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Original Article

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Optimizing Surgical Strategies for Preventing Proximal Junctional Complications: A Systematic Review and Meta-analysis of Operative Techniques in Adult Spinal Deformity

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Objective: Proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) are common complications following long-segment spinal fusion, particularly in adult spinal deformity (ASD) correction surgery. Various surgical techniques have been proposed to prevent these complications, but high-quality evidence remains limited. This study aimed to evaluate the effectiveness of surgical strategies for preventing PJK and PJF after ASD correction or long-segment spinal fusion in adults.
Methods: A systematic search was conducted in PubMed, Embase, and the Cochrane Library through March 2025. Eligible studies included adults who underwent ASD surgery or long-segment (≥4 levels) posterior spinal fusion, comparing PJK or PJF incidence across surgical techniques such as tethering, hook fixation, prophylactic vertebral augmentation, rod characteristics, and upper instrumented vertebra (UIV) level. Odds ratios (ORs) with 95% confidence intervals (CIs) were calculated using a random-effects model.
Results: Thirty-eight retrospective studies were included in the systematic review and 33 in the meta-analysis. Spinous process tethering reduced PJK incidence (OR, 0.35; 95% CI, 0.22–0.56). Hook fixation (OR, 0.34; 95% CI, 0.21–0.55) and prophylactic vertebral augmentation (OR, 0.58; 95% CI, 0.35–0.95) reduced PJF incidence. Lower PJK rates were observed with UIV at T10 or above (OR, 0.15; 95% CI, 0.03–0.64) and lower PJF rates with UIV at L1 or above (OR, 0.29; 95% CI, 0.14–0.61).
Conclusion: Surgical strategies such as tethering, hook fixation, and prophylactic vertebral augmentation may reduce the risk of PJK/PJF. Additionally, placing the UIV at or slightly above T10 may enhance junctional stability. Further prospective studies are needed to validate these findings and guide preventive strategies.

Keywords: Proximal junctional kyphosis, Proximal junctional failure, Adult spine deformity, Surgical procedures

INTRODUCTION

Adult spinal deformity (ASD) refers to a spectrum of pathologies that primarily affect thoracolumbar spinal alignment as patients age.[1] ASD encompasses various conditions, including scoliosis, sagittal malalignment, kyphosis, spondylolisthesis, rotatory subluxation, and axial plane deformity, with degenerative scoliosis being the most prevalent form.[2] The prevalence of scoliosis increases with age, showing an almost linear rise from the fifth to eighth decade of life.[3] Notably, Schwab et al. reported an ASD prevalence of 68% in individuals older than 60 years.[4]

With the global trend of population aging, the prevalence of

ASD has increased and has become an area of growing interest.[5] Although nonoperative management is often the first-line approach, evidence supporting its effectiveness remains relatively limited.[6] Surgical correction of ASD typically requires long-segment fusion combined with complex procedures such as pedicle subtraction osteotomy or vertebral column resection.[1,2,5] Despite the complexity of these procedures, prior studies have shown that surgical treatment provides superior pain relief and functional improvement compared with nonoperative care.[6-9] In recent years, the frequency of surgical interventions has increased, accompanied by a rise in complex procedures and hospital admissions.[10,11]

Although surgical correction offers advantages over nonoperative management, it is associated with high complication and morbidity rates, particularly in older adults.[12] Among these complications, proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) are well-recognized, especially after long-segment spinal fusion. Glattes et al.[13] defined PJK as a proximal junctional angle of at least 10° or more from the preoperative measurement. Hostin et al.[14] defined PJF as a structural complication at or near the upper instrumented vertebra (UIV), including vertebral fracture, posterior ligamentous disruption, instrumentation failure, or the need for proximal extension of the fusion within 6 months postoperatively. However, numerous alternative definitions have been proposed by different authors.[15-17]

Despite variability in definitions, PJK and PJF are generally considered part of a spectrum of proximal junctional complications following ASD correction surgery.[18] PJK occurs in approximately 20%–40% of surgically treated patients,[13,19,20] while PJF occurs in 2%–18%.[14,20-22] PJF is often regarded as a severe, symptomatic form of PJK, commonly presenting with pain, neurological deficits, and reduced quality of life.[18,19,21-23] These complications also substantially increase the likelihood of revision surgery,[21,24] which can be particularly burdensome for older patients with multiple comorbidities.[12,25]

Given these risks, prevention of PJK and PJF is often more critical than treatment, especially in older or medically complex patients. Various surgical techniques, including hooks, tethers, and prophylactic vertebroplasty, have been introduced to reduce the incidence of proximal junctional complications.[26-28] However, these techniques remain in the early stages of clinical adoption, and robust evidence is lacking, as most available studies are retrospective. Additionally, there is substantial variability in surgical strategies, with no established consensus on optimal preventive methods.

In this meta-analysis, we focused on surgical techniques proposed to prevent PJK and PJF in ASD correction or long-segment fusion surgery. Specifically, we evaluated the effects of tethers, hooks, prophylactic vertebroplasty, rod characteristics, and UIV level to support more evidence-based surgical strategies in clinical practice.

MATERIALS AND METHODS

1. Search Strategy

This systematic review and meta-analysis was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) 2020 guidelines.[29] The study protocol was registered in PROSPERO (CRD420251107159). An electronic search was performed in PubMed, the Cochrane Library, and Embase to identify studies published through March 2025 that reported and compared the effectiveness of surgical techniques for preventing PJK and PJF, using the keywords "proximal junctional kyphosis," "proximal junctional failure," and "spine disease." The full search strategy is provided in the Supplementary Methods 1-3. Only eligible full-text articles published in nonpredatory journals and written in English were included, with no restrictions on study design.

2. Study Selection

Two reviewers independently screened studies using predefined inclusion and exclusion criteria. Studies were included if they involved adult patients (> 18 years) who underwent surgery for ASD or long-segment posterior surgery (≥ 4 levels) and compared the incidence of PJK or PJF based on preventive surgical techniques. Comparative studies of any design (randomized controlled trials, prospective, or retrospective) were eligible. Preventive techniques of interest included tethering, hook fixation, prophylactic vertebral augmentation, rod characteristics, and UIV level. Studies were excluded if they did not evaluate a preventive surgical strategy. Specifically, we excluded nonsurgical management studies (e.g., osteoporosis or sarcopenia treatment), radiographic-only analyses (e.g., alignment predictors), and observational comparison studies lacking a defined preventive intervention (e.g., demographic or clinical risk-factor analyses comparing PJK vs. non-PJK). Studies involving patients who did not undergo surgery were excluded, as were studies focusing on Scheuermann kyphosis, early-onset scoliosis, adolescent idiopathic scoliosis, or congenital scoliosis. Non-English publications and studies in predatory journals listed in Beall's list[30] were also excluded. Disagreements between reviewers were resolved through discussion and consensus.

3. Data Extraction

Two reviewers independently extracted data from each included study. Extracted variables included the first author, publication year, study design, patient diagnosis, type of surgery, definition of PJK or PJF used, type of intervention, follow-up duration, and incidence of PJK or PJF. Revision surgery owing to PJK or PJF was collected as a secondary outcome. During extraction, studies were grouped into 5 intervention categories: tethering, hook fixation, prophylactic vertebral augmentation, rod characteristics, and UIV level. When multiple studies appeared to share overlapping patient populations within an intervention category, the study with the largest sample size or most complete dataset was selected to avoid duplication bias. Potential overlaps were identified by cross-checking institutions, author groups, study periods, and inclusion criteria. Two reviewers independently assessed possible duplicates, resolving discrepancies through discussion.

4. Assessing the Quality of Studies

Two reviewers independently assessed the risk of bias using the Newcastle-Ottawa Scale (NOS). Discrepancies were resolved by discussion and, when needed, consultation with a senior author. As this meta-analysis included only observational studies, the NOS—designed for evaluating nonrandomized studies—was used.[31] Risk of bias was assessed across 3 domains: selection, comparability, and outcome assessment. Scores of 7–9 were considered high quality, 4–6 moderate quality, and 0–3 low quality.

Funnel plots were not used to assess publication bias, as their reliability is limited in meta-analyses with fewer than 10 studies, according to Egger et al.[32] To further evaluate the robustness of our findings and the impact of individual studies or potential bias, a leave-one-out (LOO) sensitivity analysis was performed.[33]

5. Statistical Analysis

A random-effects model with inverse variance weighting was applied to account for expected heterogeneity arising from variations in patient populations, surgical techniques, and study methodologies. Because PJK and PJF represent a pathological continuum affecting the proximal junction, the meta-analysis used the reported definitions from the original studies despite definitional variability. Odds ratios (ORs) with 95% confidence intervals (CIs) were calculated to estimate effect sizes for PJK, PJF, and revision surgery due to PJK or PJF across the different surgical interventions. Revision surgery owing to PJK was initially grouped with PJF but was analyzed separately when direct PJF assessment was not feasible. Heterogeneity was assessed using the I^2 statistics, with values of 25%, 50%, and 75% considered low, moderate, and high heterogeneity, respectively, according to Higgins et al.[34] All analyses were performed using R v4.4.2 (R Core Team 2024), primarily utilizing the meta (v8.0.1)[35] package.

RESULTS

1. Study Selection

The study selection process is illustrated in Fig. 1. Forty-two studies[20,23,26-28,36-72] were included in the data extraction process. Among them, 4 studies[41-44] were excluded because of overlapping patient populations, resulting in 38 studies[20,23,26-28,36-40,45-72] included in the final systematic review. Although studies of all designs were eligible for inclusion, all screened studies were retrospective. The included studies were categorized into 5 groups: tethering, hook fixation, prophylactic vertebral augmentation, rod characteristics, and level of UIV. Of these, 33 studies[20,23,26-28,45-72] were included in the meta-analysis, based on methodological and clinical considerations described in subsequent sections.

2. Quality Assessment of Studies

The quality assessment of the 38 studies included in the systematic review using the NOS is presented in Supplementary Table 1. Across all studies, the selection domain ranged from 3–4, the comparability domain from 1–2, and the outcome domain from 2–3, resulting in total scores between 7 and 9, indicating high methodological quality. Although a formal GRADE assessment was not performed, the overall certainty of the evidence was judged as low to moderate because all included studies were retrospective.

The inclusion criteria and radiologic outcome definitions were clearly stated in most studies, and measurement methods were adequately described. In the comparability domain, studies that performed multivariate analyses or matched comparisons for key confounders (e.g., age, bone quality, alignment) received higher scores, whereas those without adjustment were downgraded. In the outcome domain, studies with unclear or subjective definitions of PJK/PJF were also downgraded by one point. Information on assessor blinding was generally absent owing to the retrospective design, but this was considered acceptable given the objectivity of radiologic outcomes.

3. Tethering

Six studies[26,37,40,41,59,65] were initially included in the data extraction process; however, the study by Buell et al.[41] was exclud-

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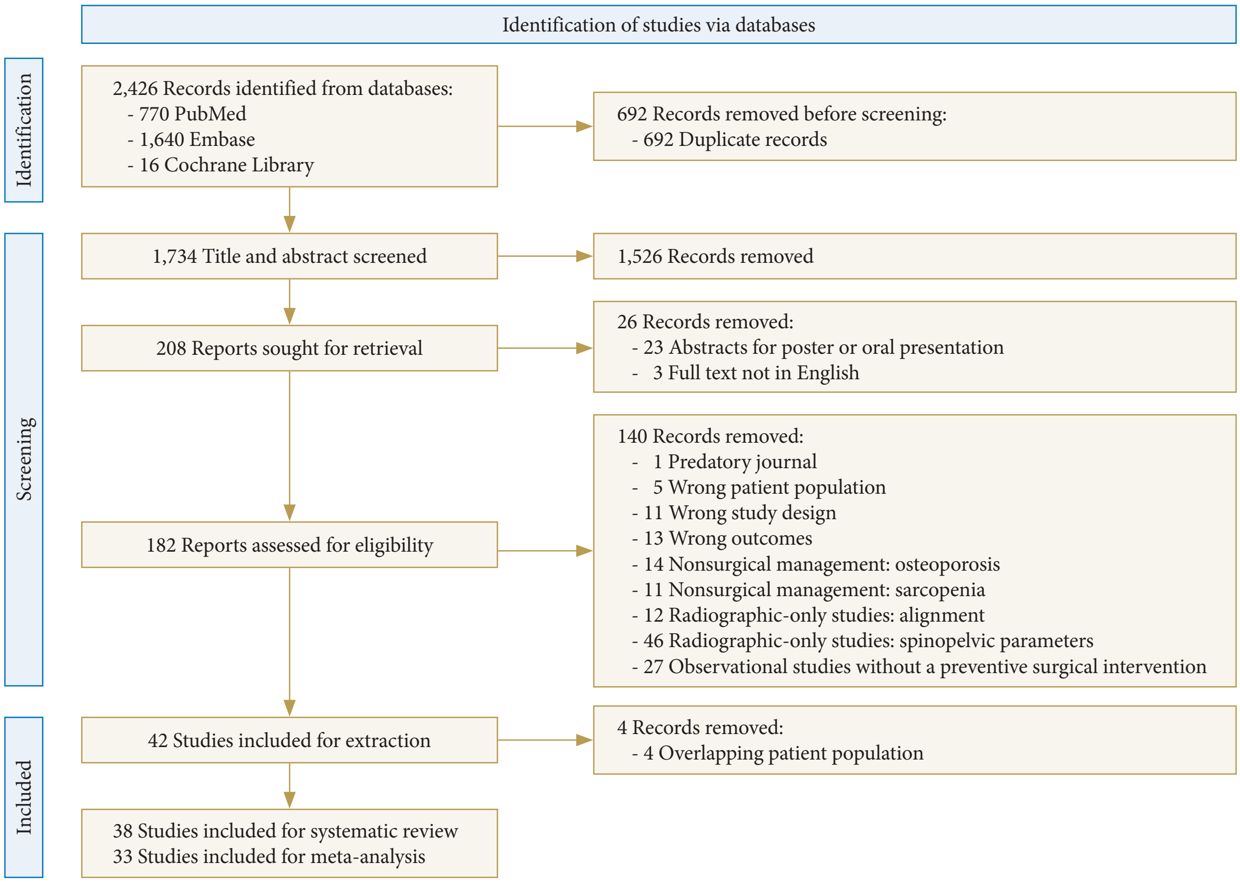

Fig. 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) flow diagram of the search process.

ed because of overlapping patient populations. The characteristics of the remaining 5 studies[26,37,40,59,65] included in the systematic review that evaluated the efficacy of tethering are summarized in Table 1. Among these, 3 studies[26,59,65] were included in the meta-analysis of spinous process tethering. Mikula et al.[37] was excluded for reporting combined PJK and PJF rates, and Yagi et al.[40] was excluded for reporting sublaminar tethering.

Spinous process tethering showed lower PJK rates (OR, 0.35; 95% CI, 0.22–0.56; $I^2 = 1.7\%$) (Fig. 2A), without a statistically significant difference in revision surgery rates for PJK or PJF (Fig. 2B).

4. Hook Fixation

Fourteen studies[23,27,42,43,47,53,54,56,57,59,60,66,67,72] were initially included in the data extraction process; however, 3 studies[42,43,54] were excluded because of overlapping patient populations. The characteristics of the remaining 11 studies[23,27,47,53,56,57,59,60,66,67,72] included in the systematic review that evaluated the efficacy of hook fixation are summarized in Table 2. All 11 studies were included in the meta-analysis.

The use of hooks showed lower PJF rates (OR, 0.34; 95% CI, 0.21–0.55; $I^2 = 0.0\%$) (Fig. 3B), without a statistically significant difference in PJK rates (Fig. 3A).

5. Prophylactic Vertebral Augmentation

Eight studies[28,45,51,54,57,59,60,66] were included in the data extraction, systematic review, and meta-analysis, with no overlapping patient populations and no exclusions. The characteristics of the 8 studies that evaluated the efficacy of prophylactic vertebral augmentation at UIV or UIV+1 are summarized in Table 3.

Prophylactic vertebral augmentation at UIV or UIV+1 was associated with lower PJF rates (OR, 0.58; 95% CI, 0.35–0.95; $I^2 = 21.8\%$) (Fig. 4B), without a statistically significant difference in PJK rates (Fig. 4A).

6. Rod Characteristics

Seven studies[20,36,49,52,57,62,64] were included in the data extraction process and systematic review, with no exclusions due to overlapping patient populations. The characteristics of these 7 studies evaluating the efficacy of rod characteristics are summarized

Table 1. Characteristics of included studies using tether

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Buell et al.[26] 2019	Retrospective	ASD patients with diagnosis of scoliosis and/or global sagittal malalignment	Instrumented segmental posterior spine fusion (may have also had anterior approach procedure) at a minimum > 6 motion segments	PJK (1) PJA ≥ 10° (2) Progression of PJA ≥ 10° greater than the corresponding preoperative measurement	PE tether (TO; n = 64) 5 mm woven PE Mersilene tape passed through hole of UIV+1 and UIV-1 spinous processes and tightened securely	No tether (n = 64)	PJK	26.7% (32/120; TO: 22/64, TC: 10/56) vs. 45.3% (29/64), p = 0.011 Follow-up period: mean (range), 20 (3–56) mo
					PE tether + crosslink (TC; n = 56) Placement of a standard crosslink between the UIV-1 and UIV-2 spinous processes Then PE tape passed around the crosslink and through UIV+1 spinous process		Revision surgery for PJF	6.7% (8/120; TO: 6/64, TC: 2/56) vs. 4.7% (3/64) Follow-up period: mean (range), 20 (3–56) mo
Line et al.[59] 2020	Retrospective	ASD -Scoliosis > 20° -SVA > 5 cm -PT > 25° -TK > 60°	≥ 5 Spine levels fused posteriorly	PJF (1) PJA ≥ 28° (2) ΔPJA ≥ 21.6° (3) PJ anterolisthesis ≥ 8 mm (upper thoracic); 3 mm (lower thoracic) (4) ΔPJ anterolisthesis ≥ 8 mm (upper thoracic); 3 mm (lower thoracic)	Tether (n = 62) Insertion of PE tether at the spinolaminar junction of the UIV+1 and/or UIV+2	None (n = 390) No use of surgical implants to prevent PJF	PJF	16.1% (10/62) vs. 20.3% (79/390), NS Minimum 1-yr follow-up
							Surgery for PJF	3.2% (2/62) vs. 8.4% (33/390), NS Minimum 1-yr follow-up
Mikula et al.[37] 2022	Retrospective	Patients who underwent pelvic fixation to UIV at T1 to T6 with minimum 12-mo follow-up	Instrumented fusion extending from the pelvis to an UIV between T1 and T6	PJK Change in PJA of at least 10° between the immediate postoperative and final follow-up standing radiographs PJF (1) Proximal junctional fracture (2) Fixation failure (3) Kyphosis requiring extension of the fusion	Tether (n = 15) Proximal junctional tether between the UIV and UIV+1 (Mersilene tape)	No tether (n = 31) Also, excluding 35 patients (14 with PJK/PJF) with UIV soft landing	PJK/PJF	4/15 vs. 9/31 Average follow-up of 38 mo

(*Continued*)

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Table 1. Characteristics of included studies using tether (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Rabinovich et al.[65] 2021	Retrospective	ASD - PT ≥ 25° - SVA ≥ 5 cm - TK (T5–T12) ≥ 60° - Coronal Cobb angle ≥ 20° - PI–LL mismatch ≥ 10°	≥ 5 Instrumented levels with pedicle screw fixation to the pelvis and/or sacrum	PJK (1) PJA ≥ 10° (2) Progression of PJA ≥ 10° greater than the corresponding preoperative measurement	PE tether (n = 42) 5-mm woven PE Mersilene tape passed through hole of UIV+1 and UIV-1 spinous process base and tightened by hand	No tether (n = 61)	PJK	29.4% (25/85) vs. 60.7% (37/61), p = 0.0002 Minimum 1-yr follow-up (mean, 45.4 mo)
					PE tether + crosslink (n = 43) Placement of a standard crosslink between the UIV-1 and UIV-2 spinous processes Then PE tape passed around the crosslink and through UIV+1 spinous process		Revision surgery for PJK	2.4% (2/85) vs. 8.2% (5/61), p = 0.129 Minimum 1-yr follow-up (mean, 45.4 mo)
Yagi et al.[40] 2022	Retrospective	ASD - Cobb angle ≥ 20° - C7-SVA ≥ 5 cm - PT ≥ 25°	Fusion from the sacrum to the lower thoracic spine (T9, T10, T11)	PJK (1) PJA > 10° (2) PJA at least 10° greater than the corresponding preoperative measurement PJF (1) Increase in PJA ≥ 20° compared with the baseline value with concomitant deterioration of at least 1 SRS-Schwab sagittal modifier grade from immediately after the operation (2) Any type of PJK requiring revision	Sublaminar tether (n = 41) (1) UIV+1 lamina exposed (2) Ligamentum flavum proximal and distal to the UIV+1 lamina was partially removed so that sublaminar banding could be introduced (3) Sublaminar band was then passed under the UIV+1 lamina using a set of 5-mm width PE tapes (Nesplon; Alfresa Pharma, Osaka, Japan)	Control (n = 158)	PJK	22% (7/32) vs. 44% (14/32), p = 0.06 2-yr follow-up Propensity score-matched patients (n = 32 in each group)
							PJF	2.4% (1/41) vs. 17.1% (27/158), p = 0.10 2-yr follow-up

PJK, proximal junctional kyphosis; PJF, proximal junctional failure; ASD, adult spine deformity; PJA, proximal junctional angle; PE, polyethylene; UIV, upper instrumented vertebra; NS, not significant; PT, pelvic tilt; SVA, sagittal vertical axis; TK, thoracic kyphosis; PI, pelvic incidence; LL, lumbar lordosis.
PJA: sagittal Cobb angle measured from the caudal endplate of the UIV to the cephalad endplate of UIV+2.

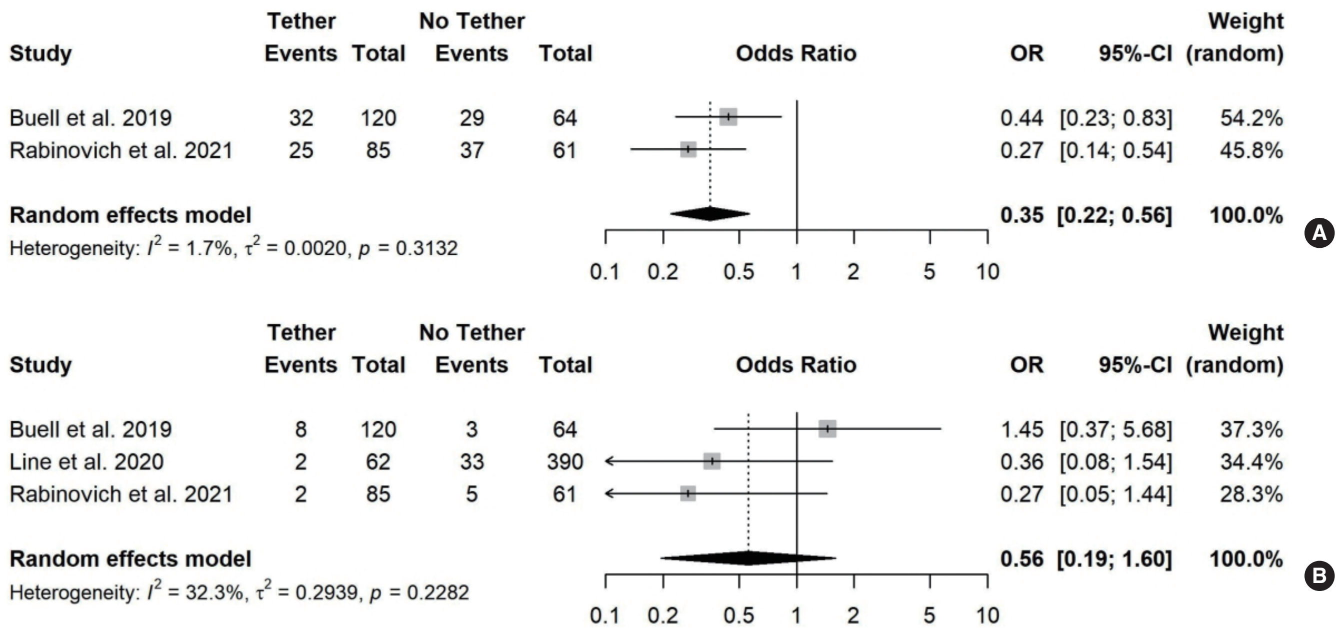

Fig. 2. Meta-analysis of the effect of spinous process tethering. (A) PJK rates. (B) revision surgery due to PJK or PJF. PJK, proximal junctional kyphosis; PJF, proximal junctional failure; OR, odds ratio; CI, confidence interval.

in Table 4. Among these, 6 studies[20,49,52,57,62,64] were included in the meta-analysis comparing rod alloys (cobalt chromium [CoCr] vs. titanium [Ti]); Charles et al.[36] was excluded for reporting combined PJK/PJF rates.

When comparing CoCr and Ti rods, there were no statistically significant differences in PJK or PJF rates (Supplementary Fig. 1).

7. Level of UIV

Twenty-one studies[20,23,38,39,44,46-48,50,54,55,57,58,61,63,66,68-72] were initially included in the data extraction process; however, the study by Wang et al.[44] was excluded because of an overlapping patient population. The characteristics of the remaining 20 studies[20,23,38,39,46-48,50,54,55,57,58,61,63,66,68-72] included in the systematic review that evaluated the effect of UIV level are summarized in Table 5.

UIV levels were grouped into ranges using cutoffs of T6 (T6 and above vs. T7 and below), T8 (T8 and above vs. T9 and below), T10 (T10 and above vs. T11 and below), and L1 (L1 and above vs. L2 and below). Sixteen studies[20,46,48,50,54,55,57,58,61,63,66,68-72] were included in the meta-analysis. Tian et al.[39] was excluded for reporting combined PJK and PJF rates, and 3 studies[23,38,47] were excluded for using a UIV cutoff at T7.

1) UIV cutoff of T6 (T6 and above vs. T7 and below)

Nine studies[20,46,48,50,55,61,66,70,72] were included in the meta-analysis. There was no statistically significant difference in PJK or PJF rates when the UIV cutoff was set at T6 (Figs. 5A and 6A).

2) UIV cutoff of T8 (T8 and above vs. T9 and below)

Six studies[20,48,55,57,61,71] were included in the meta-analysis. There was no statistically significant difference in PJK or PJF rates when the UIV cutoff was set at T8 (Figs. 5B and 6B).

3) UIV cutoff of T10 (T10 and above vs. T11 and below)

Five studies[54,58,63,68,69] were included in the meta-analysis. When the UIV level was set at T10 and above, PJK rates were lower compared with UIV levels at T11 and below (OR, 0.15; 95% CI, 0.03–0.64; I^2 = 79.9%) (Fig. 5C). However, there was no statistically significant difference in PJF rates when the UIV cutoff was set at T10 (Fig. 6C).

4) UIV cutoff of L1 (L1 and above vs. L2 and below)

Four studies[54,58,68,69] were included in the meta-analysis. There was no statistically significant difference in PJK rates when the UIV cutoff was set at L1 (Fig. 5D). However, when the UIV level was set at L1 and above, PJF rates were lower compared with UIV levels at L2 and below (OR, 0.29; 95% CI, 0.14–0.61, I^2 = 0.0%) (Fig. 6D).

8. Sensitivity Analysis

To examine the robustness of the pooled estimates and the

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Table 2. Characteristics of included studies using hook

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Byun et al.[47] 2022	Retrospective	ASD	Fusion at more than 5 levels	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value PJF Presence of PJK with (1) Fracture of the vertebral body of the UIV or UIV+1 (2) Pulling out of screws at UIV (3) Posterior ligamentous disruption	UIV hook (n = 7)	No UIV hook (n = 71)	PJK	57.1% (4/7) vs. 29.6% (21/71)
Hassanzadeh et al.[53] 2013	Retrospective	Spinal deformity - Scoliosis - Kyphosis - Kyphoscoliosis	Instrumentation involving ≥ 5 spinal levels	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from baseline	TP hook (n = 20) Hook blade was immediately lateral to the lateral edge of the pedicle.	Pedicle screw (n = 27)	PJK	0 (0/20) vs. 29.6% (8/27), p = 0.023 Minimum 2-yr follow-up
Kim et al.[56] 2014	Retrospective	Adult scoliosis	Fusions greater than 5 levels	PJK PJA > 10°	Hook (n = 66) - Bilateral (n = 24) - Unilateral (n = 42)	None (n = 140)	PJK	18/66 vs. 52/140 Minimum 2-yr follow-up
							PJK requiring Surgery	3/66 vs. 19/140 Minimum 2-yr follow-up
Kim et al.[23] 2008	Retrospective	ASD Adult scoliosis (n = 106) Sagittal imbalance syndrome (n = 55)	Posterior segmental spinal instrumentation (≥ 5 levels)	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value	Hook (n = 99) Hybrid (proximal hook, distal pedicle screw) or hook	None (n = 62) Pedicle screw	PJK	42/123 vs. 20/38, p = 0.041 Minimum 5-yr follow-up
Lazaro et al.[57] 2023	Retrospective	Subset of ASLS-1 patients	Posterior instrumented fusion/fixation of ≥ 7 vertebral levels including the sacrum/pelvis	PJK (1) PJA ≥ 10° (2) At least 10° of greater PJA than preop measurement PJF (1) Change in PJA > 20° compared with the preoperative measurement (2) Fracture of UIV and/or UIV+1 with > 20% vertebral height loss (3) Screw dislodgment (4) Spondylolisthesis of UIV+1 relative to UIV of > 3 mm	Hook (n = 39) Bilateral transverse process hooks Pedicle screw on one side with a pedicle hook on the other side.	None (n = 114) No use of PJF prophylaxis	PJF	6/39 vs. 38/114 Mean follow-up 4.3-yr (range, 0.1–6.1 yr)

(*Continued*)

Table 2. Characteristics of included studies using hook (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Line et al.[59] 2020	Retrospective	ASD - Scoliosis > 20° - SVA > 5 cm - PT > 25° - TK > 60°	≥ 5 spine levels fused posteriorly	PJF (1) PJA ≥ 28° (2) ΔPJA ≥ 21.6° (3) PJ anterolisthesis ≥ 8 mm (upper thoracic); 3 mm (lower thoracic) (4) ΔPJ anterolisthesis ≥ 8 mm (upper thoracic); 3 mm (lower thoracic)	TP hook (n = 115) TP hook placed at UIV	None (n = 390) No use of surgical implants to prevent PJF	PJF	7% (8/115) vs. 20.3% (79/390), $p < 0.05$ Minimum 1-yr follow-up
							Surgery for PJF	8.7% (10/115) vs. 8.4% (33/390) Minimum 1-yr follow-up
Nicholls et al.[60] 2017	Retrospective	ASD	Segmental posterior instrumented fusion from the sacrum cephalad, to span a minimum of 5 levels (up to at least L1)	PJK (1) PJA ≥ 10° (2) Progression of PJA > 10° than preop measurement	Hook (n = 28) Hook on UIV	None (n = 408) Pedicle screw	PJK	3.6% (1/28) vs. 38% (155/408), $p < 0.001$ 34.9 ± 21.3-mo follow-up
Park et al.[27] 2025	Retrospective	ASD - PI-LL mismatch ≥ 10° - PT ≥ 25° - C7-SVA ≥ 5 cm - Coronal Cobb angle ≥ 30°	Fusion from the lower thoracic spine (T8–11) to the sacrum.	PJK PJA > 20° PJF Any case requiring revision surgery because of proximal junctional complications	TP hook (n = 65) Bilateral hooks were placed over the TP at the UIV+1 level One- or 2-level TP hook were at the discretion of the surgeons	No-TP hook (n = 88) Pedicle screw	PJK	23.1% (15/65) vs. 29.5% (26/88), $p = 0.461$ 57.3 ± 38.4-mo follow-up
							PJF	4.6% (3/65) vs. 10.2% (9/88), $p = 0.239$ 57.3 ± 38.4-mo follow-up
Safaee et al.[66] 2021	Retrospective	ASD	The mean number of levels fused was 10 (range 6–16)	PJF Symptomatic PJK with hardware failure requiring reoperation	TP hook (n = 102) Only for UT (T1–6) UIV, UIV+1	No hook (n = 18) For UT (T1–6)	PJF	2/102 vs. 0/18 Minimum 12-mo follow-up
Tsutsui et al.[67] 2022	Retrospective	Deg. ASD - Scoliosis - Kyphosis - Kyphoscoliosis	Instrumented fusion from the pelvis to T9 or T10	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from baseline	TP hook (n = 28) TP hook at the UIV level	Pedicle screw (n = 25)	PJK	35.7% (10/28) vs. 8.0% (2/25), $p = 0.012$ 1-yr radiographic follow-up

(*Continued*)

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Table 2. Characteristics of included studies using hook (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Yoshie et al.[72] 2023	Retrospective	ASD	Long instrumented fusion surgery from the thorax to the pelvis (minimum 6 levels)	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value	Hook (n = 39) Hook at UIV	Pedicle screw (n = 21)	PJK	18/39 vs. 7/21, p = 0.416 Minimum 1-yr clinical follow-up

PJK, proximal junctional kyphosis; PJF, proximal junctional failure; ASD, adult spine deformity; PJA, proximal junctional angle; UIV, upper instrumented vertebra; TP hook, transverse process hook; SVA, sagittal vertical axis; PT, pelvic tilt; TK, thoracic kyphosis; PI, pelvic incidence; LL, lumbar lordosis; C7-SVA, C7-sagittal vertical axis; UT, upper thoracic; Deg, degenerative.
PJA: sagittal Cobb angle measured from the caudal endplate of the UIV to the cephalad endplate of UIV+2.
ASLS-1: prospective, multicenter, consecutive series of patients from a National Institutes of Health sponsored study designed to assess operative versus nonoperative treatment of adults with symptomatic lumbar scoliosis.
Line et al. (2020): incidence of surgery for PJF for hook (8.7%; 10) was greater than incidence of PJF for hook (7%; 8) because hook group had 7 patients treated surgically for junctional kyphosis that was less severe than the radiographic criteria used for PJF in this manuscript, and 3 patients that met criteria for PJF as defined in this study that were treated surgically.
Nicholls et al. (2017), Park et al. (2025): follow-up period in mean ± standard deviation form.

potential influence of bias and individual studies, LOO sensitivity analyses were conducted. LOO analysis was applied to 2 comparisons that showed high or relatively higher heterogeneity compared with other statistically significant results: the effect of prophylactic vertebral augmentation on PJF rates (Supplementary Fig. 2A) and PJF rates according to UIV level with a cutoff at T10 (Supplementary Fig. 2B).

In the analysis of prophylactic vertebral augmentation on PJF rates (Fig. 4B), the pooled OR was 0.58 (95% CI, 0.35–0.95) with an I^2 of 21.8%. Although this level of heterogeneity is not concerning in absolute terms, it was relatively higher than in other statistically significant pooled results. Across all LOO analyses, the OR remained below 1.0, ranging from 0.47 to 0.70. While omission of some studies led to a loss of statistical significance, the direction of the effect remained consistent, indicating that prophylactic vertebral augmentation reduced the risk of PJF.

Similarly, in the analysis of UIV level with a cutoff at T10 on PJK rates (Fig. 5C), the pooled OR was 0.15 (95% CIm 0.03–0.64) with substantial heterogeneity (I^2 = 79.9%). Across all LOO analyses, the OR remained below 1.0, ranging from 0.07 to 0.26. Excluding the studies by Kang et al.[54] and Lee et al.[58] resulted in 95% CIs that included 1.0, indicating a loss of statistical significance. Despite this, the effect direction remained consistent, suggesting that selecting a UIV at or above T10 reduced the risk of PJK. Notably, heterogeneity dropped markedly (I^2 = 8.8%), with a lower pooled OR (0.07) and a narrower 95% CI (0.02–0.21), when the study by Park et al.[63] was omitted. This suggests that the Park et al.[63] study contributed substantially to the heterogeneity observed among the 4 included studies,[54,58,63,68] and that excluding it resulted in a more pronounced reduction in PJK risk and improved precision of the estimate.

DISCUSSION

This meta-analysis evaluated surgical strategies proposed to prevent PJK and PJF. Although the mechanisms underlying these complications remain incompletely understood, several studies have attempted to clarify the biomechanical and anatomical factors contributing to their development.

Among the proposed mechanisms, elevated mechanical stress resulting from the abrupt transition between the rigid instrumented segment and the mobile adjacent segments is one of the most widely accepted explanations.[5,22,73,74] A cadaveric study demonstrated that longer instrumentation increases adjacent segment motion and intradiscal pressure, thereby elevating stress at the adjacent level.[75] Increased segmental hypermobility at the prox-

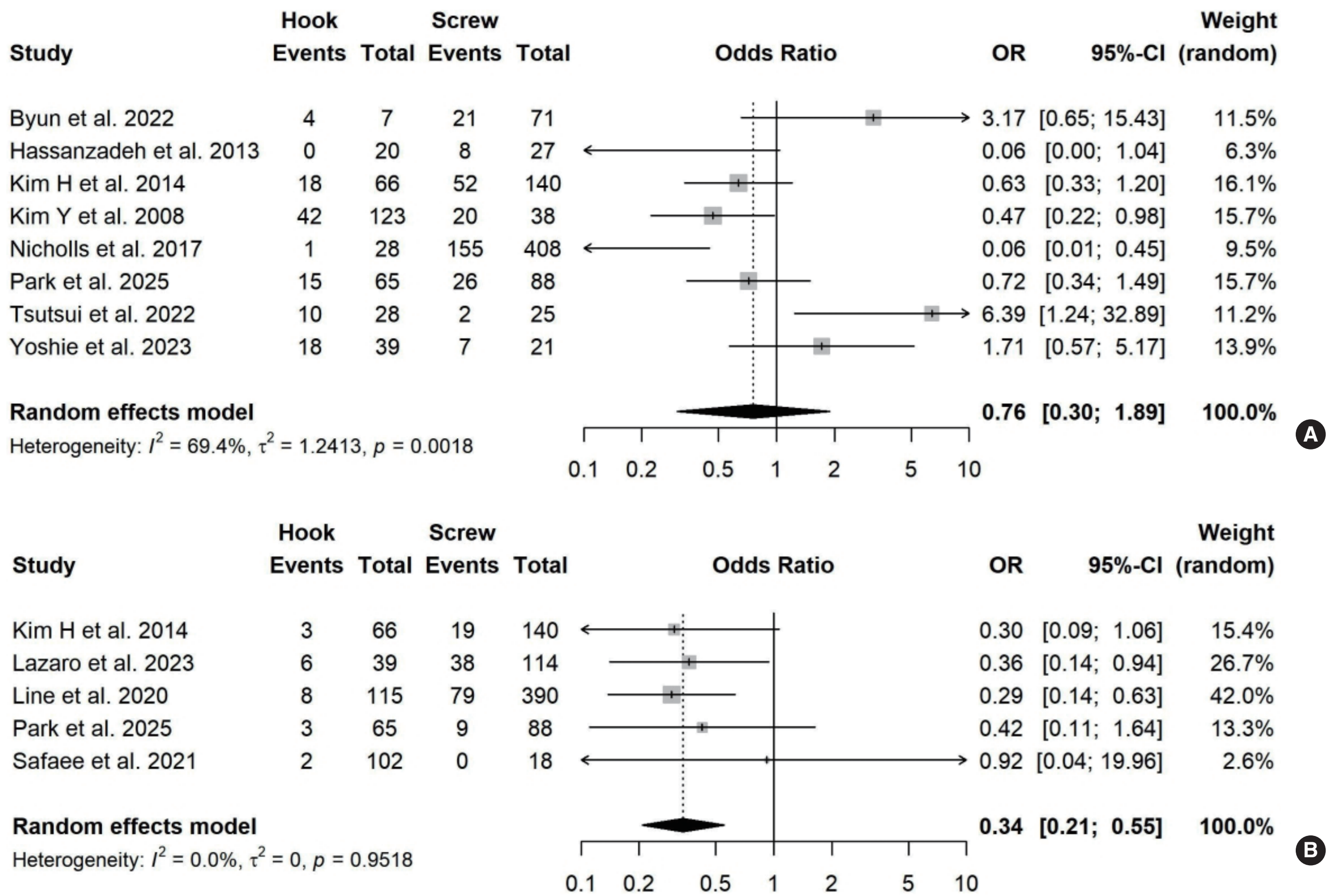

Fig. 3. Meta-analysis of the effect of hook fixation. (A) PJK rates. (B) PJF rates. PJK, proximal junctional kyphosis; PJF, proximal junctional failure; OR, odds ratio; CI, confidence interval.

imal junction has also been implicated as a contributor to mechanical instability. Furthermore, disruption of posterior spinal structures has been shown to decrease flexion stiffness, potentially increasing instability at adjacent motion segments.[76] Accordingly, recent surgical techniques have focused on mitigating these mechanical stresses to reduce the incidence of PJK and PJF. Despite growing interest, the current body of evidence remains limited, with considerable variability in surgical approaches and most studies being retrospective.

The UIV ≥T10 subgroup analysis showed substantial heterogeneity (I^2 = 79.9%), indicating notable variability among the included studies. Although a random-effects model was used, such heterogeneity inherently limits the reliability of the pooled estimate. In addition, the sensitivity analysis revealed a loss of statistical significance when certain studies were excluded; thus, these findings should be interpreted cautiously.

Further exploration identified Park et al.[63] as the primary source of heterogeneity in the analysis of PJK rates using the T10 cutoff. When this study was excluded, heterogeneity markedly decreased (I^2 = 8.8%), and the pooled effect became statistically significant, with a smaller OR and narrower CI. This may be due to the broader definition of PJK in that study, which included vertebral fractures at UIV or UIV+1 and instrumentation failures—criteria more commonly associated with PJF in other literature. Although statistical significance was lost in some LOO analyses, the consistent effect direction supports the robustness of our findings.[77]

Although the number of included studies was limited and heterogeneity existed across UIV levels, our meta-analysis showed that spinous process tethering had a preventive effect on PJK. One study investigating sublaminar tethering also reported significantly lower PJF rates in a propensity score-matched cohort.[40] Posterior tethers are thought to reduce mechanical stress at the proximal junction through several biomechanical mechanisms. A finite element analysis by Bess et al.[78] demonstrated that posterior tethers create a more gradual transition in range of motion across the proximal junction, reducing the abrupt stiffness mismatch associated with pedicle screws or hooks. Additional-

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Table 3. Characteristics of included studies using prophylactic vertebroplasty

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Bartolozzi et al.[45] 2024	Retrospective	ASD	Fusion of thoracolumbar junction to sacrum or pelvis	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from imme diate postoperation	PMMA VP (n = 57) Injected into the pedicles bilaterally at the UIV and UIV+1 in patients considered at risk	None (n = 45)	PJK	55.4% (31/57) vs. 38.6% (17/45), p = 0.097 Median follow-up: 41 mo
							PJF	10.7% (6/57) vs. 15.9% (7/45), p = 0.443 Median follow-up: 41 mo
Ghobrial et al.[28] 2017	Retrospective	ASD - Lumbar Cobb angle > 20° - PT > 25° - SVA > 5 cm - Central sacral vertical line > 2 cm - TK > 60°	Long-segment posterior fusion (> 5 levels)	PJK > 10° of postoperative PJA	PMMA VP (n = 38) At UIV, UIV+1	None (n = 47)	PJK	23.7% (9/38) vs. 36.2% (17/47), p = 0.020 Mean follow-up: 25.2 mo
							PJF	0% (0/38) vs. 12.8% (6/47), p = 0.031 Mean follow-up: 25.2 mo
Han et al.[51] 2019	Retrospective	ASD - Deg. flat back - Postoperative flat back - Deg. scoliosis - Posttraumatic kyphosis	Pedicle subtraction osteotomy Vertebral column resection Posterior interbody fusion	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value	Prophylactic VP (n = 28) Cement augmentation at the UIV, UIV+1	Non-prophylactic VP (n = 56)	PJK	46.4% (13/28) vs. 46.4% (26/56), p = 1.000 At least 1-yr follow-up
							PJF	39.3% (11/28) vs. 32.1% (18/56), p = 0.516 At least 1-yr follow-up
Kang et al.[54] 2024	Retrospective	ASD Deg. lumbar kyphoscoliosis	Long-segment fusion surgery (≥ 4 levels) with ACR followed by posterior instrumentation	PJK Increases of PJA (1) PJA ≥ 28° (2) Changes of PJA ≥ 22° PJF (1) Vertebral fracture at the UIV or UIV+1 (2) Subluxation between these levels (3) Failure of UIV fixation (4) Necessity for proximal fusion extension	Cement (n = 35) Cement augmentation at the UIV	None (n = 48)	PJK	3/35 vs. 9/48 Minimum 2-yr follow-up
							PJF	5/35 vs. 20/48 Minimum 2-yr follow-up

(*Continued*)

Table 3. Characteristics of included studies using prophylactic vertebroplasty (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Intervention	Control	Outcome	Result (intervention vs. control)
Lazaro et al.[57] 2023	Retrospective	Subset of ASLS-1 patients	Posterior instrumented fusion/fixation of ≥7 vertebral levels including the sacrum/pelvis	PJK (1) PJA ≥ 10° (2) At least 10° of greater PJA than preop measurement PJF (1) Change in PJA > 20° compared with the preoperative measurement (2) Fracture of UIV and/or UIV+1 with > 20% vertebral height loss (3) Screw dislodgment (4) Spondylolisthesis of UIV+1 relative to UIV of > 3 mm	Cement (n = 7) Cement at the UIV and/or UIV+1	None (n = 114) No use of PJF prophylaxis	PJF	2/7 vs. 38/114 Mean follow-up: 4.3 yr (range, 0.1–6.1 yr)
Line et al.[59] 2020	Retrospective	ASD database - Scoliosis > 20° - SVA > 5 cm - PT > 25° - TK > 60°	≥ 5 Spine levels fused posteriorly	PJF (1) PJA ≥ 28° (2) ΔPJA ≥ 21.6° (3) PJ anterolisthesis ≥ 8 mm (UT)/3 mm (LT) (4) ΔPJ anterolisthesis ≥ 8 mm (UT)/3 mm (LT)	Cement (n = 58) Injection of PMMA cement at the UIV and UIV+1	None (n = 390) No use of surgical implants to prevent PJF	PJF Surgery for PJF	12.1% (7/58) vs. 20.3% (79/390) Minimum 1-yr follow-up 5.2% (3/58) vs. 8.4% (33/390) Minimum 1-yr follow-up
Nicholls et al.[60] 2017	Retrospective	ASD patients	Segmental posterior instrumented fusion from the sacrum cephalad, to span a minimum of 5 levels (up to at least L1)	PJK (1) PJA ≥ 10° (2) Progression of PJA > 10° than preop measurement	Vertebroplasty (n = 39)	None (n = 408)	PJK	43.6% (17/39) vs. 35.4% (142/401), p = 0.199 34.9 ± 21.3-mo follow-up
Safaee et al.[66] 2021	Retrospective	ASD	The mean number of levels fused was 10 (range, 6–16)	PJF Symptomatic PJK with hardware failure requiring reoperation	Vertebroplasty (n = 160) Only for LT(T7–12) at UIV, UIV+1	None (n = 39) For LT(T7–12)	PJF	13/160 vs. 5/39 Minimum 12-mo follow-up

PJK, proximal junctional kyphosis; PJF, proximal junctional failure; ASD, Adult spine deformity; PJA, Proximal junctional angle; PMMA, polymethylmethacrylate; VP, vertebroplasty; UIV, upper instrumented vertebra; SVA, sagittal vertical axis; PT, pelvic tilt; TK, thoracic kyphosis; Deg., degenerative; ACR, anterior column realignment; UT, upper thoracic; LT, lower thoracic.
PJA: sagittal Cobb angle measured from the caudal endplate of the UIV to the cephalad endplate of UIV+2.
ASLS-1: prospective, multicenter, consecutive series of patients from a National Institutes of Health sponsored study designed to assess operative versus nonoperative treatment of adults with symptomatic lumbar scoliosis.
Nicholls et al. (2017): follow-up period in mean ± standard deviation form.

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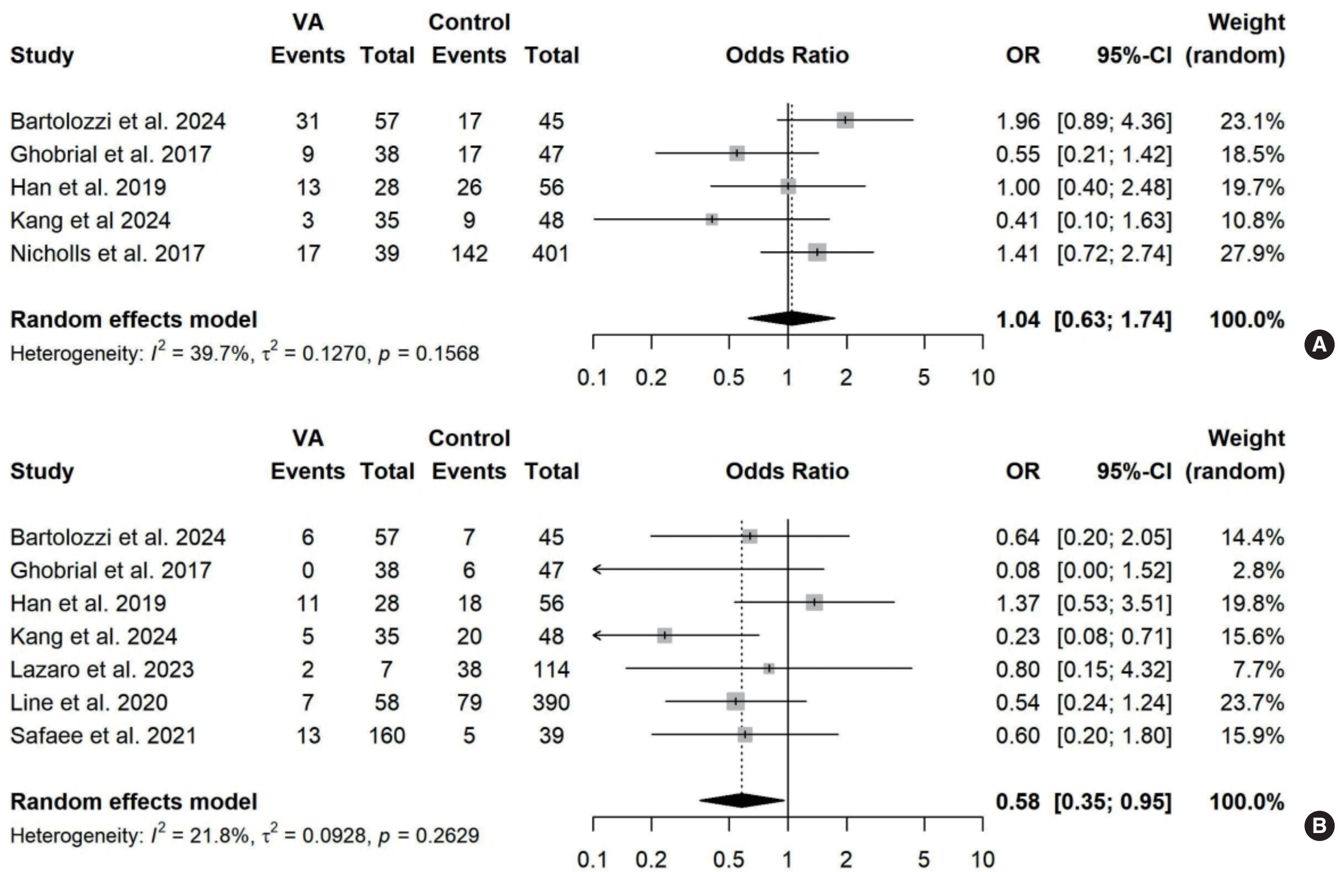

Fig. 4. Meta-analysis of the effect of prophylactic vertebral augmentation at UIV or UIV+1. (A) PJK rates. (B) PJF rates. UIV, upper instrumented vertebra; VA, vertebral augmentation; PJK, proximal junctional kyphosis; PJF, proximal junctional failure; OR, odds ratio; CI, confidence interval.

ly, at high UIV levels, posterior tethers effectively reduce anterior column compressive forces and mitigate tensile stress on the posterior ligamentous complex.[79]

In our meta-analysis, hook fixation was associated with a significantly lower incidence of PJF, although its effect on PJK rates was not significant. A cadaveric study by Metzger et al.[80] showed that supralaminar hooks at the UIV reduced hypermobility at the adjacent segment compared with pedicle screws. Hooks provide a smoother transition of motion between the rigid fused segment and the mobile adjacent levels, thereby reducing stress concentration at the proximal junction and potentially lowering the risk of PJK.[81,82] Even in osteoporotic spines, combining hooks with sublaminar wires may offer biomechanical advantages by reducing proximal junctional stress.[83] However, given their limited effect on PJK, hook constructs may not be sufficient as standalone preventive measures and may be more effective when combined with soft tissue preservation techniques such as tethers.

Osteoporosis is a known risk factor for both PJK and PJF.[22,73] Low Hounsfield unit values at UIV and UIV+1 are specifically associated with increased risk.[84,85] Vertebroplasty is known to increase vertebral body strength,[86,87] which may explain our finding that prophylactic vertebral augmentation at UIV or UIV+1 reduced PJF risk. However, this localized increase in stiffness may alter load distribution and heighten stress at adjacent levels, potentially leading to adjacent segment fractures.[88] Because this mechanism parallels that of bony failure in PJF, careful consideration is needed when applying prophylactic vertebral augmentation. In this context, systemic osteoporosis treatment with anabolic agents may serve as a complementary strategy by addressing underlying bone fragility.[89,90]

Different rod alloys exhibit varying stiffness properties. While stiffer rods such as CoCr may reduce mechanical failure due to rod breakage, they may increase segmental stiffness at the fused levels, potentially contributing to PJK.[52] However, our meta-analysis found no statistically significant difference in PJK or PJF rates between CoCr and Ti rods. This may be because multiple factors, including rod number, rod diameter, and alignment correction, likely play a more significant role in junctional outcomes

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Table 4. Characteristics of included studies comparing rod types

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Rod characteristic	Outcome	Result
Charles et al.[36] 2024	Retrospective	ASD Coronal Cobb angle ≥ 20° SVA ≥ 5 cm PT ≥ 25° TK ≥ 60°	Posterior fusion from T9, T10 or T11 to the pelvis were included (8–10 fusion level)	PJK Kyphosis increase of ≥ 10° from immediate postoperative radiograph PJF (1) UIV or UIV+1 vertebral body fracture was present (2) Proximal instrumentation failure (3) PJK requiring revision surgery	Rod alloy (CoCr vs. Ti)	PJK/PJF	19.7% (35/178) vs. 19.8% (23/116) Minimum 2 yr follow-up
					Rod diameter (5.5 mm vs. 6.0 mm)	PJK/PJF	21.8% (43/197) vs. 13.5% (13/96)
					No. of rods (2 vs. 4)	PJK/PJF	21.4% (31/145) vs. 17.2% (27/157)
Durand et al.[49] 2022	Retrospective	Adult degenerative or idiopathic scoliosis - Maximum Cobb angle ≥ 20° - SVA ≥ 5 cm - PT ≥ 25° - TK ≥ 60°	Fusion of more than or equal to 5 levels with LIV at the sacro-pelvis	PJF (1) PJA ≥ 28° (2) ΔPJA ≥ 22° (3) Lithesis ≥ 8 mm/3 mm (upper thoracic/thoracolumbar level)	Rod alloy (CoCr vs. Ti vs. stainless steel)	PJF	13.1% (41/313) vs. 8.9% (10/113) vs. 16.2% (12/74) Postoperative follow-up 2 yr
					Rod diameter (5.5 mm vs. 6.0 mm vs. 6.35 mm/quarter inch)	PJF	12.1% (41/340) vs. 12.5% (7/56) vs. 14.8% (16/108) Postoperative follow-up 2yr
Han et al.[52] 2017	Retrospective	ASD	Posterior spinal fusion surgeries to the sacrum	PJK (1) PJA ≥ 10° (2) At least 10° more than the preoperative value	Rod alloy (CoCr vs. Ti) CoCr with multiplerod constructs Ti with two-rod constructs	PJK	60.0% (12/20) vs. 26.5% (9/34), p = 0.015 Minimum of 1-yr follow-up postoperatively
						Reoperation for PJK	10% (2/20) vs. 2.9% (1/34), p = 0.548 Minimum of 1-yr follow-up postoperatively
Lazaro et al.[57] 2023	Retrospective	Subset of ASLS-1 patients	Posterior instrumented fusion/fixation of ≥ 7 vertebral levels including the sacrum/pelvis	PJK (1) PJA ≥ 10° (2) At least 10° of greater PJA than preop measurement PJF (1) Change in PJA > 20° compared with the preoperative measurement (2) Fracture of UIV and/or UIV+1 with > 20% vertebral height loss (3) Screw dislodgment (4) Spondylolisthesis of UIV+1 relative to UIV of > 3 mm	Rod alloy (CoCr vs. Ti vs. stainless steel)	PJF	40/135 vs. 3/16 vs. 1/7 Mean follow-up: 4.3 yr (range, 0.1–6.1 yr)

(*Continued*)

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Table 4. Characteristics of included studies comparing rod types (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	Rod characteristic	Outcome	Result
Maruo et al.[20] 2013	Retrospective	ASD	Posterior long instrumented fusion surgery (≥6 vertebrae) to the sacrum	PJK (1) PJA ≥ 10° (2) At least 10° of greater PJA than preoperative measurement	Rod alloy (CoCr vs. Ti vs. stainless steel)	PJK	6/12 vs. 3/7 vs. 28/71, Minimum 2 yr of clinical follow-up
Park et al.[62] 2024	Retrospective	Symptomatic degenerative spinal deformities Lumbar kyphosis Thoracolumbar scoliosis	Biomechanically stable T10 as the UIV, and iliac screw insertion	PJK (1) PJA ≥ 10° (2) Increase of PJA ≥ 10° compared to the preop measurement PJF (1) Need for revision surgery because of vertebral fracture at the UIV or UIV+1 (2) Subluxation between the UIV and UIV+1 (3) Failure of fixation (4) Development of a neurological deficit	Rod alloy (CoCr 5.5 mm vs. Ti 6.0 mm)	PJK	25/83 vs. 24/71, $p = 0.625$ Within 1 yr after surgery
Pennington et al.[64] 2025	Retrospective	ASD patients - Coronal Cobb angle ≥ 20° - SVA ≥ 5 cm - PT ≥ 25° - TK ≥ 60°	Long-segment thoracolumbosacral fusion for ASD with a UIV in upper thoracic spine (T1–6)	PJK Increase of ≥ 10° in the PJA	Rod alloy (CoCr vs. Ti)	PJK	13/56 vs. 2/20, $p = 0.33$ Minimum 1-yr follow-up

PJK, proximal junctional kyphosis; PJF, proximal junctional failure; ASD, Adult spine deformity; SVA, sagittal vertical axis; PT, pelvic tilt; TK, thoracic kyphosis; UIV, upper instrumented vertebra; PJA, Proximal junctional angle.
PJA: sagittal Cobb angle measured from the caudal endplate of the UIV to the cephalad endplate of UIV+2.
ASLS-1: prospective, multicenter, consecutive series of patients from a National Institutes of Health sponsored study designed to assess operative versus nonoperative treatment of adults with symptomatic lumbar scoliosis.

Table 5. Characteristics of included studies according to UIV level

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	UT	LT	Outcome	Result (UT vs. LT)
Buell et al.[46] 2021	Retrospective	ASD database - Scoliosis > 20° - C7-SVA > 5 cm - PT > 25° - TK > 60°	Posterior instrumented fusion (including operations performed with an anterior approach) from sacro-pelvis to thoracic spine	No info	UT (n = 51) T1–6	LT (n = 93) T7–12	Reoperation for PJK	9.8% (5/51) vs. 8.6% (8/93), p = 0.810 2-yr follow-up
Byun et al.[47] 2022	Retrospective	ASD	Fusion at more than 5 levels	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value PJF Presence of PJK with (1) Fracture of the vertebral body of the UIV or UIV+1 (2) Pulling out of screws at UIV (3) Posterior ligamentous disruption	UT (n = 6) T7 or above	LT (n = 72) T8 or below	PJK	16.7% (1/6) vs. 33.3% (24/72)
Daniels et al.[48] 2020	Retrospective	ASD - Scoliosis > 20° - SVA > 5 cm - PT > 25° - TK > 60°	Fusion from the sacrum/ilium to the LT or UT spine	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value PJF (1) PJA ≥ 28° (2) ΔPJA ≥ 21.6° (3) PJ anterolisthesis ≥ 8 mm (UT)/3 mm (LT) (4) ΔPJ anterolisthesis ≥ 8 mm (UT)/3 mm (LT)	UT (n = 134) T1–6	LT (n = 169) T9–12	PJK PJF	23.9% (32/134) vs. 33.1% (56/169) 2-yr follow-up 17.9% (24/134) vs. 22.5% (38/169) 2 yr follow-up
Fujimori et al.[50] 2014	Retrospective	ASD SVA > 40 mm	Fusion from the sacrum to the thoracic spine	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value	UT (n = 31) T1–5	LT (n = 49) T7-T12	PJK PJK requiring surgery	32% (10/31) vs. 41% (20/49), p = 0.4 At least 2-yr follow-up 6.4% (2/31) vs. 10% (5/49), p = 0.6 At least 2-yr follow-up

(*Continued*)

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Table 5. Characteristics of included studies according to UIV level (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	UT	LT	Outcome	Result (UT vs. LT)
Kang et al.[54] 2024	Retrospective	ASD Deg. lumbar kyphoscoliosis	Long-segment fusion surgery (≥4 levels) with ACR followed by posterior instrumentation	PJK Increases of PJA (1) PJA≥28° (2) Changes of PJA≥22° PJF (1) Vertebral fracture at the UIV or UIV+1 (2) Subluxation between these levels (3) Failure of UIV fixation (4) Necessity for proximal fusion extension	≥T10 (n=50)	T11–L1 (n=33) ≤L2 (n=21)	PJK PJF	1/50 vs. 8/33 vs. 7/21, p<0.1 Minimum 2-yr follow-up 7/50 vs. 13/33 vs. 10/21, p=0.1 Minimum 2-yr follow-up
Kim et al.[55] 2014	Retrospective	ASD	Long fusions (≥5 levels) to the sacrum/pelvis	PJK angle sagittal Cobb angle between the UIV and the UIV+2	UT (n=91) T1–6	LT (n=107) T9–L1	Revision for PJK	3/91 vs. 2/107, p=0.45 Average follow-up of 2.5 yr (range, 2.0–3.2 yr)
Kim et al.[23] 2008	Retrospective	ASD - Adult scoliosis (n=106) - Sagittal imbalance syndrome (n=55)	Posterior segmental spinal instrumentation (≥5 levels)	PJK (1) PJA≥10° (2) At least 10° of progression in the PJA from preoperative value	UT (n=99) >T8	LT (n=62) T8 and below	PJK	34/99 vs. 28/62, p=0.17 Minimum 5 yr follow-up
Lazaro et al.[57] 2023	Retrospective	Subset of ASLS-1 patients	Posterior instrumented fusion/fixation of ≥7 vertebral levels including the sacrum/pelvis.	PJK (1) PJA≥10° (2) at least 10° of greater PJA than preoperative measurement PJF (1) Change in PJA>20° compared with the preoperative measurement (2) Fracture of UIV and/or UIV+1 with>20% vertebral height loss (3) Screw dislodgment (4) Spondylolisthesis of UIV+1 relative to UIV of>3 mm	UT (n=67) T1–4 MT (n=20) T5–8	LT (n=73) T9–12	PJF	18/67 vs. 4/20 vs. 24/73, p=0.4794 Mean follow-up: 4.3 yr (range, 0.1–6.1 yr)
Lee et al.[58] 2014	Retrospective	Lumbar Deg, kyphosis	Surgical correction of a sagittal imbalance due to LDK	PJK (1) Aggravation of PJA more than 10° than initial postop and last follow-up (2) Spontaneous vertebral compression fracture on the proximal junctional level	Over T10 (n=17) T11–L1 (n=12)	Below L2 (n=18)	PJK	3/17 vs. 9/12 vs. 17/18 Minimum follow-up 2 yr (mean, 3.8 yr; range, 2–5 yr)

(*Continued*)

Table 5. Characteristics of included studies according to UIV level (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	UT	LT	Outcome	Result (UT vs. LT)
Maruo et al.[20] 2013	Retrospective	ASD	Posterior long instrumented fusion surgery (≥6 vertebrae) to the sacrum	PJK (1) PJA ≥ 10° (2) At least 10° of greater PJA than preop measurement	Proximal (n = 25) T2–5	Distal (n = 65) T9–L1	PJK	44% (11/25) vs. 40% (26/65), p = 0.730 Minimum 2-yr clinical follow-up
O'Shaughnessy et al.[61] 2012	Retrospective	Walking adult patients (> 18 yr) who underwent the primary surgical treatment of their scoliosis	Posterior instrumented fusion to the sacrum more than 6 levels	PJK PJA ≥ 20°	UT (n = 20) T2–5	LT (n = 38) T9–12	PJK	10% (2/20) vs. 18.4% (7/38), p = 0.476 Minimum follow-up 2 yr
							Surgical PJK	0% (0/20) vs. 2.6% (1/38), p = 1.000 Minimum follow-up 2 yr
Onafowokan et al.[38] 2024	Retrospective	ASD	Spine fusion from the thoracic spine to the pelvis	PJK (1) PJA ≥ 28° (2) At least 20° of progression in the PJA from preoperative value PJF (1) Revision surgery due to PJK (2) PJA ≥ 15°, in the presence or absence of evidence of vertebral body fracture, implant fracture or displacement, or disruption of the osseo-ligamentous complex	UT (n = 84) T1–7	LT (n = 148) T8–L1	PJK	48.7% (41/84) vs. 62.8% (93/148), p = 0.048 Follow-up for 5 yr
							Revision for PJK	31.3% (26/84) vs. 39.8% (59/148), p = 0.018 Follow-up for 5 yr
Park et al.[63] 2023	Retrospective	ASD	≥ 4 Level fusion to the sacrum/pelvis	PJK (1) PJA ≥ 15° (2) Fracture at UIV or UIV+1 (3) Pullout of UIV fixation or need for proximal extension of fusion	UT (n = 74) T10 or above	LT (n = 167) T11 or below	PJK	41.9% (31/74) vs. 54.5% (91/167) Follow-up for average 5 yr
Safaee et al.[66] 2021	Retrospective	ASD	The mean number of levels fused was 10 (range, 6–16)	PJF Symptomatic PJK with hardware failure requiring reoperation	UT (n = 120) T1–6	LT (n = 199) T7–12	PJF	2/120 vs. 18/199 Minimum 12-mo follow-up
Tian et al.[39] 2024	Retrospective	Degenerative type ASD	Thoracolumbar fusion involving 5 or more segment	PJK (1) PJA ≥ 10° (2) At least 10° greater PJA from the preop measurement PJF (1) Proximal junctional fracture (2) Fixation failure (3) Kyphosis requiring cranial extension of the fusion	Above T8 (n = 37)	T8–10 (n = 62) Below T10 (n = 50)	PJK/PJF	14/37 vs. 22/62 vs. 9/50, p = 0.068 Minimum 24-mo follow-up

(*Continued*)

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Table 5. Characteristics of included studies according to UIV level (Continued)

Study	Study type	Diagnosis	Surgery	PJK/PJF definition	UT	LT	Outcome	Result (UT vs. LT)
Wang et al.[68] 2016	Retrospective	Deg. scoliosis	Instrumented segmental posterior spinal fusion at a minimum 4 motion segments	PJK (1) PJA ≥ 10° (2) At least 10° of g reater PJA than preop measurement	Above T10 (n = 17)	T11–L1 (n = 43) Below L2 (n = 39)	PJK	1/17 vs. 13/43 vs. 4/39 Minimum 2-yr follow-up (mean, 2.8 yr; range, 2–6 yr)
Wang et al.[69] 2021	Retrospective	Adult degenerative lumbar disease: Degenerative scoliosis or kyphosis Lumbar stenosis Lumbar spondylolisthesis	Posterior instrumented fusion of 4 or more segments	PJF (1) Fracture of the UIV or UIV+1 (2) Pedicle screw loosening (3) Pedicle screw dislodgment (4) Pullout of instrumentation at the UIV	Above T10 (n = 53)	T11–L1 (n = 34) Below L2 (n = 17)	PJF	10/53 vs. 5/34 vs. 8/17 Minimum 2-yr follow-up
Yao et al.[70] 2021	Retrospective	ASD	Posterior fusion for more than 5 levels	PJK (1) PJA ≥ 10° (2) At least 10° greater than the preoperative value Nonbony PJK PJK caused by disc and ligamentous lesions Bony PJK PJK caused by bone failure	UT (n = 29) T1–6	LT(n = 27) T7–12	PJK	11/29 vs. 10/27 Minimum 1-yr follow-up
Ye et al.[71] 2023	Retrospective	ASD - Coronal Cobb angle > 20° - C7-SVA > 5 cm - PT > 25° - TK > 60°	Posterior instrumented spinal fusion of ≥ 5 zvertebrae	PJK At least 20° increase of PJA than baseline	UT (n = 538) ≥ T8	LT (n = 774) ≤ T9	PJK	129/538 vs. 131/774, p = 0.002 Minimum 1-yr follow-up
Yoshie et al.[72] 2023	Retrospective	ASD	Long instrumented fusion surgery from the thorax to the pelvis (minimum 6 level)	PJK (1) PJA ≥ 10° (2) At least 10° of progression in the PJA from preoperative value	UT (n = 6) T1–6	LT (n = 54) T7–12	PJK	2/6 vs. 24/54, p = 0.689 Minimum follow-up of 1 yr

UIV, upper instrumented vertebra; PJK, proximal junctional kyphosis; PJF, proximal junctional failure; ASD, Adult spine deformity; C7-SVA, C7 sagittal vertical axis; PT, pelvic tilt; TK, thoracic kyphosis; PJA, Proximal junctional angle; SVA, sagittal vertical axis; Deg., Degenerative; ACR, anterior column realignment.
PJA: sagittal Cobb angle measured from the caudal endplate of the UIV to the cephalad endplate of UIV+2.
ASLS-1: prospective, multicenter, consecutive series of patients from a National Institutes of Health sponsored study designed to assess operative versus nonoperative treatment of adults with symptomatic lumbar scoliosis.

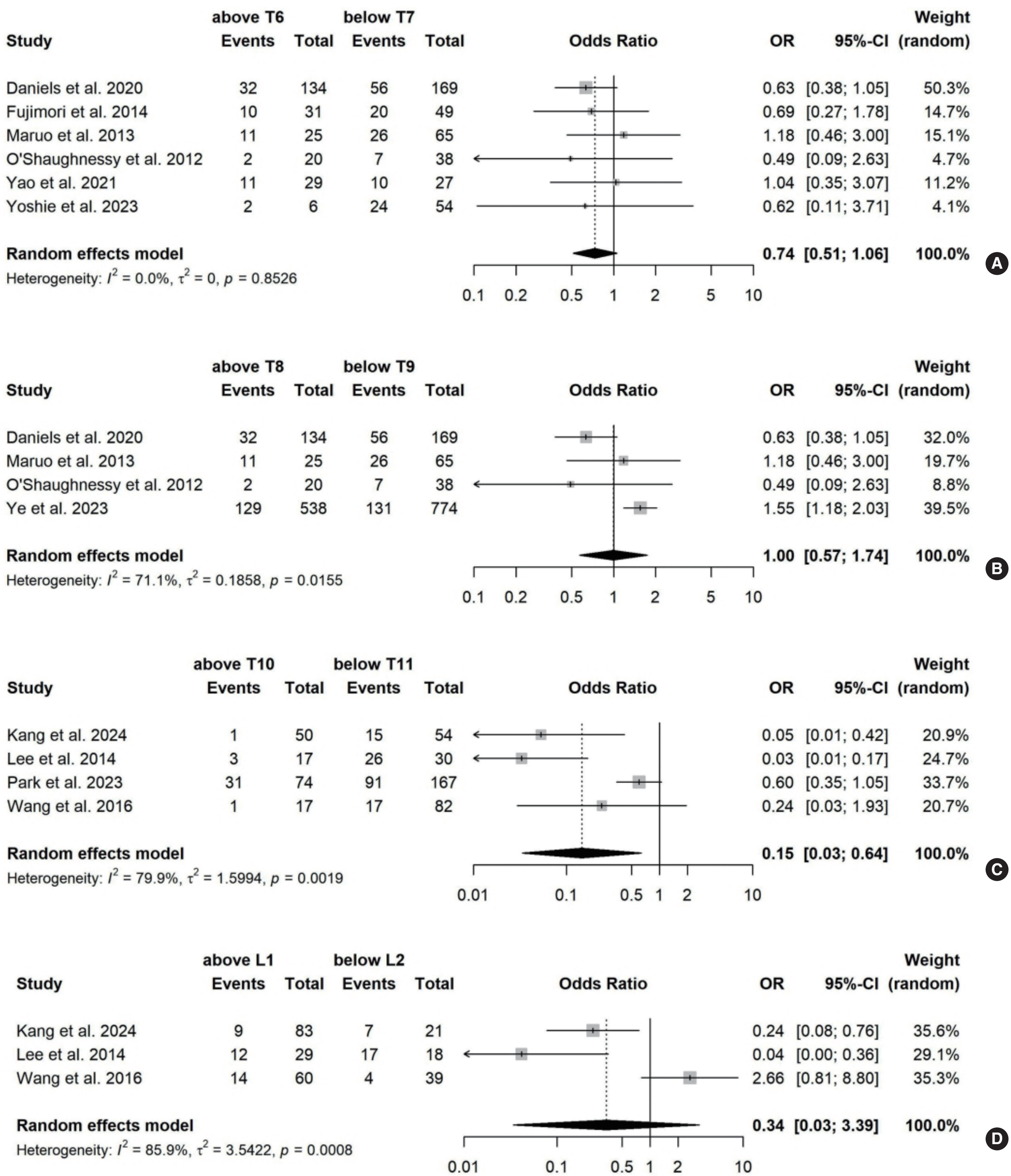

Fig. 5. Meta-analysis of the effect of UIV level on PJK rates. (A) With a cutoff of T6 (T6 and above vs. T7 and below). (B) With a cutoff of T8 (T8 and above vs. T9 and below). (C) With a cutoff of T10 (T10 and above vs. T11 and below). (D) With A cutoff of L1 (L1 and above vs. L2 and below). UIV, upper instrumented vertebra; PJK, proximal junctional kyphosis; OR, odds ratio; CI, confidence interval.

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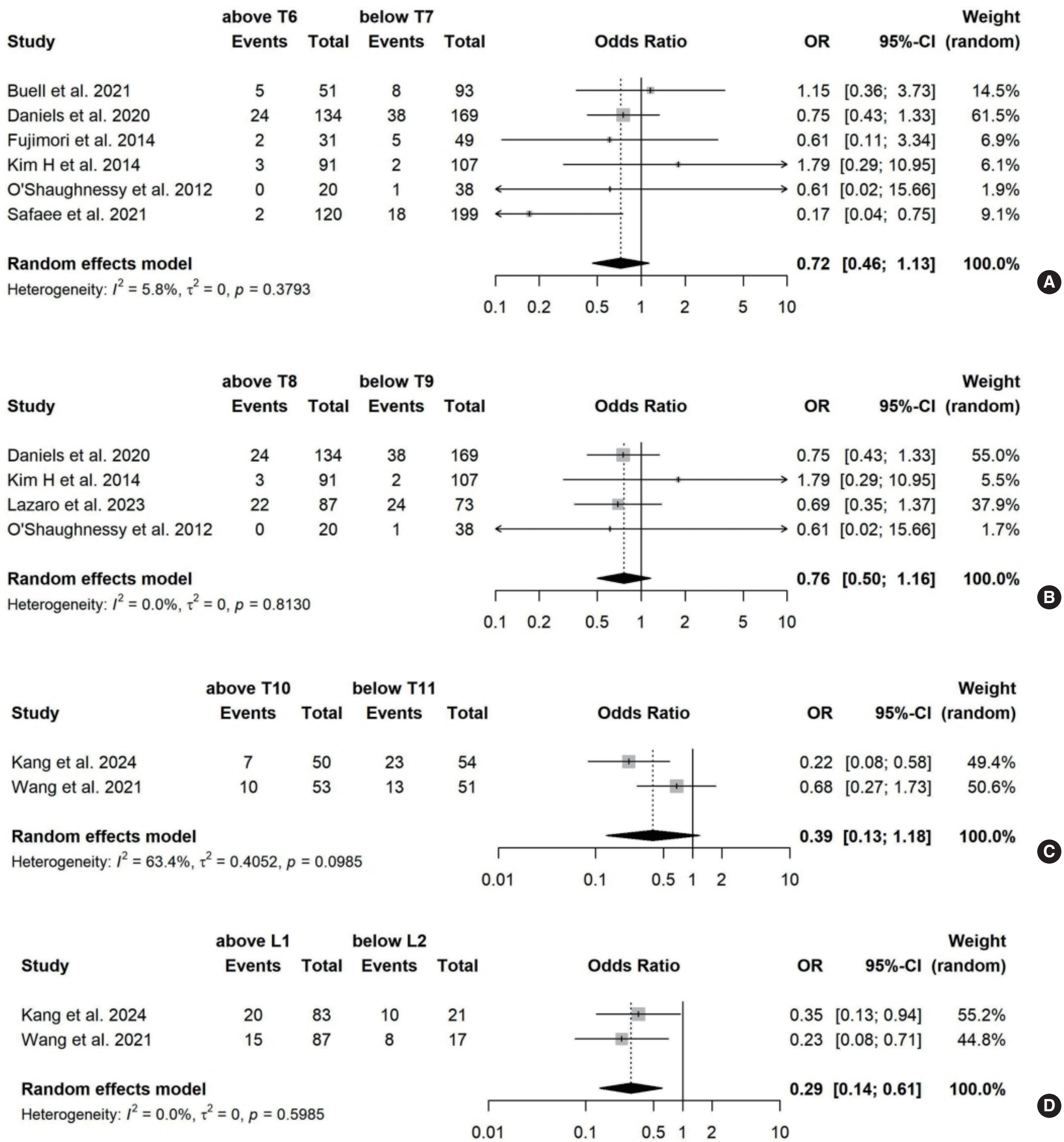

Fig. 6. Meta-analysis of the effect of UIV level on PJF rates. (A) With a cutoff of T6 (T6 and above vs. T7 and below). (B) With a cutoff of T8 (T8 and above vs. T9 and below). (C) With a cutoff of T10 (T10 and above vs. T11 and below). (D) With a cutoff of L1 (L1 and above vs. L2 and below). UIV, upper instrumented vertebra; PJF, proximal junctional failure; OR, odds ratio; CI, confidence interval.

than rod stiffness alone.[36]

There was no significant difference when the UIV cutoff was set at T6 or T8. Although the rib cage provides additional stability, particularly in the upper thoracic spine, where true ribs are present,[91] patients undergoing correction surgery with UIV above T6 often have more severe ASD,[92] which may confound outcomes. This may explain why no significant difference was observed in PJK or PJF rates despite the added rib cage stability. A similar confounding effect may exist for the T8 cutoff. Additionally, T8 is often located near the apex of thoracic kyphosis,[93] a region subject to increased mechanical stress, which may complicate its suitability as a UIV level.[92]

When the UIV cutoff was set at T10, patients with UIV at ≥ T10 showed a lower incidence of PJK in our meta-analysis. Although lower thoracic levels (including false ribs) provide less stability than upper thoracic segments, vertebrae above T10 still benefit from rib cage support.[94,95]

Moreover, the thoracolumbar junction (TLJ), a transitional zone between the rigid thoracic spine and the mobile lumbar spine, is inherently subjected to mechanical stress.[96] This makes it especially vulnerable to osteoporotic fractures, as reflected in clinical data showing a high prevalence of osteoporotic vertebral fractures at the TLJ, particularly in older individuals.[97] When instrumentation of the mobile lumbar spine extends to the TLJ, stress concentration and hypermobility at the proximal junction may be exacerbated, potentially increasing the risk of PJK or PJF. Consistent with this mechanism, our meta-analysis showed a reduced incidence of PJK when the UIV was placed at T10 or above, thereby avoiding the mechanically vulnerable TLJ. Some studies have suggested that TLJ instrumentation may be considered in selected cases, such as younger patients (< 70 years) without osteoporosis.[98] However, based on our findings and the biomechanical considerations outlined above, we recommend avoiding the TLJ as the UIV in vulnerable populations, particularly those with osteoporosis. We further suggest that future meta-analyses and prospective studies incorporate subgroup analyses focusing on osteoporotic patients to clarify the specific risks associated with UIV selection at the TLJ in this population.

Furthermore, UIV at L1 or above showed a lower incidence of PJF in our meta-analysis, which can be explained from multiple perspectives. First, this group includes patients with UIV at T10 or above, levels that have already demonstrated protective effects against PJK, likely because of rib cage support and avoidance of the TLJ. Second, when the UIV ends at L2 or below, particularly in osteoporotic patients, increased weight-bearing stress may lead to mechanical failure, supported by finite element analysis and clinical evidence showing increased adjacent segment stress and degeneration following short lumbar fusion.[99,100] Third, limited correction due to the shorter construct of UIV at L2 or below may contribute to the higher rate of mechanical complications. A recent study reported that short fusion resulted in significant loss of sagittal alignment and a higher incidence of PJK, likely reflecting undercorrection.[101] Therefore, future studies or meta-analyses stratifying outcomes by the degree of sagittal correction, rather than fusion length alone, may provide a more nuanced understanding of risk factors for junctional complications.

Based on our findings, setting the UIV proximal to the TLJ, specifically above T10, may help reduce the incidence of PJK and PJF. Although the stabilizing effect of the rib cage diminishes below the true rib region, even false ribs may provide partial biomechanical support.[91,94] However, selecting a very proximal UIV level should be carefully considered on a case-by-case basis, taking into account the patient's overall condition, surgical morbidity, and alignment goals. Therefore, a UIV at T10 or slightly higher may provide a balance between achieving mechanical stability and minimizing surgical invasiveness.

Given the heterogeneous and multifactorial nature of PJK and PJF pathogenesis, a single preventive technique may not be universally effective. Additionally, patients vary widely in osteoporosis severity, comorbidities, and alignment goals, further limiting the applicability of a uniform preventive strategy. Moreover, even within the same patient, mechanical stress may differ depending on the UIV level. A biomechanical study by Yagi et al. found that at lower UIV levels, although tethers offer some biomechanical benefit, they do not sufficiently reduce compressive stress, and significant stress concentrations persist, suggesting the need for additional prophylactic measures such as vertebroplasty.[79]

From a patient-centered perspective, preventive strategies may be prioritized differently according to individual risk profiles. For example, augmentation may be particularly advantageous for patients with severe osteoporosis, whereas tethers may be more appropriate in cases requiring rigid deformity correction. This aligns with previous comprehensive reviews emphasizing that optimal prevention of mechanical complications requires multifactorial, patient-specific approaches integrating surgical, radiologic, and bone quality factors.[102] However, direct comparative evidence across these subgroups remains limited, and future studies stratified by bone quality, age, and deformity severity are warranted to refine individualized preventive strategies.

This study has some limitations. First, this review focused solely on surgical techniques for preventing PJK and PJF. Therefore, other potential risk factors, such as age, sex, bone mineral density, sagittal alignment, and comorbidities that could act as confounders, were beyond the scope of this analysis.

Second, all included studies were retrospective, and the number of available studies was limited. This also made it impossible to adjust for previously noted nonsurgical confounders, as the

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small number of studies did not allow meaningful subgroup analyses. Regarding surgical factors, although we performed analyses based on UIV levels in the overall dataset, the limited sample size prevented additional subgroup analyses for each surgical technique (e.g., hooks, tethers) by UIV level or by specific definitions of PJK and PJF used in individual studies. Furthermore, the levels at which preventive techniques (e.g., hooks, tethers, cement) were applied varied across studies, potentially contributing to clinical heterogeneity and limiting the interpretability of the pooled estimates. Nonetheless, sensitivity analyses demonstrated consistent directions of effect, supporting the overall robustness of the findings despite such variability. Additionally, although a random-effects model was applied, this statistical method cannot eliminate inherent between-study heterogeneity.

Third, the retrospective designs and absence of prospective or randomized studies limited the ability to control for bias. In several studies, the decision to apply preventive strategies was left to the surgeon's discretion. This may have led to the preferential selection of patients with more favorable bone quality, alignment, or overall clinical condition, introducing potential selection bias. Although all included studies scored high on the NOS, such inherent bias cannot be fully controlled and should be considered when interpreting the pooled estimates.

Fourth, definitions of PJK and PJF varied across studies. Because of the limited number of studies in each subgroup, we were unable to perform stratified or sensitivity analyses based on specific definitions. This heterogeneity may have influenced the pooled estimates. However, as PJK and PJF are commonly considered part of a pathological spectrum at the proximal junction, the meta-analysis used reported rates according to each study's definitions, despite variability.

Fifth, formal assessment of publication bias (e.g., funnel plots or Egger test) was not feasible because each comparison included fewer than 10 studies. Therefore, small-sample publication bias cannot be excluded.

Finally, despite our efforts to minimize duplicate inclusion from overlapping patient populations, some studies may still have included overlapping cohorts, especially those from the same institutions or authorship groups, which may have introduced unintended duplication into the pooled estimates.

CONCLUSION

This meta-analysis suggests that preventive surgical strategies such as tethering, hooks, and prophylactic vertebral augmentation may help reduce the risk of PJK and PJF. However, given the heterogeneity in application levels and patient selection across studies, these results should be interpreted with caution. Rather than dismissing any technique based on limited evidence, we cautiously recommend that these modalities be tailored and combined according to individual patient and surgical contexts. UIV selection should also be made carefully, taking into account each patient's alignment goals and the stability characteristics of the thoracic spine. While placing the UIV slightly above T10 may offer improved stability, consistent with our findings, care should be taken to avoid unnecessarily proximal fixation.

Despite the inherent limitations of this meta-analysis, including its reliance on retrospective studies, we believe these findings contribute to a more evidence-based approach to preventing PJK and PJF. Nevertheless, as all included studies were retrospective observational cohorts, high-quality prospective and randomized controlled studies are needed to validate these results, reduce confounding, and establish clearer clinical consensus on optimal preventive strategies.

NOTES

Supplementary Materials: Supplementary Methods 1-3, Supplementary Table 1, and Supplementary Figs. 1-2 are available at https://doi.org/10.14245/ns.2551254.627.

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