

The Impact of Upper Instrumented Vertebra Orientation on Proximal Junctional Kyphosis: A Novel and Fixed Parameter, Fused Spinopelvic Angle

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Study Design. A retrospective study.

Objectives. To evaluate the impact of upper instrumented vertebra (UIV) orientation including the fused spinopelvic angle (FSPA) on proximal junctional kyphosis (PJK).

Summary of Background Data. PJK is a challenging complication after adult spinal deformity (ASD) surgery. Some studies proposed UIV orientation act as a risk factor of PJK, but there remain debates because UIV orientation is changed by position. Therefore, we investigated the relationship between the FSPA, a novel parameter for the relationship between UIV and pelvis which did not change by position, and PJK.

Materials and Methods. ASD patients who underwent long-segment fusion to the pelvis and followed up for more than two years were included. Comparative analysis was performed on spinopelvic parameters including UIV orientation parameters (UIV slope angle and FSPA) between PJK and non-PJK group. Binary

regression analysis was conducted to find out the risk factors for PJK. And correlation analysis was conducted to find out the parameters that affect the FSPA.

Results. A total of 190 patients were included. PJK incidence was 13.2% (25/190). PJK group showed a significantly greater postoperative UIV slope (21.3° vs. 18.8° , $P=0.041$) and significantly lesser postoperative FSPA (-0.9° vs. 4.5° , $P<0.001$). In binary regression analysis, only FSPA acted as a risk factor of PJK (odds ratio = 0.920, $P=0.004$). The FSPA has strong positive correlation with pelvic incidence (PI)-lumbar lordosis (LL) ($r=0.666$, $P<0.001$) and negative correlation with lordosis distribution index (LDI) ($r=-0.228$, $P=0.004$).

Conclusion. The FSPA is a fixed parameter which is not dependent on position. A reduction of the FSPA increases the risk for PJK. The FSPA can be adjusted through PI-LL and LDI. Thus, surgeons should increase the FSPA by adjusting the PI-LL and LDI during ASD surgery to prevent PJK.

Key words: adult spinal deformity, lumbar distribution index, pelvic incidence, proximal junctional kyphosis, upper instrumented vertebra

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The goal of surgical correction of adult spinal deformity (ASD) is to restore the sagittal balance and achieve solid arthrodesis.¹ Restoration of appropriate sagittal balance can clinical symptoms and prevent decompensation.² Although reconstructive spine surgery has various approaches for restoring the sagittal balance, the complexity of these surgeries increases the risk of early and late complications.^{3,4}

Proximal junctional kyphosis (PJK) is one such complication, with an incidence ranging from 6% to 62%.^{5,6} The risk factors for PJK include age, sex, a low bone mineral density, comorbidities, inadequate restoration of the global sagittal balance, an anterior or posterior approach, lumbar lordosis (LL) correction degree, and the upper instrumented vertebrae (UIV) level.^{5–9} However, these risk factors remain controversial, and other risk factors exist.¹⁰ Among the risk factors, UIV

orientation was reported to be significantly associated with PJK in some studies; however, the strength of this association varies across studies.^{11,12}

Thus, we investigated the effects of UIV orientation on PJK in patients who had undergone surgical treatment for ASD. To better reflect the relationship between the pelvis and the UIV, we measured a novel parameter, the fused spinopelvic angle (FSPA), and investigated its relationship with PJK. Furthermore, we analyzed the factors that could adjust the FSPA to lower the risk of PJK.

MATERIALS AND METHODS

Patient Selection

This study was a retrospective review of consecutive patients with ASD treated between 2013 and 2019. The inclusion criteria were as follows: (1) patients with ASD accompanied by sagittal malalignment [sagittal vertical axis (SVA) > 50 mm, pelvic incidence (PI)-LL mismatch > 10°, and pelvic tilt (PT) > 25°] with a minimum follow-up of two years after deformity correction; (2) patients who underwent deformity correction and long-segment fusion¹³ with the lowermost instrumented vertebra set at the S1 level by a single surgeon in a single institution; (3) patients with a single etiology of degenerative lumbar kyphosis (DLK), redefined as the drop body syndrome (DBS).^{14,15} The latter included patients who clearly showed atrophy of the back musculature on magnetic resonance imaging (a diagnostic criterion for DLK), as well as clinical signs including walking difficulty with stooping, inability to lift heavy objects to the front, difficulty in climbing slopes, and need for elbow support when working in the kitchen, resulting in hard corns on the extensor surfaces.¹⁶⁻¹⁸

Patients were divided into PJK and non-PJK groups depending on the presence of PJK at the last follow-up after surgery.

Radiographic Measurements

Sagittal alignment was evaluated using lateral 14×36-inch full spine radiographs obtained with the patients standing in a neutral, unsupported, “fists-on-clavicle” position.¹⁹ All digital radiographs were evaluated preoperatively, postoperatively, and at the last follow-up using validated software (Surgimap, Nemaris Inc., New York, NY).²⁰

We evaluated the PI, sacral slope (SS), PT, thoracic kyphosis (TK), thoracolumbar junction (TL), LL, lumbosacral junction (LS), lumbar distribution index (LDI; [L4-S1/L1-S1]×100, %),^{21,22} and SVA. The PI, PT, and SS were measured using a standing lateral radiograph of the pelvis according to the methods described in previous reports.²³ Sagittal Cobb angles were measured for TK (T5-12), TL (T10-L2), LL (L1-S1), and LS (L4-S1).¹¹

The proximal junctional angle (PJA) was defined as the angle between the lower endplate of the UIV and the superior endplate of two vertebrae above the UIV. PJK was defined in accordance with the following criterion: proximal junction sagittal Cobb angle ≥ 10° with a change in the angle of at least 10° greater than the preoperative measurement.²⁴

UIV Orientation Measurements

The UIV slope was defined as the angle between the lower endplate of the UIV and the horizontal line. The FSPA was defined as the angle between the line connecting the center of the lower endplate of the UIV to the midpoint of the bicoxofemoral axis, and the line connecting the center of the sacral endplate to the midpoint of the bicoxofemoral axis (Figure 1). The FSPA was considered positive if the line that passed through the UIV was anterior to the line that passed through the sacrum.

Relationship Between the FSPA and ASD Surgery

There are several guidelines for LL correction in the surgical treatment of ASD to achieve an optimal sagittal balance. Of these, the SRS-Schwab classification by Schwab *et al*^{25,26} proposed $LL = PI \pm 9^\circ$ as the standard for correction, and this is widely used for ASD treatment. In light of recent reports that proportional parameters can lower the incidence of mechanical complications, LDI was also considered in the surgical management of ASD.²⁷⁻²⁹ Thus, in this study, we analyzed the correlation of the FSPA with these two most common parameters considered in ASD surgery.

Statistical Analysis

The Student *t* test and the Mann-Whitney test were used to evaluate the differences in the radiographic parameters between the two groups. A binary logistic regression analysis was performed for the UIV orientation parameters and PJK. To determine the factors that can adjust the FSPA, we

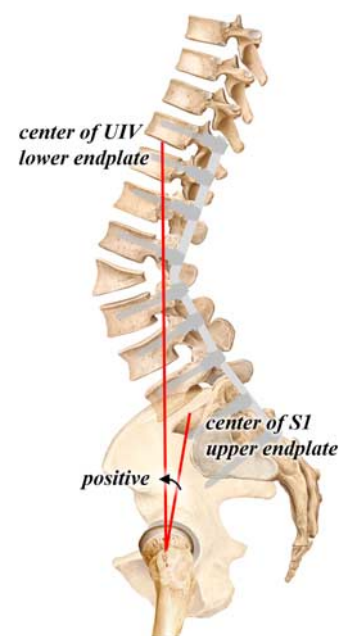


FIGURE 1. Measurement of the fused spinopelvic angle. The fused spinopelvic angle was defined as the angle between the line connecting the center of the lower endplate of the UIV to the midpoint of the bicoxofemoral axis, and the line connecting the center of the sacral endplate to the midpoint of the bicoxofemoral axis. The fused spinopelvic angle was considered positive if the line that passed through the UIV was anterior to the line that passed through the sacrum. UIV indicates upper instrumented vertebra. full color
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performed correlation and multilinear regression analyses for the FSPA. All statistical calculations were performed using SPSS version 25.0 (IBM Corp., Armonk, NY). Statistical significance was set at $P < 0.05$.

RESULTS

Baseline Characteristics

Table 1 shows the baseline characteristics of the patients. At the time of the study, the database included 210 patients. After applying the inclusion criteria, 190 patients were selected. The average age at surgery was 71.6 years, and the average follow-up period was of 44.9 months. Ninety-two patients underwent pedicle subtraction osteotomy, and 98 underwent multilevel lateral lumbar interbody fusion with posterior column osteotomy.³⁰ There were no significant differences between the non-PJK and PJK groups with respect to the demographic characteristics, such as age (71.3 *vs.* 73 yr; $P = 0.157$), body mass index (24.1 *vs.* 25.5 kg/cm²; $P = 0.101$), and bone mineral density (0.997 *vs.* 0.962 g/cm²; $P = 0.448$) (Supplemental Digital Content 1, <http://links.lww.com/BRS/B932>).

Radiographic Parameters

Table 2 presents the radiographic parameters of the two groups. PJK was detected in 25 patients (13.2%) at the last follow-up. The radiographic parameters did not differ

between the two groups, except for postoperative TK (PJK group *vs.* non-PJK group: 37.5° *vs.* 24.2°; $P < 0.001$).

UIV Orientation and PJK Occurrence

The PJK group showed a significantly greater postoperative UIV slope (21.3° *vs.* 18.8°, $P = 0.041$; Table 2) and a significantly lower postoperative FSPA (−0.9° *vs.* 4.5°, $P < 0.001$). However, multiple regression analysis revealed that only the FSPA was a risk factor for PJK ($\beta = -0.083$; odds ratio: 0.920; 95% CI: 0.869–0.975; $P = 0.004$; Table 3).

Correlation and Multilinear Regression Analyses for the FSPA

The FSPA had a strongly positive correlation with the PI-LL ($r = 0.666$, $P < 0.001$). In other words, the PI-LL decreased as the LL correction degree increased, resulting in a decrease in the FSPA. And the FSPA had a strongly negative correlation with the LDI ($r = -0.228$; $P = 0.004$). As the lower LL correction increased, the lever arm of the fused segments increased, causing the line between the UIV and the femoral head to shift posteriorly; the FSPA became negative.

Multilinear regression analysis (Table 4) of the PI-LL and LDI led to a predictive formula for the FSPA ($R^2 = 0.456$; $P = 0.000$). After establishing the significance of each path, it was noted that as the PI-LL increased, the FSPA (standardized coefficients β : 0.636) also increased; conversely, as the LDI increased, the FSPA (standardized coefficients β : −0.198) decreased. The regression formula was as follows: $FSPA = 16.501 + 0.550 \times PI-LL - 0.117 \times LDI$.

DISCUSSION

UIV Orientation and PJK

Among ASD patients with long-segment fusion up to the lower thoracic level, Lafage *et al*¹¹ reported that the UIV inclination (slope of UIV with reference to the vertical line) was greater in patients with PJK than in those without PJK. The UIV inclination that they used was measured with reference to the lower endplate of the UIV; therefore, it is a parameter identical to the UIV slope in our study. However, the posterior leaning of the UIV can change with the position, and is thus, not an objective parameter. Lafage *et al*¹¹ also stated that the UIV slope with reference to the upper endplate of the UIV is not associated with PJK. However, because this angle is influenced by the onset of PJK, it may not be significant. Meanwhile, Smith *et al*¹² reported that the UIV angle (same as the UIV slope in our study) is not associated with the incidence of acute proximal junctional fractures. This inconsistency regarding the effects of the UIV slope on PJK across studies may be attributable to the fact that the UIV slope is a positional parameter that changes with variations in the standing posture. In the present study, although the UIV slope differed between the 2 groups, binary logistic regression analysis revealed that the UIV slope was not a risk factor

TABLE 1. Demographics and Baseline Data

Variables	
Sex	
Male	4
Female	186
Age at operation (yr)	71.6 ± 5.7
BMI (kg/cm ²)	24.82 ± 3.1
BMD (g/cm ²)	0.994 ± 0.23
Follow-up (mo)	44.9 ± 37.7
UIV	
T9	1
T10	186
T11	2
T12	1
LIV	
Sacrum	190
Sacropelvic fixation with iliac screws	190
Surgical method	92
PSO multilevel LLIF PCO	98
<i>Data are presented as mean ± SD.</i>	
<i>BMD indicates bone mineral density; BMI indicates body mass index; LIV, lowermost instrumented vertebra; LLIF, lateral lumbar interbody fusion; PCO, posterior column osteotomy; PSO, pedicle subtraction osteotomy; UIV, uppermost instrumented vertebra.</i>	

TABLE 2. Comparison of Radiographic Parameters

Variables	Non-PJK Group (N = 165)	PJK Group (N = 25)	P
PI (°)	55.5 ± 10.7	54.0 ± 9.9	0.505
SS (°)			
Preoperative SS	24.5 ± 13	21.5 ± 11.9	0.272
Postoperative SS	47.2 ± 9.4	44.2 ± 8.6	0.136
PT (°)			
Preoperative PT	31.0 ± 13.4	32.6 ± 13.7	0.592
Postoperative PT	10.9 ± 9.4	11.0 ± 9.3	0.962
SVA (mm)			
Preoperative SVA	201.0 ± 67.9	207.4 ± 52.2	0.648
Postoperative SVA	-13.8 ± 27.6	-3.9 ± 25.5	0.091
TK (°)			
Preoperative TK	4.3 ± 13.5	6.4 ± 11.4	0.512
Postoperative TK	24.2 ± 11.2	37.5 ± 8.3	<0.001**
LL (°)			
Preoperative LL	2.9 ± 19.5	3.4 ± 27.3	0.906
Postoperative LL	-68.3 ± 10.9	-69.1 ± 7.7	0.423
LS junction angle (, °)			
Preoperative LS	-5.6 ± 16	-10.8 ± 14.5	0.133
Postoperative LS	-26.9 ± 10.4	-26.0 ± 9.9	0.679
PJA (°)			
Preoperative PJA	0.1 ± 6.2	1.7 ± 7.8	0.245
Postoperative PJA	7.3 ± 5.2	8.4 ± 4.9	0.156
Postoperative PI-LL	-13.0 ± 9.5	-14.7 ± 9.9	0.104
LL correction (°)	70.1 ± 19.6	72.5 ± 26.7	0.600
Postoperative LDI (%)	39.3 ± 13.6	38.0 ± 12.8	0.223
Postoperative UIV slope (°)	18.8 ± 5.3	21.3 ± 3.6	0.041*
Postoperative fused spinopelvic angle (°)	4.5 ± 7.4	-0.9 ± 6.3	<0.001**

Data are presented as mean ± SD.
 LDI indicates lordosis distribution index; LL, lumbar lordosis; LS, lumbosacral; PI, pelvic incidence; PJA, proximal junctional angle; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis; UIV, upper instrumented vertebra.
 *Statistically significant (P < 0.05).
 **Statistically significant (P < 0.01).

for PJK. Hence, we considered a parameter that reflects the relationship between the pelvis and the UIV and is not influenced by the position.

Relationship Between the FSPA and the Pelvis

The PI is the most commonly used anatomical pelvic parameter that is not influenced by the position. It is defined as the angle between the line perpendicular to the sacral

plate and the line connecting the center of the sacral endplate to the midpoint of the bicoxofemoral axis.³¹ It determines the overall shape of the spine by establishing the orientation of the pelvis and the spine. Thus, individuals with a large PI show a large LL and TK curvatures with a greater SS.^{21,32} In patients with ASD, when long-segment fusion up to S1 is performed, the whole spine from the UIV to the pelvis is corrected as a single fixed curvature. Because the fused spinal segments from the UIV to the pelvis can only move within the hip joint, the FSPA, which is the angle between the lower endplate and the sacral endplate with reference to the hip joint, can be considered a fixed parameter, and is useful for analyzing the curvature of the fused segments from the UIV to the pelvis. Because the FSPA is not affected by position, it can better indicate the relationship between the pelvis and the UIV. Furthermore, just as PI and SS can affect LL, the FSPA can contribute to the PJA and TK.

TABLE 3. Risk Factors of PJK†

	P	OR	95% CI
Postoperative fused spinopelvic angle (°)	0.004*	0.920	0.869–0.975

†Binary logistic regression analysis
 OR indicates odds ratio; PJK indicates proximal junctional kyphosis.
 *Statistically significant (P < 0.05)

TABLE 4. Multilinear Regression Analysis for the Fused Spinopelvic Angle†						
	Unstandardized Coefficients		Standardized Coefficients β	t	Significance	VIF
	B	SE				
Constant	16.501	1.467		11.248	<0.001	
PI-LL	0.550	0.046	0.636	11.898	<0.001*	1.002
LDI	-0.117	0.032	-0.198	-3.708	<0.001*	1.002

†R: 0.675; R²: 0.456; Durbin-Watson: 1.858
 LDI indicates lumbar distribution index; LL, lumbar lordosis; PI, pelvic incidence; VIF, variance inflation factor.
 *Statistically significant (P-value < 0.05)

Fused Spinopelvic Angle and Proximal Junctional Kyphosis

In our study, the FSPA was significantly smaller in the PJK group than in the non-PJK group (-0.9° vs. 4.5° ; $P < 0.001$; Figures 2, 3). This means that the line between the UIV and the femoral head was more posteriorly shifted in the PJK group. A reduced FSPA was identified as a risk factor for PJK (Table 3). Individuals with a large PI have greater LL, and thus, larger TK; this contributes to the maintenance of the sagittal balance.³³ However, patients with long-segment fusion only have a short segment above the UIV, which makes it difficult to maintain the sagittal balance with proper thoracic compensation. Thus, as the FSPA decreases, the UIV is displaced further posterior to the pelvis, resulting in a larger UIV slope; this requires increased TK

to maintain an optimal balance. However, a fixed segment cannot increase the TK, and the stress is focused on the UIV. This seems to have been the underlying cause of the increased TK along with the FSPA in the PJK group. In particular, because the long segment is fixed rigidly, the stress is further concentrated on the relatively more flexible UIV, thereby elevating the risk of PJK. As the FSPA is position-independent, it seems to be a more accurate indicator of the relationship between PJK and UIV than the posterior inclination of the UIV proposed by Lafage *et al.*¹¹

Applying the FSPA for ASD Surgery

In this study, the FSPA was strongly correlated with the PI-LL and LDI (Table 4). This means that the FSPA can be modulated

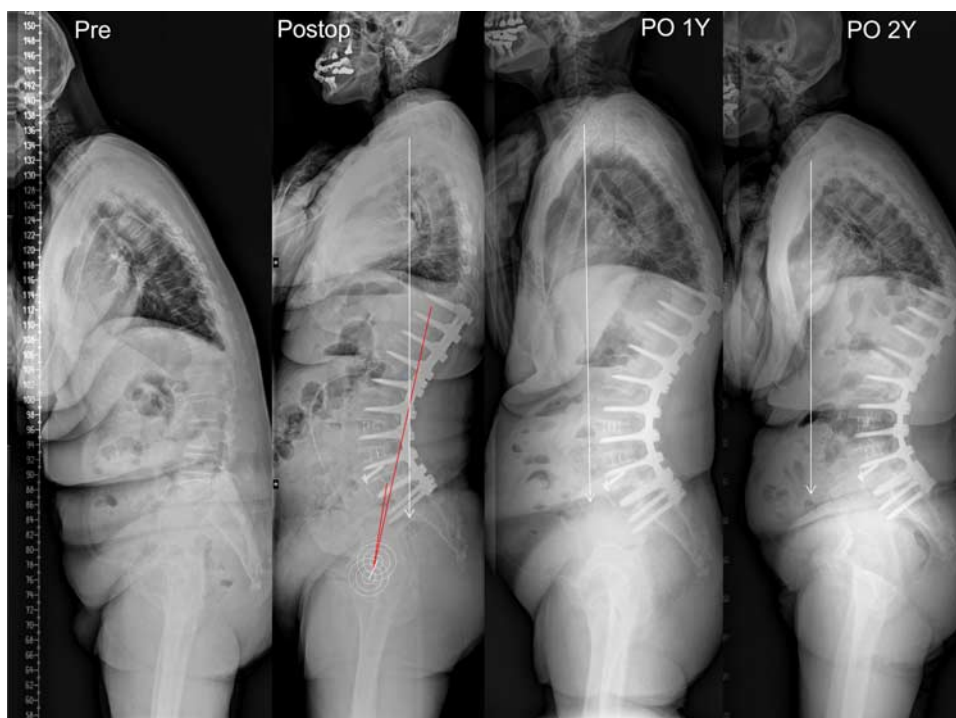


FIGURE 2. This 69-year-old female presented to us with degenerative sagittal imbalance (SVA +170 mm, TK 22°, LL -11°, PI 54°, PT 31°, SS 23°). We performed ALIF on L5-S1 and posterior column osteotomy with LLIF on L3-L5. After surgery, PJK was occurred with UIV fracture. The fused spinopelvic angle was -2.4°. PI-LL was -15° (SVA -45 mm, TK 45°, LL -69°, PT 16°, SS 37°). One year after surgery, sagittal decompression and PJK were progressed (SVA +73 mm, PJA 48°). Sagittal decompression and PJK were more worsen at postoperative two years follow-up period (SVA +112 mm, PJA 54°). ALIF indicates anteriorlumbar interbody fusion; PI-LL, pelvic incidence-lumbar lordosis; PJK, proximal junctional kyphosis; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis; UIV, upper instrumented vertebra. full color
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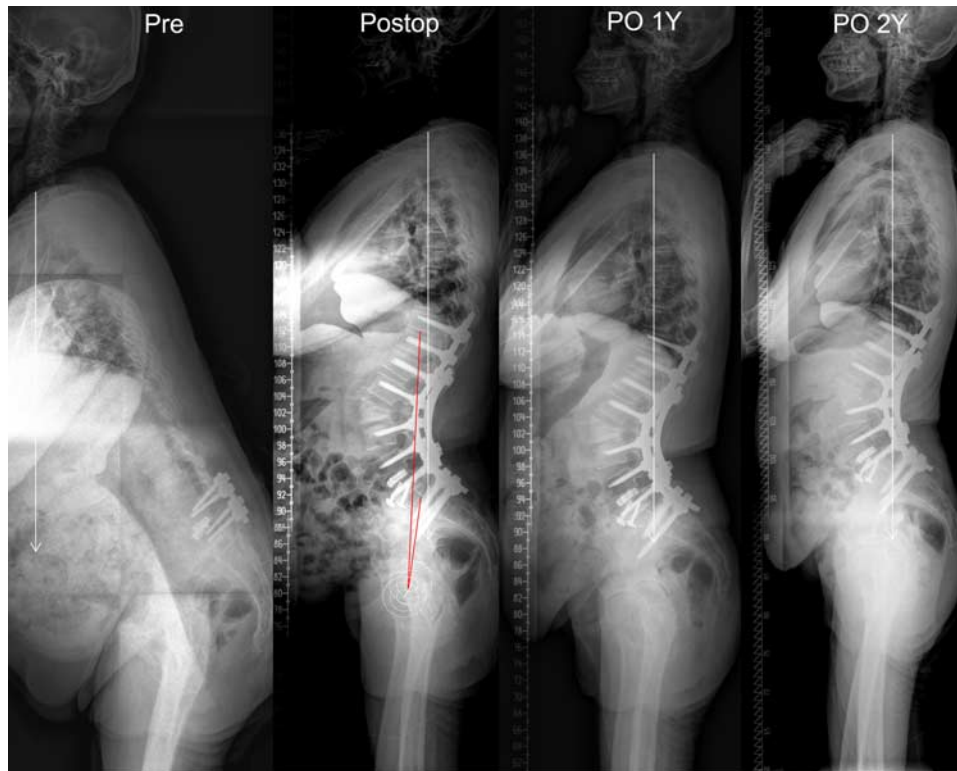


FIGURE 3. This 60-year-old female presented to us with degenerative sagittal imbalance with PLIF on L4-L5 state (SVA +230 mm, TK -4° , LL -15° , PI 67° , PT 27° , SS 40°). We performed ALIF on L5-S1 and pedicle subtraction osteotomy on L2 with applying accessory rod. After surgery, the fused spinopelvic angle was 8.5° . PI-LL was -15° (SVA -26 mm, TK 32° , LL -82° , PT 7° , SS 59°). Postoperative one-year whole spine lateral radiograph showing normal sagittal alignment (SVA +5 mm) without occurrence of PJK. Sagittal alignment is maintained optimal (SVA +6 mm) without occurrence of PJK at postoperative two years follow-up period. ALIF indicates anteriorlumbar interbody fusion; LDI, lordosis distribution index; PI-LL, pelvic incidence-lumbar lordosis; PLIF, posterior lumbar interbody fusion; PJK, proximal junctional kyphosis; PT, pelvic tilt; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis; UIV, upper instrumented vertebra. full color online

by the PI-LL and LDI. This study analyzed a single etiology of ASD, which is known as DLK, and redefined as DBS.³³ DLK is a disease caused by overall degenerative changes in the back extensor muscles; it is characterized by more severe degenerative fatty changes and an extremely large preoperative SVA. Because of these pathological characteristics of DLK, sufficient LL correction is recommended for patients with DBS. Several studies have revealed that sufficient LL correction lead to clinical and radiological improvements in patients with DLK.³⁴ Therefore, we generally performed sufficient LL correction in this study, which led to further reduction in the PI-LL. With decreasing PI-LL, the FSPA decreased ($r = 0.666$; $P < 0.001$) and the PJK risk increased. Hence, although sufficient LL correction is essential to achieve good clinical outcomes and an optimal sagittal balance in patients with DLK, the cut-off value for PJK prevention should be further examined.

Yilgor *et al*^{27,28} reported that an ideal LDI ranges from 50% to 80%, and a lower LDI results in a lower global alignment and proportion score, thereby increasing the prevalence of mechanical complications. However, in our study, there was no significant difference in the postoperative LDI between the 2 groups. Furthermore, multiple regression analysis revealed that the LDI was not a risk factor for PJK. Only the FSPA was identified as a crucial

risk factor for PJK, and correlation and multilinear regression analyses revealed that an increased LDI led to a reduced FSPA. This seems to be attributable to the fact that this study was conducted on patients with a single etiology (DLK), and almost all patients underwent sufficient LL correction. Excessive LL correction increases upper and lower lordosis, resulting in a decreased LDI. The average LDI of our patients (39%) was lower than the ideal LDI; however, Im *et al*³⁵ reported that there are no problems in maintaining an optimal balance in patients with DLK as long as an appropriate LL correction is achieved, even if overcorrection decreases the LDI. If surgeons attempt to increase the LDI through excessive LL correction in patients with DLK, as in this study, upper lordosis will increase, and the UIV will be more posterior to the pelvis. Then, TK needs to be increased to maintain the sagittal balance, which can intensify the stress inflicted on the UIV. However, an ideal LDI is still an unresolved problem; therefore, additional analysis is needed for this group of patients.

Limitations

This study had several limitations. First, it only included patients with UIV in the lower thoracic segment. Lafage *et al*¹¹ analyzed cases with UIV at the upper thoracic level and

reported that UIV posterior inclination is also associated with PJK in these cases. We are planning to analyze the relationship between the FSPA and PJK in patients with UIV in the upper thoracic level. Second, sufficient LL correction was performed in all cases because only cases with a single etiology (DLK) were examined. Hence, it seems that reducing the LDI increases the FSPA, and thus, reduces the PJK risk. However, increasing the LDI is important in other cases of ASD that often have ideal LL correction. The correlation between the LDI and FSPA may be different in these cases. Thus, additional studies are needed on patients who have undergone a LL undercorrection or an ideal LL correction. Third, intraoperative determination of FSPA could be difficult. FSPA can be determined during operation, however, through intraoperative portable x-ray imaging which includes the femur and the proximal portion of instrumentation. Furthermore, any existing reduction in the FSPA can be corrected to produce an optimal FSPA through rod-bending adjustments and manipulation of the spine table in an effort to reduce lordosis. Despite these limitations, this study shows that the FSPA, a fixed novel parameter, is a risk factor for PJK, and that the FSPA can be adjusted through the PI-LL and LDI. Furthermore, a key strength of this study is that 200 cases of a single disease entity treated by a single surgeon in a single institution were examined.

CONCLUSION

The FSPA is a fixed parameter for the relationship between the pelvis and the UIV, which is independent of positioning. A reduction in the FSPA increases the risk of PJK. The FSPA can be adjusted using the PI-LL and LDI. Thus, surgeons should try to increase the FSPA by adjusting the PI-LL and LDI during a spine reconstruction surgery for ASD in order to prevent PJK.

➤ Key Points

- ❑ The FSPA is a fixed parameter for the relationship between pelvis and UIV, which is not changed by positioning.
- ❑ The group with PJK showed significantly lower FSPA values compared with the non-PJK group (-0.9° vs. 4.5° , $P < 0.001$). A reduced FSPA was associated with the development of PJK (odds ratio = 0.920, $P = 0.004$).
- ❑ The FSPA demonstrated a positive correlation with PI-L ($r = 0.666$, $P < 0.001$) and negative correlation with LDI ($r = -0.228$, $P = 0.004$).
- ❑ In ASD surgery, surgeons should try to increase the FSPA by adjusting the PI-LL and LDI to prevent PJK.

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