Check for updates

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

Thomas J. Buell[1], Ching-Jen Chen[1], John C. Quinn[2], Avery L. Buchholz[3], Marcus D. Mazur[1], Jeffrey P. Mullin[1], James H. Nguyen[1], Davis G. Taylor[1], Shay Bess[4], Breton G. Line[4], Christopher P. Ames[5], Frank J. Schwab[6], Virginie Lafage[6], Christopher I. Shaffrey[1], Justin S. Smith[1]

■ 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° and >10° 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 post-operative 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 post-operative 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

From the [1]Department of Neurological Surgery, University of Virginia Health System, Charlottesville, Virginia; [2]Department of Neurological Surgery, University of Texas Health Science Center, Houston, Texas; [3]Department of Neurological Surgery, Medical University of South Carolina, Charleston, South Carolina; [4]Denver International Spine Center, Presbyterian St. Luke's/Rocky Mountain Hospital for Children, Denver, Colorado; [5]Department of Neurological Surgery, University of California, San Francisco, California; and [6]Department of Orthopaedic Surgery, Hospital for Special Surgery, New York, New York, USA

To whom correspondence should be addressed: Thomas J. Buell, M.D.
[E-mail: tjb4p@hscmail.mcc.virginia.edu]

Citation: World Neurosurg. (2019) 121:e96-e103.
https://doi.org/10.1016/j.wneu.2018.08.242

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

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° and >10° 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.

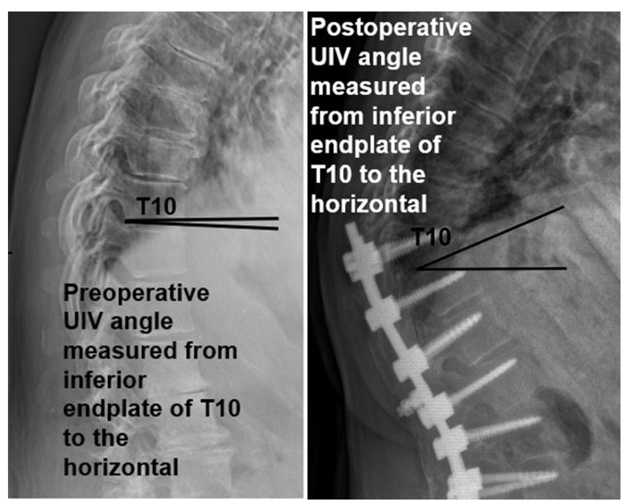

Figure 1. Upper instrumented vertebra (UIV) angle was measured between the inferior endplate of the UIV and horizontal (as shown in this standing long-cassette lateral radiograph). In this example of a patient who developed proximal junctional kyphosis, the preoperative and postoperative UIV angle measured −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.

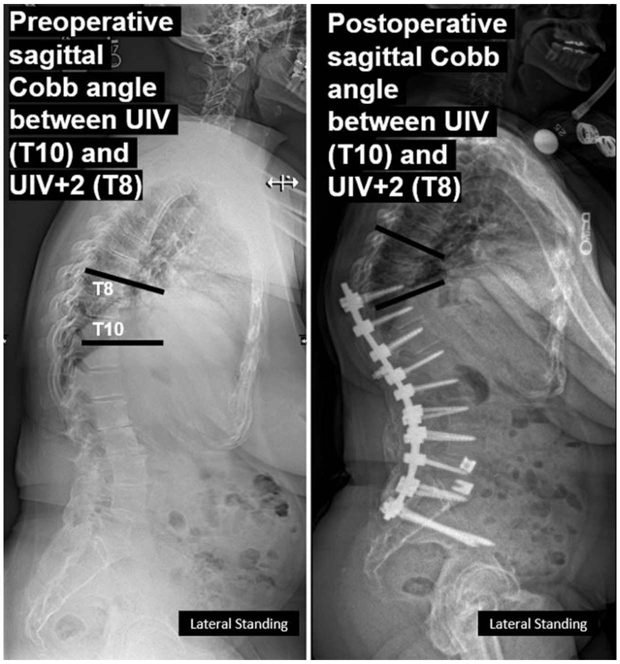

Figure 2. Preoperative (*left panel*) and postoperative (*right panel*) standing long-cassette lateral radiographs of a patient with adult spinal deformity who presented with severe lower back pain secondary to positive global sagittal malalignment (C7-plumbline) with possible pseudarthrosis of a previous L3-S1 fusion. The preoperative and postoperative proximal junctional angle (PJA) measure 15° and 40°, respectively. PJA was measured from the upper instrumented vertebra (UIV) inferior endplate to the UIV+2 superior endplate. Abnormal proximal junctional kyphosis was defined as PJA that was 1) ≥10° and 2) ≥10° greater than the corresponding preoperative measurement.

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%]; χ^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° ± 15.13° vs. -2.14° ± 18.65°; P = 0.034), preoperative UIV angle (2.37° ± 13.04° vs. -3.57° ± 15.64°; P = 0.026), postoperative PT (20.87° ± 7.74° vs. 26.12° ± 11.69°; P = 0.007), postoperative TK (32.77° ± 12.26° vs. 47.22° ± 10.35°; P < 0.001), change in total LL (16.55° ± 16.60° vs. 23.55° ± 18.80°; P = 0.034), change in ULL (14.96° ± 13.92° vs. 25.73° ± 19.13°; P = 0.001), and change in UIV angle (12.23° ± 12.20° vs. 22.45° ± 16.38°; 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° ± 6.90° vs. 20.58° ± 13.57°; P = 0.047) and greater postoperative UIV angle (21.83° ± 8.14°

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

				Binary Logistic Regression*		
	Non-PJK (n = 71)	**PJK (n = 49)**	***P* Value†**	**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 (χ^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 (χ^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 (χ^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 χ^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 χ^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° ± 8.69°; P = 0.026) compared with non-tethered patients in the PJK group. Tether use was also associated with greater changes in ULL (32.43° ± 18.89° vs. 19.42° ± 17.93°; P = 0.017) and UIV angle (29.00° ± 17.22° vs. 16.65° ± 13.40°; 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 heterogenous 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 ($26.78° \pm 6.90°$ vs. $20.58° \pm 13.57°$) 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 clincal signs and symtpoms.[8,11,13] Luo et al. recently performed a meta--analysis[13] 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.

REFERENCES

1. Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A, Edwards C 2nd. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. *Spine (Phila Pa 1976)*. 2005;30:1643-1649.
2. Mendoza-Lattes S, Ries Z, Gao Y, Weinstein SL. Proximal junctional kyphosis in adult reconstructive spine surgery results from incomplete restoration of the lumbar lordosis relative to the magnitude of the thoracic kyphosis. *Iowa Orthop J*. 2011;31:199-206.
3. Kim YJ, Bridwell KH, Lenke LG, Glattes CR, Rhim S, Cheh G. Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum

five-year follow-up. *Spine (Phila Pa 1976)*. 2008;33:2179-2184.

4. Kim YJ, Bridwell KH, Lenke LG, Rhim S, Cheh G. Sagittal thoracic decompensation following long adult lumbar spinal instrumentation and fusion to L5 or S1: causes, prevalence, and risk factor analysis. *Spine (Phila Pa 1976)*. 2006;31:2359-2366.

5. Bridwell KH, Lenke LG, Cho SK, Pahys JM, Zebala LP, Dorward IG, et al. Proximal junctional kyphosis in primary adult deformity surgery: evaluation of 20 degrees as a critical angle. *Neurosurgery*. 2013;72:899-906.

6. Yagi M, Akilah KB, Boachie-Adjei O. Incidence, risk factors and classification of proximal junctional kyphosis: surgical outcomes review of adult idiopathic scoliosis. *Spine (Phila Pa 1976)*. 2011;36:E60-E68.

7. Lee GA, Betz RR, Clements DH 3rd, Huss GK. Proximal kyphosis after posterior spinal fusion in patients with idiopathic scoliosis. *Spine (Phila Pa 1976)*. 1999;24:795-799.

8. Reames DL, Kasliwal MK, Smith JS, Hamilton DK, Arlet V, Shaffrey CI. Time to development, clinical and radiographic characteristics, and management of proximal junctional kyphosis following adult thoracolumbar instrumented fusion for spinal deformity. *J Spinal Disord Tech*. 2015;28:E106-114.

9. Kim HJ, Yagi M, Nyugen J, Cunningham ME, Boachie-Adjei O. Combined anterior-posterior surgery is the most important risk factor for developing proximal junctional kyphosis in idiopathic scoliosis. *Clin Orthop Relat Res*. 2012;470:1633-1639.

10. Lonner BS, Ren Y, Newton PO, Shah SA, Samdani AF, Shufflebarger HL, et al. Risk factors of proximal junctional kyphosis in adolescent idiopathic scoliosis—the pelvis and other considerations. *Spine Deform*. 2017;5:181-188.

11. Maruo K, Ha Y, Inoue S, Samuel S, Okada E, Hu SS, et al. Predictive factors for proximal junctional kyphosis in long fusions to the sacrum in adult spinal deformity. *Spine (Phila Pa 1976)*. 2013;38:E1469-E1476.

12. Smith JS, Klineberg E, Lafage V, Shaffrey CI, Schwab F, Lafage R, et al. Prospective multicenter assessment of perioperative and minimum 2-year postoperative complication rates associated with adult spinal deformity surgery. *J Neurosurg Spine*. 2016;25:1-14.

13. Luo M, Wang P, Wang W, Shen M, Xu G, Xia L. Upper thoracic versus lower thoracic as site of upper instrumented vertebrae for long fusion surgery in adult spinal deformity: a meta-analysis of proximal junctional kyphosis. *World Neurosurg*. 2017;102:200-208.

14. Ghobrial GM, Eichberg DG, Kolcun JPG, Madhavan K, Lebwohl NH, Green BA, et al. Prophylactic vertebral cement augmentation at the uppermost instrumented vertebra and rostral adjacent vertebra for the prevention of proximal junctional kyphosis and failure following long-segment fusion for adult spinal deformity. *Spine J*. 2017;17:1499-1505.

15. Sandquist L, Carr D, Tong D, Gonda R, Soo TM. 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.

16. Lange T, Schmoelz W, Gosheger G, Eichinger M, Heinrichs CH, Boevingloh AS, et al. Is a gradual reduction of stiffness on top of posterior instrumentation possible with a suitable proximal implant? A biomechanical study. *Spine J*. 2017;17:1148-1155.

17. Metzger MF, Robinson ST, Svet MT, Liu JC, Acosta FL. Biomechanical analysis of the proximal adjacent segment after multilevel instrumentation of the thoracic spine: do hooks ease the transition? *Global Spine J*. 2016;6:335-343.

18. Thawrani DP, Glos DL, Coombs MT, Bylski-Austrow DI, Sturm PF. Transverse process hooks at upper instrumented vertebra provide more gradual motion transition than pedicle screws. *Spine (Phila Pa 1976)*. 2014;39:E826-E832.

19. Facchinello Y, Brailovski V, Petit Y, Brummund M, Tremblay J, Mac-Thiong JM. Biomechanical assessment of the stabilization capacity of monolithic spinal rods with different flexural stiffness and anchoring arrangement. *Clin Biomech (Bristol, Avon)*. 2015;30:1026-1035.

20. Facchinello Y, Brailovski V, Petit Y, Mac-Thiong JM. Monolithic superelastic rods with variable flexural stiffness for spinal fusion: simplified finite element analysis of an instrumented spine segment. *Conf Proc IEEE Eng Med Biol Soc*. 2014;2014:6605-6608.

21. Helgeson MD, Shah SA, Newton PO, Clements DH 3rd, Betz RR, Marks MC, et al. Evaluation of proximal junctional kyphosis in adolescent idiopathic scoliosis following pedicle screw, hook, or hybrid instrumentation. *Spine (Phila Pa 1976)*. 2010;35:177-181.

22. Buell TJ, Buchholz AL, Quinn JC, Bess S, Line BG, Ames CP, et al. A pilot study on posterior polyethylene tethers to prevent proximal junctional kyphosis after multilevel spinal instrumentation for adult spinal deformity [e-pub ahead of print]. *Oper Neurosurg (Hagerstown)*. 2018. https://doi.org/10.1093/ons/opy065.

23. Buell TJ, Taylor DG, Chen CJ, Shaffrey CI, Smith JS, Bess S. Letter to the Editor. Proximal junctional kyphosis and proximal junctional failure [e-pub ahead of print]. *J Neurosurg Spine*. 2018:1-2. https://doi.org/10.3171/2018.5.SPINE18636.

24. Buell TJ, Mullin JP, Nguyen JH, Taylor DG, Garces J, Mazur MD, et al. A novel junctional tether weave technique for adult spinal deformity: 2-dimensional operative video [e-pub ahead of print]. *Oper Neurosurg (Hagerstown)*. 2018. https://doi.org/10.1093/ons/opy148.

25. Bess S, Harris JE, Turner AW, LaFage V, Smith JS, Shaffrey CI, et al. The effect of posterior polyester tethers on the biomechanics of proximal junctional kyphosis: a finite element analysis. *J Neurosurg Spine*. 2017;26:125-133.

26. Watanabe K, Lenke LG, Bridwell KH, Kim YJ, Koester L, Hensley M. Proximal junctional vertebral fracture in adults after spinal deformity surgery using pedicle screw constructs: analysis of morphological features. *Spine (Phila Pa 1976)*. 2010;35:138-145.

27. Hostin R, McCarthy I, O'Brien M, Bess S, Line B, Boachie-Adjei O, et al. Incidence, mode, and location of acute proximal junctional failures after surgical treatment of adult spinal deformity. *Spine (Phila Pa 1976)*. 2013;38:1008-1015.

28. O'Leary PT, Bridwell KH, Lenke LG, Good CR, Pichelmann MA, Buchowski JM, et al. Risk factors and outcomes for catastrophic failures at the top of long pedicle screw constructs: a matched cohort analysis performed at a single center. *Spine (Phila Pa 1976)*. 2009;34:2134-2139.

29. Fujimori T, Inoue S, Le H, Schairer WW, Berven SH, Tay BK, et al. Long fusion from sacrum to thoracic spine for adult spinal deformity with sagittal imbalance: upper versus lower thoracic spine as site of upper instrumented vertebra. *Neurosurg Focus*. 2014;36:E9.

30. Scheer JK, Lafage V, Smith JS, Deviren V, Hostin R, McCarthy IM, et al. Maintenance of radiographic correction at 2 years following lumbar pedicle subtraction osteotomy is superior with upper thoracic compared with thoracolumbar junction upper instrumented vertebra. *Eur Spine J*. 2015;24(suppl 1):S121-S130.

31. Ha Y, Maruo K, Racine L, Schairer WW, Hu SS, Deviren V, et al. Proximal junctional kyphosis and clinical outcomes in adult spinal deformity surgery with fusion from the thoracic spine to the sacrum: a comparison of proximal and distal upper instrumented vertebrae. *J Neurosurg Spine*. 2013;19:360-369.

32. Lafage R, Line BG, Gupta S, Liabaud B, Schwab F, Smith JS, et al. Orientation of the upper-most instrumented segment influences proximal junctional disease following adult spinal deformity surgery. *Spine (Phila Pa 1976)*. 2017;42:1570-1577.

33. Freeman GH, Halton JH. Note on an exact treatment of contingency, goodness of fit and other problems of significance. *Biometrika*. 1951;38:141-149.

34. Steyerberg EW, Vickers AJ, Cook NR, Gerds T, Gonen M, Obuchowski N, et al. Assessing the performance of prediction models: a framework for traditional and novel measures. *Epidemiology*. 2010;21:128-138.

35. Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F. The impact of positive sagittal balance in adult spinal deformity. *Spine (Phila Pa 1976)*. 2005;30:2024-2029.

36. Schwab F, Dubey A, Gamez L, El Fegoun AB, Hwang K, Pagala M, et al. Adult scoliosis: prevalence, SF-36, and nutritional parameters in an elderly volunteer population. *Spine (Phila Pa 1976)*. 2005;30:1082-1085.

37. Teles AR, Mattei TA, Righesso O, Falavigna A. Effectiveness of operative and nonoperative care for adult spinal deformity: systematic review of the literature. *Global Spine J*. 2017;7:170-178.

38. Smith JS, Lafage V, Shaffrey CI, Schwab F, Lafage R, Hostin R, et al. Outcomes of operative and nonoperative treatment for adult spinal

deformity: a prospective, multicenter, propensity-matched cohort assessment with minimum 2-year follow-up. Neurosurgery. 2016;78:851-861.

39. Bridwell KH, Baldus C, Berven S, Edwards C 2nd, Glassman S, Hamill C, et al. Changes in radiographic and clinical outcomes with primary treatment adult spinal deformity surgeries from two years to three- to five-years follow-up. Spine (Phila Pa 1976). 2010;35:1849-1854.

40. Bridwell KH, Glassman S, Horton W, Shaffrey C, Schwab F, Zebala LP, et al. Does treatment (nonoperative and operative) improve the two-year quality of life in patients with adult symptomatic lumbar scoliosis: a prospective multicenter evidence-based medicine study. Spine (Phila Pa 1976). 2009;34:2171-2178.

41. Smith JS, Shaffrey CI, Berven S, Glassman S, Hamill C, Horton W, et al. Operative versus nonoperative treatment of leg pain in adults with scoliosis: a retrospective review of a prospective multicenter database with two-year follow-up. Spine (Phila Pa 1976). 2009;34:1693-1698.

42. Smith JS, Shaffrey CI, Berven S, Glassman S, Hamill C, Horton W, et al. Improvement of back pain with operative and nonoperative treatment in adults with scoliosis. Neurosurgery. 2009;65:86-93 [discussion 93-94].

43. Kim HJ, Boachie-Adjei O, Shaffrey CI, Schwab F, Lafage V, Bess S, et al. Upper thoracic versus lower thoracic upper instrumented vertebrae endpoints have similar outcomes and complications in adult scoliosis. Spine (Phila Pa 1976). 2014;39:E795-E799.

44. Lafage R, Bess S, Glassman S, Ames C, Burton D, Hart R, et al. Virtual modeling of postoperative alignment after adult spinal deformity surgery helps predict associations between compensatory spinopelvic alignment changes, overcorrection, and proximal junctional kyphosis. Spine (Phila Pa 1976). 2017;42:E1119-E1125.

45. Been E, Barash A, Pessah H, Peleg S. A new look at the geometry of the lumbar spine. Spine (Phila Pa 1976). 2010;35:E1014-E1017.

46. Faundez AA, Richards J, Maxy P, Price R, Leglise A, Le Huec JC. The mechanism in junctional failure of thoraco-lumbar fusions. Part II: analysis of a series of PJK after thoraco-lumbar fusion to determine parameters allowing to predict the risk of junctional breakdown. Eur Spine J. 2018;27(suppl 1):139-148.

Conflict of interest statement: S.B., research support: K2M, Innovasis, NuVasive, Medtronic, DePuy Synthes, Stryker, Zimmer Biomet; consultant: K2M, Allosource; patent: K2M, Innovasis; B.G.L., consultant: ISSGF; C.P.A., consultant: Medtronic, DePuy Synthes, Stryker; royalties: Zimmer-Biomet, Stryker; research support: UCSF; patent: Fish & Richardson PC; F.J.S., consultant: Zimmer-Biomet, K2M, Nuvasive, Medicrea, MSD; research support: SRS, AOSpine, DePuy Spine Synthesis, ISSGF; stock holder: Nemaris Inc; V.L., consultant: Nemaris Inc, Nuvasive, Medicrea, DePuy Synthes; stockholder: Nemaris Inc; non—study-related support: SRS, NIH, DePuy Synthes, ISSGF; C.I.S., consultant: Medtronic, Nuvasive, Zimmer-Biomet, K2M; royalties: Medtronic, Nuvasive, Zimmer-Biomet; stockholder: Nuvasive; grant: NIH, DOD, NACTN; J.S.S., royalties: Zimmer-Biomet; consultant: Zimmer-Biomet, Cerapedics, Nuvasive, K2M, AlloSource; honorarium: Zimmer-Biomet, Nuvasive, K2M; research support: DePuy Synthes, ISSGF; fellowship support: NREF, AOSpine.

Received 25 May 2018; accepted 31 August 2018

Citation: World Neurosurg. (2019) 121:e96-e103.
https://doi.org/10.1016/j.wneu.2018.08.242

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***

1878-8750/$ - see front matter