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Se-Jun Park, Jin-Sung Park, Dong-Ho Kang, Chong-Suh Lee and Hyun-Jun Kim

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Risk Factors for Recurrent Proximal Junctional Failure Following Adult Spinal Deformity Surgery: Analysis of 60 Patients Undergoing Fusion Extension Surgery for Proximal Junctional Failure

SE-JUN PARK, MD, PhD[1]; JIN-SUNG PARK, MD, PhD[1]; DONG-HO KANG, MD[1]; CHONG-SUH LEE, MD, PhD[2]; AND HYUN-JUN KIM, MD[3]

[1]*Department of Orthopedic Surgery, Sungkyunkwan University School of Medicine, Seoul, South Korea;* [2]*Department of Orthopedic Surgery, Haeundae Bumin Hospital, Busan, South Korea;* [3]*Department of Orthopedic Surgery, Hanyang University Guri Hospital, Hanyang University School of Medicine, Guri-si, Gyeonggi Province, South Korea*

ABSTRACT

Background: Despite numerous studies identifying risk factors for proximal junctional failure (PJF), risk factors for recurrent PJF (R-PJF) are still not well established. Therefore, we aimed to identify the risk factors for R-PJF following adult spinal deformity (ASD) surgery.

Methods: Among 479 patients who underwent ≥5-level fusion surgery for ASD, the focus was on those who experienced R-PJF at any time or did not experience R-PJF during a follow-up duration of ≥1 year. PJF was defined as a proximal junctional angle (PJA) ≥28° plus a difference in PJA ≥22° or performance of revision surgery regardless of PJA degree. The patients were divided into 2 groups according to R-PJF development: no R-PJF and R-PJF groups. Risk factors were evaluated focusing on patient, surgical, and radiographic factors at the index surgery as well as at the revision surgery.

Results: Of the 60 patients in the final study cohort, 24 (40%) experienced R-PJF. Significant risk factors included greater postoperative sagittal vertical axis (OR = 1.044), overcorrection relative to age-adjusted pelvic incidence–lumbar lordosis (PI–LL; OR = 7.794) at the index surgery, a greater total sum of the proximal junctional kyphosis severity scale (OR = 1.145), and no use of the upper instrumented vertebra cement (OR = 5.494) at the revision surgery.

Conclusions: We revealed that the greater postoperative sagittal vertical axis and overcorrection relative to age-adjusted pelvic incidence–lumbar lordosis at the index surgery, a greater proximal junctional kyphosis severity scale score, and no use of upper instrumented vertebra cement at the revision surgery were significant risk factors for R-PJF.

Clinical Relevance: To reduce the risk of R-PJF after ASD surgery, avoiding under- and overcorrection during the initial surgery is recommended. Additionally, close assessment of the severity of PJF with timely intervention is crucial, and cement augmentation should be considered during revision surgery.

Level of Evidence: 3.

Other and Special Categories

Keywords: Recurrent proximal junctional failure, Risk factors, Cement augmentation, Proximal junctional kyphosis severity scale, Overcorrection, Undercorrection

INTRODUCTION

Proximal junctional failure (PJF) following adult spinal deformity (ASD) surgery is widely recognized as a significant complication, often a more severe form of proximal junctional kyphosis (PJK).[1,2] PJF frequently results in severe pain, neurological deficits, and progressive deformity, ultimately requiring fusion extension surgery in 10% to 20% of patients.[3–5] Revision surgery for PJF generally involves extending the fusion proximally to correct the kyphotic segment and stabilize the spine. However, a few patients experience recurrent PJF (R-PJF) after revision surgery, which may necessitate re-revision surgery.[6]

Numerous studies have reported various risk factors for primary PJF including older age, low bone quality, greater preoperative sagittal imbalance, excessive surgical correction of sagittal imbalance, fusion to the sacrum, and ending fusion at the thoracolumbar junction.[1,2,6–8] However, the risk factors for R-PJF have been poorly documented. Recently, 2 studies on R-PJF have reported greater preoperative sagittal imbalance and greater correction of the sagittal vertical axis (SVA) as significant risk factors for R-PJF development.[9,10] However, more complex mechanisms, other than preoperative SVA and its changes, may be involved in the development of R-PJF. We assumed that the initial correction status after the index surgery and the severity of PJF at the time of revision surgery may affect the risk of R-PJF.

Despite extensive studies on the development of PJF, R-PJF and subsequent re-revision surgery cannot be completely avoided after ASD surgery. When revision surgery is performed due to PJF development, it is even more important not to develop R-PJF because performing re-revision surgery would impose a significant physical and emotional burden on both surgeons and patients. Therefore, identifying the risk factors for R-PJF is necessary to optimize surgical outcomes after revision surgery and avoid subsequent surgeries. Thus, we sought to identify the risk factors for R-PJF in patients receiving fusion extension surgery for PJF after ASD surgery.

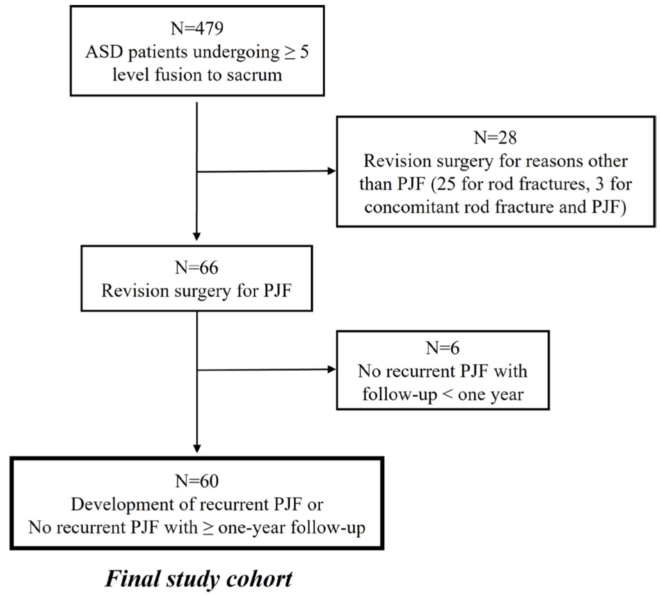

Figure 1. Flowchart of the patient selection process.

MATERIALS AND METHODS

This study was approved by the institutional review board of our institution. The requirement for informed consent was waived owing to the retrospective nature of this study.

Study Design

This was a retrospective case series, and all patient records were retrieved from a prospective ASD database at our hospital. The study cohort comprised consecutive patients who underwent surgery for degenerative ASD between 2012 and 2022. The inclusion criteria at the time of index surgery were as follows: age ≥60 years; ASD radiographically defined by an SVA of ≥50 mm, pelvic incidence–lumbar lordosis (PI–LL) mismatch of ≥10°, pelvic tilt (PT) of ≥25°, or coronal Cobb angle of ≥30°; and ≥5 fused vertebral levels, all including the sacrum. Pelvic fixation is routinely performed using conventional iliac screws, except in patients involving L5 to S1 fusion due to prior surgery.

A total of 479 patients met the inclusion criteria. After excluding 28 patients who received revision surgery for reasons other than PJF (rod fracture in 25 patients and concomitant rod fracture and PJF in 3 patients), 66 patients received revision surgery for PJF development. Among them, those who experienced R-PJF at any time or had a follow-up duration of ≥1 year in patients without R-PJF were included in the final study cohort (Figure 1).

In this study, R-PJF was defined either radiographically by a proximal junctional angle (PJA) of ≥28° and a difference in PJA of ≥22° according to the recent definition by Lovecchio et al[11] or clinically by the performance of revision surgery for junctional complications regardless of PJA degree. The patients were divided into 2 groups according to the development of R-PJF: no R-PJF and R-PJF. Potential risk factors were compared between the 2 groups.

Presumed Risk Factors of R-PJF

The primary focus of this study was to identify the risk factors for R-PJF. Therefore, we examined these variables before and after revision surgery. Additionally, factors potentially affecting R-PJF development during the index surgery were evaluated. The variables considered in this study encompass patient, surgical, and radiographic factors. The risk factor analyses are presented chronologically.

At the time of after-index surgery, total fusion levels, pelvic fixation, and postoperative radiographic parameters of the PI, LL, PI–LL, sacral slope (SS), PT, thoracic kyphosis (TK), T1 pelvic angle (TPA), SVA, and the gravity line to the hip axis (GL-HA) were analyzed. In this study, the GL-HA, previously introduced by Hyun et al,[12] is defined as the distance between the vertical line drawn from the center of the acoustic meatus to the ground and the center of both femoral heads on sagittal radiographs. When the hip center is anterior to the GL, it is assigned a negative value and vice versa. In addition, global sagittal alignment after the index surgery was evaluated using the previously established metrics of age-adjusted PI–LL, Global Alignment and Proportion score, and SRS-Schwab PI–LL modifier.

The age-adjusted PI–LL target was calculated using the previously reported formula: PI–LL= (age – 55)/2 + 3.[13,14] Undercorrection relative to age-adjusted PI–LL was defined as exceeding the suggested target range (eg, >10 years); matched correction relative to the age-adjusted PI–LL target indicates current values within a ±10-year range from the calculated ideal target; and overcorrection was defined as PI–LL being less than the suggested target range (eg, <10 years).[15]

At the revision surgery, the patient, surgical, and radiographic factors were evaluated separately. Patient factors included age, sex, bone mineral density (measured by femoral densitometry), presence of osteoporosis, history of osteoporosis treatment, body mass index, American Society of Anesthesiologists (ASA) grade, smoking history, and comorbidities of hypertension and diabetes mellitus. Surgical factors included the time gap between the index and revision surgeries, mode of PJF (ligamentous, bony, or implant/bone interface failure), performance of laminectomy, number of levels extended, final upper instrumented vertebra (UIV) level (T1 – T4, T5 – T8, or T9 – T10), Hounsfield units at the UIV and UIV + 1,[16] uppermost screw angle at the UIV level, use of a hook at the UIV + 1 level, and use of UIV cement.

Radiographic parameters, such as PI–LL, LL, SS, PT, TK, TPA, SVA, GL-HA, and PJA, were measured before and after the revision surgery. The PJA was measured from the caudal endplate of the UIV to the cranial endplate of the 2 supra-adjacent vertebrae. Differences in radiographic parameters before and after the revision surgery were included in the analysis. Finally, the severity of PJF was assessed at the revision surgery using the proximal junctional kyphosis severity scale (PJKSS) introduced by the Hart–International Spine Study Group.[17,18] This scoring system comprises 6 categorical components as follows: neurological deficit, focal pain, instrumentation problem, change in kyphosis/posterior ligamentous complex, UIV/UIV + 1 fracture, and UIV level. Each component was further categorized, and a specific point value was assigned to each category, with a maximum PJKSS total score of 15.

Statistical Analysis

Data are presented as frequencies with percentages for categorical variables and as means with SDs for continuous variables. Univariate analyses comparing variables between the 2 groups were performed using the χ^2 test or Fisher's exact test for categorical variables and the independent *t* test or Wilcoxon rank-sum test for continuous variables. Multivariate stepwise regression analyses were performed using all significant variables ($P < 0.05$) in the univariate analysis to identify the risk factors for R-PJF. Statistical analyses were performed by professional statisticians using SPSS (version 27.0.0; IBM Corp., Armonk, NY, USA). The significance was set at $P < 0.05$.

RESULTS

A total of 60 patients were included in the final study cohort (Figure 1). There were 51 women and 9 men with a mean age of 70.8 years at the time of the index surgery. The mean fusion length at the index surgery was 7.3 levels. Of the 60 patients, 24 (40.0%) developed R-PJF (R-PJF group), whereas 36 (60.0%) did not (no R-PJF group). Among the 24 patients in the R-PJF group, 20 patients underwent re-revision surgery at the time of data review. The reasons for the re-revision surgery included UIV/UIV + 1 fractures in 11 patients, myelopathy without fractures in 7, rod fractures in 1, and screw pull-out in 1.

When comparing operative variables after the index surgery, no significant differences in total fusion levels or pelvic fixation were observed between R-PJF and no R-PJF groups. Regarding radiographic parameters, significant differences in SVA (19.0 vs 39.0 mm, P = 0.005) and GL-HA (–10.9 vs –29.1 mm, P = 0.031) were noted between the 2 groups (Table 1). However, there were no significant differences in other radiographic parameters including PI, LL, PI–LL, SS, PT, TK, and TPA. Regarding global alignment assessment metrics, only the correction relative to the age-adjusted PI–LL was significantly different between the 2 groups. The no R-PJF group included more patients with matched correction than the R-PJF group (61.1% vs 25.0%), whereas the R-PJF group had more patients with overcorrection than the no R-PJF group (41.7% vs 16.7%; P = 0.018).

At the time of revision surgery, patient factors such as age, sex, *T*-score, osteoporosis, history of osteoporosis treatment, body mass index, ASA grade, smoking status, and comorbidities were not significantly different between the 2 groups (Table 2). Regarding surgical factors, the uppermost screw angle was significantly greater (cranially directed) in the R-PJF group than in the no R-PJF group (1.0° vs –0.5°, P = 0.037). In addition, cement augmentation at the UIV was more frequently performed in the no R-PJF group than in the R-PJF group (33.3% vs 8.3%, P = 0.031; Table 2).

Regarding radiographic variables at the revision surgery, the conventional radiographic parameters of LL, PI–LL, SS, PT, TK, TPA, SVA, and GL-HA

Table 1. Comparison of variables at the index surgery.

Variables	No R-PJF (*N* = 36)	R-PJF (*N* = 24)	*P*
Total fusion levels	7.5 ± 1.8	7.0 ± 1.3	0.320
Pelvic fixation	20 (55.6%)	13 (54.2%)	1.000
Pelvic incidence (°)	52.4 ± 6.2	49.8 ± 6.9	0.070
Lumbar lordosis (°)	43.2 ± 13.8	40.9 ± 15.8	0.276
PI–LL (°)	9.1 ± 13.2	8.9 ± 14.6	0.473
Sacral slope (°)	31.8 ± 8.7	28.6 ± 8.9	0.087
Pelvic tilt (°)	19.4 ± 6.6	19.5 ± 8.0	0.491
Thoracic kyphosis (°)	25.2 ± 10.7	22.1 ± 9.5	0.124
T1 pelvic angle (°)	17.0 ± 7.7	17.0 ± 9.4	0.491
Sagittal vertical axis (mm)	19.0 ± 30.1	39.0 ± 26.5	**0.005**
Gravity line to hip axis (mm)	–10.9 ± 32.9	–29.1 ± 38.4	**0.031**
Age-adjusted PI–LL			**0.018**
Undercorrection	8 (22.2%)	8 (33.8%)	
Matched correction	22 (61.1%)	6 (25.0%)	
Overcorrection	6 (16.7%)	10 (41.7%)	
Global alignment and proportion score			0.180
Proportioned	10 (27.8%)	2 (8.3%)	
Moderately disproportioned	10 (27.8%)	9 (37.5%)	
Severely disproportioned	16 (44.4%)	13 (54.2%)	
Scoliosis research society-Schwab PI–LL modifier			0.510
PI–LL < 10°	24 (66.7%)	13 (54.2%)	
PI–LL 10°–20°	5 (13.9%)	6 (25.0%)	
PI–LL > 20°	7 (19.4%)	5 (20.8%)	

Abbreviations: PI–LL, pelvic incidence–lumbar lordosis; R-PJF, recurrent proximal junctional failure.
Note: Data presented as mean ± SD or *n* (%). Bold *P* values indicate statistical significance.

were not significantly different between the 2 groups (Table 3). Regarding the PJKSS system(Table 4) a significant difference was observed only in the UIV/UIV + 1 fracture component; compression fractures were more frequent in the R-PJF group than in the no R-PJF group, whereas burst/chance fractures were more common in the no R-PJF group than in the R-PJF group (*P* = 0.026). In addition, the total PJKSS scores were significantly higher in the R-PJF group than in the no R-PJF group (9.1 points vs 8.1 points, *P* = 0.023). After revision surgery, postoperative SS was the only significant variable, with a greater value observed in the no R-PJF group compared with the R-PJF group (30.4° vs 25.8°, *P* = 0.025; Table 5). Post-pre changes did not show significance for all radiographic parameters.

Multivariate analysis demonstrated that greater SVA (OR = 1.044, 95% CI = 1.015–1.074, *P* = 0.003) and overcorrection relative to the age-adjusted PI–LL at the index surgery (OR = 7.794, 95% CI = 1.214–50.024, *P* = 0.030), the greater total sum of PJKSS scores before the revision surgery (OR = 1.415, 95% CI = 1.007–1.989, *P* = 0.045), and no use of UIV cement at revision surgery (OR = 5.494, 95% CI = 1.105–27.027, *P* = 0.037) were significant risk factors for the development of R-PJF (Table 6).

Table 2. Comparison of patient and surgical factors at the time of revision surgery.

Variables	No R-PJF (*N* = 36)	R-PJF (*N* = 24)	*Paa*
Patient factors at the revision surgery			
Age, y	73.6 ± 6.9	70.5 ± 6.0	0.076
Women	31 (86.1%)	20 (83.3%)	0.768
Femoral neck BMD (*T*-score)	–1.4 ± 1.3	–1.5 ± 1.3	0.704
Osteoporosis	7 (19.4%)	6 (25.0%)	0.609
Osteoporosis treatment[a]			0.906
None	20 (55.6%)	15 (62.5%)	
Anabolic agents	11 (30.6%)	7 (29.1%)	
Antiresorptive agents	5 (13.8%)	2 (8.4%)	
Body mass index	27.1 ± 3.8	26.3 ± 2.8	0.392
ASA grade	2.2 ± 0.4	2.3 ± 0.4	0.807
Smoking	5 (13.8%)	2 (8.3%)	0.330
Hypertension	23 (63.9%)	18 (75.0%)	0.410
Diabetes mellitus	13 (54.2%)	11 (45.8%)	0.592
Surgical factors at the revision surgery			
Time from index op to revision surgery (mo)	22.7 ± 17.2	32.7 ± 22.3	0.226
Failure modes causing revision surgery			0.166
Disc and ligamentous failure	11 (30.6%)	5 (20.8%)	
Bony failure	19 (52.8%)	18 (75.0%)	
Implant/bone interface failure	6 (16.7%)	1 (4.2%)	
Performance of laminectomy	22 (61.1%)	9 (37.5%)	0.687
No. of fusion levels extended	4.0 ± 2.5	4.2 ± 2.7	0.840
Final UIV level			0.743
T1–T4	5 (13.9%)	3 (12.5%)	
T5–T8	12 (33.3%)	6 (25.0%)	
T9–T10	19 (52.8%)	15 (62.5%)	
Hounsfield unit of UIV	172.1 ± 57.1	160.5 ± 44.8	0.202
Hounsfield unit of UIV + 1	186.6 ± 55.2	167.0 ± 41.8	0.072
Uppermost screw angle (°)[b]	–0.5 ± 3.2	1.0 ± 2.6	**0.037**
Hook fixation at UIV + 1 level	11 (30.6%)	5 (20.8%)	0.404
UIV cement	12 (33.3%)	2 (8.3%)	**0.031**

Abbreviations: ASA, American Society of Anesthesiologists; BMD, bone mineral density; R-PJF, recurrent proximal junctional failure; UIV, uppermost instrumented vertebra.
Note: Data are presented as mean ± SD or *n* (%). Bold *P* values indicate statistical significance.
[a]Anabolic agents include teriparatide, and antiresorptive agents include denosumab or bisphosphonate.
[b]Positive value represents the cranial inclination of the pedicle screw relative to the upper endplate.

Representative Case

A 75-year-old woman presented with R-PJF. Preoperatively, the PI, LL, and PI–LL were 61°, 37°, and 24°, respectively. After corrective surgery, LL improved to 66° with a PI–LL of –5°. This PI–LL was overcorrected relative to her age-adjusted PI–LL target. PJF occurred 1 month postoperatively, with a PJKSS score of 10 points. Although fusion extension surgery was

Table 3. Comparison of radiographic parameters at the revision surgery.

Radiographic Parameters	No R-PJF (*N* = 36)	R-PJF (*N* = 24)	*P*
Lumbar lordosis (°)	39.2 ± 16.3	37.3 ± 16.5	0.337
Pelvic incidence–lumbar lordosis (°)	12.9 ± 15.9	14.8 ± 14.9	0.328
Sacral slope (°)	24.8 ± 1.6	23.1 ± 2.0	0.256
Pelvic tilt (°)	28.1 ± 9.9	29.1 ± 10.2	0.356
Thoracic kyphosis (°)	30.6 ± 18.7	29.1 ± 15.9	0.376
T1 pelvic angle (°)	27.8 ± 10.4	27.6 ± 5.3	0.460
Sagittal vertical axis (mm)	63.8 ± 50.2	63.1 ± 48.9	0.477
Gravity line to hip axis (mm)	0.5 ± 64.9	8.1 ± 54.4	0.318
Proximal junctional angle (°)	30.7 ± 17.0	29.1 ± 14.3	0.356

Abbreviation: R-PJF, recurrent proximal junctional failure.

performed, R-PJF developed again. Finally, the fusion was extended to T4 (Figure 2).

DISCUSSION

Preventing R-PJF and PJF is an essential component for the success of ASD surgery. We found that a considerable number of patients (40.0%) suffered from R-PJF after revision surgery for PJF. In this study, 4 significant variables were identified as the risk factors for R-PJF: 2 of these are variables at the index surgery and the others at the revision surgery. As mentioned in the introduction, we also need to evaluate the situation at the index surgery in investigating R-PJF after revision surgery for PJF. Higher postoperative SVA and overcorrection relative to the age-adjusted PI–LL at the index surgery, higher total sum of PJKSS scores, and no use of UIV cement at the revision surgery were significant risk factors for R-PJF.

The postoperative SVA at the index surgery was significantly greater in the R-PJF group than in the no R-PJF group. Although the value of postoperative SVA (39.0 mm) is within the optimal range for SVA

Table 5. Comparison of radiographic parameters after revision surgery.

Radiographic Parameters	No R-PJF (*N* = 36)	R-PJF (*N* = 24)	*P*
After revision surgery			
LL (°)	39.2 ± 13.8	34.9 ± 14.2	0.244
Pelvic incidence–LL (°)	13.1 ± 14.1	14.9 ± 12.9	0.311
SS (°)	30.4 ± 9.3	25.8 ± 7.7	**0.025**
Pelvic tilt (°)	23.9 ± 12.9	28.0 ± 15.1	0.132
TK (°)	26.5 ± 13.3	23.7 ± 13.0	0.219
TPA (°)	20.6 ± 8.0	21.4 ± 6.1	0.342
SVA (mm)	41.4 ± 35.9	35.3 ± 46.6	0.284
GL-HA (mm)	–7.6 ± 37.6	–16.2 ± 55.4	0.239
PJA (°)	8.4 ± 5.2	9.0 ± 7.2	0.340
Post-pre changes			
Δ LL (°)	–0.4 ± 6.0	–2.4 ± 6.9	0.110
Δ SS (°)	–6.1 ± 11.8	–5.1 ± 7.7	0.351
Δ TK (°)	–4.1 ± 9.0	–5.4 ± 8.7	0.298
Δ TPA (°)	–7.2 ± 10.7	–6.2 ± 6.7	0.340
Δ SVA (mm)	–22.4 ± 52.9	–27.8 ± 51.2	0.349
Δ GL-HA (mm)	–8.1 ± 63.9	–24.3 ± 59.9	0.164
Δ PJA (°)	–22.3 ± 18.4	–20.1 ± 15.6	0.935

Abbreviations: GL-HA, gravity line to hip axis; LL, lumbar lordosis; PJA, proximal junctional angle; R-PJF, recurrent proximal junctional failure; SS, sacral slope; SVA, sagittal vertical axis; TK, thoracic kyphosis; TPA, T1 pelvic angle.
Note: Data presented as mean ± SD. Bold *P* values indicate statistical significance.

Table 4. Comparison of PJKSS scores at the revision surgery.

PJKSS components		No R-PJF (*N* = 36)	R-PJF (*N* = 24)	*P*
Neurological deficit				0.107
0 pt	None	5 (13.9%)	0 (0%)	
2 pt	Radicular pain	18 (50.0%)	11 (45.8%)	
4 pt	Myelopathy	13 (36.1%)	13 (54.2%)	
Focal pain				0.319
0 pt	None	5 (13.9%)	1 (4.2%)	
1 pt	VAS ≤4	1 (2.8%)	0 (0%)	
3 pt	VAS ≥5	30 (83.3%)	23 (95.8%)	
Instrumentation problem				0.115
0 pt	None	15 (41.7%)	6 (25.0%)	
1 pt	Partial fixation loss	16 (44.4%)	17 (70.8%)	
2 pt	Complete fixation loss	5 (13.9%)	1 (4.2%)	
Change in kyphosis/PLC integrity				0.731
0 pt	0°–10°	8 (22.2%)	5 (20.8%)	
1 pt	10°–20°	12 (33.3%)	6 (25.0%)	
2 pt	> 20° or PLC failure	16 (44.4%)	13 (54.2%)	
UIV/UIV +1 fracture				**0.026**
0 pt	None	12 (33.3%)	5 (20.8%)	
1 pt	Compression fracture	13 (36.1%)	17 (70.8%)	
2 pt	Burst/chance fracture	11 (30.6%)	2 (8.3%)	
3 pt	Translation	0 (0%)	0 (0%)	
Level of UIV				0.729
0 pt	Thoracolumbar junction	30 (83.3%)	21 (87.5%)	
1 pt	Upper thoracic	6 (16.7%)	3 (12.5%)	
Total sum of PJKSS		8.1 ± 2.0	9.1 ± 2.1	**0.023**

Abbreviations: PJKSS, proximal junctional kyphosis severity scale; PLC, posterior ligamentous complex; R-PJF, recurrent proximal junctional failure; UIV, uppermost instrumented vertebrae; VAS, visual analog scale.
Note: Data presented as *n* (%) or mean ± SD. Bold *P* values indicate statistical significance.

Table 6. Stepwise regression analysis of the risk factors for recurrent proximal junctional failure.

Variables	*P*	Exp (B)	95% CI
At the index surgery			
Postoperative sagittal vertical axis (mm)	**0.003**	1.044	1.015–1.074
Correction relative to age-adjusted pelvic incidence–lumbar lordosis	**0.027**		
Matched correction	–	Reference	
Undercorrection	0.088	3.633	0.717–18.408
Overcorrection	**0.030**	7.794	1.214–50.024
At the revision surgery			
Proximal junctional kyphosis severity scale score	**0.045**	1.415	1.007–1.989
No uppermost instrumented vertebra cement	**0.037**	5.494	1.105–27.027

Note: Bold *P* values indicate statistical significance.

correction, it may indicate a potential undercorrection during the index surgery. This assumption is consistent with the correction amount relative to age-adjusted PI–LL. Undercorrection was significantly more frequently observed in the R-PJF group than in the no R-PJF group (33.8% vs 22.2%, respectively). Thus, in addition to overcorrection, which will be discussed later, undercorrection is also a risk factor for R-PJF. The alignment in undercorrection, similarly in overcorrection, represents a state of "lack of harmony." The failure to achieve sufficient correction puts the patient's center of gravity anteriorly.[19] As reported by Elysee et al, undercorrection results in a relatively larger SVA, increasing the bending moment on the UIV.[20] We speculate that such high mechanical loading at the junction may be the leading cause of PJF and R-PJF. This hypothesis aligns with those of previous studies reporting the effect of residual deformity in the fused segment on the surgical outcome after revision surgery. Rothenfluh et al have reported that patients with a residual PL–LL mismatch of >10° exhibit a 10-fold higher risk for receiving revision surgery compared with controls in which sagittal alignment was maintained (PI–LL mismatch <10°) after lumbar fusion surgery.[21] Furthermore, Clohisy et al have suggested that any residual deformities should be addressed and corrected in planning for revision surgery for PJF to prevent R-PJF.[22] Thus, an undercorrection relative to the age-adjusted PI–LL during the

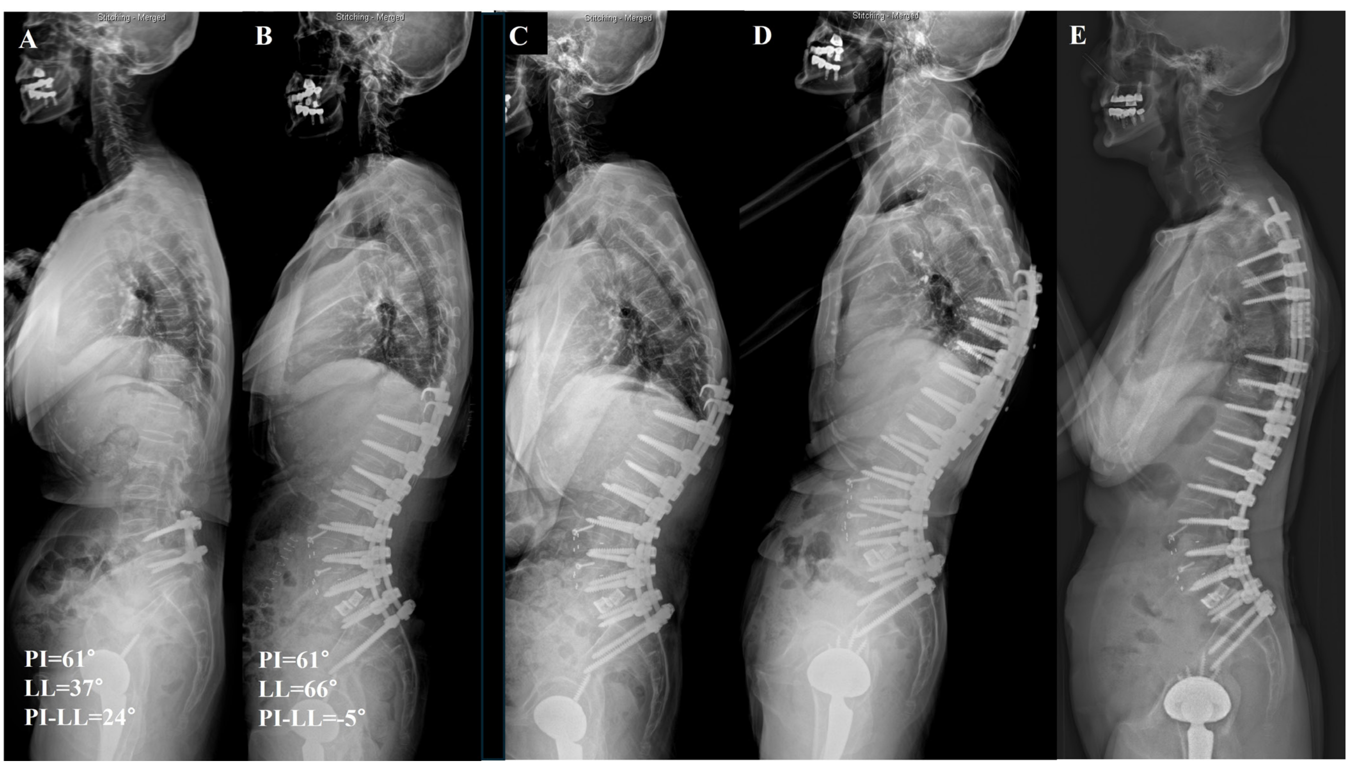

Figure 2. A case of a 75-year-old woman developing recurrent proximal junctional failure (R-PJF). (A) Preoperatively, her pelvic incidence (PI), lumbar lordosis (LL), and pelvic incidence–lumbar lordosis (PI–LL) were 61°, 37°, and 24°, respectively. (B) After corrective surgery, LL improved to 66° with a PI–LL of –5°. This PI–LL was overcorrected relative to her age-adjusted PI–LL target. (C) Proximal junctional failure occurred 1 month postoperatively with a proximal junctional kyphosis severity scale score of 10 points. (D) Although fusion extension surgery was performed, R-PJF occurred again. (E) Finally, the fusion was extended to T4.

index surgery may affect not only the occurrence of PJF but also the risk of the development of R-PJF.

On the other hand, since Lafage et al introduced the concept of age-adjusted alignment in 2016,[13] numerous studies have reported that overcorrection relative to the age-adjusted PI–LL is a risk factor for PJF.[23–25] This study revealed that overcorrection relative to the age-adjusted PI–LL is the strongest risk factor for R-PJF (OR = 7.794). Once the PI–LL is overcorrected, reciprocal kyphogenic forces are imposed at the proximal junction to maintain a neutral alignment, leading to the development of PJF.[26] Even after neutralizing this force through fusion extension surgery, the previously fused part of the spine that was overcorrected continues to function as a lever arm. This lever arm redirects kyphogenic forces to the unfused segments, potentially leading to R-PJF. However, unlike undercorrection, which can be corrected with procedures such as 3-column osteotomy or anterior column realignment to address residual deformities,[27] once overcorrection occurs during the index surgery, converting it to the matched correction status is hardly possible. Therefore, careful attention should be paid to avoid both overcorrection and undercorrection during index surgery, thus reducing the risk of R-PJF.

In the present study, a higher PJKSS score was a significant risk factor for R-PJF. The PJKSS system, representing the severity of PJK, was introduced by the Hart–International Spine Study Group and includes 6 categorical characteristics with a total score of 15.[17] The PJKSS has been validated in terms of strong correlations with health-related quality of life outcomes and the likelihood of revision surgery.[17] We identified an association between a higher PJKSS score (a more severe state of PJF) and R-PJF development. Considering its components, the PJKSS score increases over time after PJF by aggravating neurological deficit, focal pain, instrumentation problems, and kyphotic changes. Therefore, it is recommended to carry out revision surgery promptly upon the initial detection of PJF to avoid the progression to R-PJF since the PJKSS score usually increases over time after the development of PJF. The progression of kyphotic deformity after PJF development was documented in a recent study. Park et al have reported on the risk factors for fracture progression after the development of proximal junctional fractures. They have demonstrated that overcorrection relative to the age-adjusted PI–LL contributed to fracture progression during follow-up, again underscoring the importance of avoiding overcorrection during index surgery.[23]

Finally, the use of cement at the UIV level during revision surgery significantly reduced the risk of R-PJF. However, the effect of prophylactic vertebroplasty on preventing PJF after ASD surgery remains inconclusive.[28] Bartolozzi et al reported that no evidence supports the positive impact of cement vertebroplasty against PJF development.[29] Conversely, Goodarzi et al and Gassie et al demonstrated that the use of cement at the UIV level decreased the likelihood of PJF,[30,31] aligning with the result of our study. Surgeons often hesitate to use cement because of the high risk of cement extravasation, reported in 5.1% to 48.3% of cases.[32–35] However, Zygourakis et al reported that even when cement leakage occurred, most patients experienced no noticeable complications from the leakage.[32] Additionally, Bartolozzi et al mentioned the lack of evidence of complications or reoperations being associated with the use of cement.[29] A noteworthy point is that the use of cement is a modifiable risk factor under the control of the surgeon. Therefore, given the multifactorial etiology of R-PJF, if R-PJF can be reduced, the cautious application of cement at the UIV level during revision surgery could be considered part of a comprehensive effort.

This study has several limitations. First, the relatively small sample size limited the statistical power. However, considering that the total number of patients for initial screening was 479, the final cohort size may be sufficient for the analysis. Second, this study predominantly included patients with UIV in the lower thoracic spine, which may limit the generalizability of our findings to patients who underwent fusion to the upper thoracic spine. Finally, patients in the no R-PJF group may develop R-PJF in the future. Nevertheless, considering most R-PJFs (19/24, 79.2%) developed within 1 year after revision surgery in this study cohort, only a few patients may develop R-PJF later.

CONCLUSION

Greater postoperative SVA and overcorrection relative to the age-adjusted PI–LL at the index surgery, greater total sum of PJKSS score, and no use of UIV cement augmentation at the revision surgery were significant risk factors for R-PJF following ASD surgery. To mitigate the risk of R-PJF, it is recommended to avoid both under- and overcorrection during index surgery, closely monitor the severity of PJF, and consider the use of cement augmentation during revision surgery.

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Corresponding Author: Hyun-Jun Kim, Department of Orthopedic Surgery, Hanyang University Guri Hospital, Hanyang University School of Medicine, Gyeongchun-ro 153, Guri-si, Gyeonggi-do, 11923, South Korea; hyunjun89.kim@gmail.com