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Original Article

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Proximal Junctional Failure Development Despite Achieving Ideal Sagittal Correction According to Age-Adjusted Alignment Target in Patients With Adult Spinal Deformity: Risk Factor Analysis of 196 Cases Undergoing Low Thoracic to Pelvic Fusion

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Objective: To identify the risk factors for proximal junctional failure (PJF) after adult spinal deformity (ASD) surgery despite ideal sagittal correction according to age-adjusted alignment target.
Methods: The study included patients who underwent low thoracic to pelvic fusion for ASD and obtained ideal correction according to age-adjusted pelvic incidence minus lumbar lordosis. PJF was defined either radiographically as a proximal junctional angle (PJA) of > 28° plus a difference in PJA of > 22° or clinically as revision surgery for proximal junctional complications. Clinical and radiographic variables were assessed to identify the risk factors for PJF.
Results: The final study cohort consisted of 196 patients, of whom 170 were women (86.7%), with an average age of 68.3 years. During mean follow-up duration of 45.9 months, PJF occurred in 43 patients (21.9%). Multivariate logistic regression analysis revealed that old age (odds ratio [OR], 1.063; 95% confidence interval [CI], 1.001–1.129; $p = 0.046$), large preoperative sagittal vertical axis (OR, 1.007; 95% CI, 1.001–1.013; $p = 0.024$), nonuse of a transverse process (TP) hook (OR, 5.556; 95% CI, 1.205–19.621; $p = 0.028$), and high lumbar distribution index (LDI) (OR, 1.136; 95% CI, 1.109–1.164; $p < 0.001$) were significant risk factors for PJF development.
Conclusion: A sizeable proportion of patients (21.9%) developed PJF despite achieving ideal sagittal correction. Using TP hooks with avoiding excessive LDI can be helpful to further mitigate the risk of PJF development in this patient group.

Keywords: Adult spinal deformity, Ideal correction, Pelvic incidence minus lumbar lordosis, Risk factors, Proximal junctional failure

INTRODUCTION

Proximal junctional failure (PJF) is a well-known mechanical complication following long instrumented fusion for adult spinal deformity (ASD). Unlike proximal junctional kyphosis (PJK), which is frequently asymptomatic, PJF represents a structural failure that can result in substantial clinical consequences, increased deformity, and necessity for revision surgery.[1,2] The incidence of PJF ranges from 1.4% to 19%, with a revision rate of up to 47%.[3-7]

Adequate correction of sagittal malalignment is crucial in preventing PJF after ASD surgery.[5,8-15] Among various surgical targeting tools, including the Scoliosis Research Society (SRS)–Schwab classification, Global Alignment Proportion (GAP) score, and age-adjusted alignment scheme, age-adjusted pelvic incidence (PI)–lumbar lordosis (LL) has been widely accepted metric to provide the ideal LL correction target.[8,15-17] Since the first introduction of age-adjusted alignment concept by Lafage et al.,[8,18] several follow-up studies verified the clinical usefulness of the age-adjusted PI–LL scheme in term of PJF prevention as well as good clinical outcomes.[5,12,16,19]

However, it is reported that PJF occurs in up to 23.7% of patients even after they achieved ideal correction according to the age-adjusted PI–LL target in ASD surgery.[5,12,16,19] This implies that age-adjusted PI–LL goal alone cannot completely prevent the PJF development, suggesting that factors other than age-adjusted PI–LL are also affecting the occurrence of PJF. This imperfection of age-adjusted PI–LL scheme in predicting PJF may be attributable to the heterogeneity of the ASD population such as varying demographic factors, surgical techniques, and radiographic variables. Considering that achieving pertinent sagittal correction (e.g., according to age-adjusted PI–LL) is prioritized among various surgical considerations in ASD surgery, an in-depth analysis is required to investigate which factors other than age-adjusted PI–LL are responsible for PJF development. Therefore, this study aims to identify the risk factors for PJF development among patients who achieved ideal sagittal correction according to age-adjusted alignment goal in ASD surgery.

MATERIALS AND METHODS

This study was approved by the Institutional Review Board of Samsung Medical Center (IRB No. 2024-04-043). Obtaining informed consent was waived due to the retrospective nature of the study.

1. Study Cohort

This study was retrospective case series using prospectively collected data from ASD database in Samsung Medical Center. The study cohort included consecutive patients who underwent long fusion surgery for degenerative-type ASD from 2013 to 2022. The inclusion criteria were as follows: sagittal plane deformities defined by C7 sagittal vertical axis (C7–SVA) ≥ 50 mm, PI–LL mismatch $\geq 10°$, or pelvic tilt (PT) $\geq 25°$; low thoracic (T9–11) to pelvic fusion; ideal correction according to the age-adjusted PI–LL target; and a minimum follow-up duration ≥ 2 years. All the surgeries were performed by 4 attending spine surgeons. Pelvic extension was routinely carried out using the conventional iliac screws, except in cases of prior L5–S1 fusion surgeries. We specifically included patients whose uppermost instrumented vertebra (UIV) was located in the low thoracic spines, as low thoracic to pelvic fusion is the most common procedure for the surgical treatment of ASD at our institution. We also aimed to reduce the fusion length-related bias, as stopping at the upper thoracic spine or thoracolumbar junction would show different biomechanical characteristics compared with stopping at the low thoracic spine.[20-21] The age-adjusted PI–LL target was calculated based on the previously reported formula: PI–LL = (age–55)/2+3.[8,22] Ideal correction according to the age-adjusted PI–LL target indicates current PI–LL values within a ± 10-year range relative to the calculated PI–LL target.[22] Patients were excluded if they had nondegenerative deformity such as neuromuscular, inflammatory, or other pathological etiologies; did not develop PJF without reaching 2-year follow-up duration; underwent revision procedures for reasons other than PJF, such as rod fractures; or lacked appropriate radiographic data.

2. Definition of PJF

PJF was defined either radiographically, as a proximal junctional angle (PJA) > 28° plus a difference in PJA of > 22° according to the recent definition by Lovecchio et al.,[23] or clinically, as the necessity for revision surgery for junctional complications. Various clinical and radiographic variables were compared between patients who developed PJF (PJF group) and those who did not develop PJF for at least 2 years postoperatively (non-PJF group).

Patient factor included sex, age, the American Society of Anesthesiologists (ASA) physical status classification grade, body mass index (BMI), T-score on bone mineral density (BMD), osteoporosis (i.e., the lowest T-score of ≤ -2.5 in spine or hip BMD), perioperative use of teriparatide, diabetes mellitus (DM), and smoking status. Surgical variables included whether the surgery was a revision case, anterior lumbar interbody fusion (ALIF) at L5–S1, lateral lumbar interbody fusion (LLIF) or anterior column realignment (ACR) at or above L4–5 segment, pedicle subtraction osteotomy (PSO), number of interbody fusion levels, number of total fusion levels, UIV location, transverse process (TP) hook fixation at the UIV+1, cement augmentation at the UIV, and follow-up period.

To analyze the radiographic factors, the PI, LL, PI–LL, sacral slope (SS), PT, thoracic kyphosis, T1 pelvic angle, and C7–SVA were measured preoperatively and postoperatively (at 6 weeks after surgery). Lower LL (LLL, defined as L4–S1 lordosis) and lumbar distribution index (LDI, defined as [L4–S1 lordosis/L1–S1 lordosis × 100]) were measured only on postoperative radiographs. If PJF developed within 6 weeks postoperatively, immediate postoperative radiographs were obtained. In addition to conventional radiographic parameters, the correction status was evaluated using legacy assessment metrics. First, adherence of age-adjusted PI–LL goal was evaluated. However, since this study included only patients who achieved ideal correction relative to this target, postoperative PI–LL offset was evaluated instead. Postoperative PI–LL offset was determined as the difference between the current and target PI–LL values, with a positive value indicating overcorrection according to the calculated target. Second, SRS–Schwab's PI–LL sagittal modifier was evaluated: 0 (PI–LL < 10°); + (PI–LL 10°–20°); and ++ (PI–LL > 20°).[17] Third, the GAP score was determined according to the original categories: proportional (score ≤ 2 points), moderately disproportional (score = 3–6 points), and severely disproportional (score ≥ 7 points).[15] Last, the Roussouly type was determined using methods previously published by Pizones et al.[24,25] The first group was categorized as the "theoretical" Roussouly types (i.e., preoperative Roussouly types) according to PI values: type 1: PI < 45°, LL apex at or below L4–5 space; type 2: PI < 45°, LL apex above the L4; type 3: 45° ≤ PI < 60°; and type 4: PI ≥ 60°. The second group was the "current" Roussouly types (i.e., postoperative Roussouly types): type 1: SS < 35°, LL apex at or below L4–5 space; type 2: SS < 35°, LL apex above above the L4; type 3: 35° ≤ SS < 45°; and type 4: SS ≥ 45°. If the theoretical and current Roussouly types matched, the sagittal alignment was considered appropriately restored according to the Roussouly classification.

3. Statistical Analysis

Categorical variables are shown as frequencies and percentages, and continuous variables as means with standard deviations. Univariate analyses were conducted by comparing variables between the 2 groups using chi-square test or Fisher exact test for categorical variables and using independent t-test or Wilcoxon rank-sum test for continuous variables. To identify risk factors for PJF, a multivariate logistic regression with stepwise method was performed using variables with p-values less than 0.10 in the univariate analyses. A receiver operating characteristic (ROC) curve analysis was conducted to determine the cutoff values with providing the area under the curve (AUC). Statistical analyses were performed out by professional statisticians using IBM SPSS Statistics ver. 27.0 (IBM Co., Armonk, NY, USA). Significance was set at $p < 0.05$.

RESULTS

1. Baseline Data

After screening 432 patients undergoing ASD surgery, 196 patients who achieved ideal correction according to age-adjusted PI–LL were included in the current study (Table 1). The majority of the patients were female (86.7%), with an average age of 68.3 years. The mean BMI was 25.9 kg/m², and the mean T-score was -1.3. Teriparatide was administered perioperatively in 21 patients (10.7%). The PI–LL and C7–SVA were 36.9° ± 20.6° and 74.6 ± 61.6 mm, respectively. ALIF (at L5–S1 level) and LLIF (at or above L4–5 level) were performed in 81 (41.3%) and 84 patients (42.9%), respectively. ACR and osteotomy were performed in 64 (32.7%) and 30 patients (15.3%), respectively. Regarding the UIV levels, 38 patients (19.4%) stopped at T9, 132 (67.3%) at T10, and 26 (13.3%) at T11. TP hook fixation at the UIV+1 and cementing at the UIV were performed in 25 patients (12.8%) and 39 patients (19.9%), respectively. During mean follow-up duration of 45.9 months, 43 patients (21.9%) experienced PJF (PJF group), whereas 153 patients (78.1%) did not (non-PJF group).

2. Univariate Analysis

In the comparison of patient factors, no significant differences were found between the groups in terms of sex, ASA PS classification grade, BMI, T-score, osteoporosis, perioperative use of teriparatide, DM, or smoking status (Table 2). Only age differed significantly between the 2 groups (67.6 years vs. 70.4 years, $p = 0.009$). Regarding baseline radiographic parameters, no significant differences were observed in all sagittal parameters. Preoperative C7–SVA was greater in the PJF group compared to the non-PJF group albeit without statistical significance (89.2 mm vs. 69.8 mm, $p = 0.056$). Regarding operative variables, there were no significant differences between the groups with regard

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Table 1. Baseline data for overall cohort (n = 196)

Variable	Value
Demographic data	
Female sex	170 (86.7)
Age (yr)	68.3 ± 6.7
ASA PS classification grade	2.1 ± 0.5
BMI (kg/m^2)	25.9 ± 4.2
T-score on BMD	-1.3 ± 1.4
Osteoporosis	36 (18.4)
Perioperative use of teriparatide	21 (10.7)
DM	36 (18.4)
Smoking	6 (3.1)
Radiographic parameters	
PI (°)	53.8 ± 9.9
LL (°)	16.9 ± 20.9
PI–LL (°)	36.9 ± 20.6
SS (°)	22.7 ± 11.4
PT (°)	31.2 ± 10.9
TK (°)	14.2 ± 13.7
TPA (°)	31.2 ± 12.4
C7–SVA (mm)	74.6 ± 61.6
Surgical data	
Revision case	67 (18.4)
ALIF at L5–S1	81 (41.3)
LLIF at ≥ L4–5 space	84 (42.9)
ACR at ≥ L4–5 space	64 (32.7)
PSO	30 (15.3)
No. of interbody fusion levels	3.7 ± 0.9
No. of total fusion levels	8.1 ± 0.8
UIV levels	
T9	38 (19.4)
T10	132 (67.3)
T11	26 (13.3)
TP hook fixation at UIV+1	25 (12.8)
Cementing at UIV	39 (19.9)
Follow-up period (mo)	45.9 ± 26.6

Values are presented as number (%) or mean ± standard deviation.
ASA PS, American Society of Anesthesiology physical status; BMI, body mass index; BMD, bone mineral density; DM, diabetes mellitus; PI, pelvic incidence; LL, lumbar lordosis; SS, sacral slope; PT, pelvic tilt; TK, thoracic kyphosis; TPA, T1 pelvic angle; SVA, sagittal vertical axis; ALIF, anterior lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; ACR, anterior column realignment; PSO, pedicle subtraction osteotomy; TP, transverse process; UIV, uppermost instrumented vertebra.

Table 2. Comparison of baseline data for PJF development

Variables	Non-PJF (n = 153)	PJF (n = 43)	p-value
Patient factors			
Female sex	128 (87.1)	42 (85.7)	0.808
Age (yr)	67.6 ± 6.7	70.4 ± 6.2	0.009*
ASA PS classification grade	2.1 ± 0.5	2.1 ± 0.5	0.929
BMI (kg/m^2)	25.8 ± 4.5	26.4 ± 3.2	0.427
T-score on BMD	-1.3 ± 1.5	-1.5 ± 1.2	0.429
Osteoporosis	25 (17.0)	11 (22.4)	0.394
Perioperative use of teriparatide	20 (13.1)	7 (16.3)	0.267
DM	26 (17.7)	10 (20.4)	0.670
Smoking	5 (3.4)	1 (2.0)	0.693
Radiographic parameters			
PI (°)	54.1 ± 9.7	52.9 ± 10.4	0.444
LL (°)	18.1 ± 20.9	13.2 ± 20.7	0.161
PI–LL (°)	36.0 ± 21.0	39.6 ± 19.1	0.292
SS (°)	22.8 ± 10.7	22.4 ± 13.4	0.834
PT (°)	31.4 ± 10.7	30.4 ± 10.4	0.596
TK (°)	14.9 ± 13.8	12.0 ± 13.3	0.192
TPA (°)	30.9 ± 12.8	32.1 ± 11.3	0.574
C7–SVA (mm)	69.8 ± 60.7	89.2 ± 62.7	0.056
Surgical factors			
Revision case	50 (34.0)	17 (34.7)	0.931
ALIF at L5–S1	59 (40.1)	22 (44.9)	0.558
LLIF at ≥ L4–5 space	62 (42.2)	22 (44.9)	0.739
ACR at ≥ L4–5 space	43 (29.3)	21 (42.9)	0.079
PSO	22 (15.0)	8 (16.3)	0.819
No. of interbody fusion levels	3.7 ± 1.0	3.8 ± 0.8	0.526
No. of total fusion levels	8.1 ± 0.7	8.0 ± 0.8	0.680
TP hook fixation at UIV+1	23 (15.6)	2 (4.1)	0.036*
Cementing at UIV	30 (19.6)	9 (20.9)	0.982
Follow-up period (mo)	47.5 ± 26.0	40.2 ± 27.6	0.126

Values are presented as number (%) or mean ± standard deviation.
PJF, proximal junctional failure; ASA PS, American Society of Anesthesiology physical status; BMI, body mass index; BMD, bone mineral density; DM, diabetes mellitus; PI, pelvic incidence; LL, lumbar lordosis; SS, sacral slope; PT, pelvic tilt; TK, thoracic kyphosis; TPA, T1 pelvic angle; SVA, sagittal vertical axis; ALIF, anterior lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; ACR, anterior column realignment; PSO, pedicle subtraction osteotomy; TP, transverse process; UIV, uppermost instrumented vertebra.
*$p < 0.05$, statistically significant differences.

to the revision cases, ALIF at L5–S1, LLIF or ACR at ≥ L4–5, PSO, number of interbody and total fusion levels, cementing at the UIV, and follow-up period. However, TP hook fixation at

Table 3. Comparison of postoperative radiographic factors for PJF development

Variable	Non-PJF (n = 153)	PJF (n = 43)	p-value
Conventional radiographic parameters			
PI (°)	54.3 ± 9.8	52.4 ± 9.6	0.238
LL (°)	45.6 ± 9.3	44.1 ± 9.0	0.319
LLL (°)	26.5 ± 9.8	31.3 ± 9.0	0.003*
LDI (%)	58.8 ± 20.4	72.0 ± 18.9	< 0.001*
PI–LL (°)	8.8 ± 5.6	8.4 ± 5.7	0.686
SS (°)	33.5 ± 8.1	33.3 ± 8.7	0.896
PT (°)	20.7 ± 6.7	19.1 ± 7.1	0.160
TK (°)	25.9 ± 9.6	25.8 ± 11.4	0.964
TPA (°)	16.8 ± 7.0	18.2 ± 7.2	0.678
C7–SVA (mm)	18.2 ± 29.4	26.6 ± 28.8	0.084
Correction status evaluation metrics			
Age-adjusted PI–LL			
Matched correction	153 (100)	43 (100)	1.000
Offset between target and actual PI–LL (°)†	0.5 ± 5.2	2.3 ± 5.4	0.038*
SRS–Schwab PI–LL modifier			0.874
0 (< 10°)	90 (61.2)	32 (65.3)	
+ (10°–20°)	54 (36.7)	16 (32.7)	
++ (> 20°)	3 (2.0)	1 (2.0)	
GAP score			0.167
Proportioned	12 (13.0)	6 (21.4)	
Moderately disproportioned	47 (51.1)	17 (60.7)	
Severely disproportioned	33 (35.9)	5 (17.9)	
Restoration relative to Roussouly type			0.234
Appropriate	95 (64.6)	27 (55.1)	
Nonappropriate	52 (35.4)	22 (44.9)	

Values are presented as mean ± standard deviation or number (%).
PJF, proximal junctional failure; PI, pelvic incidence; LL, lumbar lordosis; LLL, lower lumbar lordosis; LDI, lumbar distribution index; SS, sacral slope; PT, pelvic tilt; TK, thoracic kyphosis; TPA, T1 pelvic angle; SVA, sagittal vertical axis; SRS, Scoliosis Research Society; GAP, Global Alignment Proportion.
*$p < 0.05$, statistically significant differences. †Positive values indicates that current alignment is relatively over-corrected to the age-adjusted PI–LL target.

UIV+1 was performed more frequently in the non-PJF group than in the PJF group (15.6% vs. 4.1%, p = 0.036).

Regarding postoperative radiographic factors (Table 3), no significant differences were observed between the 2 groups in all conventional radiographic parameters, except for LLL and LDI, both of which were significantly larger in the PJF group compared to the no-PJF group (31.3° vs. 26.5°, p = 0.003 for LLL; 72.0% vs. 58.8%, p < 0.001 for LDI). Similar to the preoperative C7–SVA, postoperative C7–SVA was greater in the PJF group compared to the non-PJF group without statistical significance (26.6 mm vs. 18.2 mm, p = 0.084). Regarding the correction status assessment, the PI–LL offset was significantly greater in the PJF group compared to the non-PJF group (2.3° vs. 0.5°, p = 0.038). However, other global alignment metrics, including the SRS–Schwab's PI–LL sagittal modifier, GAP score, and Roussouly type algorithm, showed no differences in PJF development.

Table 4. Multivariate stepwise regression analysis for PJF development

Variable	p-value	Odds ratio	95% CI
Age (yr)	0.046*	1.063	1.001–1.129
Preoperative C7–SVA (mm)	0.024*	1.007	1.001–1.013
Nonuse of TP hook at UIV+1	0.028*	5.556	1.205–19.621
LDI (%)	< 0.001*	1.136	1.109–1.164

PJF, proximal junctional failure; CI, confidence interval; SVA, sagittal vertical axis; TP, transverse process; UIV, uppermost instrumented vertebra; LDI, lumbar distribution index.
*$p < 0.05$, statistically significant differences.

3. Multivariate Analysis for PJF Risk Factors

Multivariate logistic regression analysis revealed that old age (odds ratio [OR], 1.063; 95% confidence interval [CI], 1.001–1.129; p = 0.046), high preoperative C7–SVA (OR, 1.007; 95% CI, 1.001–1.013; p = 0.024), nonuse of TP hook at the UIV+1 (OR, 5.556; 95% CI, 1.205–19.621; p = 0.028), and high LDI (OR, 1.136; 95% CI, 1.109–1.164; p < 0.001) were significant risk factors for PJF development (Table 4).

4. Cutoff Values of LDI According to Roussouly Types

There were 10 patients with Roussouly type 1, 26 with Roussouly type 2, 110 with Roussouly type 3, and 50 with Roussouly type 4. The cutoff values of LDI were calculated on the ROC curve analysis according to each Roussouly type (Fig. 1). For Roussouly type 1, the cutoff value of LDI could not be calculated because this analysis did not reach statistical significance due to small number of patients. The cutoff values of LDI were calculated as 70.9%, 66.6%, and 61.8% in Roussouly types 2, 3, and 4, respectively (AUC = 0.781; 95% CI, 0.632–0.931; p = 0.011 for Roussouly type 2; AUC = 0.746; 95% CI, 0.628–0.865; p < 0.001 for Roussouly type 3; AUC = 0.776; 95% CI, 0.642–0.909; p = 0.007 for Roussouly type 4).

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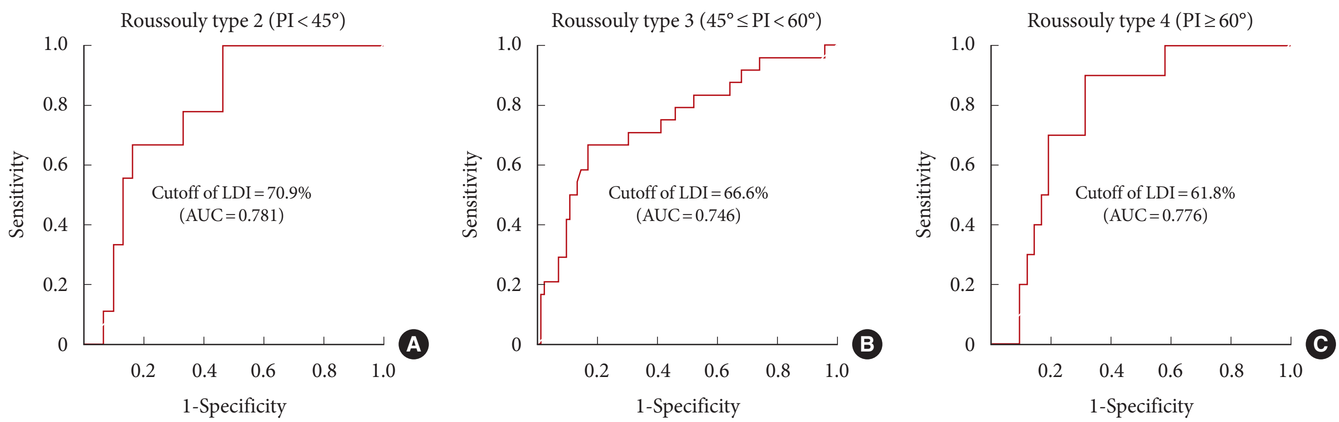

Fig. 1. Receiver operating characteristic curve analysis to calculate the cutoff values of LDI according to Roussouly types. The cutoff values of LDI were calculated as 70.9%, 66.6%, and 61.8% in Roussouly types 2, 3, and 4, respectively (AUC = 0.781; 95% CI, 0.632–0.931; p = 0.011 for Roussouly type 2; AUC = 0.746; 95% CI, 0.628–0.865; p < 0.001 for Roussouly type 3; AUC = 0.776; 95% CI, 0.642–0.909; p = 0.007 for Roussoyly type 4). LDI, lumbar distribution index; AUC, area under the curve; CI, confidence interval; PI, pelvic incidence.

Table 5. PJF rates according to use of hook and LDI values in 3 preoperative Roussouly types

Risk factors	PJF rates (number of patients)	p-value
Preoperative Roussouly type 2 (n = 26)		0.436
TP hook fixation+LDI < 70.9%	0% (0/2)	
TP hook fixation+LDI ≥ 70.9%	0% (0/1)	
Nonuse of TP hook+LDI < 70.9%	21.4% (3/14)	
Nonuse of TP hook+LDI ≥ 70.9%	44.4% (4/9)	
Preoperative Roussouly type 3 (n = 110)		0.003*
TP hook fixation+LDI < 66.6%	0% (0/4)	
TP hook fixation+LDI ≥ 66.6%	14.3% (1/7)	
Nonuse of TP hook+LDI < 66.6%	12.9% (8/62)	
Nonuse of TP hook+LDI ≥ 66.6%	43.2% (16/37)	
Preoperative Roussouly type 4 (n = 50)		< 0.001*
TP hook fixation+LDI < 61.8%	0% (0/6)	
TP hook fixation+LDI ≥ 61.8%	8.0% (2/25)	
Nonuse of TP hook+LDI < 61.8%	25.0% (1/4)	
Nonuse of TP hook+LDI ≥ 61.8%	40.0% (6/15)	

LDI, lumbar distribution index; PJF, proximal junctional failure; TP, transverse process.
*p < 0.05, statistically significant differences.

5. Stratified PJF Rates According to the Risk Factors

Since only TP hook fixation and LDI were surgically modifiable factors among the 4 risk factors, the PJF rates were calculated according to the presence or absence of these 2 risk factors in each Roussouly type (Table 5). In Roussouly type 2, the PJF rates showed a tendency to increase as with more risk factors albeit statistical significance (probably due to small number of patients) (Fig. 2). Roussouly types 3 and 4 showed significantly higher PJF rates as with more risk factors.

DISCUSSION

Although adequate correction of sagittal alignment significantly decreased the risk of PJF after ASD surgery, it cannot completely prevent the occurrence of PJF likely due to its multifactorial causes.[1,26-28] In this study, a considerable number of patients (21.9%) developed PJF despite achieving ideal sagittal correction. The incidence of PJF in the present study was comparable to those in previous studies, which have reported PJF incidence of 11.5%–23.7% in patients with ideal correction according to the age-adjusted PI–LL target.[5,12,16,19] Since the pertinent PI–LL correction (e.g., age-adjusted PI–LL correction) in long fusion surgery for ASD is most commonly prioritized, factors other than the optimal PI–LL correction need to be identified to further mitigate the risk of PJF. In the current study, old age, high preoperative C7–SVA, nonuse of a TP hook, and high LDI were risk factors for PJF development in patients who achieved ideal correction according to the age-adjusted PI–LL.

Old age is well-documented risk factor for the occurrence of PJF in the literature.[4,29-31] The fact that age was significant risk factor even though it was already embedded in the target PI–LL goal, which is ([age–55]/2+3), suggests this scheme may not be perfect one. In addition, other age-related factors, such as sarcopenia and reduced recruiting capacity of compensatory mechanisms, may be also responsible for PJF development, rather

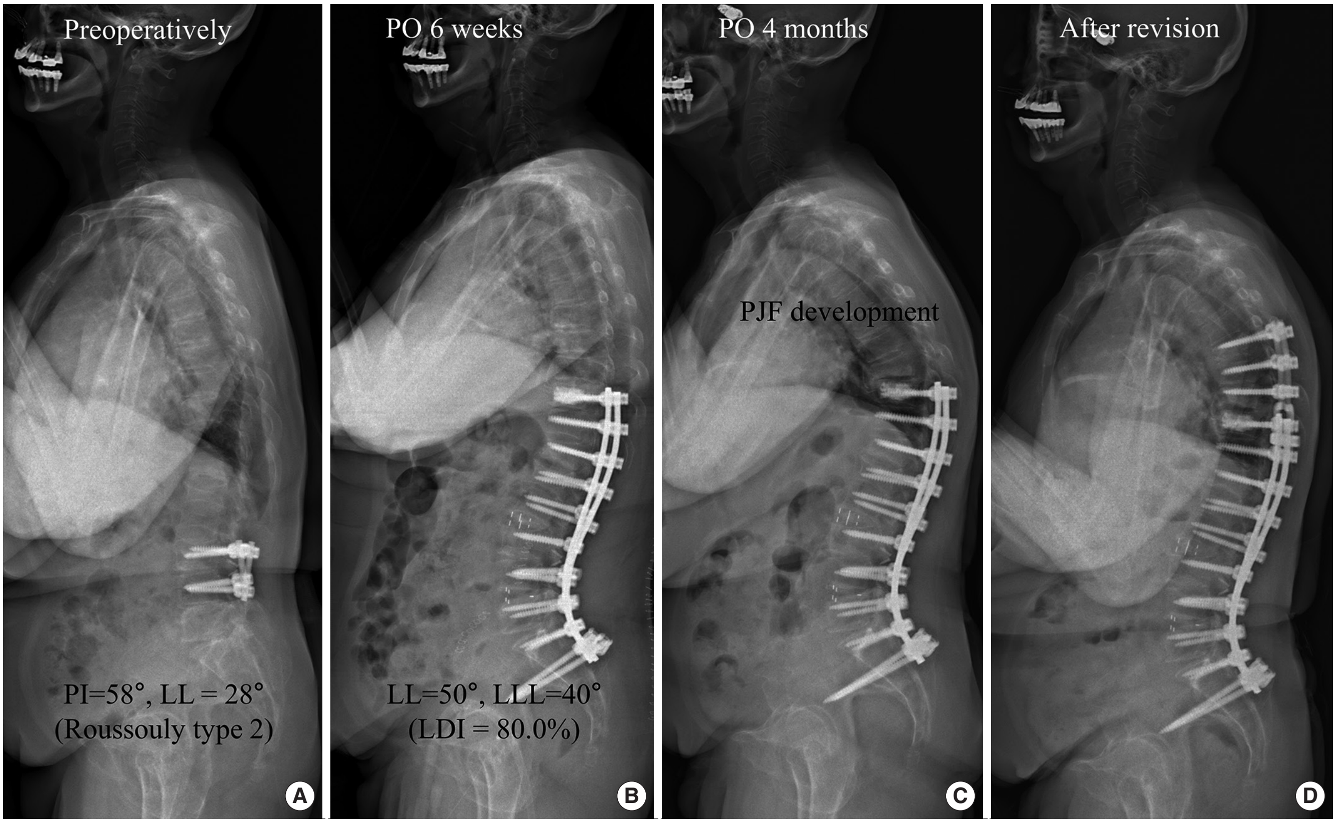

Fig. 2. An example of a 75-year-old female patient with a flatback deformity. (A) Preoperatively, her PI and LL was 58° and 28°, respectively. Her lumbar curve shape was belonged to the Roussouly type 2. (B) She underwent corrective surgery from T10 to pelvis. Postoperatively, her LL was restored to 51° showing matched correction relative to the age-adjusted PI–LL target. Given that LLL was 40°, her LDI was calculated as 80.0%. (C) Four months after surgery, she developed PJF with a vertebral facture at the UIV+1 level. (D) Revision surgery was performed due to progressive neurologic deficit. PI, pelvic incidence; LL, lumbar lordosis; LLL, lower lumbar lordosis; LDI, lumbar distribution index; PJF, proximal junctional failure; UIV, uppermost instrumented vertebra; PO, postoperative.

than age itself as proposed in the previous studies.[32-34] High preoperative C7–SVA has been also a well-recognized risk factor for PJF.[4,35] Patients with higher preoperative C7–SVA necessarily require greater amount of correction to reach the matched PI–LL correction goal compared to those with lower preoperative C7–SVA. This great amount of correction would in turn impose the reciprocal stress at the proximal junction, provoking PJF development. Additionally, increased preoperative C7–SVA may reflect the weak compensatory function, which is also associated with old age and weak musculature in the thoracolumbar area. Although old age and increased preoperative C7–SVA were significant risk factors in the multivariate analysis, their odds ratios was not that high. In addition, it may be difficult to apply these risk factors to the real clinical practice because those are nonmodifiable factors.

Nonuse of TP hook at the UIV+1 was the strongest risk factor for PJF development (OR, 5.556). Theoretically, the use of a TP hook at the top of construct is superior to pedicle screw-only fixation in decreasing the risk of PJK by minimizing the abrupt change in stiffness from fixed vertebrae to nonfused segments (that is, soft landing). Several biomechanical studies have demonstrated that the TP hook reduces stress at the proximal junction by allowing gradual decrease of segmental motion than the pedicle screw-only construct.[36-38] However, the effect of TP hook to prevent PJF development has been debated in previous studies. Hassanzadeh et al.[39] have shown that TP hooks were associated with reduced PJK incidence and better functional scores compared to the pedicle screws. Conversely, Tsutsui et al.[40] have found that PJK incidence was significantly higher in the TP hook group (35.7%) compared to the pedicle screw group (8.0%) in spinopelvic fusion surgery for ASD. Meanwhile, Matsumura et al.[41] have observed no significant difference in the PJF incidence between the TP hook and pedicle screw fixation. These inconsistent clinical results concerning the effect of hook fixation may

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be attributable to the differences in postoperative correction status among the studies. Since PJF occurrence is primarily affected by the correction status (e.g., overcorrection),[5,12,14,16,18] the effectiveness of any preventive techniques should be evaluated under conditions of ideal sagittal correction. A study by Line et al.[19] involving 625 ASD patients found that using preventive surgical implants (e.g., TP hooks) alone is less effective in preventing PJF; however, preventive techniques were effective when the ideal sagittal correction is obtained. These findings are in agreement with our results, which show that TP hook fixation is effective in preventing PJF in patients who had achieved adequate sagittal correction. Therefore, we recommend the use of a TP hook at the most proximal segment as a soft-landing procedure to reduce junctional stress, along with adequate sagittal correction.

Finally, a high LDI was a significant risk factor for PJF. The LDI represents the proportion of the lower LL within the entire LL, indicating the shape of the LL. Although the age-adjusted PI–LL scheme has provided us with the target LL, this metric has a missing point with the absence of a lordosis shape. Even in patients achieving the same amount of lordosis angle, the lordosis shape may differ among patients with different LDI values. Thus, adding the LDI component to the optimal PI–LL correction could compensate for the missing point of lordosis-targeting schemes, further decreasing the PJF risk. In the present study, LDI was significantly higher in the PJF group compared to the non-PJF group (72.0% vs. 58.8%, $p < 0.001$). Since the optimal values of LDI were suggested as 50%–80% (aligned state) in the original GAP score system,[15] the mean values of LDI in both non-PJF and PJF groups in this study fell within the optimal range relative to the LDI classification of GAP scoring system. However, the normal range of LDI in the original GAP score has been criticized due to its inaccuracy to predict PJF development. Tobert et al.[42] observed no significant differences in the failure rates among hypolordotic, aligned, or hyperlordotic LDI categories, suggesting this categorization of LDI cannot explain the PJF occurrence well. Several authors reported that excessive LDI is associated with PJF development. Park et al.[14,43] suggested that a higher LDI would result in a longer lever arm from the apex of the LL to the UIV, potentially shifting the UIV more posteriorly, thereby increasing PJF risk. To determine the upper limit of LDI value not to provoke the PJF, the cutoff values of LDI was calculated on ROC curve analysis. Considering the normal LDI values vary according to Roussouly types (or PI values), the cutoff values of LDI were calculated separately in the Roussouly types. The calculated cutoff values of LDI were 70.9%, 66.6%, and 61.8% in Roussouly types 2, 3, and 4, respectively, of which values seem to be reasonable, given that the normal LDI values were reported as 66.6%, 63.6%, and 60.6% in Roussouly types 2, 3, and 4, respectively in a recent a multiethnic alignment normative study.[44] Although the lower limit of the optimal LDI was not established in the current study, we thought that a significantly decreased LDI (e.g., greater LL correction in the upper lumbar region) could lead to a significant increase in reciprocal kyphogenic force at the proximal junction, resulting in PJF.[45,46] Further study is needed to establish the optimal range of LDI.

The presence of these 2 modifiable risk factors (nonuse of a TP hook and excessive LDI) differentiated the actual PJF rates (Table 5). Although no statistical difference in PJF rates according to the risk factors was observed in Roussouly type 2 ($p = 0.436$), the PJF rates clearly increased proportionally as with more risk factors. This nonsignificant statistical power may be due to small number of patients. Considering the above 4 risk factors comprehensively, we recommended the use of a TP hook at UIV with avoiding excessive LDI, particularly in elderly patients with high preoperative C7–SVA.

This study has a few limitations. First, this was a retrospective study involving patients from a single institution, although they were selected consecutively from a prospectively collected database. Second, only patients with UIV located in the lower thoracic spine (T9–11) were included, limiting generalizability to patients undergoing fusion to upper thoracic spine. Nevertheless, our inclusion criteria regarding UIV placement may be advantageous in minimizing fusion length-related bias, given the distinct biomechanical characteristics between the lower and upper thoracic levels. Third, although we demonstrated that TP hook is a strong preventive factor against PJF development, TP hook was utilized in only 25 of 196 patients (12.8%). This small number of patients with TP hook could lead to bias in our results. Finally, we could not calculate the LDI cutoff value for Roussouly type 1 owing to a small number of patients ($n = 10$). It is reported that the patients with Roussouly type 1 take up a very small portion among all patients undergoing deformity surgeries.[24] Therefore, further research using a larger study cohort is warranted to determine the optimal LDI in patients with Roussouly type 1. The normal LDI of Roussouly type 1 is reported as approximately 80%.[47] However, when operating on a patient with Roussouly type 1, it is necessary to reconsider whether it should be restored to the same Roussouly type 1 postoperatively. Although several studies recommend that the postoperative sagittal alignment better follow the original preoperative Roussouly types,[25,34] it may be technically very difficult to make the lower LL approximately 80% of total lordosis because it is not always possible to create a large angle at the lower lumbar segment. Additionally, a recent study reported that the conversion from preoperative Roussouly type 1 to postoperative Roussouly type 2 can be allowed since its conversion did not affect the surgical outcomes compared with restoration to the original Roussouly type 1.[48] This means that it may not be necessary to maintain a "normal" large LDI of Roussouly type 1, but the LDI corresponding to Roussouly type 2 can be allowed for treating patients with Roussouly type 1.

CONCLUSION

A sizeable proportion of patients (21.9%) developed PJF despite achieving ideal sagittal correction according to the age-adjusted PI–LL target. The risk factors for the PJF were old age, high preoperative C7–SVA, nonuse of TP hook, and high LDI. Therefore, use of TP hooks at the UIV+1 with avoiding excessive LDI is recommended to further mitigate PJF development, even if patients achieved adequate PI–LL correction.

NOTES

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