



Alignment Risk Factors for Proximal Junctional Kyphosis and the Effect of Lower Thoracic Junctional Tethers for Adult Spinal Deformity

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■ **OBJECTIVE:** The aims of this retrospective cohort study were to 1) identify new alignment risk factors for proximal junctional kyphosis (PJK) in adult spinal deformity (ASD) patients with lower thoracic upper instrumented vertebra (UIV) and 2) determine the effect of junctional tethers on PJK and UIV alignment.

■ **METHODS:** We analyzed consecutive ASD patients who underwent posterior instrumented fusion with lower thoracic UIV (T9-T11). Posteriorly anchored junctional tethers were used more recently for ligamentous augmentation to prevent PJK. In addition to regional and global parameters, upper segmental lumbar lordosis (ULL) versus lower segmental lumbar lordosis and UIV angle (measured from UIV inferior endplate to horizontal) were assessed. Primary outcome of PJK was defined as proximal junctional angle $>10^\circ$ and $>10^\circ$ greater than the corresponding preoperative measurement. Univariable and multivariable analyses were performed.

■ **RESULTS:** The study cohort comprised 120 ASD patients (mean age, 67 years) with minimum 1-year follow-up. Preoperative ULL ($P = 0.034$) and UIV angle ($P = 0.026$) were associated with PJK. No independent preoperative alignment risk factors of PJK were identified in

multivariable analysis. Tether use was protective against PJK (odds ratio, 0.063 [0.016–0.247]; $P < 0.001$). PJK in tethered patients was more common with greater postoperative ULL ($P = 0.047$) and UIV angle ($P = 0.026$).

■ **CONCLUSIONS:** Junctional tethers significantly reduced PJK in ASD patients with lower thoracic UIV. In tethered patients, PJK was more common with greater postoperative lordosis of the upper lumbar spine and greater UIV angle. This finding suggests potential benefit of tethers to mitigate effects of segmental lumbar and focal UIV malalignment that may occur after deformity surgery.

INTRODUCTION

Proximal junctional kyphosis (PJK) remains a common problem after multilevel instrumented spine surgery for adult spinal deformity (ASD). The reported rates of PJK after scoliosis surgery vary widely from 7% to 46%.^{1–13} Because PJK may warrant revision surgery, various preventive techniques have been proposed, including vertebral cement augmentation, multi-level stabilization screws, transverse process hooks at the upper

Key words

- Adjacent segment disease
- Adult spinal deformity
- Complication
- Proximal junctional kyphosis
- Scoliosis
- Spinal fusion
- Tethers

Abbreviations and Acronyms

- ASD:** Adult spinal deformity
CI: Confidence interval
LL: Lumbar lordosis
LLL: Lower segmental lumbar lordosis
n: Number
OR: Odds ratio
PI: Pelvic incidence
PJA: Proximal junctional angle
PJK: Proximal junctional kyphosis
PT: Pelvic tilt
SVA: Sagittal vertical axis

TK: Thoracic kyphosis

UIV: Upper instrumented vertebra

ULL: Upper segmental lumbar lordosis

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instrumented vertebra (UIV), proximal transition rods of reduced diameter, and hybrid constructs.¹⁴⁻²¹ We previously reported our experience with posteriorly-anchored, polyethylene junctional tethers as a novel anti-PJK technique and demonstrated its safety and efficacy in ASD patients undergoing multilevel (>6 levels) posterior spinal instrumentation.²²⁻²⁴

The pathophysiology of PJK remains incompletely understood^{8,25}; however, many investigators agree that it is likely multifactorial and may involve a combination of surgical, radiographic, alignment, and patient-related risk factors.^{2-6,9,26-28} A possible risk factor for PJK may be location of the UIV in the lower thoracic spine.^{5,13,27,29,30} The proximal segment of long fusions with lower thoracic UIV experience distinct biomechanical stresses compared to those with upper thoracic UIV.²⁷ This situation may be reflected by the distinct failure mechanisms based on UIV location: the most common failure modes in the lower versus upper thoracic spine are vertebral fracture versus soft tissue disruption/subluxation (without fracture or instrumentation failure).^{27,31} Another possible PJK risk factor reported by Lafage et al.³² is the presence of a more posterior construct inclination at the proximal terminus of fusion constructs.

Although certain regional and global radiographic spinopelvic parameters have been identified as PJK risk factors,²⁻⁶ the effects of segmental lumbar and focal UIV alignment on PJK have not been fully investigated.³² Also, the protective role of lower thoracic junctional tethers against PJK and its potential effect on segmental or focal UIV alignment are incompletely understood. Therefore, the aims of this retrospective cohort study were to 1) identify new alignment risk factors for PJK in ASD patients with lower thoracic UIV and 2) investigate effects of lower thoracic junctional tethers on PJK and UIV alignment.

METHODS

We retrospectively reviewed an institutional review board–approved, prospectively-collected single-center database of ASD patients who underwent posterior instrumented fusion with UIV in the lower thoracic spine (T9-T11). All operations were performed by the 2 senior authors between 2012 and 2016. Inclusion criteria were: 1) diagnosis of scoliosis and/or global sagittal malalignment (i.e., abnormal sagittal vertical axis [SVA], thoracic kyphosis, lumbar lordosis [LL], and/or pelvic incidence to LL mismatch); 2) age >18 years; 3) deformity correction with instrumented segmental posterior spinal fusion (may have also had anterior approach procedure) at >6 motion segments; 4) pedicle screw instrumentation without transitional rods or hooks at the UIV; and 5) availability of complete radiographic data with preoperative, early postoperative (within 3 months), and standing long-cassette films at final follow-up ≥ 1 year. Patients were excluded if there was: 1) preoperative diagnosis of degenerative spine disease without significant scoliosis or global sagittal malalignment; 2) evidence of active vertebral osteomyelitis/discitis; or 3) revision spine surgery without change in UIV.

Radiographic Measurements

Standing posteroanterior and lateral long-cassette (14 × 36 in) radiographs at preoperative baseline, early postoperative follow-up, and at final follow-up were reviewed for all patients. The

following parameters were measured: SVA, pelvic tilt (PT), pelvic incidence (PI), lumbar lordosis (LL), upper segmental lumbar lordosis from L1 to L4 (ULL), lower segmental lumbar lordosis from L4 to S1 (LLL), and T5-T12 sagittal Cobb angle (thoracic kyphosis [TK]). The angle between the line drawn parallel to the UIV inferior endplate and the horizontal was defined as the UIV angle (Figure 1). (+) UIV angle has the most anterior part of the UIV inferior endplate above the horizontal, and (–) UIV angle has the most anterior part of the UIV inferior endplate below the horizontal. Abnormal PJK was defined as a sagittal Cobb angle measured from the UIV inferior endplate and UIV+2 superior endplate that was $>10^\circ$ and $>10^\circ$ greater than the corresponding preoperative measurement (Figure 2). Radiographic data were collected and reviewed independent of the 2 senior operating surgeons.

Tethering Technique

The anti-PJK tethering technique at our institution has been previously described in detail.²² Briefly, all tethers consisted of 5 mm woven polyethylene Mersilene tape (Ethicon, Somerville, New Jersey, USA) on a blunt needle. Tethers were placed using 1 of 2 techniques: polyethylene tape only (passed through base of UIV+1 and UIV–1 and tied securely) or tape with crosslink (passed through base of UIV+1 and tied to crosslink between UIV–1 and UIV–2). Tether use was dependent on the time period that the patient underwent surgery (tethers were used in all patients treated after September 2013 for one surgeon and January 2015 for the other surgeon, whereas no tethers were used before those respective dates), and hence, selection bias may be partially mitigated.

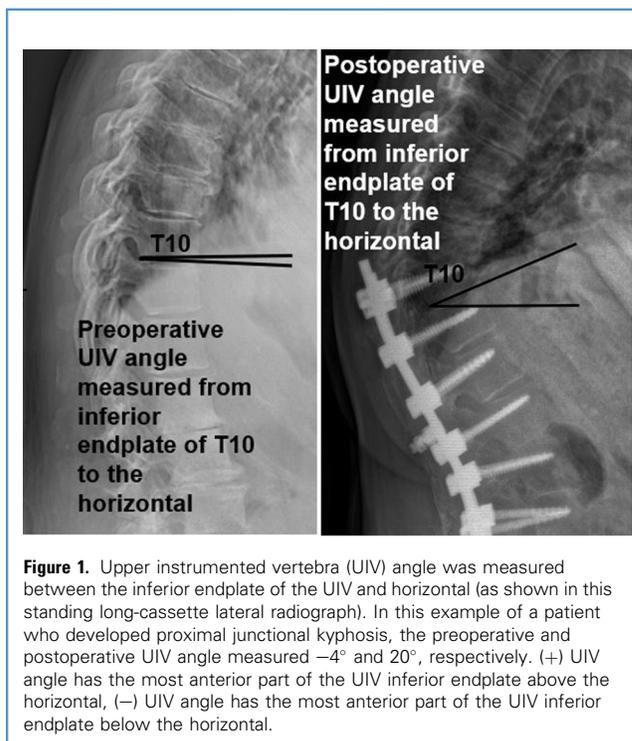
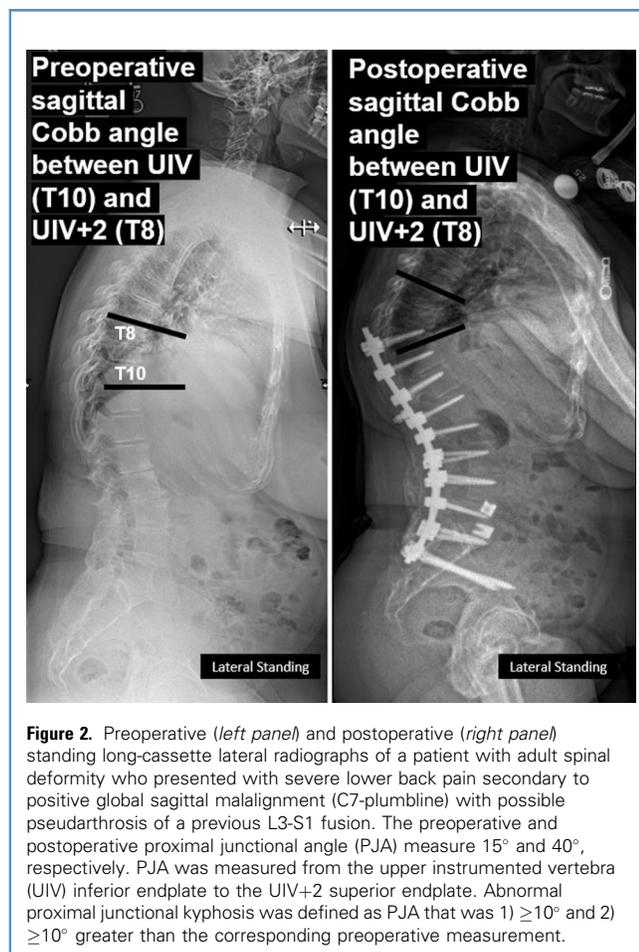


Figure 1. Upper instrumented vertebra (UIV) angle was measured between the inferior endplate of the UIV and horizontal (as shown in this standing long-cassette lateral radiograph). In this example of a patient who developed proximal junctional kyphosis, the preoperative and postoperative UIV angle measured -4° and 20° , respectively. (+) UIV angle has the most anterior part of the UIV inferior endplate above the horizontal, (–) UIV angle has the most anterior part of the UIV inferior endplate below the horizontal.



Statistical Analysis

Patients were dichotomized into 2 groups (PJK and non-PJK) based on development of PJK on radiographic review. Patient demographics, surgical data, and preoperative and early postoperative sagittal plane radiographic parameters were compared using independent sample Student *t* test, Pearson χ^2 test, Fisher-Freeman-Halton exact test,³³ or Fisher exact test, as appropriate. All tests were 2-tailed and *P* values of <0.05 were considered statistically significant. Variables that reached statistical significance on univariate analyses were entered in a stepwise multivariable binary logistic regression model. Test for goodness-of-fit was assessed using the Hosmer-Lemeshow test.³⁴ Subgroup analysis was performed for those who developed PJK. Data are presented as mean and standard deviation for continuous variables, and as percentages for categorical variables. SPSS version 24.0 (released 2016. IBM Corp., Armonk, New York, USA) was used to perform all analyses.

RESULTS

Univariate Analyses of Demographics, Surgical, and Sagittal Plane Radiographic Parameters

In total, 120 (89%) of 135 eligible patients had minimum 1-year follow-up and were included in this study (mean follow-up, 28

months [range, 12–57 months]); 64% were women and the mean age was 67.3 years. Patient demographics and surgical data are presented in **Table 1**. PJK was observed in 49 of 120 patients (41%), and tethers were less commonly used in the PJK group compared with the non-PJK group (23/49 [47%] vs. 50/71 [70%]; $\chi^2 = 6.710$; *P* = 0.010). No significant differences in age at surgery, sex, preoperative body mass index, number of instrumented vertebrae, UIV location (T9-T11), use of pelvic fixation, 3-column osteotomy, or surgical approach (posterior-only vs. 2-stage anterior-posterior) were found between the 2 groups. There were no intraoperative or postoperative complications in this study that could be attributed to use of tethers.

Table 1 also details the preoperative and postoperative spinopelvic parameters for PJK and non-PJK groups. Preoperative SVA (6.83 ± 6.74 vs. 9.28 ± 6.38 cm; *P* = 0.048), preoperative ULL ($4.77^\circ \pm 15.13^\circ$ vs. $-2.14^\circ \pm 18.65^\circ$; *P* = 0.034), preoperative UIV angle ($2.37^\circ \pm 13.04^\circ$ vs. $-3.57^\circ \pm 15.64^\circ$; *P* = 0.026), postoperative PT ($20.87^\circ \pm 7.74^\circ$ vs. $26.12^\circ \pm 11.69^\circ$; *P* = 0.007), postoperative TK ($32.77^\circ \pm 12.26^\circ$ vs. $47.22^\circ \pm 10.35^\circ$; *P* < 0.001), change in total LL ($16.55^\circ \pm 16.60^\circ$ vs. $23.55^\circ \pm 18.80^\circ$; *P* = 0.034), change in ULL ($14.96^\circ \pm 13.92^\circ$ vs. $25.73^\circ \pm 19.13^\circ$; *P* = 0.001), and change in UIV angle ($12.23^\circ \pm 12.20^\circ$ vs. $22.45^\circ \pm 16.38^\circ$; *P* < 0.001) were significantly different between the 2 groups. Other measured spinopelvic parameters were not significantly different between the 2 groups.

Multivariable Analysis

Results of multivariable analysis are also detailed in **Table 1**. Variables that reached statistical significance on univariate analyses were included in the multivariable logistic regression model, and included: use of polyethylene tether, preoperative SVA, preoperative ULL, preoperative UIV angle, postoperative PT, postoperative TK, change in total LL, change in ULL, and change in UIV angle. Polyethylene tether use demonstrated a protective effect against PJK (odds ratio [OR], 0.063 [0.016–0.247]; *P* < 0.001) in the multivariable analysis. There were no independent preoperative alignment risk factors of PJK that were identified in the multivariable model. Postoperative PT (OR, 1.099 [1.020–1.185]; *P* = 0.013) and postoperative TK (OR, 1.164 [1.090–1.243]; *P* < 0.001) were significantly associated with PJK.

Revision Surgery for Proximal Junctional Failure

Seven patients (4 had tethers) required revision surgery for PJK. Mean age was 66.43 ± 4.28 years, 57% (4/7) were women, and mean time between the index operation and revision was 11.71 ± 5.28 months. Indications for revision surgery because of PJK included severe back pain (86% [6/7]), lower extremity radicular pain (43% [3/7]), thoracic radicular pain (43% [3/7]), and/or focal neurologic deficit (29% [2/7]). Although not statistically significant, there was a lower revision rate for PJK when comparing tether and non-tether cohorts (5% vs. 6%; *P* > 0.05).

PJK Subgroup Analysis

Table 2 details the preoperative and the early postoperative radiographic parameters between tether and non-tethered patients in the PJK cohort. Tether use was associated with greater postoperative ULL ($26.78^\circ \pm 6.90^\circ$ vs. $20.58^\circ \pm 13.57^\circ$; *P* = 0.047) and greater postoperative UIV angle ($21.83^\circ \pm 8.14^\circ$

Table 1. Comparison of Baseline Patient Demographics, Surgical Data, and Sagittal Plane Radiographic Parameters Between Proximal Junctional Kyphosis and Non-Proximal Junctional Kyphosis Groups

	Non-PJK (n = 71)	PJK (n = 49)	P Value†	Binary Logistic Regression*		
				Odds Ratio	95% Confidence Interval	P Value
Age (years), mean (SD)	66.49 (7.96)	68.47 (8.46)	0.195	—	—	—
Sex, female/male	41/30	36/13	0.077 ($\chi^2 = 3.117$)	—	—	—
Body mass index, kg/m ² (SD)	29.28 (4.64)	29.47 (5.88)	0.843	—	—	—
Number of instrumented vertebrae (SD)	9.63 (0.68)	9.76 (0.56)	0.306	—	—	—
Upper instrumented vertebra, n (%)			0.710	—	—	—
T9	4 (5.63)	3 (6.12)				
T10	43 (60.56)	33 (67.35)				
T11	24 (33.80)	13 (26.53)				
Posterior polyethylene tether, n (%)	50 (70.42)	23 (46.94)	0.010 ($\chi^2 = 6.710$)	0.063	0.016–0.247	<0.001
Pelvic fixation, n (%)	66 (92.96)	47 (95.92)	0.699	—	—	—
3-column osteotomy, n (%)	14 (19.72)	8 (16.33)	0.637 ($\chi^2 = 0.223$)	—	—	—
Posterior-only approach, n (%)	65 (91.55)	47 (95.92)	0.470	—	—	—
Preoperative						
Sagittal vertical axis, cm (SD)	6.83 (6.74)	9.28 (6.38)	0.048	1.032	0.869–1.226	0.717
Pelvic tilt, ° (SD)	24.72 (9.07)	26.31 (10.11)	0.370	—	—	—
Pelvic incidence, ° (SD)	51.28 (11.65)	53.04 (12.40)	0.430	—	—	—
Lumbar lordosis, ° (SD)	31.51 (18.32)	27.67 (18.33)	0.262	—	—	—
Pelvic incidence–lumbar lordosis mismatch, ° (SD)	19.42 (18.79)	24.22 (18.57)	0.169	—	—	—
Thoracic kyphosis, ° (SD)	20.86 (15.95)	23.50 (12.44)	0.338	—	—	—
Upper segmental lordosis L1-L4, ° (SD)	4.77 (15.13)	−2.14 (18.65)	0.034	0.990	0.930–1.054	0.753
Lower segmental lordosis L4-S1, ° (SD)	24.96 (15.60)	26.98 (13.58)	0.464	—	—	—
Upper instrumented vertebra angle, ° (SD)	2.37 (13.04)	−3.57 (15.64)	0.026	1.039	0.939–1.150	0.461
Postoperative						
Sagittal vertical axis, cm (SD)	3.17 (4.31)	4.68 (3.89)	0.052	—	—	—
Pelvic tilt, ° (SD)	20.87 (7.74)	26.12 (11.69)	0.007	1.099	1.020–1.185	0.013
Pelvic incidence, ° (SD)	48.97 (10.69)	50.20 (10.41)	0.532	—	—	—
Lumbar lordosis, ° (SD)	48.06 (8.56)	51.22 (10.26)	0.069	—	—	—
Pelvic incidence–lumbar lordosis mismatch, ° (SD)	0.92 (11.45)	−1.02 (10.90)	0.355	—	—	—
Thoracic kyphosis, ° (SD)	32.77 (12.26)	47.22 (10.35)	<0.001	1.164	1.090–1.243	<0.001
Amount of correction						
Sagittal vertical axis, cm (SD)	−3.66 (5.84)	−4.33 (6.54)	0.556	—	—	—

Bold values represent statistically significant comparisons ($P < 0.05$) and the associated odds ratios with 95% confidence intervals.

PJK, proximal junctional kyphosis; SD, standard deviation.

*Multivariable analysis, using nonimputed data set. Hosmer-Lemeshow goodness-of-fit test $\chi^2 (8) = 6.433$, $P = 0.599$.

†Univariate analysis with comparison of non-PJK versus PJK groups analyzed with independent sample Student t test (2-tailed), Pearson χ^2 test, Fisher-Freeman-Halton exact test, or Fisher exact test.

Continues

Table 1. Continued

	Non-PJK (n = 71)	PJK (n = 49)	P Value [†]	Binary Logistic Regression*		
				Odds Ratio	95% Confidence Interval	P Value
Lumbar lordosis, ° (SD)	16.55 (16.60)	23.55 (18.80)	0.034	1.023	0.968–1.081	0.419
Upper segmental lordosis L1-L4, ° (SD)	14.96 (13.92)	25.73 (19.13)	0.001	0.947	0.881–1.017	0.136
Lower segmental lordosis L4-S1, ° (SD)	1.34 (14.14)	2.92 (11.06)	0.080	—	—	—
Upper instrumented vertebra angle, ° (SD)	12.23 (12.20)	22.45 (16.38)	<0.001	1.066	0.965–1.178	0.210

Bold values represent statistically significant comparisons ($P < 0.05$) and the associated odds ratios with 95% confidence intervals.

PJK, proximal junctional kyphosis; SD, standard deviation.

*Multivariable analysis, using nonimputed data set. Hosmer-Lemeshow goodness-of-fit test $\chi^2(8) = 6.433$, $P = 0.599$.

[†]Univariate analysis with comparison of non-PJK versus PJK groups analyzed with independent sample Student t test (2-tailed), Pearson χ^2 test, Fisher-Freeman-Halton exact test, or Fisher exact test.

vs. $16.27^\circ \pm 8.69^\circ$; $P = 0.026$) compared with non-tethered patients in the PJK group. Tether use was also associated with greater changes in ULL ($32.43^\circ \pm 18.89^\circ$ vs. $19.42^\circ \pm 17.93^\circ$; $P = 0.017$) and UIV angle ($29.00^\circ \pm 17.22^\circ$ vs. $16.65^\circ \pm 13.40^\circ$; $P = 0.007$) compared with no tether use in the PJK group after surgery.

DISCUSSION

ASD is a highly prevalent disease that has been associated with significant pain and disability.^{35,36} In appropriately selected cases, surgery significantly improves clinical symptoms and patients' quality of life^{37,42}; however, PJK is encountered after sagittal realignment surgery and at times may warrant reoperation.¹⁻¹³ Reported risk factors for PJK after long instrumented posterior spinal fusion include: older age at surgery (>55 years), obesity, preoperative comorbidities (i.e., osteopenia/osteoporosis), severe preoperative or residual postoperative global sagittal malalignment, marked correction of sagittal malalignment, smaller LL compared with TK postoperatively, combined anterior and posterior spinal fusion (vs. posterior only), and fusion to the sacrum.^{2-6,9,26-28}

There is debate whether UIV location in the upper thoracic versus lower thoracic spine is a risk factor for PJK.³¹ Kim et al.^{9,43} identified UIV location from T1 to T3 as a PJK risk factor; however, the study cohort was heterogeneous and included all age groups: 36.8% of the patients were <18 years (adolescent idiopathic scoliosis), and only 27.7% of the patients were in the age group (>50 years old) that is more representative of reported ASD surgical cohorts.⁴³ Most studies indicated higher incidence of PJK with UIV in the lower thoracic spine or thoracolumbar region compared with the upper thoracic spine.^{5,13,27,29,30} The most common modes of failure are different in the lower versus upper thoracic spine; vertebral fracture was commonly encountered in the lower thoracic spine compared with soft tissue disruption/subluxation (without fracture or instrumentation failure) in the upper thoracic spine.^{27,31} To include a more homogenous patient cohort, our study cohort included only those ASD patients with T9-T11 UIV.

Table 2. Subgroup Analysis of Proximal Junctional Kyphosis Patients Dichotomized Based on Use of Posterior Polyethylene Tethers

	Tether (n = 23)	No Tether (n = 26)	P Value*
Sagittal vertical axis, cm (SD)			
Preoperative	9.58 (7.57)	9.00 (5.24)	0.755
Postoperative	4.13 (3.09)	5.17 (4.44)	0.349
Delta	-5.46 (7.84)	-3.33 (5.07)	0.260
Lumbar lordosis, ° (SD)			
Preoperative	24.30 (21.51)	30.65 (14.78)	0.242
Postoperative	51.48 (8.08)	51.00 (12.02)	0.870
Delta	27.17 (20.67)	20.34 (16.73)	0.208
Upper segmental lordosis L1-L4, ° (SD)			
Preoperative	-5.65 (18.80)	0.96 (18.31)	0.219
Postoperative	26.78 (6.90)	20.58 (13.57)	0.047
Delta	32.43 (18.89)	19.42 (17.93)	0.017
Lower segmental lordosis L4-S1, ° (SD)			
Preoperative	27.96 (10.86)	26.12 (15.77)	0.641
Postoperative	24.00 (6.25)	24.12 (12.99)	0.968
Delta	-3.96 (11.80)	-2.00 (10.52)	0.542
Upper instrumented vertebra angle, ° (SD)			
Preoperative	-7.17 (17.70)	-0.38 (13.09)	0.131
Postoperative	21.83 (8.14)	16.27 (8.69)	0.026
Delta	29.00 (17.22)	16.65 (13.40)	0.007

Bold values represent statistically significant comparisons ($P < 0.05$).

SD, standard deviation.

*Comparison of tether versus non-tether proximal junctional kyphosis patients analyzed with independent sample Student t test (2-tailed).

To our knowledge, this study is the first to simultaneously investigate lower thoracic focal UIV alignment and upper versus lower segmental LL as a predictor of PJK. Recently, Lafage et al.³² reported that a more posterior construct inclination at the proximal segments of long fusions was present in ASD patients who developed PJK. Their study suggested that the orientation of the proximal fused segments has a critical impact on focal changes at the UIV.³² This finding is consistent with our univariate results; namely, greater postoperative correction of ULL and UIV angle were significantly associated with PJK.

This study is also the first to investigate the protective effects of junctional tethers against PJK in the context of segmental lumbar and focal UIV alignment. Consistent with our previous experience,²² use of posterior polyethylene tethers was protective against PJK in both univariable and multivariable analyses. In further subgroup analysis of the patients who developed PJK ($n = 49$), tether use was associated with greater postoperative (both the absolute measurement and amount of correction) upper segmental LL and UIV angle compared with no tether use. We hypothesize that tether use provides additional junctional support at the proximal terminus of constructs, and that greater focal or segmental sagittal realignment at the proximal fused segments may be achieved without a compensatory mechanism (i.e., PJK) to counteract these forces.^{32,44} Also, greater postoperative lordosis of the upper lumbar spine demonstrated in the tethered PJK group compared with the non-tethered PJK group ($26.78^\circ \pm 6.90^\circ$ vs. $20.58^\circ \pm 13.57^\circ$) may represent nonphysiologic or nonharmonious deformity correction.⁴⁵ In the normal adult spine, the lower lumbar segments account for most of overall lumbar lordosis.⁴⁵ Therefore, in our study, tether use may have partially mitigated nonphysiologic biomechanical stresses produced from upper segmental lumbar (and possibly focal UIV) malalignment or overcorrection. A recent study by Faundez et al. confirms the importance of a harmonious curve distribution of lumbar lordosis (ULL and LLL) after thoracosacral spine fusion. The investigators reported that exaggerated ULL may increase the lever arm and bending moment at the thoracolumbar junction, resulting in junctional breakdown.⁴⁶

The presence of PJK alone does not constitute an absolute indication for reoperation. In this study, we revised patients with PJK (with an extension of their fusion to the upper thoracic spine) when there was severe, progressively worsening pain (back pain, lower extremity radicular pain, and/or thoracic radicular pain), significant focal neurologic deficits, and/or ambulatory difficulty. Although PJK is common after long segment fusion operations, revision rates for PJK (i.e., surgical PJK) are variable, which may reflect an inconsistency between radiographic findings and clinical signs and symptoms.^{8,11,13} Luo et al. recently performed a meta-analysis¹³ and reported an incidence of 6.7% for surgical PJK. Our results are comparable, and we also reported lower revision rates

with use of junctional tethers (5% vs. 6%; $P > 0.05$). We hypothesize that a larger cohort is necessary to show statistically significant differences in surgical PJK rates between tethered and non-tethered patients.

It is important to recognize the limitations of our study, which is retrospective in nature with weakness and biases inherent in its design. Therefore, this study may be subject to selection and observer biases. However, tether use was dependent on the time period that the patient underwent surgery (tethers were used in all patients treated after September 2013 for one surgeon and January 2015 for the other surgeon, whereas no tethers were used before those respective dates), and hence, selection bias may be partially mitigated. Also, we acknowledge that patients in the tether group had significantly different baseline sagittal measurements (SVA, ULL, and UIV angle) on univariate analyses. However, these baseline differences were accounted for in the multivariable analysis. After controlling for these baseline differences, as well as postoperative alignment changes, tether use was still protective against PJK.

Another limitation is that the early occurrence of PJK in some cases precluded the ability to obtain a follow-up radiograph without the presence of PJK and the accompanying compensatory changes. Therefore, whether greater postoperative PT and TK are risk factors for the development of PJK (we found postoperative PT [$P = 0.013$] and TK [$P < 0.001$] significantly associated with PJK in our multivariable model) or are a compensatory consequence of PJK needs further study. Although poor-quality radiographs were excluded and standard techniques for obtaining long-cassette scoliosis radiographs were used, radiographic measurements may be variable because of image quality, technique, and observer reliability. It is unknown if our findings are generalizable to all patients undergoing spine surgery, particularly those without a diagnosis of ASD such as adolescent idiopathic scoliosis. Further studies are necessary to better define the role of focal or segmental UIV alignment in the lower thoracic spine, as well as the effects of junctional tethers on treatment outcomes and rates of surgical PJK.

CONCLUSIONS

Posteriorly-anchored junctional tethers significantly reduced postoperative occurrence of PJK in ASD patients with UIV in the lower thoracic spine. In tethered patients, PJK was more common with greater postoperative lordosis of the upper lumbar spine and greater postoperative UIV angle. This finding suggests potential benefit of junctional tethers to mitigate the effects of segmental lumbar and focal UIV malalignment that may occur after spinal deformity surgery. Prospective studies are warranted to further investigate the efficacy of lower thoracic junctional tethers and their effects on UIV alignment for ASD.

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