional relationship. The average stature was 1695.29±73.12 mm in males, 1599.24±61.18 mm in females, and 1647.98±82.64 mm in all subjects. The mean (Standard deviation) of the measurement variables was 95.84±5.13 mm for SW, 110.55±9.60 mm for SL, 93.73±6.56 mm for LOL, and 92.74±6.80 mm for ROL. The ratio of the measurement variables to stature was as follows: the mean SW ratio was 0.58±0.03, the SL ratio was 0.67±0.05, the LOL ratio was 0.56±0.04, and the ROL ratio was 0.56±0.04. The stature, LOL, and ROL were significantly longer in males than females ($p<0.001$, $p=0.009$, $p=0.027$). The model to estimate stature (y, mm) based on sacral measurement variables (x, mm) was derived with the following results: S=1109.468+5.619SW ($p=0.004$), S=1238.762+3.701SL ($p<0.001$), S=1107.396+5.767LOL ($p<0.001$), and S=1137.014+5.510ROL ($p<0.001$). We proposed a sacrum-based regression model for estimating stature, considering sex differences and measurement variables like SW, SL, LOL, and ROL. This model is expected to be useful in forensic anthropology and related fields.

Keywords : Sacrum, Stature estimation, Computed tomography, 3D reconstruction

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INTRODUCTION

The sacrum is a triangular bone formed by the fusion of five vertebrae, and it is an important bone that plays a central role in the axis of the body. The posterior foramina are located lateral to the median sacral crest and give off the posterior sacral rami for each sacral spinal nerve. The articular surface of the sacroiliac joint on the lateral aspect of the sacrum is L-shaped [1,2]. Pelvic bones are structures that exhibit pronounced sexual dimorphism, and previous studies on this subject have been widely reported. In particular, morphological differences, such as the transverse diameters of the pelvic inlet or outlet between males and females, serve as important criteria for sex estimation [3]. The sacrum, as a significant component of the pelvic girdle, is also presumed to exhibit morphological differences influenced by sex [4]. However, studies on the morphological differences of the sacrum remain relatively limited compared to those on the pelvis.

The anatomical variations of the sacrum, including numerical and morphological differences such as sacralization, lumbarization, and sacral hiatus anomalies, have a profound impact on clinical practices and outcomes in anesthesiology, surgery, and obstetrics [5]. The morphological variations of the sacral hiatus may influence the success rate of caudal epidural injections [6]. Furthermore, the anatomy of the sacrum may play a significant role in the development of spondylolisthesis [7].

Identifying individuals is one of the most complex tasks in forensic science, with investigators primarily focusing on determining ancestry, sex, age, and stature as key attributes of biological identity [8]. Most methods of estimating stature from the skeletons are targeted to the long bones [9]. For sex estimation, skull and pelvis are known to be the most useful bones [8]. However, those bones are often fractured after serious traumatic damage, which may be caused by natural disasters, plane crashes, or wars [10]. Moreover, long bones of extremities may be damaged if unidentified corpses are left unattended [11]. In cases where those long bones, skull and pelvis are unavailable, other parts of the human skeleton should be used for sex and stature estimation [8].

Therefore, a bone that is likely to be unaffected by factors such as age and sex, and to be well-preserved even in decomposed remains, would hold significant value. The sacrum, a dense bone located between the iliac bones, emerges as a strong candidate for this purpose [11]. Previous studies to estimate stature or sex by the sacrum were examined on various races. In Chinese population, posterior sacrococcygeal length and length of the auricular surface were highly effective in sex determination [8]. In Spanish population, the Mid-sacral transverse line and Superior transverse line demonstrated the most significant sexual dimorphism [12]. In Japanese cadavers, posterior sacral length and posterior sacrococcygeal length demonstrated the highest accuracy for stature estimation [10]. In South African population, anterior sacral heights of S1 and S2 in black population proved most reliable for stature estimation [1]. However, the studies focusing on stature or sex estimation using the sacrum in Korean populations are exceptionally rare.

The purpose of this study was to investigate the correlation between sacral measurements and sex and stature by reconstructing PMCT data in 3D, thereby proposing a regression model that can predict stature. This study has the potential to be applied in various fields, such as forensic medicine and morphology.

MATERIALS AND METHODS

This study utilized PMCT images from a total of 67 subjects (34 males, 33 females) derived from the Korean population, taken at the National Forensic Service between January and December 2022. This study was approved by the Ethics Committee of the National Forensic Service (Institutional Review Board number: 906-211116-HR-003-02). Only adults over the age of 30 were included, considering the morphological maturity of sacrum. The mean (±Standard deviation, SD) age of the subjects was 51.5±41.4 years (range: 30~75 years). Fig. 1 presents the distribution of age by sex. In this study, all sacrums that have fracture, surgical marks, malformation or things obstructing field of vision are completely excluded.

1. PMCT image acquisition and 3D modeling

As a data collector, PMCT equipment (Aquilion PRIME TSX-303A, CANON Medical Systems Corp., Tokyo, Japan) at the headquarters of the National Forensic Service was used. The imaging parameters were set to a tube voltage of 120 kVp, a pitch factor of 0.637, a slice thickness of 1.0 mm, an increment of 0.8 mm, and a rotation time of 0.6 seconds. For clearer view of data, measurements were per-

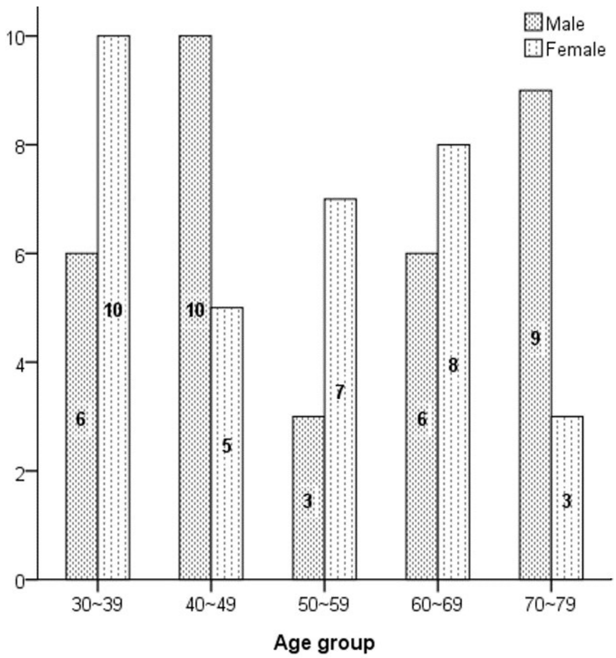

Fig. 1. Sex and age distribution of Korean cadavers (n = 67).

formed under bone settings (Window width 1500, window level 500). The PMCT images were provided in DICOM file format. 3D modeling was done by Mimics (Version 22.0, Materialise, Leuven, Belgium) in a way that Mimics generate 3D models based on DICOM data according to coronal, sagittal, and axial planes. 3D images of the sacrum were taken by modifying Hounsfield Unit (HU) values, which are related to grayscale. A new mask function was applied to create a sacrum model by adjusting the threshold values from a minimum of 40 HU to a maximum of 1350 HU. Subsequently, the sacrum was measured using the calculate part function.

2. Sacral measurements and ratios

In sacrum, this research defined the four measurable landmarks and two researchers each measured the length of the landmarks with the scale tools inherent in Mimics program. The following are the definitions of the four landmarks (Fig. 2): SW (Sacral width): The widest distance between the left and right side of sacrum. SL (Sacral length): The maximum vertical distance between the promontory and sacrococcygeal joint. LOL (Left oblique length): Length of connecting between left part of SW with sacrococcygeal joint. ROL (Right oblique length): Length of connecting between right part of SW with sacrococcygeal joint. In order to seek a proportional relationship between sacral measurements and stature, the SW/SL/LOL/ROL ratio was calculated by dividing the value of measurement landmarks by cadaver's stature (Fig. 3). Since sexual morphology and other variables can affect the results, we classified the results by sex and calculated them including mean and SD.

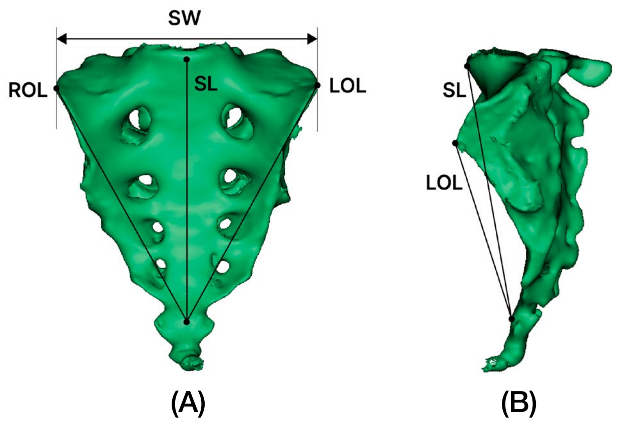

Fig. 2. 3D reconstruction of PMCT images using mimics version 22.0. (A) Anterior view; (B) Lateral view; SW, Sacral width; SL, Sacral length; LOL, Left oblique length; ROL, Right oblique length.

3. Statistical analysis

In statistics, this study mainly used IBM, SPSS Statistics version 23.0 (IBM Co., Armonk, NY, USA) for handling and calculating statistical data. The intraclass correlation coefficient (ICC) was used as a way to reduce measurement error and promote statistical validity. Following the guidelines of Cicchetti [13], the ICC can be interpreted as "excellent" between 0.75 and 1.00, "good" between 0.60 and 0.74, "fair" between 0.40 and 0.59, and "poor" below 0.40. The independent sample t-test was used to investigate whether the sex is related to sacral morphology measurements. To analyze and specify the relationship between sacral measurements and stature, correlation analysis was used. In this case, the higher the Pearson correlation coefficient (R) and Adjusted R-squared (R^2) are, the closer the relationship between two variables may be. Ultimately, to create a regression model capable of predicting the stature from sacral measurements, linear regression analysis was performed. All the *p*-value used in this study under 0.05 was regarded as statistically significant.

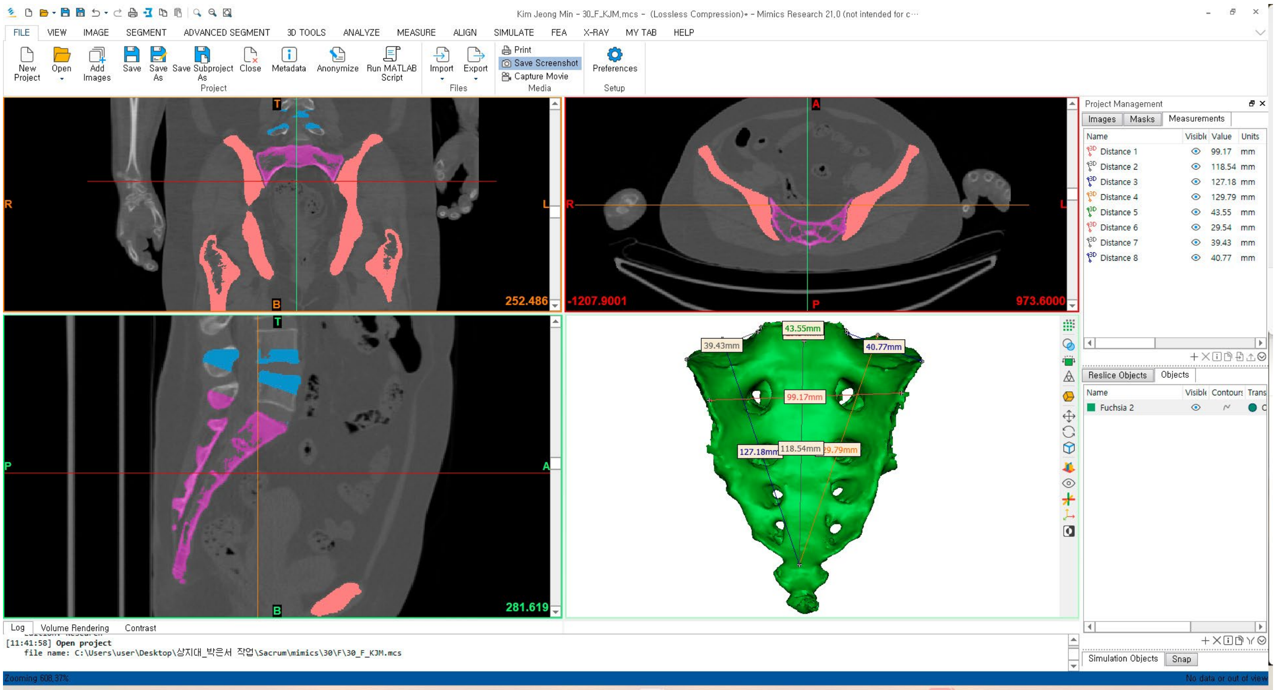

Fig. 3. Measurement variables of the sacrum.

RESULTS

The inter-class correlation coefficients for the measurement parameters indicated high reliability, with Cronbach's alpha values ranging from 0.862 to 0.972, all falling within the 'excellent' reliability category (Table 1). The average stature was 1695.29±73.12 mm in male, 1599.24±61.18 mm in female, and 1647.98±82.64 mm in all subjects. For SW, males had an average of 95.18±5.29 mm, whereas females had a mean of 96.52±4.96 mm. For SL, males showed a mean value of 112.43±8.99 mm, while females had a mean of 108.62±9.96 mm. For LOL, the male average was 95.75±6.56 mm, whereas the female mean was 91.64±5.97 mm. For ROL, males had an average of 94.53±7.12 mm, and females had a mean of 90.89±6.02 mm. There was no significant difference between sex in SW ($p=0.288$) and SL ($p=0.105$). However, the average of LOL ($p=0.009$) and ROL ($p=0.027$) were notably larger in males than in females (Table 2).

Table 3 shows the comparison of the ratios of each measured variable to height. For the SW ratio, the mean value for males was 0.56±0.02%, while for females, it was 0.60±0.02%. Regarding the SL ratio, males had an average of 0.66±0.04%, whereas females had a mean of 0.67±0.05%. For SW ($p=0.288$) and SL ratio ($p=0.105$), there were no significant difference between males and females. For the LOL ratio, the male average was 0.56±0.03%, while the female mean was 0.57±0.03%. Regarding the ROL ratio, males had an average of 0.55±0.03%, and females had a mean of 0.56±0.03%. The LOL ($p=0.009$) and ROL ratio ($p=0.027$) indicated statistically significant differences between sexes (Table 3, Fig. 4).

Table 1. Inter-class correlation coefficients for all measurements

Parameter	Inter-class correlation	
	ICC	95% CI
SW	.862	.775~.915
SL	.972	.954~.983
LOL	.910	.853~.944
ROL	.889	.819~.932

SW, Sacral width; SL, Sacral length; LOL, Left oblique length; ROL, Right oblique length.

Tables 4~6 present the linear regression analysis of stature in relation to each measured variables for all subjects, males, and females, respectively. In unknown sex, LOL (R=0.458) showed the strongest correlation, followed by ROL (R=0.454), SL (R=0.430), and SW (R=0.349).

Table 2. Comparison of sacral morphology measurement parameters by sex

Parameter (mm)	Male (n = 34)	Female (n = 33)	Total	*p*
Stature	1695.29 ± 73.12	1599.24 ± 61.18	1647.98 ± 82.64	< 0.001
SW	95.18 ± 5.29	96.52 ± 4.96	95.84 ± 5.13	.288
SL	112.43 ± 8.99	108.62 ± 9.96	110.55 ± 9.60	.105
LOL	95.75 ± 6.56	91.64 ± 5.97	93.73 ± 6.56	.009
ROL	94.53 ± 7.12	90.89 ± 6.02	92.74 ± 6.80	.027

SW, Sacral width; SL, Sacral length; LOL, Left oblique length; ROL, Right oblique length. The data are expressed by mean ± SD.

Table 3. Comparison of the ratios of each measured variable to height (Mean, SD, median, IQR and range)

Ratio (%)	Male (n = 34)			Female (n = 33)			Total			*p*
	Madian (IQR)	Range	mean ± SD	Madian (IQR)	Range	mean ± SD	Madian (IQR)	Range	mean ± SD	
SW ratio	0.55 (0.54, 0.58)	0.49 to 0.61	0.56 ± 0.02	0.60 (0.58, 0.62)	0.54 to 0.66	0.60 ± 0.02	0.58 (0.55, 0.60)	0.49 to 0.66	0.58 ± 0.03	.288
SL ratio	0.66 (0.62, 0.69)	0.52 to 0.74	0.66 ± 0.04	0.66 (0.64, 0.71)	0.57 to 0.81	0.67 ± 0.05	0.66 (0.64, 0.70)	0.52 to 0.81	0.67 ± 0.05	.105
LOL ratio	0.56 (0.54, 0.59)	0.47 to 0.62	0.56 ± 0.03	0.56 (0.53, 0.60)	0.52 to 0.67	0.57 ± 0.03	0.56 (0.53, 0.59)	0.47 to 0.67	0.56 ± 0.04	.009
ROL ratio	0.56 (0.54, 0.58)	0.46 to 0.61	0.55 ± 0.03	0.56 (0.53, 0.60)	0.48 to 0.66	0.56 ± 0.03	0.56 (0.54, 0.59)	0.46 to 0.66	0.56 ± 0.04	.027

SW, Sacral width; SL, Sacral length; LOL, Left oblique length; ROL, Right oblique length. IQR, Interquartile range; SD, Standard deviation.

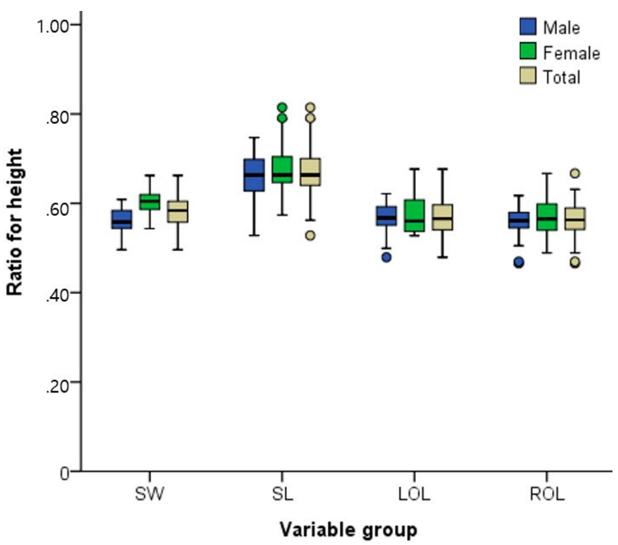

Fig. 4. A boxplot showing the ratio between each measurement variable of height.

The Adj R^2 values of unknown sex were 0.108 for SW, 0.173 for SL, 0.198 for LOL, and 0.194 for ROL. All measurements of unknown sex were considered statistically significant ($p < 0.01$) (Table 4). In males, SW (R = 0.537) showed the highest correlation. The Adj R^2 values of male were 0.266 for SW, 0.132 for SL, 0.206 for LOL, and 0.232 for ROL. All measurements presented statistically significant correlation with stature in male ($p < 0.05$) (Table 5). In females, SW (R = 0.524) showed the highest correlation, as well as in males. The Adj R^2 values of female were 0.251 for SW, 0.132 for SL, 0.004 for LOL, and 0.00 for ROL. Only SW ($p = 0.002$) and SL ($p = 0.021$) had significant results in females, while LOL ($p = 0.295$) and ROL ($p = 0.273$) not being statistically significant (Table 6).

DISCUSSION

In this study, morphological analysis was performed using 3D reconstruction of CT images. The sacrum is a bone derived from the vertebrae. During the development process, various structures of the vertebrae undergo transformation

Table 4. Linear regression formula for all measured variables (Unknown sex, n = 67). Correlation coefficient (R), Adjusted determination coefficient (Adj R^2) and Standard error of estimate (SEE)

Formula	R	Adj R^2	t	SEE	*p*
S = 1109.468 + 5.619SW	0.349	0.108	3.005	78.031	.004
S = 1238.762 + 3.701SL	0.430	0.173	3.842	75.174	<0.001
S = 1107.396 + 5.767LOL	0.458	0.198	4.156	74.017	<0.001
S = 1137.014 + 5.510ROL	0.454	0.194	4.108	74.197	<0.001

SW, Sacral width; SL, Sacral length; LOL, Left oblique length; ROL, Right oblique length.

Table 5. Linear regression formulae for males (n = 34). Correlation coefficient (R), Adjusted determination coefficient (Adj R^2) and Standard error of estimate (SEE)

Formula	R	Adj R^2	t	SEE	*p*
S = 989.103 + 7.49SW	0.537	0.266	3.599	62.650	.001
S = 1332.246 + 3.229SL	0.397	0.132	2.449	68.143	.020
S = 1183.075 + 5.349LOL	0.480	0.206	3.096	65.137	.004
S = 1206.786 + 5.178ROL	0.505	0.232	3.309	64.097	.002

SW, Sacral width; SL, Sacral length; LOL, Left oblique length; ROL, Right oblique length.

Table 6. Linear regression formulae for females (n=33). Correlation coefficient (R), Adjusted determination coefficient (Adj R^2) and Standard error of estimate (SEE)

Formula	R	Adj R^2	t	SEE	p
S = 975.159 + 6.465SW	0.524	0.251	3.427	52.941	.002
S = 1332.883 + 2.452SL	0.339	0.132	2.424	56.999	.021
Not significant	0.188	0.004	1.064	61.061	.295
Not significant	0.197	0.008	1.116	60.953	.273

SW, Sacral width; SL, Sacral length.

and fusion, resulting in a more complex shape and consequently, a variety of forms [14]. The sacrum is a bone that exhibits various morphological variations due to multiple factors. Therefore, when measuring it, 'morphological considerations' such as the sacral crest and sacral curvature must be taken into account. In this respect, sectional imaging techniques such as the sagittal plane and transverse plane may have some possibility to distort the actual bone length. On the other hand, the 3D reconstruction method has the advantage of allowing more sophisticated measurements by observing the bones in a more three-dimensional view and reflecting their shapes. Moreover, customary observation methods require the removal of soft tissue, which consumes a significant amount of time and causes fatigue. Besides, if soft tissue is not properly removed, it becomes a visual distraction. In this regard, 3D reconstruction has the advantage of efficiently saving time and costs, while providing a clearer view [15]. According to previous studies, measurements using 3D reconstruction were sometimes equal to or even more accurate than those obtained through customary methods [16]. This study also requires additional research on cadavers to determine the accuracy of the 3D method compared to direct measurements, and further studies should be conducted to ensure reliability and accuracy.

In this study on Korean subjects the SW was 95.84 mm, and the SL was 110.55 mm. In the previous literature review on South African subjects when comparing the average SW values between the white group (102.19 mm) and the black group (92.36 mm), Koreans were found to have a narrower width than whites but a wider width than blacks [1]. In terms of SL, Koreans had a longer SL compared to the white group (102.15 mm) and the black group (95.41 mm) from the South African subjects [1]. In the study on Americans the average comparison of SL (White males: 109.7 mm, Black males: 102.9 mm, White females: 108.1 mm, Black females: 102.4 mm) showed that the SL of Koreans was similar to that of white males [17]. Additionally, in the study on Chinese subjects the SW was 100.2 mm in males and 101.8 mm in females, which was similar to that of South African whites but narrower than our study results [8]. The SL was 109.9 mm in males and 104.1 mm in females, which was similar to the results of our study and those of American whites. This indicates that the width and height of the sacrum vary by race, even within the same country, and that measurements can differ widely within the same race as well. Therefore, additional research on the cultural customs and characteristics of different races is necessary for application in forensic science.

About presenting regression model that could predict stature from measurement variables, our study presented all results about male, female and mixed-sex group. In previous study targeting Malaysian, they reported that correlation between SL, SW and stature were statistically significant regardless of sex [18]. Furthermore, studies about South African and Chinese dividing each male and female group also reported correlation between SL, SW and stature were statistically significant [1,8]. Therefore by presenting a model, in various ways, that can predict stature without considering sex, we got the possibility of application according to the field situation.

In our study, among the four variables, all variables except SW were found to be larger in male than in female. This is consistent with the larger SL values in male in the studies of Dayanada et al. [19], Mishra et al. [20], and Giroux et al. [17]. In particular, the study on Chinese subjects showed that among the nine variables measured, only SW and MTDB (Maximum transverse diameter of base) were larger in females than in males, among all the variables measured in the South African subjects, only SW was found to be larger in females than in males. These results were also consistent with our study [1,8]. These results of our study align with previous morphological research, which found that the male sacrum is long and narrow, while the female sacrum is short and wide [1]. This reconfirms the morphological differences of the sacrum through quantitative measurements, and by appropriately utilizing this concept, it appears that we can further refine the models and functions for estimating sex based on the sacrum.

There was a study that reported SW values similar to ours. In the present study, the average SW was 95.18 ± 5.29 mm for males and 96.52 ± 4.96 mm for females, while a previous study on the South African population reported an average value of 96.97 ± 7.82 mm for males and 97.29 ± 8.98 mm for females [1]. In contrast, several studies reported higher values compared to this study. In a Japanese study, the average maximum breadth of sacral alae was 116.98 ± 4.98 mm for males and 115.19 ± 5.60 mm for females [21]. Another study on the Chinese population reported that the average ASW was 100.2 ± 5.4 mm in males and 101.8 ± 6.2 mm in females [8]. A Spanish study reported an average of 114.7 ± 7.1 mm for males and 113.9 ± 6.9 mm for females [12]. These discrepancies are likely due to differences in body structure among populations and variations in measurement techniques.

In this study, the average SL was 112.43 ± 8.99 mm for males and 108.62 ± 9.96 mm for females. In a Japanese study, the average anterior sacral length (ASL) was 112.8 ± 9.9 mm for males and 103.6 ± 10.8 mm for females [21]. A study on the Chinese population reported that ASL averaged 108.9 ± 10.0 mm in males and 104.1 ± 8.7 mm in females [8]. A Spanish study reported average SL values of 104.1 ± 9.9 mm for males and 96.0 ± 11.3 mm for females [12]. These results showed similar outcomes in the SL of East Asians, but the SL of Spanish females showed a significant difference. Therefore, it is necessary to accurately identify racial morphological relationships through complex additional studies on East Asians and Westerners.

In this study, the R value of the height estimation equation based on SW was 0.537 for males, 0.524 for females, and 0.347 for unknown sex. A previous study on the Thai population reported R values of 0.530 for males, 0.480 for females, and 0.340 for unknown sex, while for Malaysians with unknown sex, the R value was 0.178 [18,22]. This indicates that height estimation studies based on SW show significantly higher R values when applied separately to males or females compared to cases where sex is unknown, a trend consistent with previous research. Furthermore, this study demonstrated higher predictive power in height estimation models based on SW compared to studies on Malaysians. These findings highlight the strong predictive power of our study's height estimation model based on SW, particularly when applied to known-sex individuals, suggesting its applicability and reliability compared to previous studies.

In this study, the R value was 0.430 when a model for estimating height based on SL was applied regardless of sex (Unknown sex). In a study on Black South Africans, the R value was 0.370, while a study on Europeans reported an R value of 0.371 [1,23]. A study on the Japanese population showed an overall R value of 0.345, and the R value for Malaysians was 0.332 [21,23]. This suggests that SL may have relatively high predictive power for stature estimation in the Korean population. Additionally, it highlights the importance of considering population-specific variations in SL when developing stature estimation models, as measurement techniques and anatomical differences can influence predictive accuracy.

The present study has the following limitations. First, although morphological analysis was conducted through 3D reconstruction of CT images, there was no analysis of the error between the actual cadaver study and the reconstructed models, and further research is needed to address this gap. Second, factors such as weight, Body Mass Index (BMI), and age, which may affect stature estimation, were not considered. Third, although the study was conducted on participants aged 30 to 79, the number of subjects in each age group was insufficient, and no analysis of generational differences was performed. Fourth, the explanatory power of this study is limited due to its small sample size ($n=67$) and the moderate Adjusted R^2 values. Fifth, as this study was conducted solely on the Korean population, further validation in diverse ethnic groups is necessary to enhance the generalizability of the findings. Therefore, subsequent studies with larger sample sizes and various age groups, including diverse ethnicities, are needed to address these limitations.

CONCLUSIONS

This study developed a stature estimation model based on variables related to the sacrum. The stature estimation was analyzed by considering the differences between sexes, and there was a difference in predictive power between cases where the sex was known and unknown, depending on the variables. By presenting not only the commonly applied SW and SL but also LOL and ROL, which showed higher correlation coefficients, this study expanded the applicability of sacrum-based stature estimation models. This research provides important foundational data for stature estimation using the sacrum and is expected to be applicable in future forensic anthropology applications.

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