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Prevention of Proximal Junctional Kyphosis Using Proximal Fixation Techniques

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ABSTRACT

Background: Adult spinal deformity (ASD) is a disorder characterized by abnormal curvature of the spine resulting from progressive degeneration of spinal elements. Although operative intervention for ASD is commonplace, it is associated with several complications, including proximal junctional kyphosis (PJK) and proximal junctional failure (PJF). The objective of this review is to outline the role of proximal fixation in preventing PJK and PJF.

Methods: We conducted a literature search using the Embase, Scopus, Web of Science, CINHAL, Cochrane Library, and PubMed MEDLINE databases. We considered only studies focusing on adult patients and selected clinical studies investigating proximal fixation techniques.

Results: There was mixed evidence of the efficacy of hooks and other instrumentation methods in preventing PJK, although most studies supported the use of hooks. Selection of lower thoracic vertebrae was associated with higher rates of PJK and PJF in several studies, although the relationship was inconsistent, and many studies reported no significant difference in rates of PJK or PJF between different upper instrumented vertebra (UIV) levels. Other techniques that are not related to specific instrumentation or vertebral selection, such as adjusting UIV screw trajectory, were also referenced. However, the evidence supporting these techniques was limited.

Discussion: Despite the presence of numerous studies in the literature discussing proximal fixation strategies to reduce the incidence of PJK/PJF, the lack of prospective studies and high variability in study methods make direct comparison challenging. We could not draw strong conclusions regarding the superiority of any one technique, despite promising clinical results with a strong biomechanical basis in several studies.

Clinical Relevance: This systematic literature review showed that a variety of proximal fixation techniques have been used to prevent PJK/PJF without clear evidence in favor of any particular technique.

Level of Evidence: 3.

Lumbar Spine

Keywords: proximal junctional kyphosis, outcomes, prevention

INTRODUCTION

Over the next several decades, as the US population continues to age, the prevalence of adult spinal deformity (ASD) is expected to rise considerably. While operative intervention for ASD has been shown to be beneficial, it has been associated with relatively high rates of complications, including proximal junctional kyphosis (PJK). The prevalence of PJK among patients who have had ASD correction is generally thought to be between 17% and 39%, with some studies reporting incidence as high as 69% at 3-year follow-up.[1,2] Many patients ultimately require revision surgery for proximal junctional failure (PJF), which can incur significant morbidity and cost for patients. Furthermore, there remains a risk for recurrence of PJK even after revision surgery, with one study reporting a recurrence rate of 44% among 70 patients.[3] Because of the numerous challenges PJK presents, there has been considerable research on prevention. Several patient-specific, radiographic, and surgical risk factors for PJK have been identified.[4] Various prevention strategies have been adopted to address these risk factors, but a widely accepted algorithm has yet to emerge. One area under investigation is surgical prevention through proximal fixation. The underlying theory of this strategy is that a more gradual transition of forces to the noninstrumented spine, with less disruption of natural spine biomechanics, can prevent PJK. The objective of this review is to assess the current literature to understand the role of proximal fixation techniques in preventing PJK. We consider the options that have been studied to date, the strength of their supporting evidence, and their efficacy.

DEFINITION, RISK FACTORS, AND TIMING

The original definition of PJK was proposed by Glattes et al[5] in a retrospective study of 81 adult patients with ASD. PJK was established as a sagittal

Cobb angle of ≥10° between the upper instrumented vertebrae (UIVs) and the superior 2 levels (UIV+2) and an angle ≥10° greater than the preoperative baseline. PJF is commonly recognized as any form of PJK requiring revision surgery. This can be due to UIV or UIV+1 fracture, posterior osseo-ligamentous disruption, or failure of instrumentation at the UIV.[6] Many risk factors have been identified as possible contributors to PJK. Patient-specific risk factors such as age, body mass index, bone density, smoking, and the presence of other medical comorbidities have all been proposed. Older age has been linked to higher rates of PJK in numerous studies.[5,7–11] Several surgical risk factors are also thought to contribute to PJK. These are generally related to disruption of surrounding supportive soft tissues,[12] excessive construct rigidity,[13] choice of UIV,[14] or magnitude of deformity correction.[9] Finally, radiographic risk factors include a high preoperative sagittal vertical axis[15,16] and a high degree of thoracic kyphosis.[17,18]

PJK generally becomes apparent within the first 1 to 2 years after surgery. Kim et al[10] reported that 59% of proximal junctional angle (PJA) progression occurs within the first 8 weeks postoperatively. However, in the same study, 35% of the total PJA progression occurred more than 2 years after surgery, suggesting PJK has a progressive component as well. In contrast, PJF is often a relatively early complication. Yagi et al[19] reported that 87% of patients with PJF had undergone revision surgery within 2 years after surgery, with a mean time to revision of 10 months. Other studies have reported similar findings, with average times to revision of approximately 6 months.[6,20] There remains controversy over the clinical significance of PJK; although a considerable proportion of patients are asymptomatic, many studies report poorer functional scores and worse patient-reported pain in patients with PJK.[8,21] Patients who require revision surgery are subject to perioperative complications and considerable costs. Hart et al[22] estimated an average cost of $77,432 for revision of PJF.

PREVENTION THROUGH PROXIMAL FIXATION

The Table summarizes selected studies. These studies were reviewed independently by 2 of the authors, and their subject matter was deemed relevant to the current review. Conflicts were resolved via discussion. Studies were classified according to the author, study type, quality assessment based on the Newcastle-Ottawa Score, number of patients included, type of operative treatment utilized, mean age of included patients, minimum follow-up (if specified), prophylactic technique or implant investigated, and relationship to PJK incidence.

Hooks

The use of various hooks at the UIV has been investigated as a preventive measure. The underlying theory of this technique is that, compared with pedicle screws (PSs), hooks at the UIV provide a more gradual transition of construct stiffness to the upper, noninstrumented vertebrae and less mechanical stress. This theory has been supported by numerous biomechanical studies that demonstrate a better range of motion and less construct stiffness with the use of hooks in a multitude of animal and cadaveric models.[40–42] Photographs of PS and laminar hook constructs in a porcine model are shown in Figure 1 for reference.[43] Several clinical studies support the use of hooks at the UIV. Cazzulino et al[25] describe a "soft-landing technique" in which they used unilateral preservation of the soft-tissue sleeve combined with one or more hooks on the contralateral side in 39 patients. They observed an incidence of radiographic PJK (which they defined as PJA greater than 10°, differing from the traditional definitions) of 41% over an average of 2.2 years of follow-up. Four patients (10%) required an extension of the construct and met the criteria for PJF. They did not have a control group for comparison. Hassanzadeh et al[21] used transverse process hooks (TPHs) in 47 patients undergoing long spinal fusion, with 20 receiving a TPH and 27 receiving a PS alone as a control cohort. The minimum follow-up was set at 2 years. None of the patients in the TPH group developed PJK, while 8 patients in the PS group developed PJK ($P = 0.01$). The TPH group also had significantly higher functional scores compared with the PS group at the final follow-up ($P < 0.05$). In a multicenter study of 625 patients, Line et al[32] analyzed the effect on PJF rates with no supplementary fixation vs various implant options. Augmentation methods included TPHs, cement vertebroplasty, and tethering. PJF occurred at a rate of 20.3% in the no-augmentation group and 10.3% in the augmentation group. TPHs had the lowest rate of PJF at 7% ($n = 115$).

Despite several promising clinical studies, there is also evidence showing no association and even a negative association between hooks and PJK incidence. Matsumura et al[33] compared TPH with PS in 39 patients; 17 patients received a TPH and 22 received a PS at the UIV. The incidence of PJK (defined solely as a change in the

Table. Selected clinical studies of proximal fixation techniques in adult patients.

First Author (Year)	Study Type	Quality Assessment	No. of Patients	Treatment for ASD	Patient Age, y, Mean ± SD	Minimum Follow-up (mo)	Technique/Factor Investigated	Results	Association With PJK Incidence
Buell (2021)[23]	Retrospective cohort	Good	560	Long sacropelvic fusion	63 ± 9	24	UT vs LT UIV	No difference in reoperation rates for PJK between UT group (9.8%) and LT group (8.6%) ($P = 0.81$)	None
Burks (2019)[24]	Retrospective case series	Fair	36	Hybrid MIS-open surgical fusion, in which ≥2 most rostral levels were instrumented percutaneously	65 ± 11	12	Muscle-sparing technique at the proximal end	PJK rate, 22% ($n = 8$); similar to reported rates; no reoperations for PJK/PJF	No control for comparison; similar to reported literature rates
Cazzulino (2021)[25]	Retrospective cohort	Fair	39	Fusion using a soft-landing technique	61 ± 10	None specified; mean follow-up 26 months	TPH	Radiographic PJK in 16/39 patients at last follow-up; 4 patients met criteria for PJF with revision; 3 cases of compression fracture at the UIV or UIV+1	No control for comparison; similar to reported literature rates
Cho (2013)[26]	Retrospective cohort	Good	51	Posterior fusion; assigned to cohorts based on UIV location in relation to UEV and HV	68 ± 6 in the adjacent segment disease group, 63 ± 6 in the control	24	Selection of UIV	PJK in 5 patients, 2 requiring fusion extensions/all had UIV below UEV; junctional kyphotic angles were not different between any groups	Lower incidence of PJK with higher UIV
Daniels (2019)[27]	Retrospective cohort	Good	303	Posterior instrumentation	63 ± 9	24	UT vs LT UIV	Lower PJK rate in UT compared with LT fusions (OR, 0.49; 95% CI, 0.24–0.99); no difference in PJF (OR, 0.54; 95% CI, 0.24–1.2)	Lower incidence of PJK with higher UIV
Ha (2013)[28]	Retrospective cohort	Good	89	Various, treated 2007 to 2009	64 ± 7 (LT); 64 ± 11 (UT)	24	UT vs LT UIV	PJK in 29 patients (23 in LT, 6 in UT, $P = 0.61$); 8 revision surgeries for PJK in LT group and 2 in UT group ($P = 0.68$); higher incidence of compression fracture in LT group (16/23, 70%), higher incidence of subluxation in UT group (3/6, 50%) ($P = 0.014$)	None
Hassanzadeh (2013)[21]	Retrospective cohort	Good	47	Long (≥5 levels) spinal fusion, 2004 to 2009	46 (TPH); 51 (PS)	24	TPH	PJK in 8/27 patients in PS group compared with none in the TPH group ($P = 0.02$) between immediate postoperative and final follow-up; 2/8 underwent revision surgery; mean PJA was 6.4° ± 10° in the TPH group and 22° ± 14° in PS group ($P < 0.001$)	Lower incidence of PJK with TPH
Kaufmann (2022)[29]	Prospective cohort	Good	76	Posterior instrumentation and fusion of ≥3 levels; 2009 to 2017 at 1 center	64 ± 9 (MLSS); 55 ± 20 (control)	12	MLSS vs standard PS	PJF in 10% of MLSS group, 31% of control ($P = 0.02$); less kyphosis in MLSS group (5.2° ± 6.3° compared with control 1.3° ± 5.3°, $P = 0.01$)	Lower incidence of PJK with MLSS

Table. Continued.

First Author (Year)	Study Type	Quality Assessment	No. of Patients	Treatment for ASD	Patient Age, y, Mean ± SD	Minimum Follow-up (mo)	Technique/Factor Investigated	Results	Association With PJK Incidence
Kim (2014)[9]	Retrospective cohort	Good	198	Long (>5 levels) fusion, from a multicenter database	61 (UT); 62 (LT)	24	UT vs LT UIV	No difference in PJK angle at 1- and 2-year follow-up (UT 14° vs LT 14° at 1 year; 17° vs 19° at 2 years); 5 patients underwent a revision for PJK (3 in UT group and 2 in LT group) ($P = 0.45$)	None
Kim (2007)[30]	Retrospective cohort	Good	125	Instrumentation and fusion	52 ± 11 (T9-10); 57 ± 12 (T11-12); 62 ± 12 (L1-2)	24	UIV location (T9-10, T11-12, or L1-2)	PJK in 51% in T0-10 group, 55% in T11-12 group, 36 % in L1-2 ($P = 0.2$) at final follow-up; 1 revision for PJK in T11-12 group and 3 in L1-2 group ($P = 0.27$); final change in PJA was not different between all groups ($P = 0.46$)	None
Lafage (2017)[31]	Case-control	Good	252	Posterior fusion and instrumentation	61 ± 10	24	UT vs LT UIV	PJK in 49 % of UT UIV group vs 64 % of LT/TL group ($P = 0.02$); smaller UIV inclination between PJK and non-PJK groups when stratified into both UT ($P = 0.005$) and LT/TL ($P < 0.001$) groups	Lower incidence of PJK with higher UIV
Line (2020)[32]	Retrospective cohort	Good	625	Long (≥5 levels) spinal fusion	62 ± NA	12	No proximal fixation augmentation vs various augmentation options, including TPH	PJF in 20% of no implant group, 11% of the implant group; 115 in TPH group, 7% rate of PJF (lowest of all augmentation), but 8.7% underwent surgical revision because of discrepancies in the definition for PJF used in the study ($P < 0.05$ for aforementioned rates of PJK)	Lower risk of PJK with TPH
Matsumura (2018)[33]	Retrospective cohort	Fair	39	Corrective surgery performed, 2009 to 2013	67 ± NA	24	TPH	PJK in 18% of TPH group vs 27% in PS group ($P = 0.47$); change in PJA greater in PS group (19°) than TPH group (5°) ($P = 0.04$)	Lower incidence of PJK with TPH
O'Shaughnessy (2012)[34]	Retrospective cohort	Good	58	Fusion including the sacrum, treated 2002 to 2006	55 ± 9 (UT); 56 ± 8 (LT)	24	UT vs LT UIV	PJK in 18% of LT group, 10% of UT group ($P = 0.476$); surgical PJK 2.6% in LT group, 0 in UT group ($P > 0.99$); no other differences in complications between groups	None
Sandquist (2015)[35]	Prospective cohort	Good	15	Posterior instrumentation and fusion of ≥3 levels, 2009 to 2012 (subset from a study by Kaufmann et al)	66 ± NA	12	MLSS vs standard PS	Mean change in PJA was 4.0° (range, –0.92 to 9.13); no cases of PJK or PJF were recorded	Lower incidence of PJK with MLSS
Scheer (2015)[36]	Retrospective cohort	Good	165	PSO, from a multicenter database	60 ± 11 (UT); 60 ± 11 (LT)	24	UT vs LT/TL UIV	PJK in 52% of UT group, 48% of LT/TL group ($P = 0.85$); 11 PJK cases requiring revision, 9/11 in TL/LT group and 2/11 in UT group ($P = 0.03$)	No significant association with PJK incidence, higher incidence of PJF with lower UIV

Table. Continued.

First Author (Year)	Study Type	Quality Assessment	No. of Patients	Treatment for ASD	Patient Age, y, Mean ± SD	Minimum Follow-up (mo)	Technique/Factor Investigated	Results	Association With PJK Incidence
Tsutsui (2022)[37]	Retrospective cohort	Good	53	Fusion from pelvis to T9 or T10	73 ± 4 (TPH); 72 ± 4 (PS)	12	TPH	Higher incidence of PJK in TPH group (36%) vs PS group (8%) ($P = 0.01$); in TPH group, PJK caused in all cases by UIV or adjacent segment fracture with hook dislodgement	Higher incidence of PJK with TPH
Wang (2017)[38]	Retrospective cohort	Good	242	Posterior fusion and instrumentation of ≥4 levels, from 2004 to 2014	59 ± 6 (PAS); 60 ± 6 (MAS)	None; mean follow-up 25 ± 4 months	PAS vs MAS at UIV	PJK in 26/117 (22%) in MAS group, 30/125 (24) in PAS group ($P = 0.73$); greater change in PJA in PJK subgroup (2.9° vs 1.7°) ($P = 0.03$)	None
Yoshida (2020)[39]	Case-control	Good	113	Surgery for degenerative spinal disorders, including both ASD ($n = 45$) and non-ASD patients ($n = 68$)	67 ± 8 (ASD); 57 ± 20 (non-ASD)	12	UIV to C2 plumb line distance	PJK in 10/45 ASD patients; sub-analysis of PJK vs non-PJK patients showed significantly greater distances from UIV to both C7 and C2 plumb lines on standing and sitting radiographs for PJK group; on logistic regression analysis, UIV to C2 distance was found to be significantly associated with PJK (OR 1.2; 95% CI 1.0–1.3)	UIV farther from C2 plumb line associated with a higher incidence of PJK

Abbreviations: ASD, adult spinal deformity; CI, confidence interval;HV, horizontal vertebra; LT, lower thoracic;MAS, monoaxial screw; MIS, minimally invasive surgery; MLSS, multilevel stabilization screw; NA, not available; OR, odds ratio;PAS, polyaxial screw; PJA, proximal junctional angle; PJF, proximal junctional failure; PJK, proximal junctional kyphosis; PS, pedicle screw(s);PSO, pedicle subtraction osteotomy; TL, thoracolumbar; TPH, transverse process hooks; UEV, upper-end vertebra; UIV, upper instrumented vertebra; UT, upper thoracic.

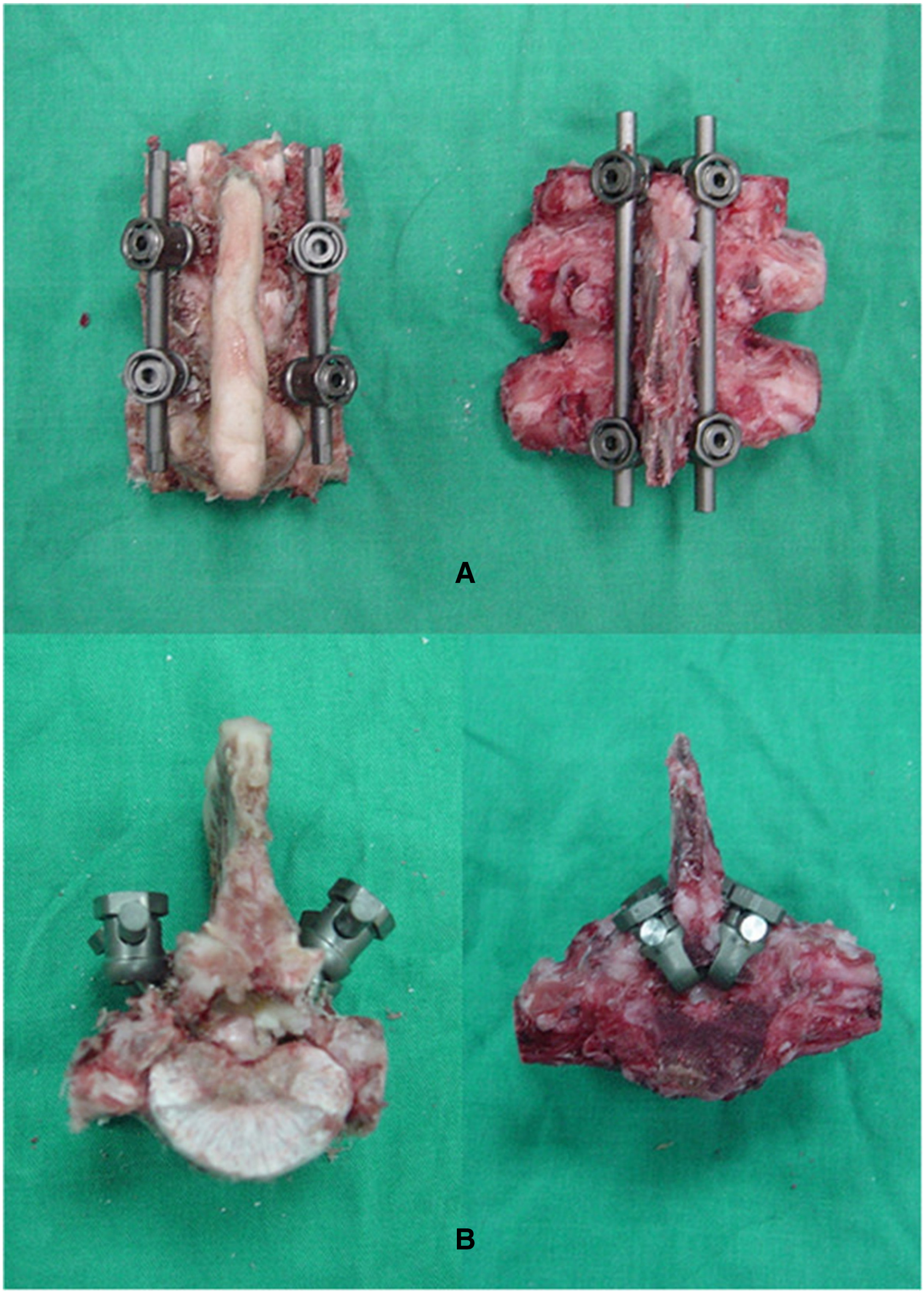

Figure 1. Posterior (A) and superior (B) views of porcine spinal constructs instrumented with traditional pedicle screws, left, and laminar hooks, right. *Source:* Reprinted from Figure 4 in Tai et al. Biomechanical comparison of different combinations of hook and screw in one spine motion unit–an experiment in porcine model. BMC Musculoskelet Disord. 2014;15:197[43] under Creative Commons CC BY license.

PJA of >20°) was 17.6% in the TPH group and 27.3% in the PS group, but this difference was not found to be statistically significant. They did find a larger change in PJA in the PS group compared with the TPH group, 19° vs 5° (P = 0.04). Only a single study found that TPHs were associated with higher rates of PJK. Tsutsui et al[37] performed a retrospective review of 28 patients with a TPH and 25 with a PS at the UIV at either T-9 or T-10. They found a significantly higher incidence of PJK in the TPH group compared with the PS group (25.7% vs 8.0%) at a 1-year follow-up. Ultimately, there is a lack of high-quality evidence supporting the use of hooks as a definitive PJK prevention measure, albeit with several promising clinical studies and sound underlying biomechanical evidence. Larger trials are needed to investigate this method further.

Another prophylactic option for PJK prevention is the use of vertebral tethers around the UIV. Operating on a similar principle as TPHs, vertebral tethers are hypothesized to provide a more gradual transition of forces from the UIV to the noninstrumented vertebrae above, therefore reducing the incidence of PJK. This effect has been demonstrated in several biomechanical studies and finite element analyses.[44–46] There is promising recent clinical evidence that suggests that various tethering techniques are effective in reducing the incidence of PJK.[47,48] However, despite this evidence, a variety of tethering techniques are under investigation, and some studies have shown that certain methods are not associated with significantly different PJK incidence.[49] Other studies have shown that tethering, while effective at reducing PJK incidence, is not demonstrably superior to other methods such as the use of hooks,[32] with an optimal instrumentation configuration remaining unclear.

Screw Techniques

Alternative screw techniques at the UIV have been implemented to achieve a similar reduction in construct stiffness. One such technique involves cranially directed transvertebral screws, which are inserted at the inferolateral aspect of the most superior pedicles. The screw is then directed obliquely and superiorly across one or more vertebral levels, depending on the technique. Sandquist et al[35] reported on PJF in a sample of 15 patients who received screws placed with this technique, termed multilevel stabilization screws (MLSSs), with at least 1-year follow-up. A 3-dimensional reconstruction of this technique is shown in Figure 2.[35] None of the 15 patients experienced PJF, and there was an average change in their sagittal Cobb angle of 4°, ranging from −0.92° to 9.13°. The same researchers published a later study of 76 patients, including 26 controls receiving standard instrumentation.[29] The MLSS group had a significantly lower incidence of PJK when compared with the control group, 10.0% vs 30.8% (P = 0.023), as well as a significantly lower PJA (1.3° ± 5.3° vs 5.2° ± 6.3°, P = 0.014). Another study investigated the role of polyaxial vs monoaxial screws as another means of reducing construct stiffness. Wang et al[38] used monoaxial screws (MAS) instead of the more frequently used polyaxial screws (PAS) in a sample of 242 patients, observing no difference in PJK rates when compared with the polyaxial screw technique (22.2% and 24.0%, respectively).

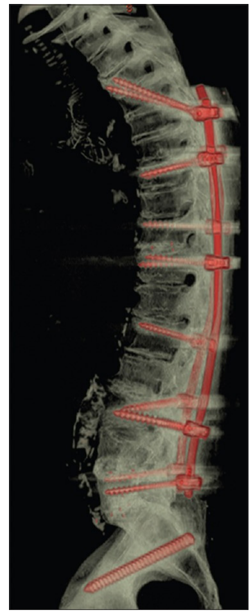

Figure 2. Three-dimensional reconstruction demonstrating a multilevel stabilization screw construct. *Source:* Reprinted from Figure 3 in Sandquist et al. Preventing proximal junctional failure in long segmental instrumented cases of adult degenerative scoliosis using a multilevel stabilization screw technique. *Surg Neurol Int*. 2015;6:112[35] under Creative Commons license CC BY.

Implant Orientation and Trajectory

It is well known that PS angle modulates mechanical stress and screw pullout strength in biomechanical models,[50] and this has led some to postulate that screw trajectory may also influence PJK. Harris et al[51] studied PS trajectory as a risk factor for PJK and found that screws angled greater than 3° cranially were associated with significantly increased incidence of PJK and PJF. The authors hypothesized that this was a result of the creation of a larger bone channel when using a caudally directed trajectory, decreasing stress and increasing pullout strength. This benefit was balanced against the risk of facet joint violation with additional caudal angulation.

In addition to screw trajectory, the mismatch between proximal rod contour and PJA has been analyzed in several studies. Yan et al[52] found that greater angle mismatch between the PJA and proximal rod contour was associated with higher rates of postoperative PJK compared with constructs with rod contours that more closely matched the PJA. Numerous additional studies support this finding. For example, in a retrospective case series, Yang et al[53] found that the cohort of patients with PJK included a significantly higher proportion of individuals with poorly matched (greater than 5°) proximal rod contouring compared with the cohort without PJK (69% vs 25%).[53] However, many of these studies were conducted with populations that included adolescent patients, making their generalizability to entirely adult populations questionable.

Soft Tissue Preservation

Violation of and excessive damage to soft tissues around the UIV are believed to contribute to the development of PJK.[54,55] Various methodologies to preserve local soft-tissue envelopes and ligamentous support have been described. These techniques are typically combined with additional instrumentation prophylaxis as opposed to being used as standalone methods. The increased use of minimally invasive surgical (MIS) techniques has led several groups to investigate MIS and hybrid fixation options for preserving soft tissue integrity. Mummaneni et al[56] compared PJK rates in circumferential MIS (cMIS) with a hybrid approach for ASD and found lower rates of PJK in the cMIS group but no difference when controlling for a number of levels fused. Burks et al[24] studied percutaneous fixation at the upper 2 instrumented levels in hybrid-MIS ASD correction in a case series of 36 patients.[24] They observed rates of PJK that were similar to those in the generally published literature but did not have a control group for comparison. Thus far, there has not been a consistently demonstrated advantage of MIS techniques compared with traditional open surgery for the prevention of PJK.

UIV Selection

The influence of UIV level on the incidence of PJK has long been debated. Generally, it is important to select a stable, neutral vertebra and a level that allows for the inclusion of spinal segments with significant baseline kyphosis. However, these decisions are not always straightforward; extension of the construct to the upper thoracic (UT) levels may be associated with its own perioperative complications and may increase overall construct stiffness. Furthermore, the involvement of higher vertebral levels may increase the risk for catastrophic PJK and devastating neurological injuries compared with shorter fusions. The literature has not yet provided clear guidance on an optimal strategy, and there is mixed evidence about a consistent relationship between the UIV level and the development of PJK.

In several studies, the selection of a more caudal UIV was related to higher rates of PJK, PJF, and the need for surgical revision. Daniels et al[27] retrospectively analyzed 303 patients and observed significantly lower rates of PJK (odds ratio [OR] 0.49, 95% confidence interval [CI] 0.24–0.99) and lower rates of PJF (OR 0.54, 95% CI 0.24–1.22) for a UT UIV compared with a lower thoracic (LT) UIV at 2-year follow-up. Cho et al[26] observed 51 patients with 2 years of follow-up and found that the rates of PJK were greater when the UIV was at or below the upper-end vertebra of the deformity, with all 5 cases (5 of 51, 10%) of PJK occurring in this group. A larger cohort study of 165 patients treated with pedicle subtraction osteotomy found a greater number of patients requiring surgical revision for PJK based on UIV location, with 2 of 11 in the UT group and 9 of 11 in the thoracolumbar (TL) group ($P = 0.0274$). However, overall rates of PJK were not significantly different between the groups.[36] In a case-control study of 252 ASD patients who underwent posterior instrumentation and fusion, Lafage et al[31] found that 63.5% of patients in the TL group developed PJK, compared with 49.2% in the UT group ($P = 0.02$). Another aspect to consider in UIV selection is the position in which patients are evaluated during preoperative imaging. Typically, patients are evaluated in a standing position for radiographs, yet many patients spend significantly larger portions of their lives sitting. Yoshida et al[39] performed a study in which both sitting and standing preoperative radiographs were used to determine the relationship of PJK to various parameters, including coronal distance to C2 and C7 plumb lines. They hypothesized that a sitting radiograph would be a better predictor of PJK as it better represents resting biomechanics. They found that a UIV that was greater than 115 mm from the C2 plumb line on sitting radiographs was significantly associated with a higher incidence of PJK on logistic regression analysis. This finding was not replicated with standing radiographs. The distance to the C7 plumb line was also investigated in this study but was not found to be significantly associated with PJK.

There have been several studies showing no relationship between UIV level and PJK incidence. In a retrospective cohort study of 58 patients, O'Shaughnessy et al[34] found no significant difference in either PJK incidence or surgical revision rates between the UT and LT groups with a minimum of 2 years follow-up. Similarly, Kim et al[9] followed 198 patients undergoing long instrumentation (>5 levels) for ASD for 2 years. When the patients were divided into UT and LT groups, their measured PJK angles and surgical revision rates were not significantly different at follow-up. Buell et al[23] conducted a retrospective analysis of 560 patients who underwent surgical correction for ASD with 2 years of follow-up. They found similar rates of reoperation for PJK in the UT and LT groups, 9.8% vs 8.6%, respectively ($P = 0.810$). Ha et al[28] compared the incidence of PJK in patients with upper fixation at either proximal thoracic (PT) or distal thoracic (DT) levels. Among the 89 patients, there were no significant differences between the PT and DT cohorts in rates of PJK, PJF, or other measured clinical outcomes. They did find, however, that vertebral compression fracture was more prevalent in the DT group, while subluxation was more prevalent in the PT group. Kim et al,[30] in a study of patients undergoing instrumentation and fusion for ASD, established 3 retrospective cohorts based on UIV location (T9-T10, T11-T12, and L1-L2) with 2 years of follow-up. There was no significant difference in overall rates of PJK (51%, 55%, and 36% for T9-T10, T11-T12, and L1-L2, respectively, $P = 0.2$). There were also no significant differences in the total change in the PJA from preoperative measurement to final follow-up ($P = 0.46$).

SUMMARY

PJK and PJF are potentially severe complications of corrective surgery for ASD, with a prevalence that is expected to increase in the United States as the population ages. Prevention of PJK and PJF will be of great importance in providing effective, high-value care and will require the development of well-defined prevention strategies. Proximal fixation techniques and surgical planning represent one subset of these strategies, although effective PJK prophylaxis will undoubtedly require a mix of surgical and patient-specific strategies. While there is compelling biomechanical and clinical data to support more in-depth clinical investigation into proximal fixation techniques such as PJK prophylaxis, current data are insufficient to draw firm conclusions about the superiority of any one method.

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