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Sacral anatomical parameters varies in different Roussouly sagittal shapes as well as their relations to lumbopelvic parameters

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Abstract

Purpose: To study the normal variations in sacral anatomical parameters in different Roussouly sagittal shapes and the association between sacral anatomical parameters and lumbopelvic parameters in healthy adults.

Methods: A cohort of 239 healthy volunteers between 18 and 45 years old was enrolled in this study. A full-spine, standing X-ray was taken for each volunteer. The following parameters were measured: the sacral table angle (STA), sacral kyphosis (SK), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL), and lumbar lordosis apex (LLA). Two hundred and thirty-nine volunteers were classified into five groups according to the Roussouly classification. The differences in sagittal parameters among the five groups were evaluated by one-way analysis of variance. The correlations between lumbopelvic parameters and sacral anatomical parameters were analyzed, and simple linear regressions were simultaneously constructed.

Result: The sacral anatomical parameters vary in different Roussouly sagittal shapes. Correlation analysis revealed that the significant correlations between sacral anatomical parameters and lumbopelvic parameters. The STA correlated with PI ($r = -.690$, $P < .001$), PT ($r = -.216$, $P = .001$), SS ($r = -.631$, $P < .001$), LL ($r = -.491$, $P < .001$), and LLA ($r = 0.515$, $P < .001$). The corresponding regression formulae were as follows: $PI = -0.991*STA + 143 (R^2 = .476)$, $LL = 0.870*STA-135.1 (R^2 = .242)$, and $LLA = 0.039*STA - 0.087 (R^2 = .265)$. The SK correlated with PI ($r = .471$, $P < .001$), PT ($r = .445$, $P = .001$), SS ($r = .533$, $P < .001$), LL ($r = .438$, $P < .001$), and the LLA ($r = -.265$, $P < .001$). The corresponding regression formulae were as follows: $PI = 0.38*SK + 27.22 (R^2 = .396)$, $LL = -0.35*SK - 35.99 (R^2 = .192)$, and $LLA = -0.01*SK + 4.25 (R^2 = .201)$.

Conclusions: The sacral anatomical parameters vary in different Roussouly sagittal shapes and have strong correlations with lumbopelvic parameters, which demonstrates that the specific lumbar shape can be affected by the sacral morphology. Moreover, the predictive models of lumbopelvic parameters based on SK and STA have been provided, which demonstrates constant sacral anatomical parameters could serve as good supplementary index of PI to predict ideal lumbar parameters.

KEYWORDS
lumbopelvic parameters, predictive models, Roussouly classification, sacral anatomical parameters, sacral kyphosis, sacral table angle

1 | INTRODUCTION

Spinopelvic sagittal alignment was found to be strongly associated with health-related quality of life in adults.[1] Various spinal shapes and many positional parameters have been described to explain human sagittal balance in the standing position.[2-4]

According to the sacral slope (SS) orientation and the shape of lumbar lordosis, Roussouly introduced five types of lumbar lordosis in the normal adult population: type I, type II, type III, type III A, and type IV.[3,5] Each type has distinct spinopelvic morphological characteristics and pathological degeneration qualities.[6] Numerous spinopelvic sagittal parameters in different Roussouly sagittal shapes have been extensively studied, whereas the normal variations in sacral anatomical parameters in different Roussouly sagittal shapes have not been studied in detail.

The sacrum is an integrated part of the pelvis and constitutes the undistorted part of the spinal curve, as well as the sacral morphology plays an essential role in sagittal balance. The sacral table angle (STA) and sacral kyphosis (SK) are widely regarded as fixed anatomic parameters in healthy adults.[7-10] These parameters could be easily observed on X-ray images. The STA is relatively widely described in studies of spondylolysis/spondylolisthesis; however, it does not receive enough attention in normal spinopelvic morphology.[7,11,12] The STA was proven to play an important role in the complex spinopelvic interaction and the development of degeneration that was initially overlooked.[13] SK gradually increases during human growth and development and remains constant as the person matures, similar to pelvic incidence (PI).[10] The anterior curving of the sacrum plays an important role during the acquisition of bipedalism and sagittal balance.[14] Previous research has proven the strong correlations among PI, the STA, and SK.[7,10] However, the correlations between sacral anatomical parameters and lumbopelvic parameters in healthy adults are still unknown.

The present study mainly aimed to study the normal variations in sacral anatomical parameters in different Roussouly sagittal shapes as well as the association between sacral anatomical parameters and pelvic-lumbar parameters in healthy adults.

2 | MATERIALS AND METHODS

2.1 | Patient population

A cohort of 252 healthy volunteers between 18 and 45 years old was recruited from our institution between September 2017 and December 2020 and enrolled in this retrospective study. The exclusion criteria were as follows[1]: lumbopelvic transitional vertebrae,[2] spinal deformity or spondylolisthesis,[3] lumbar or thoracic disease,[4] hip joint or pelvic disease,[5] history of spinal surgery, and[6] neurological or neuromuscular disease. Finally, 240 volunteers were enrolled. Written informed consent was obtained from all subjects who participated in this study, and ethical approval was provided by the institutional review board.

2.2 | Radiographic measurements

Posterior-anterior and lateral radiographic films of the subjects' full spine were obtained as the subjects stood in a standardized erect posture. Sagittal parameters were measured on lateral radiographic films. Pelvic and sacral morphology parameters consisted of STA, SK, PI, pelvic tilt (PT), and SS. Sagittal lumbar alignment parameters included lumbar lordosis (LL) and the lumbar lordosis apex (LLA). The location of the LLA,[15] defined as the most anterior lumbar vertebra or disc in the sagittal plane, was determined. Vertebrae from L1 to L5 were assigned numbers ranging

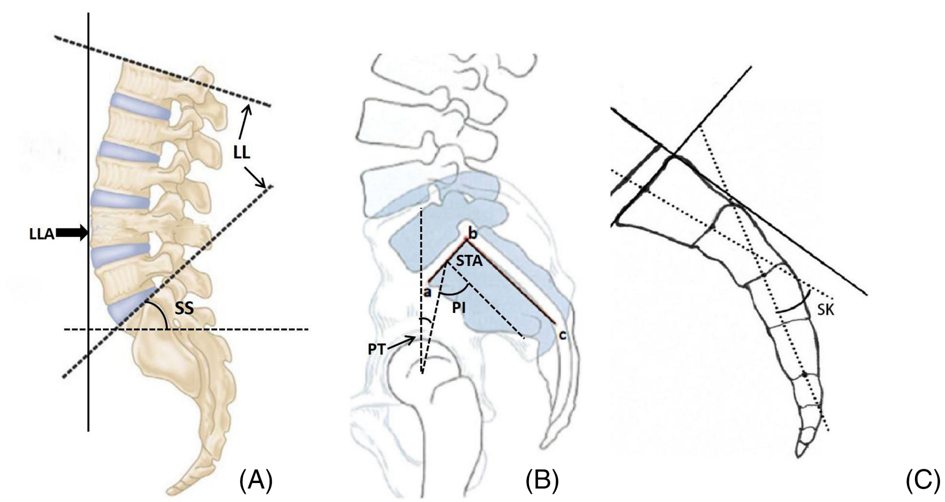

FIGURE 1 The schematic diagram shows the radiographic parameters of lumbopelvic sagittal morphology (A,B) and measurement of the STA and SK (B,C). LL, lumbar lordosis; LLA, lumbar lordosis apex; PI, pelvic incidence; PT, pelvic tilt; SK, sacral kyphosis; SS, sacral slope; STA, sacral table angle

from 1 to 5 to simplify data collection and to facilitate correlation analysis. When the apex was located at a disc between two vertebrae, a value of 0.5 was added to the superior vertebra number (Figure 1A). The STA was defined as the angle between the sacral endplate and posterior wall of the S1-2 body[7] (Figure 1B). SK was defined as the angle between the perpendicular line transecting the midpoint between the anterior and posterior borders of the superior endplate of S1 and the line transecting the midpoint between the anterior and posterior borders of the inferior endplate of S2 to S4.[10,16] (Figure 1C) The measurement was processed with the Surgimap software (Nemaris Inc., New York; Figure 2). Routine demographic data were collected. All data were assessed twice by two independent experienced clinicians, and the average value was calculated as the final result. Lordosis was recorded as negative, and kyphosis was recorded as positive. The intra- and interobserver variability was evaluated by the intraclass correlation coefficient (ICC) in enrolled volunteers. The results showed that the intra-observer ICCs for PI, PT, SS, LL, LLA, STA, and SK were .990, .982, .989, .976, .986,.933, and .984, respectively, while the interobserver ICCs were .976, .963, .968, .948, .963, .945, and .956, respectively. Both the intra- and interobserver reproducibility were excellent.

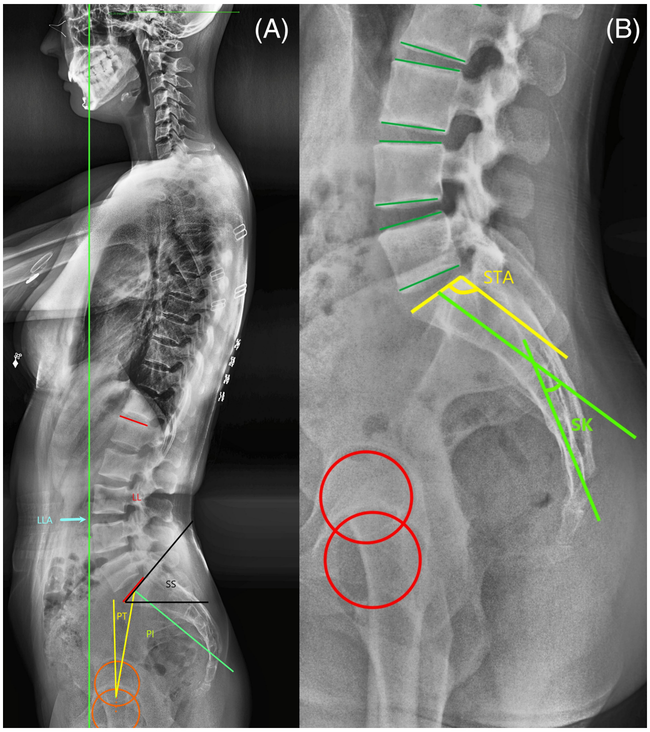

FIGURE 2 The measurements of sagittal parameters on lateral whole-spine standing radiograph. LL, lumbar lordosis; LLA, lumbar lordosis apex; PI, pelvic incidence; PT, pelvic tilt; SK, sacral kyphosis; SS, sacral slope; STA, sacral table angle;

2.3 | Different Roussouly classifications gruoping

Then, all the lateral radiographic images were classified into five different Roussouly sagittal shapes (type I, type II, type III, type III+ pelvic anteverted, or type IV) according to the shape and parameter values of the lumbar spine and pelvis[5]

The schematic diagram and detailed descriptions of different Roussouly sagittal shapes were shown in Figure 3. All the lateral radiographic films were reviewed by two experienced spinal surgeons. If controversial cases were identified, they were excluded. Finally, 239 healthy volunteers were enrolled.

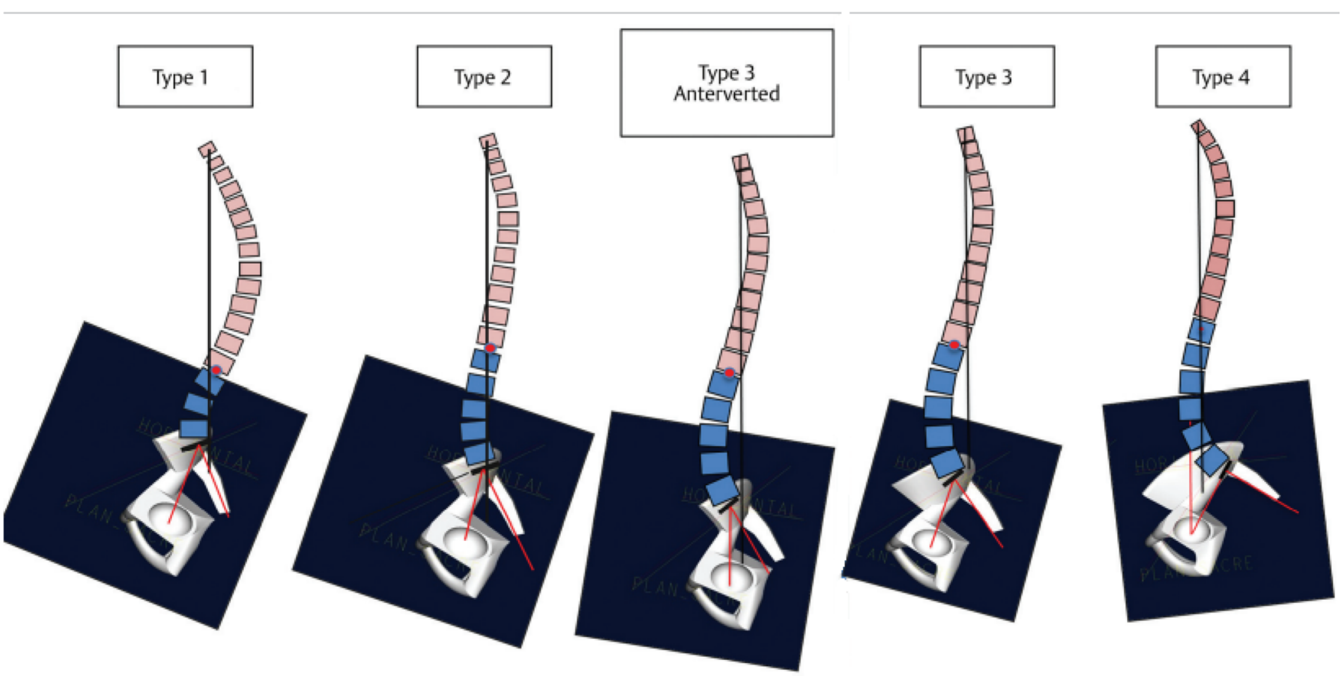

FIGURE 3 The different types of the Roussouly classification

2.4 | Statistical analysis

The data were analyzed using dedicated statistical software SPSS 21.0 (SPSS Inc., Chicago, Illinois). The normality of the data was first tested by the Shapiro-Wilk test. A 2-sided 1-way analysis of variance (ANOVA) and post hoc Tukey tests was used for comparisons among the five subgroups. The correlations between pelvic-lumbar parameters and the STA and SK in total were analyzed using the Pearson or Spearman correlation coefficient, and simple linear regressions were simultaneously conducted. All data are presented as the means and standard deviations (SDs). The statistical significance threshold was $P < .05$.

3 | RESULT

A total of 239 adults (104 females and 135 males) with a mean age of 32.5 ± 9.5 years (range 18-45 years) participated in the present study. The distribution of volunteers according to the different Roussouly

TABLE 1 Description of demographic data and radiographic parameters

Subtypes/Parameters	Total	I	II	III	IV	IIIA
Age (y)	32.6 ± 9.6	33.8 ± 8.6	33.5 ± 9.3	31.9 ± 10.8	34.4 ± 7.0	28.7 ± 8.4
Height (m)	1.75 ± 0.10	1.76 ± 0.12	1.73 ± 0.08	1.77 ± 0.10	1.75 ± 0.22	1.79 ± 0.19
BMI (kg/m^2)	20.2 ± 1.2	21.4 ± 2.6	22.1 ± 3.0	22.4 ± 2.0	21.2 ± 1.9	20.1 ± 1.4
STA (°)	100.6 ± 6.8	108.8 ± 5.2	104.2 ± 4.0	96.6 ± 4.4	92.6 ± 5.9	102.4 ± 4.1
SK (°)	43.6 ± 11.7	36.8 ± 12.0	37.1 ± 8.9	46.8 ± 10.4	51.7 ± 13.7	48.0 ± 10.2
PI (°)	44.0 ± 9.6	32.9 ± 6.7	38.4 ± 5.5	49.6 ± 5.6	58.7 ± 7.4	38.8 ± 5.2
PT (°)	11.5 ± 7.4	9.1 ± 6.8	10.8 ± 5.8	14.9 ± 6.5	12.6 ± 8.3	2.2 ± 7.3
SS (°)	32.4 ± 8.2	23.3 ± 7.0	23.4 ± 4.9	34.2 ± 5.8	45.2 ± 5.8	36.1 ± 3.6
LL (°)	−47.6 ± 12.1	−38.0 ± 14.2	−41.7 ± 8.0	−49.5 ± 9.3	−62.8 ± 8.7	−55.5 ± 7.7
LLA	3.9 ± 0.5	4.6 ± 0.4	3.9 ± 0.4	3.7 ± 0.4	3.3 ± 0.4	4.0 ± 0.3

Abbreviations: BMI, body mass index; LL, lumbar lordosis; LLA, apex of lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SK, sacral kyphosis; SS, sacral slope; STA, sacral table angle.

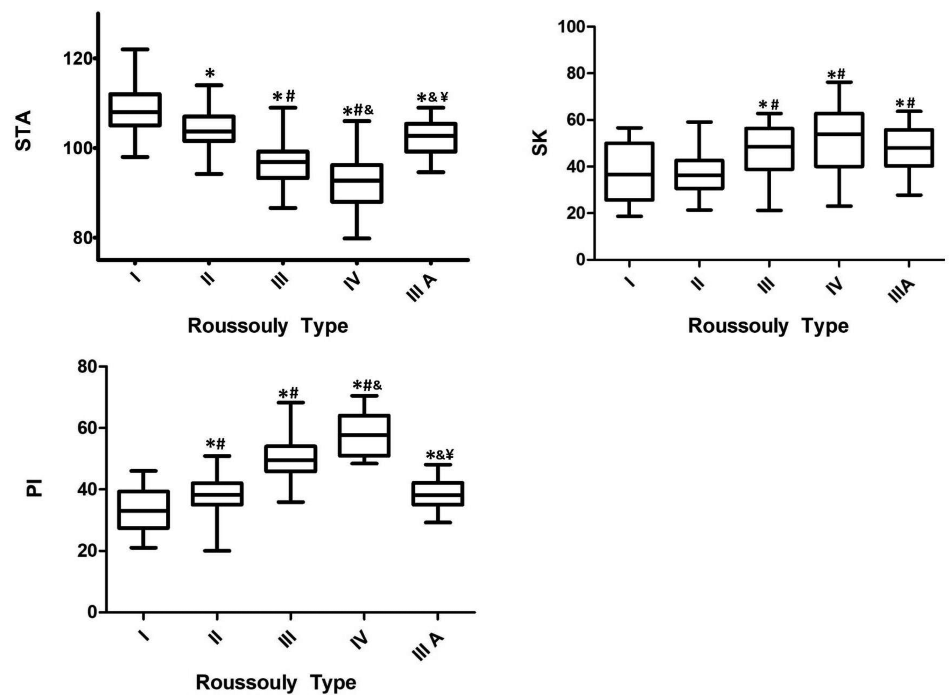

FIGURE 4 The box plot: upper horizontal of box, 75th percentile; middle horizontal line of box, 50th percentile (the median); lower horizontal line of box, 25th percentile; upper horizontal outside box, the maximum value; the lower horizontal outside box, the minimum value. (A) No significant differences in the STA were observed among the five groups. *$P < .05$ (compared with I type); #$P < .05$ (compared with II type); &$P < .05$ (compared with III type); ¥$P < .05$ (compared with IV type). (B) No significant differences in SK were observed among the five groups. *$P < .05$ (compared with I type); #$P < .05$ (compared with II type). (**C**) No significant differences in PI were observed among the five groups. *$P < .05$ (compared with I type); #$P < .05$ (compared with II type); &$P < .05$ (compared with III type); ¥$P < .05$ (compared with IV type)

sagittal shapes was as follows: 33 (13.8%) type I, 69 (28.9%) type II, 91 (38.1%) type III, 21 (8.8%) type III+ pelvic anteverted, and 25 (10.5%) type IV. The descriptive statistics and a spectrum of the normal variations in the sagittal parameters in the different groups are detailed in Table 1.

For STAs, Roussouly type I, II, and III A sagittal shapes had high STA values of 108.8 ± 5.2, 104.2 ± 4.0, and 102.5 ± 4.1, respectively. Roussouly Type III and IV sagittal shapes had low STA values of 96.6 ± 4.4 and 92.6 ± 5.9, respectively. ANOVA revealed significant differences in the STA among the five groups (P <.001). Post hoc Tukey analysis showed that there was no significant difference in STAs between type II and type III A ($P = .577$). Post hoc Tukey analysis also indicated different STA values among the other groups for which there were significant differences (P <.001). Detailed results are presented in Figure 4A.

For SK, Roussouly type I, and II sagittal shapes had low SK values of 36.8 ± 12.0 and 37.1 ± 8.9, respectively. Roussouly Type III, III A, and IV sagittal shapes had high SK values of 46.8 ± 10.4, 48.0 ± 11.7, and 51.7 ± 13.7, respectively. ANOVA revealed significant differences in SK among the five groups (P <.001). Post hoc Tukey analysis showed that there was no significant difference in SK between type I and type II ($P = 1.000$), between type III and type IV ($P = .471$), between type III and type IIIA ($P = .994$), or between type IV and type IIIA ($P = .847$). These results indicated different SK values among the other groups for which there were significant differences (P <.001). Detailed results are presented in Figure 4B.

For PI, Roussouly type I, II, and III A sagittal shapes had low PI angles of 32.9 ± 6.7, 38.4 ± 5.5, and 38.8 ± 5.2, respectively. Roussouly Type III and IV sagittal shapes had high PI angles of 49.6 ± 5.6 and 58.7 ± 7.4, respectively. ANOVA revealed significant differences in PI among the five groups (P <.001). Post hoc Tukey analysis showed that there was no significant difference in PI between type II and type IIIA ($P = .998$). Post hoc Tukey analysis also indicated different STA values among the other groups for which there were significant differences (P <.001). Detailed results are presented in Figure 4C.

TABLE 2 Correlations between pelvic-lumbar sagittal parameters and sacral table angle

Pelvic-lumbar sagittal parameters	Correlation coefficient	P value
Age (y)	.039	.576
BMI (kg/m^2)	.126	.422
Height (m)	.114	.338
SK (°)	−.264	<.001*
PI (°)	−.690	<.001*
PT (°)	−.216	.001*
SS (°)	−.631	<.001*
LL (°)	−.491	<.001*
LLA	.515	<.001*

Abbreviations: LL, lumbar lordosis; LLA, apex of lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SK, sacral kyphosis; SS, sacral slope.
*With significance.

In the whole cohort, no sex-related differences were observed in SK ($P = .464$) and STA ($P = .201$). We found there was no relationship between sacral parameters and the age, height, or BMI, whereas there was a significant correlation between sacral parameters and pelvic-lumbar parameters (Tables 2 and 3). In the whole cohort, according to Pearson correlation analysis, the STA correlated with all pelvic-lumbar parameters: PI ($r = -.690$, P <.001), PT ($r = -.216$, $P = 0.001$), SS ($r = -.631$, P <.001), and LL ($r = -.491$, P <.001). According to Spearman correlation analysis, the STA correlated with the LLA ($r = .515$, P <.001). The correlations between the pelvic-lumbar sagittal parameters and the STA are summarized in Table 2. Simple linear regression analysis also verified the correlation between STA and PI ($y = -0.991x + 143$, $R^2 = .476$, P <.001), LL ($y = 0.870x - 135.1$, $R^2 = .242$, P <.001), and LLA ($y = 0.039x - 0.087$, $R^2 = .265$, P <.001). The regression equations are displayed in Figure 5.

In addition, in the whole cohort, according to Pearson correlation analysis, SK correlated with all pelvic-lumbar parameters: PI ($r = .471$, P <.001), PT ($r = .445$, $P = .001$), SS ($r = .533$, P <.001), and LL ($r = -.438$, P <.001) (Table 2). According to Spearman correlation analysis, the STA correlated with the LLA ($r = -.265$, $P = .001$). The details are summarized in Table 3. Simple linear regression analysis also verified the correlation between SK and PI ($y = 0.38x + 27.22$, $R^2 = .396$, P <.001), LL ($y = -0.35x - 35.99$, $R^2 = .192$, P <.001), LLA ($y = -0.01x + 4.25$, $R^2 = .201$, P <.001). The regression models employed are displayed in Figure 5.

4 | DISCUSSION

Spinopelvic sagittal alignment was found to be strongly associated with health-related quality of life in adults.[1,17] To better understand sagittal balance in the human standing position, various spinal shapes and many positional parameters have been described.[2-4,18]

Roussouly classification was the first systematic sagittal classification of the spine and is widely accepted around the world. According to the SS orientation and the extent of lumbar lordosis, Roussouly first

TABLE 3 Correlations between pelvic-lumbar sagittal parameters and sacral kyphosis

Pelvic-lumbar sagittal parameters	Correlation coefficient	P value
Age (y)	.079	.320
BMI (kg/m^2)	.045	.522
Height (m)	.147	.364
PI (°)	.471	<.001*
PT (°)	.445-	.001*
SS (°)	.533	<.001*
LL (°)	−.438	<.001*
LLA	−.265	.001*

Abbreviations: LL, lumbar lordosis; LLA, apex of lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope.
*With significance.

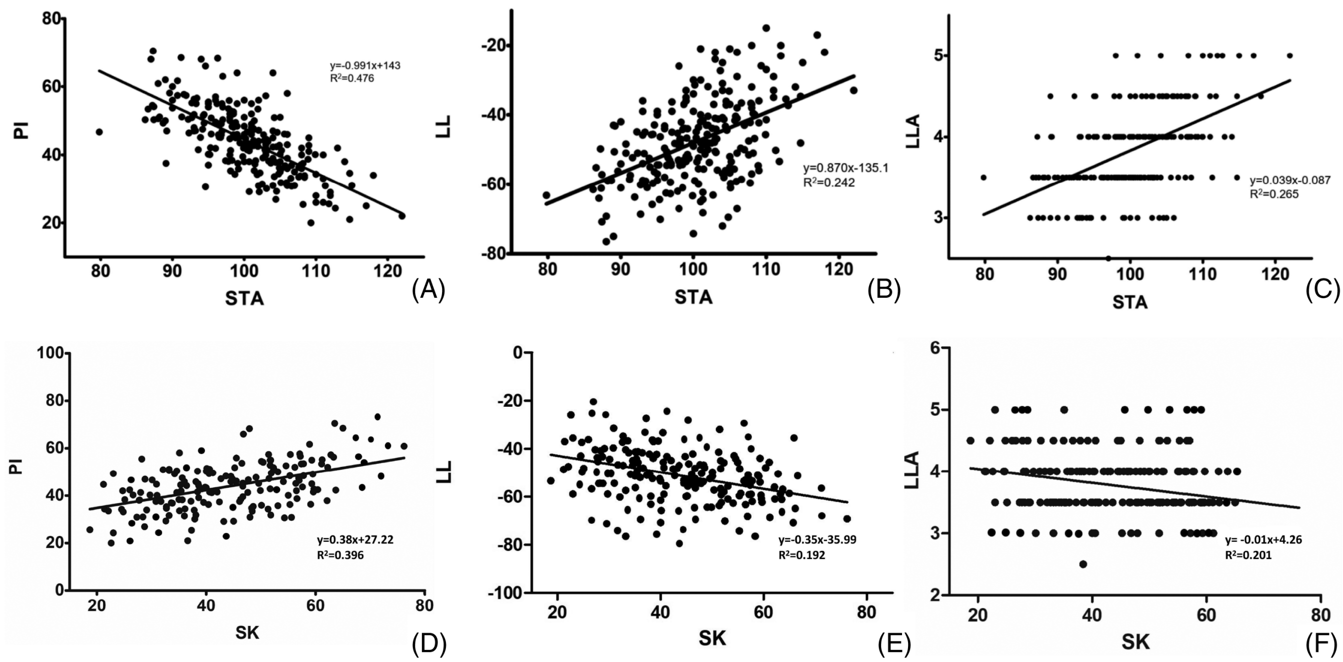

FIGURE 5 Linear correlations between the sacral anatomical parameters and pelvic-lumbar parameters. LL, lumbar lordosis; LLA, lumbar lordosis apex; PI, pelvic incidence; SK, sacral kyphosis; STA, sacral table angle

introduced four types of lumbar lordosis in healthy adults (type I, type II, type III, and type IV).[3] The four types were further detailed as follows: types 1 and 2 indicated low SS (SS < 35°), type 3 signified average SS (35° < SS < 45°), and type 4 denoted high SS (SS > 45°). Recently, an updated Roussouly classification was released by Laouissat,[5] including a type that was previously omitted: type III A+ pelvic anteverted, namely, type III A (35° < SS < 45°, PT ≤5°). Numerous spinopelvic sagittal parameters in different Roussouly sagittal shapes have been extensively studied, whereas sacral parameters have scarcely been investigated.[5,19-22]

The sacral morphology plays an important role in sagittal balance and numerous sacral parameters have been defined to explore the morphology of the sacrum.[7,20,23] In the present study, we selected the most commonly used sacral parameters (STA and SK) to explore the differences in different sagittal shapes. Another major advantage of these two chosen parameters is that they can be easily identified and visualized on lateral films. The STA has been relatively widely described in studies of spondylolysis/spondylolisthesis[7,8,11,24] but has not received enough attention in normal spinopelvic morphology studies. PI is a descriptor of sacral-pelvic morphology and attempts to quantify the transition between the lumbar spine and lower extremities, while the STA directly measures sacral morphology. SK represents the varying extent of curvature of the sacrum, and it is also an important aspect of sagittal balance.[10,14] The larger the SK value, the more curved the sacrum is.

In this study, we first studied the normal distribution of sacral anatomical parameters in healthy adults. Similar to lumbopelvic parameters, sacral anatomical parameters also demonstrated great fluctuation in healthy adults. In this study, the subjects were of Han Chinese origin, thus the results cannot be generalized to all populations. Baker reported the average values of SK, STA were 24.2 and 101.7 in adults of New Zealand.[7] McKay reported that the average SK in the UK population is 35.1.[10] Wang reported the average STA in the Canadian population is 94.9.[25] One study was carried out in Turkey and the average STA in Turkish adults is 101.3.[26] In the current study, the average values of SK, STA in the Chinese Han population were 43.6 and 100.6. The results demonstrated that sacral parameters varied among different ethnic groups.

Analysis of ANOVA and post hoc Tukey tests showed that sacral parameters vary in different Roussouly classifications: types I and II have a strong STA and small SK, and types III and IV have a weak STA and large SK. Type IIIA is especially special, and its characteristics are a strong STA and large SK. Meanwhile, we found that PI varies in different sagittal shapes. Roussouly type I, II, and III A sagittal shapes had a low angle of PI, whereas Roussouly type III and IV sagittal shapes had a high angle of PI. These results were consistent with previous studies.[1,3,5] Previous studies have also demonstrated a strong correlation between PI, STA, and SK.[7,10] A high PI is accompanied by a strong STA and a curved sacrum, whereas a low PI is along with a weak STA and a less curved sacrum. The correlation analysis performed in this study also proved these results. As we previously discussed, the morphology of the sacrum plays an important role in sagittal balance.[27] Here, we discuss those morphological differences of the sacrum in further detail. As for STA, Strube has proved that a larger STA results in a smaller SS by making the sacrum plateau more horizontal.[13] Meanwhile, a larger STA also represents greater load-bearing capacity.[26] These features are tightly coupled to spine morphology. For examples, the Roussouly type II sagittal shape is a quite vertical lumbar structure and the disks suffer the main loads. Theoretically, a strong STA is needed to adapt to mechanical loads, and this is consistent with our findings. Whereas in Roussouly type IV sagittal shape, the loading is more posterior and concentrates on the facet joints, a weak STA suit this shape well.

As for SK, previous study has demonstrated that SK gradually increase from gait acquisition until the end of the growth period. Tardieu et al. proved that a less curved sacrum does not favor the balance of the trunk.[14] A curved sacrum means a more effective force arm during pelvic rotation, which facilitates balance.[28] During the growth period, the curvature of the sacrum and the increase in lumbar lordosis adapt to each other, which is caused by the action of the extensor muscles and the tension of the strong sacrospinal ligaments.[27,29,30] In the present study, we found a positive association between LL and SK, which is a natural consequence of mutual adaption between lumbar and sacrum.

In this study, we found that there was a discordance between a small pelvis (low PI) and curved sacrum (large SK) in the Roussouly type IIIA sagittal shape, which may contribute to the particularity of this shape. The pelvis has long been regarded as a "pelvic vertebra" or the first vertebra of the spine by Dubousset,[31] and it plays a key role in connecting the spine to the lower limbs. The position of the pelvis determines the alignment of the lumbar spine and hence the alignment of the entire spine. This type has shown important characteristics of type III lumbar lordosis despite low-grade PI, which is one of the type I and II characteristics.[5,20] A discordance between a high LL and a low PI caused by a high SS was found in this shape.[5] Previous studies have demonstrated that the anteversion of the pelvis in type IIIA was caused by two reasons: fixed hip flexion contracture and hyperlordosis.[5,32] However, it is difficult to say that the Roussouly type IIIA sagittal shape is caused by hip pathology in healthy adults, and it seems difficult to infer the causal relationship between hyperlordosis and anteversion of the pelvis.

Laouissat et al conjectured that lumbar lordosis in type III A patients may be caused by low PI.[5] Type IIIA patients suffered the same pelvic characteristics (low-grade PI) as type I and II patients, but type IIIA patients showed completely different spinal sequences. In this scenario, we reasoned that there might be unknown influencing factors somewhere that made the difference. As we previously discussed, from gait acquisition to the end of the growth period, the pelvis, spine, as well as sacrum adapt to each other and provides the most economical upright posture for each individual.[29] Each Roussouly type has its unique pattern of spine growth and development. In Roussouly IIIA sagittal shape, a curved sacrum is well coupled to a curved LL, which is established in childhood while learning to stand and walk. However, further research is needed to determine the specific mechanism responsible for this change.

PI increases with growth and development and remains constant after maturity, which can only be altered by some rare pathologic processes that can modify the shape of the sacrum or the position of the acetabula.[29,33] Since PI remains unchanged, many predictive models for ideal lumbar sagittal parameters based on PI have been developed.[34,35] In the present study, the authors found that the STA and

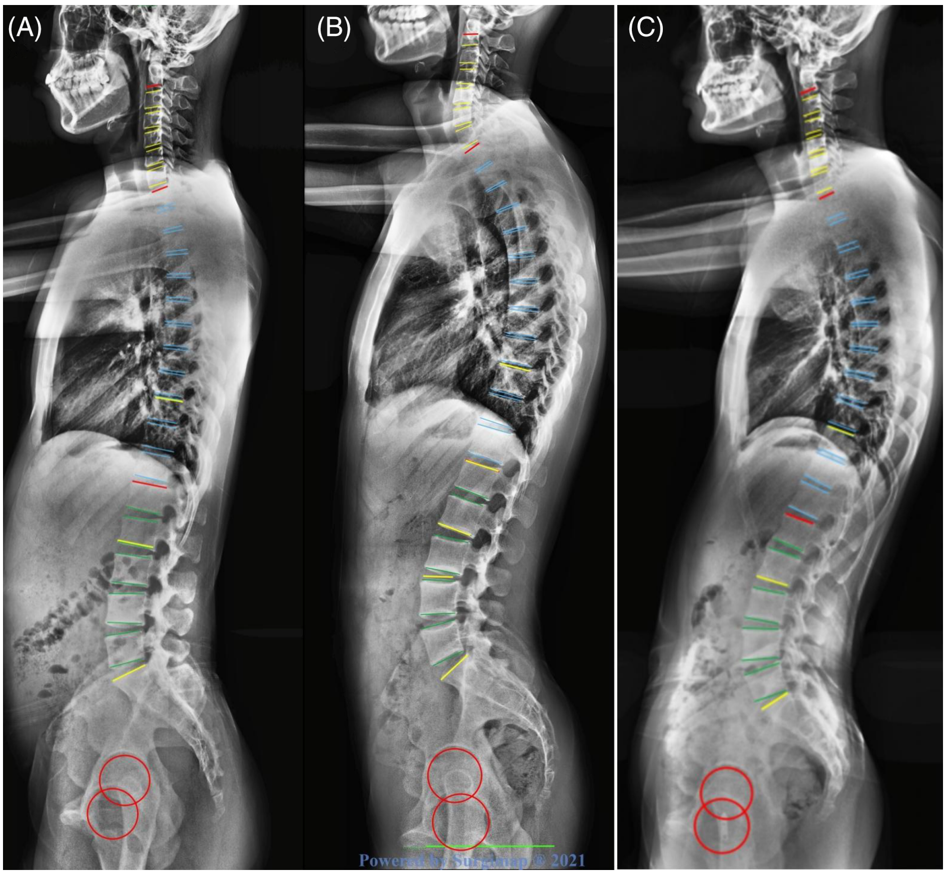

FIGURE 6 A. Male, 18 years old, with a strong STA and a less curved sacrum. STA = 107.3°, SK = 21.3°, PI = 31.0°, LL = −37.4°, and LLA = L4/5. LL, lumbar lordosis; LLA, lumbar lordosis apex; PI, pelvic incidence; SK, sacral kyphosis; STA, sacral table angle. (B) Male, 19 years old, with a strong STA and a curved sacrum. STA = 104.4°, SK = 45.3°, PI = 39.5°, LL = 62.6°, and LLA = L4. LL, lumbar lordosis; LLA, lumbar lordosis apex; PI, pelvic incidence; SK, sacral kyphosis; STA, sacral table angle. (C) Male, 18 years old, with a weak STA and a curved sacrum. STA = 92.3°, SK = 50.7°, PI = 57.7°, LL = −54.9°, and LLA = L3/4. LL, lumbar lordosis; LLA, lumbar lordosis apex; PI, pelvic incidence; SK, sacral kyphosis; STA, sacral table angle

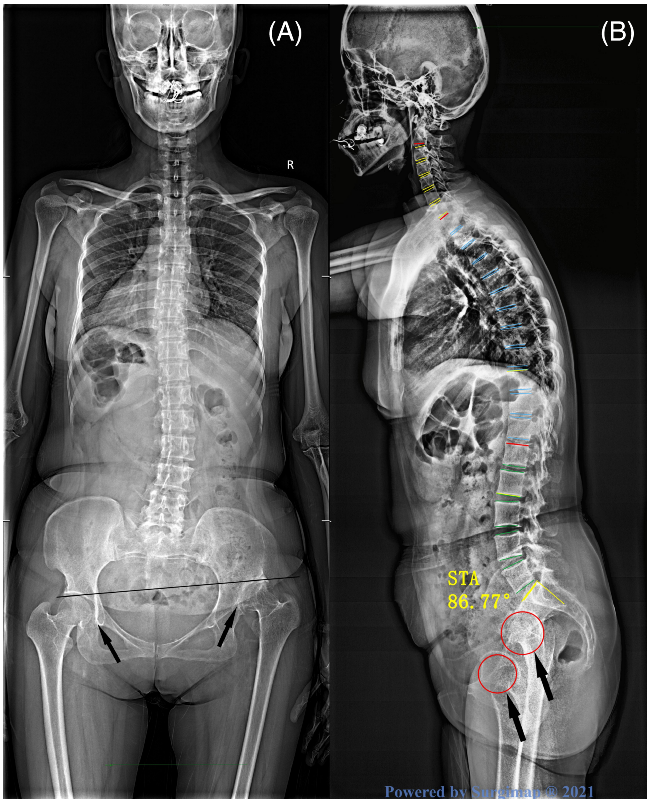

FIGURE 7 A. Male, 41 years old, anteroposterior whole-spine standing radiograph showing the congenital dislocation of the right hip. B. Lateral whole-spine standing radiograph showing PI cannot be measured precisely, but STA and SK can be measured accurately. Actual measurements: STA = 86.7°, SK = 57.1°, LLA = 3.5, LL = −59.7°. Predicted measurements based on STA, LLA = 3.39 LL = −59.41°; predicted measurements based on SK, LLA = 3.69, LL = −54.95°. LL, lumbar lordosis; LLA, lumbar lordosis apex; SK, sacral kyphosis; STA, sacral table angle

SK were also strongly correlated with lumbar sagittal parameters. There no research has been published about the correlation between such sacral anatomical parameters and lumbar sagittal parameters in healthy adults. A strong STA and weak SK always predict low PI, a narrow and small pelvic pedestal, a lower apex of lumbar lordosis, and a relatively flat and short lumbar lordosis. On the contrary, a weak STA and a strong SK are associated with high PI, a higher apex of lumbar lordosis, and a curved and long lumbar lordosis. The representative cases are shown in Figure 6. Based on the unchanged features of STA, SK, and their strong correlations with lumbar parameters, we developed regression formulas based on STA and SK to predict lumbar parameters. In some special cases such as patients with aspherical femoral heads, with subluxation following osteoarthritis of the hip, and after total hip replacement arthroplasty，PI is difficult to measure precisely due to the bilateral femoral head could not be precisely identified. In these cases, the regression equations could help a lot. Taking the case in Figure 7 as an example, PI could not be measured correctly on the full-spine lateral radiograph due to the congenital dislocation of the right hip, whereas STA and SK can be measured precisely. There are slight differences between the results calculated based on the regression equation and measured results. Another advantage of STA and SK is that they can be accurately and conveniently measured on lumbar computerized tomography and magnetic resonance imaging, which is not affected by the posture. In summary, the STA and SK could serve as good supplementary indices or alternative indices of PI to predict correct lumbar parameters.

The present study had some limitations that need further discussion and investigation. First, although we have demonstrated that sacral anatomical parameters did vary in different spinal shapes, further studies are needed to elucidate the exact mechanisms of these anatomical parameters in the spinopelvic interaction in different spinal shapes. Second, more sacral parameters cannot be measured precisely on lateral radiographic films. In our future work, we plan to acquire more sacral parameters using computerized tomography to perform more nuanced examinations.

5 | CONCLUSION

In the present study, the sacral anatomical parameters vary in different Roussouly sagittal shapes and have strong correlations with lumbopelvic parameters, which demonstrates that the specific lumbar shape can be affected by the sacral morphology. These results prompted us to examine different sagittal shapes from the perspective of the inherent sacrum differences; the potential anatomic determinants of their value should also be explored in future studies. Moreover, the predictive models of lumbopelvic parameters based on SK and STA have been provided, which demonstrates constant sacral anatomical parameters could serve as good supplementary index of PI to predict ideal lumbar parameters, especially in cases with the hip disorders.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Jianmin Sun and Guodong Wang conceived and designed the study. Nan Ru and Jianlong Li measured and recorded the data. Nan Ru wrote the article. Jianmin Sun and Xingang Cui reviewed and edited the manuscript. All authors read and approved the final manuscript.

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