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The classification of sacral foramina in a South African sample using cadaveric and osteological remains

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ABSTRACT

Sacroiliac (SI) joint fixation is a technique used for SI joint fractures, SI joint dislocations and sacral fractures. Sacral screws can be placed either into the S1 or the S2 vertebrae if S1 is insufficient. Malpositioning of the screws is a common surgical complication as sacral variations exists amongst populations. Complications associated with the misposition of screws can lead to injury of the sacral venous plexus, iliac vessels, or sacral nerve roots. Therefore, this study aimed to evaluate sacral variations in a South African sample by determining distances between the first and second sacral foramina and classifying the common types of sacra found.

A quantitative cross-sectional comparative study was conducted. One hundred and twenty (n = 120) dry human sacra and 11 formalin-fixed cadavers were measured to determine the linear distances between the first two anterior and posterior sacral foramina. Additionally, the dry human sacra were classified according to Mahato's classification system. A cadaver SI joint fixation simulation was performed by an orthopaedic surgeon.

The mean sacral promontory height was found to be 31.81 mm and 37.52 mm in osteological and cadaver specimens, respectively. The mean anterior pedicle height was significantly different for the left (18.81 mm) and right (21.67 mm) side measurements. A statistically significant difference was found between cadavers and osteological samples for all measurements taken. In the osteological sample, ancestry and age mostly influenced the variations noted.

Using Mahato's classification system, sacra with five sacral segments, auricular surfaces extending from the superior part of S1 to the middle of S3 and no accessory L5/S1 articulations had the highest prevalence of 59.17 %.

The South African sample exhibited similarities but did not fully compare to other populations. The results in this study should be considered as a reference for surgeries involving the SI joint and sacral foramina. However, where possible, the exact anatomy with possible variations of the patient should be evaluated preoperatively using X-rays and angiograms.

1. Introduction

The sacrum is an irregular, wedge shaped bone usually composed of five fused vertebrae [1]. Sacra have an anterior concavity with bilateral auricular surfaces and can vary in many ways. Some of these variations include the number of sacral segments, the location of its auricular surfaces and evidence of sacralisation or lumbarisation [2]. The sacrum forms the foundation of the vertebral column. When standing, the sacrum diffuses stress though the SI joints from the axial to the lower appendicular system [1,3,4].

Mahato described a classification system in which sacral variations are divided into five groups with subtypes to account for common to rare variations [2]. This system considers the level of the sacrum's auricular surfaces, the number of sacral segments and any accessory L5/S1 articulations.

The sacrum is a strong bone which does not frequently exhibit issues. However, when severe trauma occurs, surgical interventions might be mandatory to stabilise the pelvis. Unstable pelvi can be treated in various manners [5,6]. Operative internal fixation has shown a better prognosis by reducing mortality and increasing long-term functionality

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for the patient [5,6]. In such cases, SI joint fixation surgery is performed by inserting percutaneous screws or anterior plates. The screws are placed bilaterally traversing the SI joints [3]. Ebraheim et al., found that the sacrum is weakest below the level of the S2/3 junction. The screws are generally placed into either the sacral wing or S1 promontory, as they are the strongest parts of the sacrum. The screws are placed into the S2 vertebrae when S1 is insufficient [7]. Morphometric sacral measurements determine the location where the screws are placed as well as the size of the screw utilised [8]. Plates can be used as an alternative to screws. These plates place the bones under traction to allow for reduction of the fracture [6]. One plate is placed superiorly over the upper one third of the SI joint. A second plate may be required to increase traction and is placed superiorly over the middle one third of the SI joint. Percutaneous S1 screw placement is a less invasive surgery than anterior plate placement surgery [9]. However, accompanying the screw procedure, the patient is exposed to high levels of x-rays and potential complications. As a result, the preferred surgical technique is disputed amongst orthopaedic surgeons [9].

Surgical complications can occur such as injury or damage to the pedicle cortex, sacral canal, cauda equina, sacral nerve roots or any neighbouring neurovascular structures during inaccurate screw placement [8,10]. This can result in either acute or chronic complications that can escalate morbidity and mortality [8]. Examples of common complications include severe hypotension due to the penetration of iliac vessels, lumbosacral trunk injury leading to foot drop or peroneal pain [10]. The majority of the complications arise from sacral variations [11]. The sacra have shown great variability amongst population groups, which was mostly discovered by chance during surgical interventions, radiological examination or research studies [12]. Therefore, thorough knowledge of the prevalence of sacral variations is imperative prior to surgical interventions.

Previous studies documenting anatomical variations of sacra have mainly focused on the Indian, West Anatolian, Mexican, Egyptian and American population groups [3,8,10,13–16]. Other researchers have alluded to the prevalence of several variations that may affect the outcomes of SI joint fixation surgery, thereby emphasizing the need for further study.

Previous studies conducted between the South African population and other populations have indicated metric differences when measuring the humerus, femur, tibia, mandible and cranium [17]. Pininski et al., investigated stature determination using sacral measurements in a South African population [18]. However, with the exception of one measurement, none of the published measurements are significant to clinicians during screw placement procedures. Thus, to the researcher's knowledge, no previous morphometric sacral studies focusing on S1 and S2 for screw placement in a South African sample has been published. Therefore, the current study focused on the prevalence of sacral variations using morphometric sacral measurements in a South African sample using 120 dry human sacra and 11 formalin fixed cadaveric specimens to quantify sacral characteristics for safe screw placement. Additionally, sacra were classified into various groups according to Mahato's classification system [2].

2. Methods and materials

A quantitative cross-sectional observation study was conducted consisting of both a skeletal and formalin fixed cadaver component. Research was conducted in accordance with the South African National Health Act, Act 61 of 2003 (Ethical clearance number:109/2020) from the University of Pretoria.

2.1. Osteological component

A total of 120 dry human sacra (n = 120) were assessed which included: 30 white females, 30 white males, 30 black females and 30 black males. The rationale for the sample size was due to the availability of sacra with no visible damage which allowed for equal distribution in all the subgroups. These were procured from the Pretoria bone collection, Faculty of Health Sciences, University of Pretoria. Any sacra with severe visible damage to the areas being measured were excluded from the study.

The following eight linear parameters, which have been previously described in other studies were measured on both the anterior and posterior surfaces of the dry sacra (Fig. 1), using a digital sliding calliper of 0.1 mm accuracy [8,10,14–16,19].

Measurements taken on the sacra

TA1	Transverse distance between the left and right first anterior sacral foramina
TA2	Transverse distance between the left and right second anterior sacral foramina
SA1	Height of S1 vertebrae
SA2	Height of S2 vertebrae
PA1 (L&R)	Anterior pedicle height on the left and right
PA2 (L&R)	Distance between the inferior border of the first anterior sacral foramina and the superior border of the second anterior sacral foramina on the left and right side
PP1 (L&R)	Posterior pedicle and facet height on the left and right
PP2 (L&R)	Distance between the inferior border of the first posterior sacral foramina and the superior border of the second posterior sacral foramina on the left and right side

Lastly, each sacrum was classified according to the classification system described by Mahato [2]. The classification depended on the number of sacral segments, level of auricular surfaces and any accessory L5/S1 articulations.

2.2. Cadaveric component

A total of 11 formalin embalmed cadaver specimens (n = 11) were dissected posteriorly and anteriorly and their measurements recorded. The cadavers were obtained from the Department of Anatomy, Faculty of Health Sciences, University of Pretoria. Any cadavers with evidence of previous sacral surgery or injury to the pelvic area were excluded from the study.

With the cadaver in a supine position (Fig. 2), a vertical incision was made from the xiphoid process extending to the pubic symphysis encircling the umbilicus (B-E). Another incision was made along the inferior costal margins from the xiphoid process to the midaxillary line bilaterally (B-A & B-C). A third incision was made from the pubic symphysis extending laterally to the iliac crests on the midaxillary line (E-D & E-F).

The skin was reflected laterally and the superficial Camper's and Scarpa's fascia were removed. The muscles of the anterior abdominal wall and related fascia were reflected laterally to expose the abdominal and pelvic viscera.

The mesentery of both the small and large intestines were removed from their attachment on the posterior abdominal wall. All large vessels, in the lower abdominal and pelvic regions, were removed to fully expose the sacrum. Additionally, the rectum was retracted anteriorly towards the pubic symphysis to increase the dissection field.

To view the transverse lines on the anterior surface of the sacrum as well as the sacral promontory, the anterior longitudinal ligament had to be removed. Moreover, the anterior sacroiliac ligament was removed to measure PA1. The sacrum was cleaned to expose the first two sacral foramina, where pins were inserted to clearly indicate their location (Fig. 3A).

Linear measurements of the eight parameters (Fig. 1) were taken internally using a string. The string was measured externally using a digital sliding calliper to 0.1 mm accuracy (Fig. 3B).

With the cadaver in a prone position, the iliac crests were palpated. A

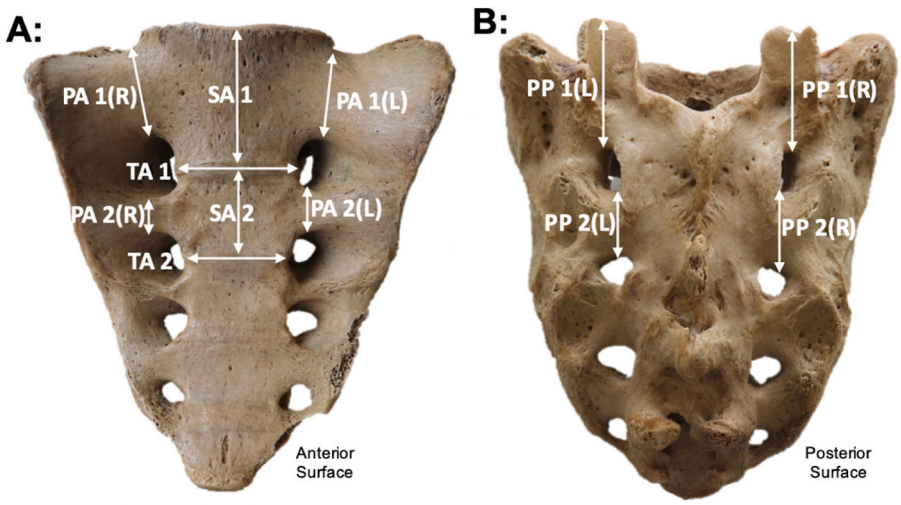

Fig. 1. Illustrative description of the measurements taken [8,10,14–16,19].
A: TA1: Transverse distance between the left and right first anterior sacral foramina; TA2: Transverse distance between the left and right second anterior sacral foramina; SA 1: Height of S1 vertebrae; SA2: Height of S2 vertebrae; PA1(L&R): Anterior pedicle height; PA2(L&R): Distance between the inferior border of the first anterior sacral foramina and the superior border of the second anterior sacral foramina
B: PP1(L&R): Posterior pedicle and facet height; PP2(L&R): Distance between the inferior border of the first posterior sacral foramina and the superior border of the second posterior sacral foramina.

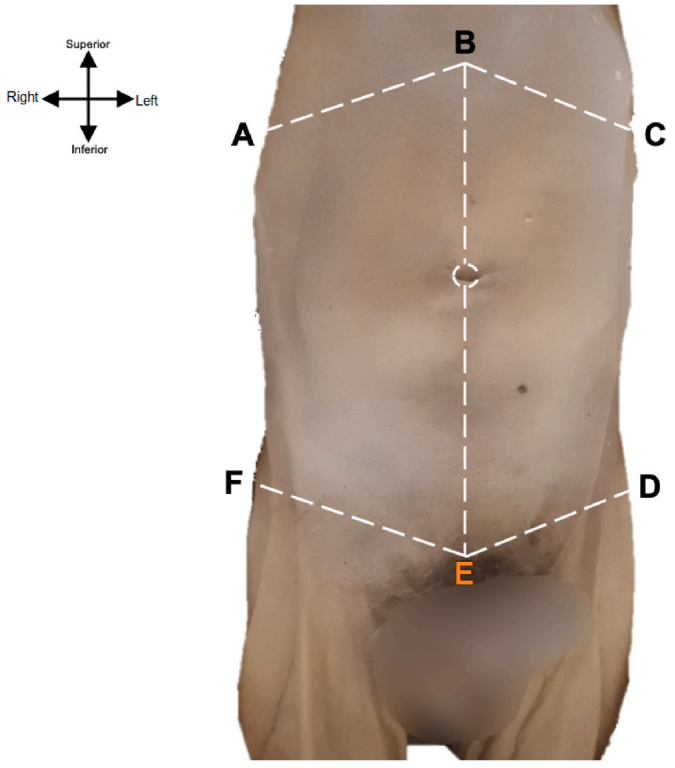

Fig. 2. Anterior incisions made on the formalin-fixed cadaver specimens.
B-A & B-C: Incisions made along inferior costal margins to the midaxillary line; **B-E:** Vertical incision from the xiphoid process to the pubic symphysis; **E-D & E-F:** Incisions made from the pubic symphysis to the iliac crests extending to the midaxillary line.

transverse incision was made approximately 4–6 cm superior to the iliac crests between the scapular lines (A-B). The coccyx (C) was palpated and an incision was made extending from the tip of the coccyx along the midline, over the median sacral crest, to midway on the line A-B. Another two incisions were made from point C to both point A and point B forming a triangular opening as indicated in Fig. 4 below.

The skin was removed, along with any superficial fat, the thoracolumbar fascia and soft tissue covering the sacrum (Fig. 5). Lastly, the posterior sacroiliac and sacrotuberous ligaments were removed to expose the posterior sacral foramina and the lumbosacral joint.

Pins were placed into the lumbosacral joint and into all the posterior sacral foramina. The same posterior measurements were taken as on the osteological component mentioned above (Fig. 1). All the measurements were taken by the primary investigator using a string and sliding digital calliper of 0.1 mm accuracy. Cadaveric sacra could not be classified according to Mahato's classification system due to their auricular surfaces not being visible [2].

A cadaveric simulation of SI joint fixation surgery using the anterior approach was performed on one formalin fixed cadaver. The simulation was performed as per the guidelines described by Banerjee et al. [20] to validate the findings made in the study without the use of imaging modalities. The simulation included the use of both screws and plates which was carried out by the orthopaedic surgeon on the study.

Add Fig. 5A, B and 5C here.

2.3. Statistical analysis

Statistical analysis was performed using IBM SPSS version 26.0 for all data collected. For all the statistical analyses, a p-value of <0.05 was considered significant. The data was initially tested for normality using a Shapiro-Wilk statistical test. The data was investigated for significant differences between left and right sides using a paired *t*-test for normally distributed data and a Wilcoxon signed-rank test for skewed data. Any measurements with no significant difference found between sides were combined into one measurement for further testing. An independent *t*-test for normally distributed data and a Mann-Whitney *U* test for skewed data was performed to assess significant differences between cadaver measurements and osteological measurements. All the data is reported using means and ranges. Additionally, median and interquartile range values are reported for skewed data. Each measurement was tested for association with four different demographic parameters namely sex, ancestry, age and BMI using a Point Biserial correlation test. The resulting correlation coefficients and p-values are reported. To ensure the accuracy and repeatability of the results obtained from the study, intra- and inter-rater reliability were determined with the use of

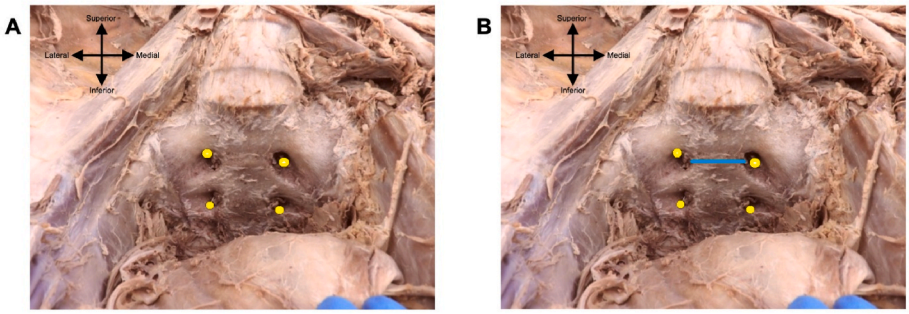

Fig. 3. The first two anterior sacral foramina exposed and the internal measurement method used.
A: The pins were used to indicate the first two anterior sacral foramina with the bladder and rectum retracted. **B:** A string was used to measure the anterior transverse distance between the first left and right sacral foramina.

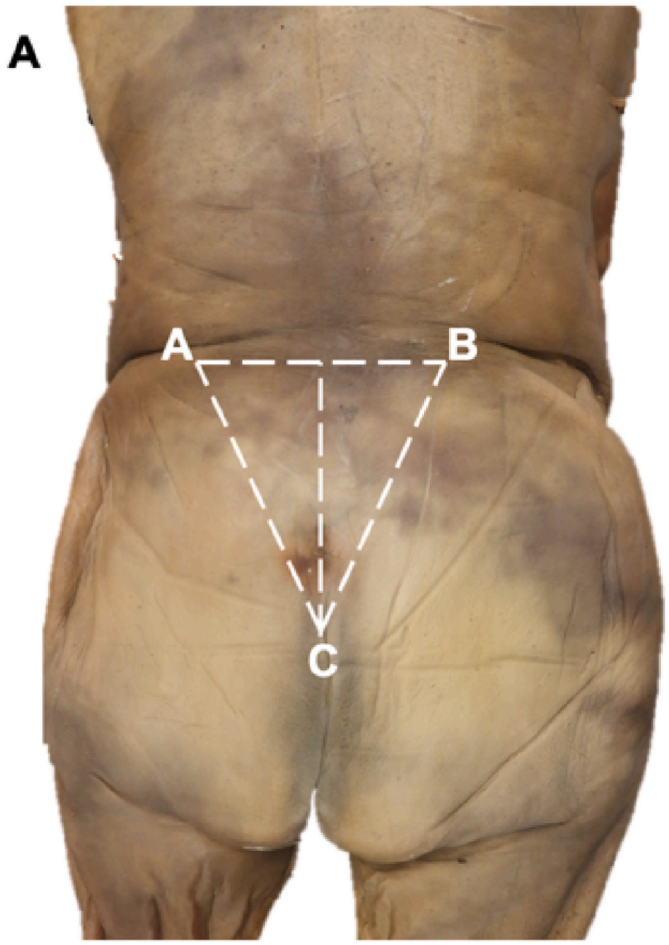

Fig. 4. Posterior incisions made on formalin-fixed cadaver specimens.
A-B: A transverse incision of 4–6 cm was made superior to iliac crests between the scapular lines; **C:** Coccyx; **C-A & C-B:** Diagonal incisions between the coccyx and points A and B; **C-½AB:** Vertical incision from the coccyx to midway along AB.

intraclass correlation coefficients (ICC). The ICC values were determined for 10 % of each sample using an independent observer.

3. Results

The age of the osteological sample ranged from 21 to 88 years (mean age = 56.33years) with a mean BMI of 20.14 kg/m^2 (range = 27.79 kg/m^2). The cadaver sample had ages ranging between 50 and 82 years with a mean age of 69.60 years (range = 32years) and a mean BMI of 23.71 kg/m^2 (range = 19.66 kg/m^2). Descriptive statistics are described for all four measurements in Table 1.

The normality tests showed that TA1, PA2 left and right for the osteological measurements were skewed. All other measurements were found to be normally distributed. Table 2 includes p-values indicating significant differences for left and right measurements. Only PA1 was statistically significant, where the right side was on average larger.

A comparison between osteological and cadaver specimens was completed to test if they had significantly different measurements. A significant difference was found for all measurements (Table 3) thereby indicating that osteological and cadaver measurements do not correspond.

Additionally, the study investigated whether a relationship existed between the measurements and specified demographics using a point-biserial correlation (Table 4). In the cadaver sample, it was found that ancestry is significant for PA2 with a weak correlation towards black ancestry ($r_{pb} = 0.467$, $p = 0.029$). PP1 showed a weak negative correlation ($r_{pb} = -0.451$, $p = 0.046$) for age which indicates that as age increases, PP1 would decrease.

In the osteological sample the study determined statistically significant relationships for each measurement. Overall, only weak correlations were found except for a moderate correlation between measurement SA1 against ancestry ($r_{pb} = -0.638$, $p = 0.000$). Additionally, ancestry had a statistically significant, weak correlation towards white ancestry for all eight measurements. With the exception of TA1, age was found to have a statistically significant weak positive correlation with all the measurements taken.

The osteological remains were classified according to Mahato's classification system (Table 5). Images of each classification found in this study are shown in Fig. 6 [2].

The most common sacral type was group IA with a prevalence of 59.17 %. Group IA (Fig. 6A) are sacra with five sacral segments, standard auricular surfaces ranging between the upper part of S1 to the middle of S3 and have no accessory L5/S1 articulations. The second most common sacral group was group IIIA (Fig. 6E) (15.83 %) which had six sacral segments, standard auricular surfaces and no accessory L5/S1 articulations. Overall five sacral segments (group I and II) was the most common number of segments in comparison to six (group III) and four segments (group IV) with 76.67 %–22.49 % and 0.83 %, respectively. Furthermore, standard level auricular surfaces (A groups) were most prevalent among the sample at 75.00 %. High-up auricular surfaces ranging from higher than S1 superiorly extending to inferiorly up to the lower S2/upper S3 limits (B groups) was observed 11.66 % whereas low-down auricular surfaces ranging between lower S1 to lower S3 levels had a prevalence of 12.50 %. Accessory articulations were observed in 7.50 % of sacra (group II). Only one sacrum had complete bilateral lumbarisation (group IIID–0.83 % - Fig. 6G) in comparison to 22.49 % of the sample showing either complete or incomplete L5 sacralisation

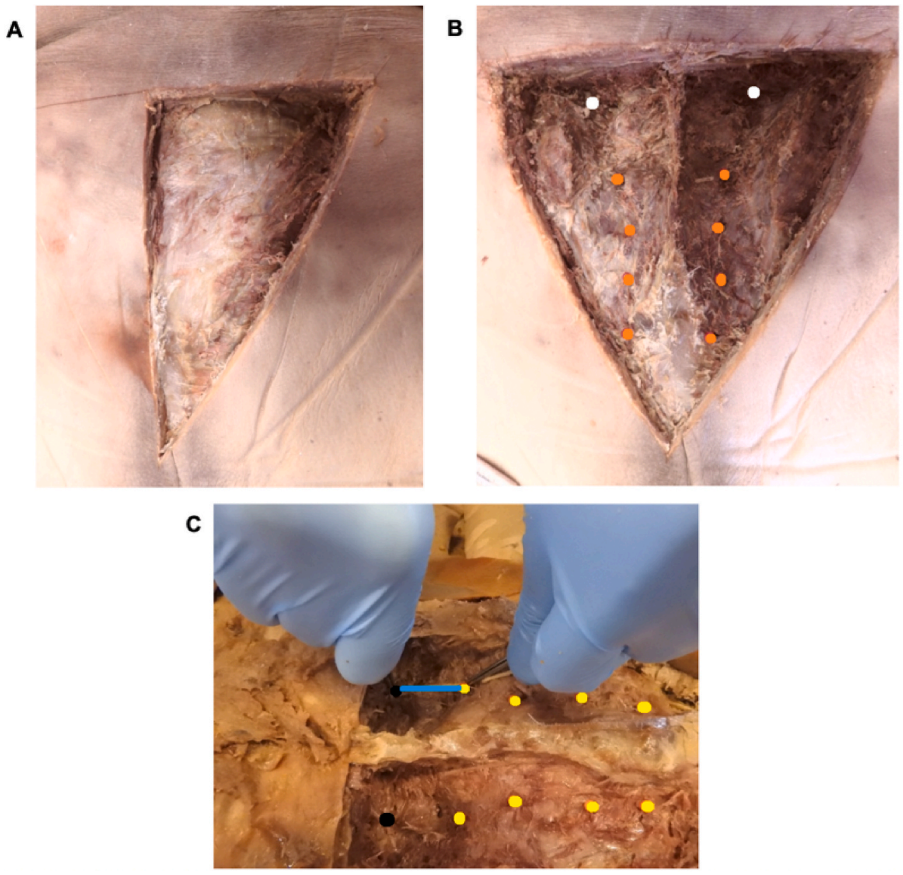

Fig. 5. Steps in posterior formalin fixed cadaver dissection.
A: Skin and superficial fat removed; **B:** Posterior sacrum fully dissected with orange coloured pins in the eight posterior foramina and white pins indicating the lumbosacral joint; **C:** A string was used to measure the vertical distance between the superior articular facet and the superior part of the first sacral foramina.

Table 1
Descriptive statistics for measurements on the median line.

Measurement	Sample	N	Mean	Range	Median*	Interquartile range*
TA1	Osteological	120	31.69	27.05	31.01	4.01
	Cadaver	11	40.60	14.44	-	-
TA2	Osteological	120	28.55	14.81	-	-
	Cadaver	11	37.81	11.10	-	-
SA1	Osteological	120	31.83	20.74	-	-
	Cadaver	11	37.52	12.31	-	-
SA2	Osteological	120	26.39	18.07	-	-
	Cadaver	11	30.37	8.36	-	-

Where N = sample size, skewed data highlighted in blue for which median and interquartile range are included*.

(group III).

Lastly, intra- and inter-rater reliability with the use of ICC were determined to ensure accuracy of results. ICC's were determined for each measurement. It was found that all ICC's were greater than 0.8 with a minimum of 0.818 and a maximum of 0.992 therefore a high intra- and inter-rater reliability was concluded.

4. Discussion

In the current study, both TA1 and SA1 had the highest standard deviation between all measurements at 4.15 mm and 3.78 mm, respectively. The high standard deviation is a representation of the first sacral vertebrae variation in the South African population. Table 4 shows that TA1's variations may be due to sex as it is a significant, weak correlation. Untested demographics may better describe TA1's variations. SA1's variations can be attributed to all of the tested demographics as they were all deemed significant. Ancestry had the strongest correlation for SA1. The South African population's TA1 and SA1 mean and standard deviation measurements are one of the largest across the compared populations in Table 6 [8,14,15,19]. The Mexican population's TA1 and SA1 are similar with the current study's TA1's mean differing by 0.64 mm and SA1's mean by 0.72 mm [8]. In addition, the Mexican population recorded similar standard deviations with their TA1 standard deviation being higher than the South African population's [8]. According to Saluja et al., S1 is the preferred vertebrae for screw placement as adjacent neurovascular structures are least likely to be affected [14]. The study has shown that S1 has significant variations within the South African population, which should be considered preoperatively.

In the study, S2 had a reduced standard deviation when compared to

Table 2
Analysis results for significant differences between left and right sides using paired sample t-tests and Wilcoxon signed rank test.

Measurement	Sample	Side	N	Mean	Range	Median*	Interquartile range*	p-value
PA1	Osteological	Left	120	18.81	15.64	-	-	0.000
		Right	120	21.67	15.03	-	-	
		Total	240	20.24	19.54	-	-	-
	Cadaver	Left	11	30.90	11.48	-	-	0.966
		Right	11	30.88	15.26	-	-	
		Total	22	30.89	15.26	-	-	-
PA2	Osteological	Left	120	12.16	15.28	11.81	3.51	0.178
		Right	120	12.50	16.62	12.19	3.16	
		Total	240	12.33	18.66	12.00	3.51	-
	Cadaver	Left	11	21.42	10.78	-	-	0.647
		Right	11	21.87	9.33	-	-	
		Total	22	21.65	10.78	-	-	-
PP1	Osteological	Left	120	28.24	17.43	-	-	0.402
		Right	120	28.52	27.18	-	-	
		Total	240	28.20	27.33	-	-	-
	Cadaver	Left	11	36.98	24.96	-	-	0.862
		Right	11	36.51	23.69	-	-	
		Total	22	36.74	24.98	-	-	-
PP2	Osteological	Left	120	15.72	13.08	-	-	0.411
		Right	120	15.54	15.61	-	-	
		Total	240	15.63	15.73	-	-	-
	Cadaver	Left	11	21.01	8.62	-	-	0.484
		Right	11	21.32	9.60	-	-	
		Total	22	21.17	10.40	-	-	-

Where N = sample size, significance indicated of $p < 0.05$ highlighted in grey, skewed data highlighted in blue for which median and interquartile range are included*.

Table 3
Comparative results for osteological and cadaver specimens.

Measurement	Sample	Side	N	Mean	Range	Median*	Interquartile range*	p-value
TA1	Comparison	-	131	32.44	27.05	31.40	5.13	0.000
TA2	Comparison	-	131	29.32	24.75	-	-	0.000
SA1	Comparison	-	131	32.30	22.56	-	-	0.000
SA2	Comparison	-	131	26.73	18.07	-	-	0.001
PA1	Comparison	Left	131	19.83	26.76	-	-	0.000
		Right	131	22.44	22.67	-	-	0.000
PA2	Comparison	-	262	13.11	21.93	12.19	3.99	0.000
PP1	Comparison	-	262	29.08	29.66	-	-	0.000
PP2	Comparison	-	262	16.09	19.60	-	-	0.000

Where N = sample size, significance indicated of $p < 0.05$ highlighted in grey, skewed data highlighted in blue for which median and interquartile range are included*.

S1's measurements. Table 4 suggests that both TA2's and SA2's variations are due to the measurements having significant, weak correlations to ancestry and age. In addition, TA2 had a significant weaker correlation to sex and SA2 to age. The current study's S2 measurements were both the highest across the compared populations in Table 6 [8,14,15,19]. TA2 moderately differed from the West Anatolian population by 1.24 mm, while SA2 differed slightly by 0.05 mm [19]. Knowledge of the South African population's S2 variations is critical for S2 fixation surgery.

In this study, overall it was found that the vertical distance between both the anterior and posterior sacral foramina as well as the vertebrae heights decrease in size inferiorly. In addition, the transverse distances between the first and second sacral foramina also decrease inferiorly. These findings are consistent with the results of the other studies shown in Table 6 [8,14,15,19].

In the study's findings, a statistically significant difference was found in the osteological sample's PA1 measurement between the left and right sides. Only the Indian population reported a significant difference for PA1 left and right [14]. The other compared populations did not report test results for the left and right measurements.

The current study's PP1 measurement had a standard deviation (3.59 mm) which is in line with the rest of the study's measurements. PP1's South African variations can be attributed to a significant weak correlation to ancestry and age, as shown in Table 4. PP1 could not be compared to other studies as, according to the current knowledge of the researchers, the same measurement has never been reported with the facet height included.

The current study's findings show that the PP2 is larger in comparison to PA2 with 15.63 mm and 12.33 mm, respectively. This is corroborated by the published work of other authors [8,14,15,19].

Table 4
Demographic correlations for the osteological and cadaver samples.

Measurement	Side	Sample	Demographic information	Correlation coefficient	p-value
TA1	-	Osteological	Sex	-0.200	0.029
			Ancestry	-0.057	0.537
			Age	0.057	0.533
			BMI	0.030	0.744
		Cadaver	Sex	-0.321	0.337
			Ancestry	-0.051	0.882
			Age	-0.254	0.479
			BMI	0.195	0.566
TA2	-	Osteological	Sex	-0.288	0.001
			Ancestry	-0.328	0.000
			Age	0.317	0.000
			BMI	0.148	0.106
		Cadaver	Sex	0.010	0.978
			Ancestry	-0.120	0.726
			Age	-0.043	0.906
			BMI	0.000	0.999
SA1	-	Osteological	Sex	-0.214	0.019
			Ancestry	-0.638	0.000
			Age	0.456	0.000
			BMI	0.206	0.000
		Cadaver	Sex	-0.106	0.755
			Ancestry	-0.407	0.214
			Age	-0.457	0.184
			BMI	-0.164	0.630
SA2	-	Osteological	Sex	-0.117	0.202
			Ancestry	-0.322	0.000
			Age	0.242	0.008
			BMI	0.207	0.023
		Cadaver	Sex	0.062	0.857
			Ancestry	0.455	0.160
			Age	-0.457	0.184
			BMI	-0.397	0.226
PA1	Left	Osteological	Sex	-0.138	0.133
			Ancestry	-0.423	0.000
			Age	0.284	0.002
			BMI	0.132	0.151
		Cadaver	Sex	-0.135	0.693
			Ancestry	0.336	0.312
			Age	-0.508	0.134
			BMI	-0.540	0.087
	Right	Osteological	Sex	-0.172	0.061
			Ancestry	-0.359	0.000
			Age	0.319	0.000
			BMI	0.114	0.214
		Cadaver	Sex	-0.104	0.762
			Ancestry	0.065	0.850
			Age	-0.423	0.223
			BMI	-0.589	0.056
PA2	-	Osteological	Sex	-0.141	0.029
			Ancestry	-0.129	0.047
			Age	0.137	0.034
			BMI	0.135	0.037
		Cadaver	Sex	-0.024	0.916
			Ancestry	0.467	0.029
			Age	0.335	0.149
			BMI	-0.053	0.816
PP1	-	Osteological	Sex	-0.101	0.119
			Ancestry	-0.312	0.000
			Age	0.234	0.000
			BMI	0.091	0.160
		Cadaver	Sex	-0.043	0.850
			Ancestry	-0.001	0.997
			Age	-0.451	0.046
			BMI	-0.201	0.369
PP2	-	Osteological	Sex	-0.013	0.845
			Ancestry	-0.422	0.000
			Age	0.398	0.000
			BMI	0.243	0.000
		Cadaver	Sex	0.225	0.314
			Ancestry	-0.262	0.239
			Age	0.086	0.719
			BMI	0.378	0.083

Where BMI = body mass index, significance indicated of $p < 0.05$ highlighted in grey, skewed data highlighted in blue

Table 5
Classification distribution of the osteological remains using Mahato's system [2].

GROUP																	
	I			II			III					IV					V
	A	B	C	A	B	C	A	B	C	D	E	A	B	C	D	E	
N	71	4	8	–	9	–	19	–	7	1	–	–	1	–	–	–	–
%	59.1	3.33	6.67	–	7.50	–	15.8	–	5.83	0.83	–	–	0.83	–	–	–	–

Where N = sample size.

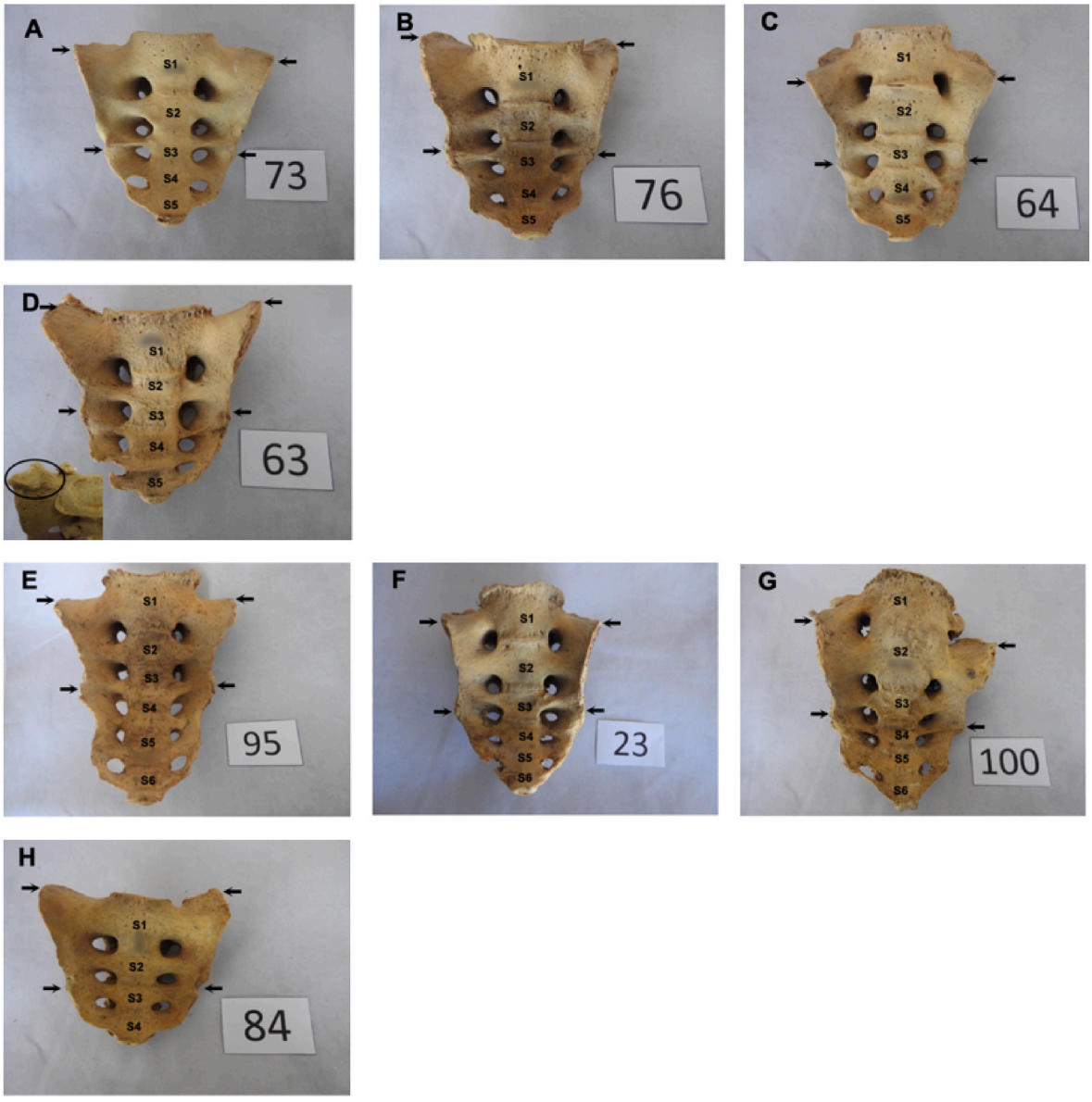

Fig. 6. Examples of the current study's classifications according to Mahato's system (2016) (the number of sacral segments are labelled, arrows indicate the auricular surface levels and an oval indicates any accessory L5/S1 articulations)
A: Group IA, **B:** Group IB, **C:** Group IC, **D:** Group IIB, **E:** Group IIIA, **F:** Group IIIC, **G:** Group IIID, **H:** Group IVB.

Variations seen in the PA2 and PP2 measurements can be as a result of demographic parameters, where weak age and ancestry correlations had the highest contribution. If the anterior and posterior pedicle heights are sufficient during posterior screw placement, it minimizes the risk of neurovascular injury, such as injury to the sacral nerve roots [14]. In the current South African sample, PA2 was closest to the Mexican population, differing by 0.23 mm [8]. Whereas PP2 showed a midpoint measurement between the West Anatolian and Mexican population [8,19].

Table 6
Comparison of sacral measurements mean and standard deviations between the current and previous studies using osteological remains.

Parameters measured (mm)			Authors				
			Current study (South African)	Saluja et al., (Indian) [14]	Arman et al., (West Anatolian) [19]	Morales-Ávalos et al., (Mexican) [8]	Hassanein (Egyptian) [15]
	Side	N	120	108	100	50	45
TA1	–		31.69 ± 4.15	30.10 ± 3.19	30.48 ± 2.78	32.33 ± 4.19	–
TA2	–		29.55 ± 2.84	27.33 ± 2.36	28.31 ± 2.81	27.83 ± 3.20	–
SA1	–		31.83 ± 3.78	29.62 ± 2.65	30.22 ± 2.35	31.11 ± 2.80	30.7 ± 0.47
SA2	–		26.39 ± 3.65	25.45 ± 2.41	26.34 ± 6.09	25.06 ± 3.94	–
PA1	Left		18.81 ± 2.96	21.07 ± 2.43	14.75 ± 2.26	20.84 ± 3.48	–
	Right		21.67 ± 2.51	20.40 ± 2.39	14.88 ± 2.38	20.51 ± 3.37	–
	Total		20.24 ± 2.46	20.74 ± 2.29	14.81 ± 2.32	20.68 ± 3.40	18.3 ± 0.49
PA2	Left		12.16 ± 2.96	11.26 ± 2.38	10.29 ± 2.11	12.70 ± 2.95	–
	Right		12.50 ± 2.84	11.39 ± 2.25	10.79 ± 2.38	12.43 ± 3.01	–
	Total		12.33 ± 2.90	11.33 ± 2.24	10.54 ± 2.25	12.56 ± 2.97	–
PP1	Left		28.24 ± 3.36	–	–	–	–
	Right		28.52 ± 3.81	–	–	–	–
	Total		28.38 ± 3.59	–	–	–	–
PP2	Left		15.72 ± 2.88	14.14 ± 2.34	15.92 ± 2.11	15.53 ± 2.57	–
	Right		15.54 ± 3.41	14.22 ± 2.37	15.92 ± 2.05	15.13 ± 2.45	–
	Total		15.63 ± 3.15	14.18 ± 2.29	15.92 ± 2.08	15.33 ± 2.50	–

Where N = sample size.

For the cadaver sample of the current study, no statistically significant differences were found for all measurements. The cadaver PP1 had a significant weak correlation to age and PA2 had a significant weak correlation to ancestry. The cadaver correlation findings are in accordance with the results reported by Ebraheim et al., in cadaver specimens from Ohio, United States [10]. In the current study, TA1 measured 40.60 ± 3.69 mm on average (range = 27.05 mm) which did not corroborate Ebraheim et al., who found it to be 29.4 ± 3.3 mm (range = 14.2 mm) [10]. The SA2 measurement in the current study was found to be significantly larger than Ebraheim et al., at 37.52 ± 2.77 mm (range = 12.31 mm) and 25.0 ± 2.3 mm (range = 8.5 mm), respectively [10]. The current study's cadaveric PA1 average measurement was determined to be 30.89 ± 4.62 mm (range = 15.26 mm), which showed great similarity to that found by Ebraheim et al., with an average of 30.2 ± 3.4 mm (range = 14 mm) [16]. The current study found PA2 to be 21.65 ± 2.83 mm and PP2 21.17 ± 2.92 mm. Both PA2 and PP2 differed greatly from Ebraheim et al., who reported PA2 to be 12.8 ± 2.5 mm and PP2 as 15.7 ± 2.9 mm [10]. To the researcher's knowledge, no other morphometric sacrum study utilizing formalin embalmed cadavers had been published. Hence the current study's cadaveric results could not be fully compared to that of other populations.

The current study found significant differences between identical measurements taken on osteological and cadaver specimens. Part of the discrepancies in measurements can be attributed to a known difference of approximately 2 mm between dry bones and fresher specimens which measure shorter and larger, respectively [21]. However, to the researcher's knowledge, the dry bones shortening distance has only been determined in long bones. Thus, the sacrum's dry bone shortening is unknown.

In the current study, the percentage of sacral variations of the osteological sample (40.83 %) was lower than that of a study conducted in a Chinese population (58.1 %) [13]. In the current study, 75 % of the 120 dry sacra had standard auricular surfaces which aligned with Mahato's 72 % of 300 sacra [4]. High-up auricular surfaces were found in 13 % of the current study's sample and in 11.66 % of Mahato's sample [4]. Nonetheless, low-down auricular surfaces were observed in 12.50 % of the current studies sample and 15 % of Mahato's sample [4]. Interestingly, in both studies, L5/S1 accessory articulations only occurred in sacra with high-up auricular surfaces [4]. The close similarities to Mahato's study sample shows that the South African population's sacra classifications markers closely resemble the southern and central Indian population [4]. Knowledge of the variations in the sacra are important to clinicians working in and around this region. However, the use of imaging such as X-rays, magnetic resonance imaging (MRI) and computer tomography (CT) imaging remains important for proper diagnosis and accurate surgical screw placement [22].

5. Limitations

The limitations of the study were the small cadaver sample size due to cadaver availability. Additionally, the study is not a true representation of the entire South African population as the cadaveric and osteological samples were not adequately racially diverse. Furthermore, the use of an intermediate string could have introduced a measurement error which in conjunction with the dry bone discrepancy, would result in a larger cadaver measurement.

6. Future direction

Further research needs to be conducted to examine a broader view of the South African population by including a more racially diverse sample. An alternative research approach could utilize radiographic or CT imaging and determine safe angular zones for SI joint fixation screw placement. Additionally, the use of osteological remains, although helpful for classifying the sacra, may not be the best way to take measurements for determining distances for SI joint fixation safe zones due to the significant difference noted in the cadaveric and osteological measurements.

7. Conclusion

SI fixation surgery requires a thorough knowledge of the sacrum, particularly that of the first and second sacral segments. The current study was carried out to provide orthopaedic surgeons with accurate details regarding anatomical sacral variations within the South African population and investigate any demographic associations.

The standard sacrum described by Mahato's group IA, had a prevalence of 59.17 % within the South African sample. The remaining 40.83 % were made up of multiple uncommon variations. The study found similarities in the South African population's sacra to other populations. The S1 vertebrae was determined to be closely related to the Mexican population. The S2 vertebrae's height closely matched the West Anatolian population's vertebrae. The S2 vertebrae's transverse distance (TA2) stood out with a difference of 1.24 mm from the closest population. PA1 was the only measurement found to have a significant difference between the sides, which was in accordance with the results

published for the Indian population. It should be noted that the South African sacra did not completely overlap with another population. Therefore, the South African sacra should be considered independently from that of other populations.

The results in this study should be considered as a reference for surgeries involving the SI joint and sacral foramina. However, if possible, the exact anatomy should be evaluated preoperatively to determine the best approach. This study further reinforces anatomical sacral variations amongst different populations.

Ethical statement

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Research was conducted in accordance to the South African National Health Act, Act 61 of 2003 under strict ethical clearance (Ethical clearance number: 109/2020) from the University of Pretoria.

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CRediT authorship contribution statement

J. van Schalkwyk: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **S. Matshidza:** Writing – review & editing, Methodology, Data curation, Conceptualization. **N. Mogale:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare they have no conflicts of interest that are directly or indirectly related to the research.

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