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A Comprehensive Analysis of the Behavior of Pelvic Incidence After Different Posterior Spinal Procedures in Elderly Patients With Spinal Deformity

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Abstract

Study Design: A retrospective case-control study.

Objective: To evaluate the behavior of pelvic incidence (PI) after different posterior spinal procedures in elderly patients with adult spinal deformity (ASD), to determine the potential associated factors with the variability in PI after spinal surgery and to comprehensively analyze its mechanisms.

Methods: Elderly patients underwent long fusion to sacrum with and without pelvic fixation were assigned to Group L+P and Group L-P, respectively. In Group L-P, those with severe sagittal deformity were selected as Group A. 20 elderly patients with severe sagittal deformity underwent short lumbar fusion were included as Group B. The following radiographic parameters were evaluated: thoracic kyphosis (TK), thoracolumbar kyphosis (TLK), lumbar lordosis (LL), PI-LL, sagittal vertical axis (SVA), T1 pelvic angle (TPA), and pelvic parameters. PI changing more than 5° ($\triangle$PI $> 5°$) was considered as substantially changed.

Results: For the whole cohort and in Group L+P, PI were not substantially changed ($\triangle$PI $\leq 5°$) after surgery. Besides the severer sagittal malalignment in patients with $\triangle$PI $> 5°$ in Group L-P, relatively larger mean age, greater proportion of female and lower preoperative PI were found than those in patients with $\triangle$PI $\leq 5°$. 70.8% of patients had substantial increase of PI in Group A, while only 10% of patients had in Group B ($P < 0.001$).

Conclusion: PI behaves differently under different conditions in elderly ASD patients. Besides severe sagittal deformity, aging, female and low preoperative PI are also the potential risk factors of PI increasing after long fusion to sacrum.

Keywords

PI variation, long spinal fusion, compensation, sagittal malalignment, sacroiliac joint

Abbreviations

PI, Pelvic Incidence; SIJ, Sacroiliac Joint; ASD, Adult Spinal Deformity; TK, Thoracic Kyphosis; TLK, Thoracolumbar Kyphosis; LL, Lumbar Lordosis; SS, Sacral Slope; PT, Pelvic Tilt; PI-LL, PI minus LL; SVA, Sagittal Vertical axis; TPA, T1 Pelvic Angle.

Introduction

Measuring the sagittal inclination of sacrum within pelvis, pelvic incidence (PI) is traditionally suggested to be a fixed value after skeletal maturity for the same individual[1,2] Because of this anatomic characteristic, PI is used along with other parameters to define individual's overall spinal sagittal curvature and alignment.[3] However, the invariability of PI is not unconditional, which is based on the fundamental hypothesis that the sacroiliac joint (SIJ) connecting sacrum to pelvis is

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immobile. In fact, SIJ is usually mobile in both women and men, especially in the elderly population.[4] Consistently, previous studies had demonstrated PI could be changed by sex, age and anterior or posterior pelvic rotation.[5,6] Therefore, treating PI as a constant value might be an oversimplification.

Recent evidences also suggested that PI could be modified by spinal procedures.[7-10] In Lee et al.'s[7] study, 11 patients with adult spinal deformity (ASD) had long fusion to sacrum and sacropelvic fixation and were shown to have a small increase in postoperative PI. They thought the sacropelvic fixation affected motion range of SIJ, which then decreased the change extent of PI. On the contrary, other authors reported a decrease of PI in some patients who underwent the same surgical procedure.[8-10] They deduced that PI was decreased due to the alteration of pelvic morphology during operation and this change of PI was fixed by iliac or sacroiliac screws after surgery. No matter which mechanism, this variation of PI should be regarded as an iatrogenic consequence.

Besides the changes during operation, PI could also alter spontaneously after posterior spinal surgeries.[7,8,11] Cecchinato et al.[8] reported an acute spontaneous increase of PI in 27 ASD patients who underwent long lumbar fusion to sacrum without pelvic fixation. Lee et al.[7] also found PI was gradually increased at different follow-up time after lumbar fusion to sacrum without pelvic fixation in 18 ASD patients. They put forward a hypothesis that long lumbar fusion to sacrum reduced the capacity to compensate a possible sagittal imbalance in lower spine, which might induce the SIJ motion and then the increase in PI. Our previous findings supported their speculation that PI spontaneously increased in elderly ASD patients with severe sagittal deformity after long lumbar fusion to sacrum, while was relatively invariable in those with minor sagittal deformity.[11]

Despite a few studies focusing on the PI variation after surgery, the data pool is still insufficient to analyze surgical or other potential factors contributing to the postoperative modification of this parameter. The purposes of this study are to evaluate the PI behavior after different posterior spinal procedures in elderly patients with spinal coronal or sagittal deformity, to determine the potential associated factors with the variability in PI after spinal surgery and to comprehensively analyze its mechanisms.

Methods

Subjects

Under the approval from the Ethics Committee of Capital Medical University Xuanwu Hospital (approval number was not needed), a retrospective analysis of ASD patients who underwent long posterior spinal fusion (PSF) from thoracic to sacrum with or without pelvic fixation between June 2016 and June 2020 at our hospital was performed. The inclusion criteria were as following: (1) aged > 60 years; (2) with complete pre- and postoperative standing radiographic images, and (3) with a minimum follow-up of 3 months. Patients with hip pathology or a surgical history of spine or pelvis were excluded. Spinal deformity was evaluated and classified according to SRS-Schwab ASD classification.[12] Based on the sagittal modifiers, sagittal morphology with PI-LL $< 10°$, SVA < 40 mm and PT $< 20°$ was defined as minor sagittal deformity in this study, while sagittal malalignment with PI-LL $> 20°$, SVA > 95 mm or PT $> 30°$ was defined as severe sagittal deformity. The other sagittal profile was defined as moderate sagittal deformity.[12,13]

Thereinto, patients underwent long fusion from thoracic to sacrum and sacropelvic fixation using sacroiliac screws were assigned to the long fusion and pelvic fixation group (Group L+P). The others without sacropelvic fixation were assigned to the long fusion without pelvic fixation group (Group L-P). In Group L-P, those with severe sagittal deformity were selected as Group A (Figure 1). In addition, 20 elderly patients with severe sagittal deformity who underwent short lumbar fusion were included as the control of Group A (Group B).

Surgical Procedures

A standard midline approach was used to expose the posterior elements via subperiosteal dissection. Spinal instrumentation was performed using all pedicle screws and titanium rods constructs, followed by decompression of stenosed segments with transforaminal lumbar interbody fusion and deformity correction with standard maneuvers. Patients with coronal imbalance were suggested to undergo sacropelvic fixation using S2 iliac screw.[14] Posterior fusion was accomplished with autograft and allograft. All the surgeries were conducted by the same team.

Data Collection and Radiographic Measurement

Demographic information such as age, sex, BMI, and surgical data were collected. Long-cassette lateral radiographs of spine and pelvis on standing were obtained pre- and postoperatively. The following parameters were measured using Surgimap software (Nemaris, Inc.) on imaging: Cobb angle, thoracic kyphosis (TK, angle between superior endplate of T5 and inferior endplate of T12), thoracolumbar kyphosis (TLK, angle between superior endplate of T10 and inferior endplate of L2), lumbar lordosis (LL, angle between superior endplate of L1 and superior endplate of S1), pelvic incidence (PI, angle between the perpendicular to sacral plate at its midpoint and the line connecting point to the middle axis of femoral heads), sacral slope (SS, angle between sacral plate and horizontal plane), pelvic tilt (PT, angle between the line connecting the midpoint of sacral plate to the axis of femoral heads and gravity line), PI-LL mismatch (PI minus LL), sagittal vertical axis (SVA, horizontal distance between C7 plumb line and the posterior-superior corner of sacrum), T1 pelvic angle (TPA, angle subtended by a line from the femoral heads to the center of the T1 vertebral body and a line from the femoral heads to the center of the superior sacral end plate).[15]

Two observers (F.M.P. and X.Y.S.) independently and blindly performed the radiographic measurements and measurements were repeated by an observer (F.M.P.) 1 week later.

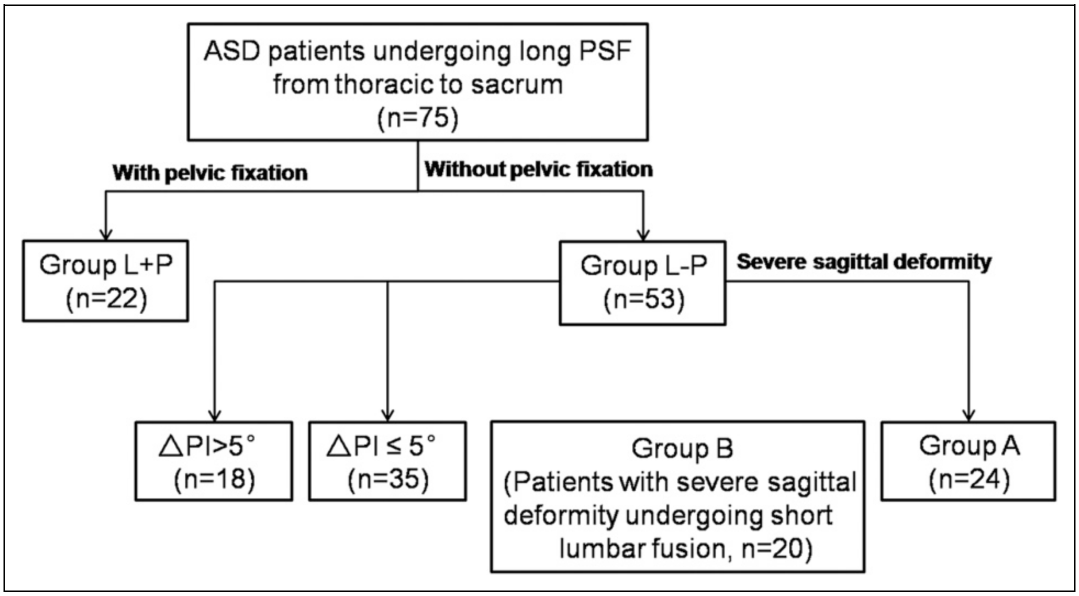

Figure 1. Flow chart of patients recruiting.

Mean values of the 2 observers' 3 measurements were recorded. Change of PI (△PI) was calculated by subtracting the preoperative value from the postoperative value. In order to eliminate the deviation during imaging and measurement, PI changing more than 5° (△PI > 5°) was considered as substantially changed.[9,16]

Statistics Analysis

SPSS version 19.0 (Chicago, IL, USA) was used to performed statistical analysis. Values were expressed as mean ± standard deviation. The intra- and inter-observer reliabilities of radiographic measurements were analyzed using intraclass correlation coefficient (ICC). Chi-square analysis was applied to assess categorical variables. Mann-Whitney *U* test was used to conducted the comparisons of continuous variables between pre- and post-operation and between different groups. Statistical significance was defined as a P value <0.05.

Results

Clinical and Radiographic Outcomes of Whole Cohort

Seventy-five elderly ASD patients (56 females and 19 males) who underwent long PSF were included in the study, with an average age of 68.3 ± 2.7 years. Thereinto, 51 patients were found with degenerative lumbar/thoracolumbar scoliosis and 45 patients were found with sagittal deformity (moderate: 21; severe: 24). Radiographic measurements were shown to have substantial intra- and interobserver reliabilities with good agreement (ICC ≥ 0.75, Table 1). For the whole cohort, coronal curve was significantly corrected from 29.8 ± 8.5° to 15.3 ± 4.4° ($P < 0.05$) and SVA was improved from 89.2 ± 30.1 mm to 60.7 ± 21.4 mm ($P = 0.092$). After mean follow-up of 8.2 ± 2.2 months, the values of PI were not substantially changed after long PSF for all the ASD patients (49.2 ± 5.5° vs. 52.4 ± 6.3°, $P = 0.245$).

Table 1. The Intraclass and Interclass Correlation Coefficients of Radiographic Measurements.

	Intra-observer ICC	Inter-observer ICC
Coronal Curve (°)	0.823	0.799
Thoracic Kyphosis (°)	0.879	0.833
Thoracolumbar Kyphosis (°)	0.856	0.831
Lumbar Lordosis (°)	0.848	0.806
Pelvic Incidence (°)	0.790	0.774
Pelvic Tilt (°)	0.787	0.791
Sacral Slope (°)	0.835	0.822
Sagittal Vertical Axis (mm)	0.794	0.778
T1 Pelvic Angle (°)	0.783	0.757

ICC indicates intraclass correlation coef.

Clinical and Radiographic Outcomes of Group L+P

Twenty-two patients were performed a long fusion from thoracic to sacrum with sacropelvic fixation using sacropelvic screws. They were 18 females and 4 males, with an average age of 66.5 ± 2.6 years and an average BMI of 25.7 ± 2.2 kg/m^2. Mean fusion levels were 9.8 ± 1.0, with a fusion range from T9 to SIJ. Mean follow-up time was 6.3 ± 2.4 months.

Coronal curve type L with minor sagittal deformity was found in 17 patients and curve type L with moderate sagittal deformity was found in 5 patients. The radiographic measurements were shown in Table 1. Except for the significant decrease of lumbar scoliosis, PI-LL and TPA, other parameters were not statistically changed (Figure 2). PI was 46.3 ± 5.3° preoperatively and 47.4 ± 6.0° postoperatively ($P = 0.265$).

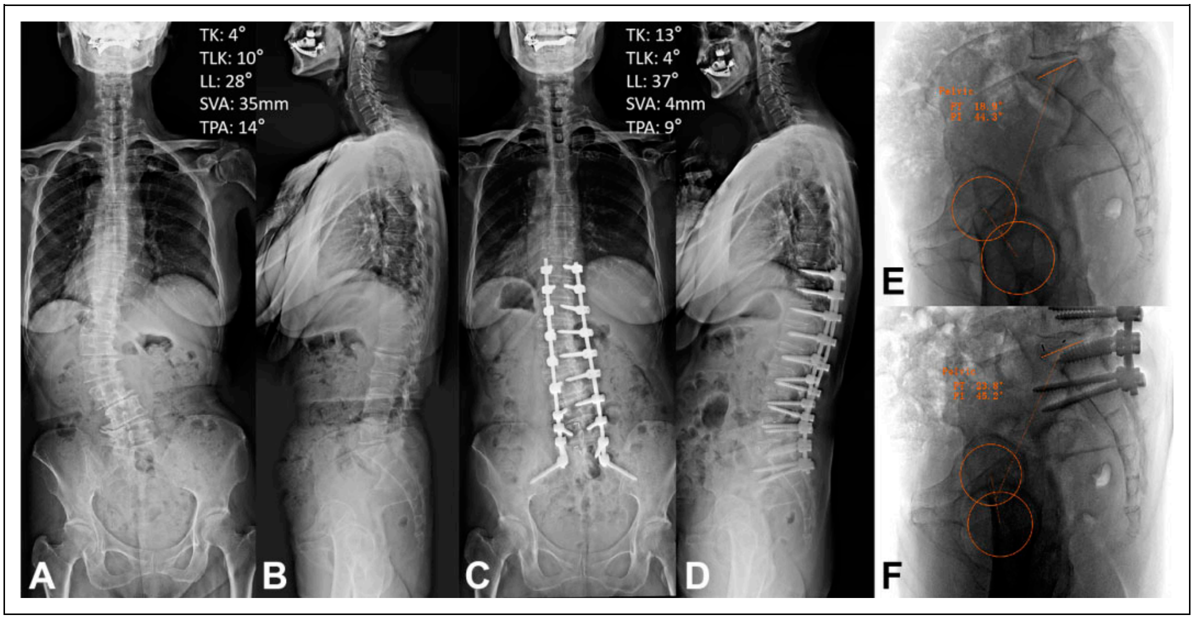

Figure 2. A and B, A 70-year-old female patient with thoracolumbar scoliosis (41°), coronal imbalance (32 mm) and moderate sagittal deformity (PI-LL = 16°, SVA = 35 mm, PT = 18°). C and D, A long fusion from T10 to S1 and sacropelvic fixation using sacroiliac screws was performed. At 1-year follow-up, coronal (12°) and sagittal malalignment were obviously corrected. E and F, PI was not substantially changed (44.3° vs. 45.2°).

Comparisons of Clinical and Radiographic Outcomes Between Patients With $\triangle PI > 5°$ and With $\triangle PI \leq 5°$ in Group L-P

Thirty-eight female and 15 male patients underwent long fusion from thoracic to sacrum without pelvic fixation. Eighteen patients were detected to have $\triangle$PI > 5°, while the others had $\triangle$PI $\leq$ 5°. Patients with $\triangle$PI > 5° had relatively larger mean age (71.6 $\pm$ 2.8 years vs. 67.8 $\pm$ 3.3 years, $P = 0.062$) and a greater proportion of female (F/M: 16/2 vs. F/M: 22/13, $P = 0.046$) than those with $\triangle$PI $\leq$ 5°. BMI (25.4 $\pm$ 1.3 kg/m^2 vs. 26.6 $\pm$ 0.9 kg/m^2, $P = 0.204$), fusion levels (8.8 $\pm$ 0.6 vs. 8.2 $\pm$ 1.1, $P = 0.233$) and follow-up time (7.4 $\pm$ 3.7 months vs. 9.2 $\pm$ 4.4 months, $P = 0.115$) were comparable between the 2 groups (Table 2).

Coronal curve type L with minor sagittal deformity, curve type L with moderate sagittal deformity and curve type S with severe sagittal deformity were found in 13, 16 and 24 patients, respectively. Comparisons of deformity classification and radiographic measurements between patients with $\triangle$PI > 5° and $\triangle$PI $\leq$ 5° were shown in Table 3. Compared with those with $\triangle$PI $\leq$ 5°, patients with $\triangle$PI > 5° had severer sagittal malalignment (more curve type S, more severe sagittal deformities, smaller Cobb angle, smaller TK, greater TLK, smaller LL, smaller SS, greater PI-LL, greater SVA and greater TPA). In addition, preoperative PI in patients with substantial changes was statistically smaller than that in those with relative constant value. After PSF, sagittal deformity was corrected with obvious change of all the sagittal spinal parameters in patients having $\triangle$PI > 5° (Figure 3), while only lumbar scoliosis was corrected in those having $\triangle$PI $\leq$ 5° (Figure 4).

Comparisons of Clinical and Radiographic Outcomes Between Groups A and B

Mean age (70.1 $\pm$ 3.1 years vs. 67.2 $\pm$ 3.0 years, $P = 0.107$), distribution of gender (F/M: 20/4 vs. F/M: 14/6, $P = 0.293$), BMI (25.7 $\pm$ 1.1 kg/m^2 vs. 26.0 $\pm$ 0.8 kg/m^2, $P = 0.431$) and follow-up time (8.6 $\pm$ 3.5 months vs. 10.7 $\pm$ 4.3 months, $P = 0.101$) were similar between the 2 groups (Table 4).

Sagittal malalignments were similar between Groups A and B, with comparable PT, PI-LL, SVA and TPA. Despite with different surgical strategies, sagittal deformities were both obvious corrected, with significant increase of LL and decrease of PI-LL, SVA and TPA. PI were not statistically changed in either group. 70.8% (17/24) of patients had substantial increase of PI in Group A (Figure 3), while 10% (2/20) of patients had in Group B ($P < 0.001$).

Discussion

PI not a constant value has been gradually recognized by some spinal surgeons.[5,6] Recent authors began to focus on the behaviors of postoperative PI and found that PI could also change after spinal surgeries.[7-9,11] Up to now, however, the present data from the few studies is insufficient to analyze the surgical or other potential factors contributing to the variation of this parameter. The current study enrolled the elderly patients undergoing different posterior spinal procedures and comprehensively analyzed the mechanisms of PI changing after PSF.

Throughout the medical literature, Lee et al.[7] first reported PI could be altered by PSF in their study, where 11 ASD subjects who underwent long fusion and sacropelvic fixation were detected to have an increase in postoperative PI (50.8 $\pm$ 7.7°

Table 2. Comparisons of Deformity Classifications and Radiographic Measurements Between Patients With △PI > 5° and △PI ≤ 5° in Group L-P.

Variables		△PI > 5° (n = 18)	△PI ≤ 5° (n = 35)	*P*
Coronal Curve Type	L	2	27	<0.001†
	S	16	8	
Sagittal Modifiers	Minor sagittal deformity	0	13	<0.001†
	Moderate sagittal deformity	1	15	
	Severe sagittal deformity	17	7	
Coronal Curve (°)	Preoperatively	8.3 ± 2.1	36.4 ± 3.9	<0.001
	Postoperatively	7.7 ± 2.5	18.4 ± 5.5	0.012
	P	0.341	<0.001	–
Thoracic Kyphosis (°)	Preoperatively	10.2 ± 4.6	33.1 ± 6.2	<0.001
	Postoperatively	18.5 ± 3.3	34.8 ± 5.0	<0.001
	P	0.030	0.469	–
Thoracolumbar Kyphosis (°)	Preoperatively	31.7 ± 7.4	15.6 ± 4.2	<0.001
	Postoperatively	11.5 ± 5.8	13.3 ± 3.6	0.375
	P	<0.001	0.361	–
Lumbar Lordosis (°)	Preoperatively	6.4 ± 9.8	40.3 ± 7.7	<0.001
	Postoperatively	28.6 ± 6.2	46.4 ± 5.9	<0.001
	P	<0.001	0.301	–
Pelvic Incidence (°)	Preoperatively	40.7 ± 1.6	54.6 ± 3.1	0.006
	Postoperatively	47.9 ± 1.9	56.5 ± 3.3	0.094
	P	0.042	0.211	–
Pelvic Tilt (°)	Preoperatively	28.5 ± 2.0	23.5 ± 3.2	0.126
	Postoperatively	23.8 ± 2.3	17.5 ± 3.7	0.114
	P	0.073	0.076	–
Sacral Slope (°)	Preoperatively	11.5 ± 4.2	29.7 ± 6.2	<0.001
	Postoperatively	23.8 ± 5.1	38.5 ± 4.0	0.008
	P	0.011	0.084	–
Pelvic Incidence minus Lumbar Lordosis (°)	Preoperatively	33.2 ± 5.4	14.7 ± 5.2	<0.001
	Postoperatively	18.7 ± 4.3	11.2 ± 4.6	0.079
	P	<0.001	0.411	–
Sagittal Vertical Axis (mm)	Preoperatively	142.6 ± 19.3	72.1 ± 11.2	<0.001
	Postoperatively	75.2 ± 12.4	60.5 ± 9.8	0.0
	P	<0.001	0.187	–
T1 Pelvic Angle (°)	Preoperatively	33.4 ± 4.1	22.8 ± 4.9	0.022
	Postoperatively	16.5 ± 4.3	18.7 ± 2.6	0.302
	P	<0.001	0.140	–

△PI > 5° indicates PI changing more than 5° from pre-operation to post-operation. △PI ≤ 5° indicates PI changing equal to or less than 5° from pre-operation to post-operation.
†Calculated by Chi-square analysis.

Table 3. Radiographic Measurements in Group L+P.

	Preoperatively	Postoperatively	*P* value
Coronal Curve (°)	42.5 ± 4.8	18.8 ± 5.1	0.005
Thoracic Kyphosis (°)	18.3 ± 6.5	22.5 ± 8.8	0.404
Thoracolumbar Kyphosis (°)	13.3 ± 5.0	6.4 ± 5.7	0.132
Lumbar Lordosis (°)	30.6 ± 9.2	42.8 ± 8.1	0.093
Pelvic Incidence (°)	46.3 ± 5.3	47.4 ± 6.0	0.265
Pelvic Tilt (°)	17.5 ± 7.7	17.8 ± 8.2	0.513
Sacral Slope (°)	28.9 ± 6.4	31.1 ± 6.5	0.149
Pelvic Incidence minus Lumbar Lordosis (°)	15.4 ± 6.6	5.0 ± 6.3	0.011
Sagittal Vertical Axis (mm)	58.7 ± 19.1	39.4 ± 12.7	0.069
T1 Pelvic Angle (°)	18.3 ± 6.7	10.2 ± 3.6	0.027

vs. 55.7 ± 10.4°, $P = 0.003$). They thought the pelvic fixation with iliac screws affected the motion range of SIJ, which then decreased the change extent of PI. Detailed mechanism how PI was increased was not described in their reports. Subsequent studies reported the opposite results that PI was decreased after the same surgical procedure in some ASD patients.[8-10] The authors gave similar and complementary speculations and interpretations of their findings. To sum up, they thought PI had already increased due to SIJ nutating to compensate for spinal sagittal malalignment and imbalance before surgery. During operation, the nutated SIJ was corrected and the increased PI was thereby restored (decreased) according to its definition. Then sacropelvic fixation stabilized pelvic morphology and sustained the value of PI after surgery.

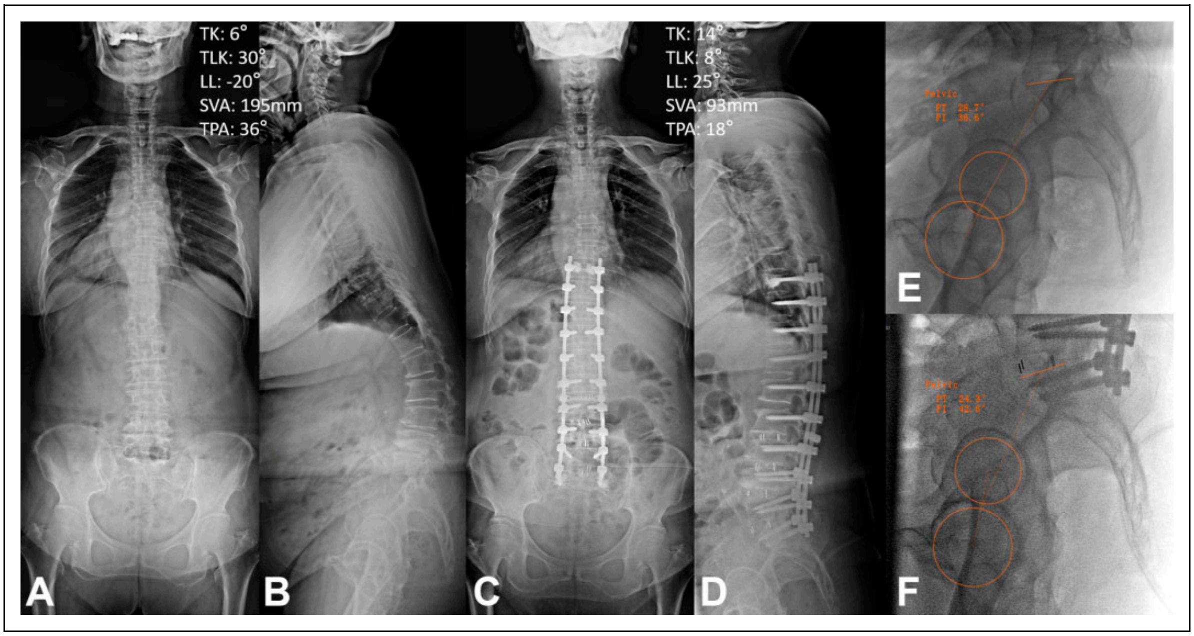

Figure 3. A and B, A 65-year-old female patient suffering from thoracolumbar kyphosis (56°) and severe sagittal deformity (PI-LL = 56°, SVA = 195 mm, PT = 28°). C and D, A long fusion from T9 to S1 without sacropelvic fixation was performed. Radiographs at 6-month follow-up showed severe sagittal deformity was obviously corrected with residual sagittal imbalance of 93mm. E and F, PI was substantially changed from 36.6° to 42.6°.

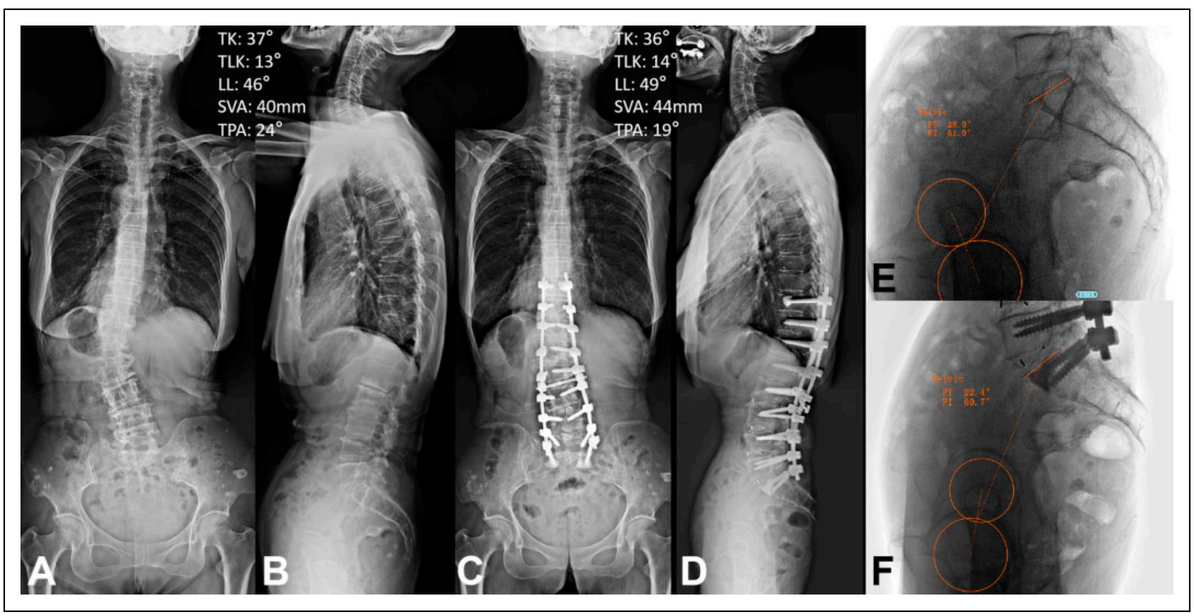

Figure 4. A and B, A 68-year-old female patient with thoracolumbar scoliosis (38°) and moderate sagittal deformity (PI-LL = 15°, SVA = 40mm, PT = 28°). C and D, A long fusion from T10 to S1 without sacropelvic fixation was performed. Radiographs at 10-month follow-up showed coronal (20°) and sagittal malalignment were obviously corrected. E and F, PI was not substantially changed (61.0° vs. 60.7°).

However, significant decrease of PI was not demonstrated ($46.3 \pm 5.3°$ vs. $47.4 \pm 6.0°$, $P = 0.265$) in the current study containing 22 elderly ASD patients after long fusion and sacropelvic fixation (Table 1 and Figure 2). We deduced the constant of PI might be owing to the stabilization of SIJ in standing before surgery or in operating table during operation. All the subjects in Group L+P were found with minor or moderate sagittal deformity based on the sagittal modifiers in SRS-Schwab ASD classification.[12] We thought if patients have no severe spinal deformity, there might not be a need for SIJ

Table 4. Comparisons of Sagittal Parameters Between Group A and Group B.

Variables		Group A (n = 24)	Group B (n = 20)	*P*
Thoracic Kyphosis (°)	Preoperatively	9.9 ± 4.3	12.7 ± 6.4	0.298
	Postoperatively	21.6 ± 5.1	16.5 ± 7.3	0.101
	P	<0.001	0.181	-
Thoracolumbar Kyphosis (°)	Preoperatively	33.4 ± 6.2	10.8 ± 4.4	<0.001
	Postoperatively	11.8 ± 5.1	17.4 ± 3.8	0.089
	P	<0.001	0.084	-
Lumbar Lordosis (°)	Preoperatively	7.7 ± 8.6	20.5 ± 6.5	0.007
	Postoperatively	30.8 ± 6.0	38.9 ± 7.2	0.100
	P	<0.001	0.002	-
Pelvic Incidence (°)	Preoperatively	42.5 ± 2.7	46.4 ± 5.2	0.142
	Postoperatively	47.8 ± 2.9	49.6 ± 5.5	0.323
	P	0.078	0.173	-
Pelvic Tilt (°)	Preoperatively	28.1 ± 2.1	22.2 ± 3.1	0.103
	Postoperatively	24.3 ± 2.8	16.9 ± 3.9	0.101
	P	0.106	0.088	-
Sacral Slope (°)	Preoperatively	13.9 ± 3.3	28.0 ± 4.9	0.010
	Postoperatively	23.4 ± 4.5	32.7 ± 4.5	0.053
	P	0.011	0.084	-
PI-LL (°)	Preoperatively	34.6 ± 5.1	29.7 ± 6.3	0.122
	Postoperatively	16.7 ± 4.2	11.3 ± 5.9	0.094
	P	0.004	0.001	-
Sagittal Vertical Axis (mm)	Preoperatively	139.3 ± 17.1	115.2 ± 15.3	0.113
	Postoperatively	80.5 ± 13.0	66.8 ± 11.2	0.211
	P	<0.001	<0.001	-
T1 pelvic Angle (°)	Preoperatively	33.6 ± 3.8	24.8 ± 6.2	0.072
	Postoperatively	17.8 ± 4.1	12.1 ± 6.9	0.101
	P	0.007	0.031	-

Group A indicates the group including patients who have severe sagittal deformity and undergo long spinal fusion from thoracic to sacrum. Group B indicates the group including patients who have severe sagittal deformity and undergo short lumbar fusion.

nutating in standing before surgery or a forced extension of hip and lumbar in prone position in operating table. In other words, pelvic morphology was relatively immobile in those with minor sagittal malalignment during surgery. After sacropelvic fixation, SIJ would be strongly stabilized,[17] which contributed to the constant value of PI after surgery.

If SIJ mobility was reserved without pelvic fixation, there would be a possibility that PI varied after surgery, especially for the elderly with lax SIJ. In Cecchinato et al.'s[8] and Lee et al.'s[7] studies, PI was found to spontaneously increase during follow-up in those who were performed long lumbar fusion to sacrum without pelvic fixation. They hypothesized that long lumbar fusion to sacrum restricted the compensation for positive sagittal imbalance in lower spine, which induced the pelvic motion and then the increase in PI. Their theory about the mechanism of PI spontaneously increasing had 2 important conditions—positive sagittal imbalance and limited lumbar compensation. Our previous study confirmed the inevitable role that global sagittal malalignment played in the disparity of PI.[11] PI was found increased after long fusion to sacrum in elderly ASD patients with severe sagittal deformity, while was relatively invariable after the same surgical procedure in those with minor sagittal deformity. Long fusion constructs to S1 leading to motion in SIJ has been demonstrated in Mushlin et al.'s biomechanical investigation of SIJ in human cadaveric specimens.[17] In sagittal malalignment, pelvic retroversion will be activated to move the gravity line back, which generates a reaction force on SIJ.[18] When the increased bending forces at L5-S1 break the elasticity of lax SIJ, the anatomical relationship between sacrum and iliac wing will be changed, resulting in an increased PI.[19] Therefore, this variation in postoperative PI could be considered as a secondary change compensating for the spinal sagittal malalignment under lax SIJ in elderly patients.[11]

When took a closer look at the potential factors contributing to postoperative modification of PI, besides severer sagittal malalignments, relatively larger mean age (71.6 ± 5.8 years vs. 67.8 ± 4.0 years, $P = 0.062$), greater proportion of female (F/M: 16/2 vs. F/M: 22/13, $P = 0.046$) and smaller preoperative PI (40.7 ± 1.6° vs. 54.6 ± 3.1°, $P = 0.006$) were also found in patients with substantial PI variation than those with minor change (Table 2). The relationship between increased PI and age have been reported in several studies, particularly in those over 60 years old.[18,19] Jean[18] proposed that the increasing PI was a consequence of SIJ degeneration. Articular cartilage and ligaments played important roles in maintaining SIJ stability.[20] With age increasing, the degeneration of sacroiliac articular cartilage would aggravate and ligaments would become laxer, which led to more SIJ mobility. With regard to gender, women were demonstrated to have 40% more average SIJ mobility

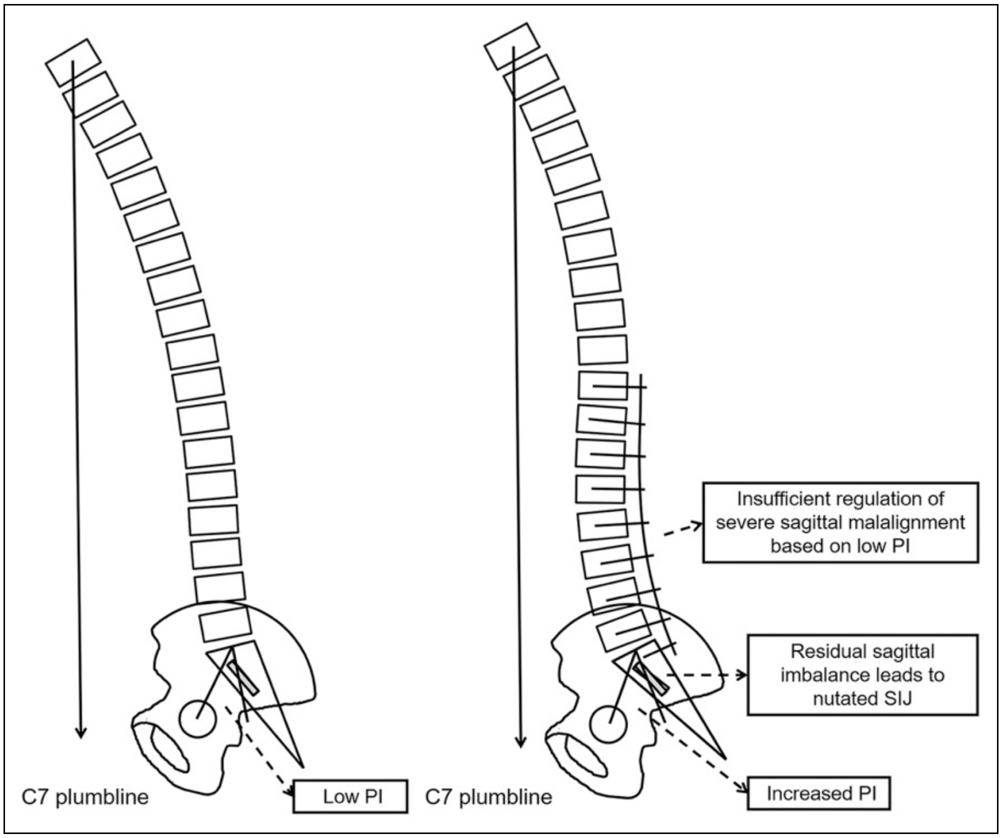

Figure 5. Sagittal profile under low PI is more likely to have sagittal malalignment and imbalance (left). In clinical practice, surgical planning involving rod contouring and types of osteotomy based on the low PI could achieve an acceptable postoperative sagittal curve, but might not be able to correct the severe sagittal imbalance completely. The limited pelvic retroversion under low PI could not compensate for the post-operative residual sagittal imbalance, which elevates the bending forces in SIJ because of the stress concentration effect at adjacent segment of long fusion. When bending forces are adopted in the lax SIJ, anutated SIJ will be induced, which alters the pelvic morphology and results in an increased PI (right).

than men.[21] More SIJ movement would lead to greater degree of PI changing. As we all know, PI influences individual's capacity to compensate for sagittal deformity via pelvic retroversion.[13,22] Patients with low PI would have insufficient ability to compensate for spinal sagittal imbalance, which could result in more and severer sagittal malalignments.[18] In clinical practice, surgical strategy planned based on a low PI involving rod contouring and types of osteotomy might not be able to completely correct the severe sagittal imbalance. Because of the limited compensatory potential under low PI, the post-operative residual sagittal imbalance could finally lead to the nutated SIJ and thereby the increased PI (Figure 5).[23] Accordingly, it is comprehensible that greater degree of PI increasing would be induced in aged female patients with low PI and severe sagittal deformity after long fusion to sacrum (Figure 3).

With the aim to evaluate the necessity of long lumbar fusion in the mechanism of PI increasing, we compared the PI behaviors between patients with or without lumbar flexibility who had similar sagittal malalignments in terms of PT, PI-LL, SVA and TPA (Table 2). Despite PI was not statistically changed in either group, 70.8% (17/24) of patients in Group A who underwent long fusion to sacrum had substantial increase (>5°) of PI, while only 10% had in Group B with short lumbar fusion. In Group B, the sagittal malalignment might be a pain relieved posture, not a primary deformity. For patients underwent short lumbar fusion, the compensatory abilities of thoracic, lumbar and pelvis were available.[24] After decompression of the responsible segment, the sagittal malalignment and imbalance would be regulated to by all the 3 mechanisms. Therefore, the shear forces on SIJ were dispersed and SIJ was less likely to be nutated, which contributed to the stability of PI value (Figure 4).

To our best knowledge, this is the first study to comprehensively analyze the surgical and other potential associated factors with the variability in PI after PSF. Our series of studies corroborated the theory that increasing PI could be regarded as the compensatory change for spinal sagittal malalignment under limited compensation of spine and mobile SIJ. The findings could provide references for clinical practice and help better selecting an optimal fusion level for elderly ASD patients, particularly in the setting of sacropelvic fixation. In patients undergoing sacroiliac motion, the elevated shear forces on SIJ would accelerate the degenerative change in SIJ and induce persistent postoperative low back pain and dysfunction.[18,25] Accordingly, sacropelvic fixation should be taken into consideration when long fusion to sacrum is planned in ASD patients with severe sagittal deformity and other potential risk factors associated with sacroiliac motion.

Limitations

Despite the above findings, several limitations are present in the current study. First, this is a retrospective study with small sample size and short follow-up. A prospective RCT design will be more credible and persuasive, but it might be hard to perform in practical work. Because the low numbers of patients in the series and only part of them willing to undergo long-segment surgery, the sample size is relatively small. A longitudinal cohort study with more subjects and long-term observation was required. Second, the identification of altered anatomies of SIJ should be confirmed by lumbosacral CT or pelvic scan, weakening the reliability of results. Third, further study is needed to evaluate the clinical implications of PI variation after long follow-up, especially the SIJ pain. Fourth, sacropelvic fixation could be performed through the SIJ fusion using sacroiliac screw and through the pelvic fixation using iliac screw. Comparison of the behavior of PI after long fusion to pelvis between sacroiliac screw fixation and iliac screw fixation would be meaningful and is needed to be further investigated.

Conclusion

PI behaves differently under different conditions in elderly ASD patients. PI would be constant after pelvic or sacropelvic fixation because of the restriction of SIJ mobility. This parameter intraoperatively varies probably because PI has been already altered before surgery. PI might increase in patients with severe sagittal deformity after long fusion to sacrum without pelvic fixation, which could be regarded as the compensatory change for malalignment under limited compensation of spine. Besides, aging, female and low preoperative PI are also the potential risk factors of PI increasing after long fusion to sacrum. PI will not increase in patients underwent short fusion to sacrum despite with severe sagittal malalignment, which could be attributed to the sharing of bending forces on SIJ by other compensatory mechanisms of spine.

Authors' Note

Weiguo Zhu and Yu Wang contribute equally to this work. This study was performed under the approval from the Ethics Committee of Capital Medical University Xuanwu Hospital. We were exempt from the requirement of patients' informed consent.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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