Spine

SPINE Volume 47, Number 13, pp 922–930

DEFORMITY

Evolution of Proximal Junctional Kyphosis and Proximal Junctional Failure Rates Over 10 Years of Enrollment in a Prospective Multicenter Adult Spinal Deformity Database

Basel Sheikh Alshabab, MD,[a] Renaud Lafage, MS,[b] Justin S. Smith, MD, PhD,[c] Han Jo Kim, MD,[b] Gregory Mundis, MD,[d] Eric Klineberg, MD,[e] Christopher Shaffrey, MD,[f] Alan Daniels, MD,[g] Christopher Ames, MD,[h] Munish Gupta, MD,[i] Douglas Burton, MD,[j] Richard Hostin, MD,[k] Shay Bess, MD,[l] Frank Schwab, MD,[a] and Virginie Lafage, PhD,[a] on behalf of the International Spine Study Group ISSG

Study Design. Retrospective cohort study.

Objective. The aim of this study was to investigate the evolution of proximal junctional kyphosis (PJK) rate over 10-year enrollment period within a prospective database.

Summary of Background Data. PJK is a common complication following adult spinal deformity (ASD) surgery and has been intensively studied over the last decade.

Methods. Patients with instrumentation extended to the pelvis and minimum 2-year follow-up were included. To investigate evolution of PJK/proximal junctional failure (PJF) rate, a moving average of 321 patients was calculated across the enrollment period. Logistic regression was used to investigate the association between the date of surgery (DOS) and PJK and/or PJF. Comparison of PJK/PJF rates, demographics, and surgical strategies was performed between the first and second half of the cohort.

Results. A total of 641 patients met inclusion criteria (age: 64 ±10 years, 78.2% female, body mass index: 28.3±5.7). The overall rate of radiographic PJK at 2 years was 47.9%; 12.9% of the patients developed PJF, with 31.3% being revised within 2-year follow-up. Stratification by DOS produced two halves. Between these two periods, rate of PJK and PJF demonstrated nonsignificant decrease (50.3%–45.5%, P=0.22) and (15.0%–10.9%, P=0.12), respectively. Linear interpolation suggested a decrease of 1.2% PJK per year and 1.0% for PJF. Patients enrolled later in the study were older and more likely to be classified as pure sagittal deformity ($P<0.001$). There was a significant reduction in the use of three-column osteotomies ($P<0.001$), an increase in anterior longitudinal ligament release ($P<0.001$), and an increase in the use of PJK prophylaxis (31.3% vs 55.1%). Logistical regression demonstrated no significant association between DOS and radiographic PJK (P=0.19) or PJF (P=0.39).

Conclusion. Despite extensive research examining risk factors for PJK/PJF and increasing utilization of intraoperative PJK prophylaxis techniques, the rate of radiographic PJK and/or PJF did not significantly decrease across the 10-year enrollment period of this ASD database.

Key words: adult spinal deformity, proximal junctional failure, proximal junctional kyphosis, rate evolution.

Spine 2022;47:922–930

From the [a]Department of Orthopedic Surgery, Northwell Health, Lenox Hill Hospital, New York, NY; [b]Department of Orthopedic Surgery, Hospital for Special Surgery, New York, NY; [c]Department of Neurosurgery, University of Virginia Medical Center, Charlottesville, VA; [d]Scripps Clinic, San Diego, CA; [e]Department of Orthopedic Surgery, University of California, Davis, Sacramento, CA; [f]Department of Neurosurgery, Duke University Medical Center, Durham, NC; [g]Department of Orthopedic Surgery, Brown University, Providence, RI; [h]Department of Neurosurgery, University of California School of Medicine, San Francisco, CA; [i]Department of Orthopedic Surgery, Washington University, St Louis, MO; [j]Department of Orthopedic Surgery, University of Kansas Medical Center, Kansas City, KS; [k]Department of Orthopedic Surgery, Baylor Scoliosis Center, Dallas, TX; and [l]Denver International Spine Center, Presbyterian St. Luke's/Rocky Mountain Hospital for Children, Denver, CO.

Acknowledgment date: January 6, 2022. First revision date: March 18, 2022. Acceptance date: March 18, 2022.

Grants, technical support, and corporate support: The International Spine Study Group (ISSG) is funded through research grants from DePuy Synthes (current), Nuvasive (current), K2M (present), Innovasis (past), Biomet (past), and individual donations. Funding sources did not play a role in investigation.

Address correspondence and reprint requests to Virginie Lafage, PhD, Lenox Hill j Northwell Health, 110 E 77th St, New York, NY 10075; E-mail: virginie.lafage@gmail.com

DOI: 10.1097/BRS.0000000000004364

As the population's life expectancy increases and the desire to stay active later in life remains a priority, more patients are seeking treatment for adult spinal deformity (ASD). The literature has shown that patients undergoing ASD correction improve substantially more than patients undergoing nonoperative management.[1–3] Improvements in surgical techniques, instrumentation, anesthesia and critical care have led to remarkable advances in surgical ASD care over the last few decades. However, ASD surgery is still associated with significant complications such as wound infection, deep venous thrombosis, rod breakage, pseudarthrosis, and junctional disease.

One of the most prevalent complications following surgical correction of ASD is proximal junctional kyphosis (PJK).[4–6] PJK has been defined in the literature by Glattes et al[7] as a proximal junctional sagittal Cobb angle ≥10° and at least 10° greater than the preoperative measurement. Subsequently, many other definitions have been introduced using various radiographic criteria.[8–10] The incidence of PJK ranges from 17% to 61.7%, although most sources report a rate between 20% and 40%.[5,7,11–13] Regardless of the radiographic criteria, PJK can become pathologic and result in proximal junctional failure (PJF). PJF is a structural failure that can result in substantial clinical consequences such as mechanical failure, risk of neurological injury, increased deformity, and the need for revision in up to 47% of affected patients.[9,14,15]

PJK arguably remains the greatest unsolved problem in ASD surgery. A PubMed search for "proximal junctional kyphosis" returned 657 results, of these, 92% were published in the last decade. This steep increase in publications is an indication of the growing interest to further understand this pathology and provide steps to potentially reduce its occurrence.[16–19] Although the literature offers abundant evidence of the effectiveness of many PJK prophylaxis techniques, there is little on the assessment of the change in our overall performance in mitigating junctional disease.

Over the last decade, reports from multicenter study groups evaluating spinal deformity surgery patients have become increasingly prevalent. Assessing patient data over time can provide high-quality patient follow-up data, which may assist in monitoring evolution in surgical techniques and outcomes. In the surgical field, there is a wide acceptance of the hypothesis that the quality of care improves with provider experience. Studies on many surgical procedures have shown that surgical volume has a significant impact on reducing adverse events.[20–22] Recent reports show that complications, in general, of ASD surgery, are decreasing,[23] but the literature is sparse in reports looking specifically at PJK rates over time.

Taking advantage of the benefits of a multicenter study group, this study sought to analyze the long-term time-dependent evolution of patient characteristics, surgical strategy, and rates of PJK and PJF at a minimum of 2 years following surgery over the last decade within a highly detailed and clinician-maintained database.

METHODS

Patient Population

This study was a retrospective review of a prospective multicenter database of patients who underwent surgical management for ASD between 2008 and 2018. After IRB approval at each of the 13 participating sites across the United States, patients were enrolled if they met the following criteria: age >18 years and spinal deformity confirmed by at least one of the following measures: scoliosis Cobb angle >20°, sagittal vertical axis (SVA) >5 cm, pelvic tilt (PT) >25°, and/or thoracic kyphosis (TK) >60°. Patients who had an active infection, malignancy, or whose spinal deformity was due to neuromuscular conditions or trauma were excluded. Patients were prospectively enrolled at each site after being informed of the study details and signing a consent form. Additional specific inclusion criteria for this current analysis were the availability of minimum 2 years' follow-up data and having instrumentation extended to the pelvis.

Data Collection

Following inclusion and exclusion of subjects, data of interest were queried, measured, and calculated. First, demographic data including age, sex, body mass index (BMI), American Society of Anesthesiologists (ASA) grade, and having a previous instrumented fusion were queried from our database. Standardized health-related quality of life (HRQOL) measures included the Oswestry Disability Index (ODI), the 36-item Short Form Health Survey (SF-36), and the Scoliosis Research Society-22r Patient Questionnaire (SRS-22r). Subsequently, surgical data collected included operative time, estimated blood loss (EBL), length of hospital stay (LOS), locations of the upper-most instrumented vertebra (UIV) and lower-most instrumented vertebra (LIV), use of interbody fusion (IBF), use of osteotomies, threecolumn osteotomy (3CO), and anterior column realignment (ACR).

All patients had full-length, free-standing spine radiographs including the femoral heads (i.e., conventional 36-inch radiograph, full-length EOS, among others). Radiographic parameters were obtained utilizing a dedicated and validated software (Spineview, ENSAM Laboratory of Biomechanics, Paris),[24] and post-treated with Matlab software (Version R2015b; MathWorks, Inc, Natick, MA). Classic spinopelvic parameters were evaluated including pelvic incidence (PI), sacral slope (SS), lumbar lordosis (LL), PI-LL, T1 pelvic angle (TPA), and sagittal vertical axis (SVA). Following calculation of relevant parameters, the SRS-Schwab classification system was employed for deformity classification; each sagittal modifier is graded (0, þ, orþþ) based on the severity (þ threshold corresponds to an ODI of 40 "severe disability"). Spinal curvature in the coronal plane was classified into one of four curve types: T: thoracic only, L: TK/lumbar only, D: double curve, N: no major curve.[25]

The proximal junctional angle (PJA) was defined as the sagittal Cobb angle between the inferior endplate of the UIV and the superior endplate of the vertebra two levels above (UIVþ2). The occurrence of PJK was reported based on different grades of severity. Radiographic criteria for Moderate PJK was defined according to Glattes definition: kyphotic PJK angle greater than 10° associated with a kyphotic change >10° between preoperative and postoperative alignment.[7] Severe PJK was defined according to Lafage criteria: kyphotic PJK angle >28° associated with a kyphotic change >22° between preoperative and

TABLE 1. Description of Demographic, Surgical Data, Preoperative, and 2-y Postoperative HRQOL and Radiographic Information

Demographic			
Age	64 ± 10	**BMI:**	28 ± 6
Sex (%F)	501 (78%)	**Previous fusion:**	208 (32%)
CCI	1.9 ± 1.7		
Surgical data			
ASA grade:	2 (2–3)	**EBL:**	1550 (1000–2500)
IBF	424 (66%)	**ACR:**	59 (9%)
Osteotomy	495 (77%)	**3CO:**	138 (22%)
Op time	433 (344–561)	**Fusion length:**	9 levels (9–15)
HRQOL			
	Preoperative	*2-y Postoperative*	
ODI	47 ± 16	**ODI:**	28 ± 20
PCS	30 ± 9	**PCS:**	39 ± 11
SRS total	2.7 ± 0.6	**SRS Total:**	3.64 ± 0.8
SRS Classification			
	Preoperative	*2-y Postoperative*	
SRS Type	N: 39% | T: 2% | ĆL: 36% | D: 23%	**SRS Type:**	N: 78% | T: 4% | ĆL: 10% | D: 8%
SRS PT	0: 28% | +: 40% | ++: 33%	**SRS PT:**	0: 42% | +: 37% | ++: 30%
SRS PI-LL	0: 26% | +: 23% | ++: 51%	**SRS PI-LL:**	0: 69% | +: 19% | ++: 13%
SRS SVA	0: 30% | +: 33% | ++: 37%	**SRS SVA:**	0: 57% | +: 30% | ++: 13%

3CO indicates three-column osteotomy; ACR, anterior column realignment; ASA, American Society of Anesthesiologists; BMI, body mass index; CCI, Charlson Comorbidity Index; EBL, estimated blood loss; HRQOL, health-related quality of life; IBF, interbody fusion; LL, lumbar lordosis; ODI, Oswestry Disability Index; PCS, Physical Composite Score; PI, pelvic incidence ; PT, pelvic tilt; SRS, Scoliosis Research Society; SVA, sagittal vertical axis.

postoperative alignment.[10] Clinical PJK is defined as PJK that required revision surgery before two years follow up. Proximal junctional failure (PJF) at 2 years was defined as either a severe radiographic PJK at 2-year follow-up visit or a clinical PJK; this is considered the main outcome of this analysis.

Statistical Analysis

After describing the cohort in terms of demographics, surgical data, pre-operative and 2-year postoperative HRQOLs, and radiographic alignment, patients were divided based on the date of surgery into two halves: first half of patients enrolled versus the second half of patients enrolled. The two halves were compared in terms of preoperative information, surgical data, HRQOLs, and radiographic classification. Continuous evolution of the different PJK/PJF rates was calculated using a moving average approach. A group of 321 patients was used to calculate the moving average. This number was identified as the minimum number of patients to determine a rate of 30% with a confidence interval of 95% and a margin of error of 5%. The moving average was calculated using consecutively enrolled patients. This approach permits a visual representation of the timeline of different PJK rates across the 10-year enrollment. Next, linear interpolation of the rate was used to quantify the change of rates in percentage per year. Statistical analysis was performed using SPSS 20.0 (IBM Corp., Armonk, NY). A P value of ≤ 0.05 was considered statistically significant.

RESULTS

Cohort Description

Out of 851 patients, 641 patients met inclusion criteria. Preoperatively, patients had a mean age of 64.0 ± 9.6 years, 501 patients (78.2%) were women, mean body mass index (BMI) was (28.3 ± 5.7) kg/m^2, and mean ASA grade was 2 (range 2–3). A total of 208 patients had a previous instrumented fusion, and the mean Charlson Comorbidity Index was (1.95 ± 1.71). Overall, the patients exhibited moderate to severe disability (ODI: 46.7 ± 16.0, Physical Composite Score: 29.8 ± 8.6. SRS: 2.71 ± 0.62). As per the SRS-Schwab classification, 252 patients (39.3%) had a pure sagittal deformity (Type N), 230 patients (35.9%) had lumbar scoliosis (Type L), and 145 patients (22.6%) had double major curvature (Type D). Pre-operative alignment demonstrated a moderate to severe sagittal deformity, with 72.4%, 69.7%, and 74.1% of the patients presenting a modifier grade of + or ++ in PT, SVA, and PI-LL, respectively. In terms of surgical data, 424 patients (66.1%) received an IBF, 59 patients (9.2%) had an ACR, 495 patients (77.2%) underwent an osteotomy, and 138 patients (21.5%) underwent 3CO. Mean operative time was 433 minutes (range: 344 – 561 minutes) and EBL was 1550 mL (range: 1000 – 2500). Postoperatively, patients showed significant improvement in patient-reported outcomes and radiographic alignment (all $P < 0.001$) (Table 1). Overall, the rate of moderate PJK was 47.9% (307 patients), and the rate of severe PJK was 9.5% (61 patients). Twenty-six patients (4.1%) had clinical PJK; 83 patients (12.9%) developed PJF.

First Half Versus Second Half

After stratification by date of surgery into two groups (first half included patients that underwent surgery between October 2008 and July 2014 [median September 2011], second half included patients that underwent surgery between July 2014 and April 2018 [median Aug 2016]), a comparison of the demographic information showed that the second half were older ($P < 0.001$) and had a trend toward lower proportion of women ($P = 0.080$) (Table 2). Comparison of the surgical data showed a significant decrease in EBL and use of 3CO, an increase in application of the ACR procedure, and increased use of PJK prophylaxis methods (31.3% vs. 55.1%, $P < 0.001$). Specifically, the use of tether augmentation had increased significantly in the second half (4.4% of total cases vs. 26.2%). No differences were found for ASA grade or operative time. Comparison of HRQOL scores showed similar pre-operative disability but a significantly lower postoperative (2 year) disability for patients operated in the second half (Table 2).

Comparison of Schwab-SRS classification showed that patients in the second half were more likely to have a pure sagittal deformity. However, sagittal modifiers showed no significant differences between the groups. Detailed comparison of alignment between first and second half demonstrated similar preoperative sagittal alignment except for TK being larger for second half (– 33° vs. – 37°, $P = 0.014$) (Table 3). Two-year postoperative alignment was also similar between the two halves, this time a similar TK but a significantly larger distal lordosis for second half (31° vs. 34°, $P = 0.002$). Both groups underwent a significant change in every parameter. Only pre to post distal lordosis (L4-S1) was not significantly different for the first group ($P = 0.58$).

Comparison of the different PJK definition rates showed no significant difference between the two groups. Moderate PJK: 161 patients (50.3%) in the first half versus 146 patients (45.5%) in the second half ($P = 0.221$). Severe PJK: 37 patients (11.6%) *versus* 24 patients (7.5%) ($P = 0.078$). Clinical PJK: 13 patients (4.1%) *versus* 13 patients (4.0%) ($P=0.576$). PJF: 48 patients (15.0%) versus 35 patients (10.9%) ($P = 0.122$).

Moving Average Across Enrolment

The moving average data were used to develop a graphical representation of the evolving trends of different rates over time. Based on a moving average of 321 patients across the total enrollment period, a small but steady decrease in all rates is apparent (Fig. 1). Linear regression was used to identify the rate of decrease per year based on each definition criteria: a decrease of 1.2% moderate PJK rate per year, a decrease of 0.9% severe PJK rate per year, a decrease of 0.2% clinical PJK rate per year, a decrease of 1.0% of PJF.

DISCUSSION

ASD surgery from 2008 to 2018 was associated with significant improvement in patient-reported outcomes. Surgery has become less invasive by fusing fewer levels and performing less aggressive three-column osteotomies which subsequently led to less blood loss. However, the rate of PJK and PJF is still high, one of 10 patients developed PJF, and almost half of our cohort had a moderate PJK at 2-year follow-up. Our results are in line with previous reports of PJK and PJF rates.[9,11,26–29] After stratification by the date of surgery into two groups, a comparison of junctional change rate between the enrollment periods shows no significant difference across the different definitions used, but a small trend for less severe PJK change at 2 years was apparent. The moving average of 321 patients illustrated the evolution across the 10-year enrollment, with a very small decrease in junctional disease rate over time.

Over the 10 years of analysis, enrolled patients were older, with a mean age of 62.6 years in the first half versus 65.5 years in the second half. Older age is a widely reported risk factor for complications overall after ASD surgery, and specifically for the development of PJK. Kim et al[30] reported on ASD patients with a 5-year follow-up and found that a higher prevalence of PJK was seen in patients older than 55 years *versus* those younger than 55 (59% vs. 31%). Another study from the same group found that patients who developed PJK had a mean age of 60 years while the ones who did not have PJK had a mean age of 50. A metaanalysis of published research up to 2015 indicated that age > 55 is a risk factor for the development of PJK.[31] Looking at the most commonly reported risk factors for PJK, it can be argued that older age acts as a proxy to indicate poor bone quality, frailty, or poor soft tissue strength but in itself, it may not be a risk factor.[9,32–34] Our results also show that more recently enrolled patients are more likely to have a pure sagittal deformity. Despite the more complex older patients, surgical treatment continued to lead to significant improvement in pain and

TABLE 2. Comparison Between First Half of Patient Enrolled and Second Half of Patient Enrolled

	First Half:	Second Half:	*P*
Demographic			
Age	63 ± 10	65 ± 9	0.000*
BMI	28 ± 6	28 ± 6	0.933*
Sex (%F)	260 (81%)	241 (76%)	0.080†
Previous fusion	95 (30%)	113 (35.2%)	0.136†
CCI	1.9 ± 1.7	2.1 ± 1.7	0.160*
Surgical data			
ASA Grade	2 (2–3)	2 (2–3)	0.994‡
EBL	2000 (1100–3000)	1400 (800–2200)	0.000‡
Op time	449 (353–556)	425 (340–565)	0.427‡
Fusion length	10 (9–15)	9 (9–15)	0.032‡
IBF	230 (72%)	194 (60%)	0.002†
ACR	0 (0%)	59 (18%)	0.000†
Osteotomy	239 (75%)	256 (81%)	0.078†
3CO	84 (35%)	54 (21%)	0.000†
HRQOL			
ODI pre	48 ± 17	46 ± 15	0.189*
PCS pre	30 ± 9	30 ± 8	0.987*
SRS Total pre	2.7 ± 0.7	2.7 ± 0.6	0.319*
ODI 2Y	30 ± 21	26 ± 19	0.008*
PCS 2Y	38 ± 11	40 ± 12	0.101*
SRS Total 2Y	3.60 ± 0.8	3.7 ± 0.8	0.139*
SRS Classification			
SRS Type pre	**N:** 31% | **T:** 4% | **ĆL:** 41% | **D:** 24%	**N:** 47% | **T:** 1% | **ĆL:** 31% | **D:** 30%	0.000†
SRS PT pre	**0:** 25% | +: 42% | ++: 33%	**0:** 30% | +: 37% | ++: 33%	0.249†
SRS PI-LL pre	**0:** 26% | +: 24% | ++: 51%	**0:** 26% | +: 23% | ++: 51%	0.954†
SRS SVA pre	**0:** 29% | +: 32% | ++: 39%	**0:** 32% | +: 34% | ++: 35%	0.545†
SRS Type 2Y	**N:** 75% | **T:** 4% | **ĆL:** 9% | **D:** 12%	**N:** 81% | **T:** 4% | **ĆL:** 11% | **D:** 4%	0.003†
SRS PT 2Y	**0:** 42% | +: 37% | ++: 21%	**0:** 42% | +: 37% | ++: 21%	0.991†
SRS PI-LL 2Y	**0:** 69% | +: 17% | ++: 14%	**0:** 68% | +: 21% | ++: 12%	0.291†
SRS SVA 2Y	**0:** 59% | +: 27% | ++: 15%	**0:** 56% | +: 33% | ++: 11%	0.136†

3CO indicates three-column osteotomy; ACR, anterior column realignment; ASA, American Society of Anesthesiologists; BMI, body mass index; CCI, Charlson Comorbidity Index; EBL, estimated blood loss; HRQOL, health-related quality of life; IBF, interbody fusion; LL, lumbar lordosis; ODI, Oswestry Disability Index; PCS, Physical Composite Score; PI, pelvic incidence ; PT, pelvic tilt; SRS, Scoliosis Research Society; SVA, sagittal vertical axis.

**Independent t test.*

†x^2 *test.*

‡*Man–Whitney U test.*

disability scores. In fact, older patients in the second half had better postoperative patientreported outcomes scores despite having similar preoperative disability scores to their younger counterparts, we may argue that the better patient selection that have a dominant sagittal deformity has helped in the improved disability scores.[35] At the same time, rates of PJF did not change significantly but presented a very modest declining trend. Therefore, regardless of the increased risk of complications in older and sicker patients, the benefit of surgical treatment may still outweigh those risks.

TABLE 3. Detailed Comparison of Radiographic Alignment Between First Half of Patients Enrolled and Second Half of Patients Enrolled

	First Half			Second Half			First vs. Second	
	Pre	2 y	*P*	Pre	2 y	*P*	Pre	Post
PI	55 ± 12	—	—	56 ± 13	—	—	0.359*	—
PT	27 ± 10	23 ± 10	< 0.001†	26 ± 10	22 ± 9	< 0.001†	0.418*	0.872*
PI-LL	22 ± 19	4 ± 15	< 0.001†	21 ± 19	4 ± 14	< 0.001†	0.582*	0.816*
L4-S1	32 ± 15	31 ± 12	0.584†	32 ± 14	34 ± 11	0.006†	0.683*	0.002*
T2-T12	−33 ± 18	−53 ± 18	< 0.001†	−37 ± 21	−54 ± 18	< 0.001†	0.014*	0.482*
TPA	26 ± 12	19 ± 11	< 0.001†	26 ± 12	19 ± 10	< 0.001†	0.424*	0.891*
SVA	83 ± 70	35 ± 55	< 0.001†	78 ± 69	33 ± 51	< 0.001†	0.329*	0.773*
Max Cobb	41 ± 21	21 ± 16	< 0.001‡	36 ± 20	18 ± 13	< 0.001‡	< 0.001§	0.071§
C7PL	38 ± 33	28 ± 22	< 0.001‡	38 ± 37	29 ± 23	0.002‡	0.359§	0.600§

LL indicates lumbar lordosis; PI, pelvic incidence ; PT, pelvic tilt; SVA, sagittal vertical axis; TPA, T1 pelvic angle.
**Independent t test.*
†Paired t test.
‡Wilcoxon Rank test.
§Man–Whitney U test.

Based on the study population, it appears that the operative strategy of enrolling surgeons for ASD surgery has changed over the last decade. Surgeons decreased their utilization of 3COs over time potentially due to high associated complication rates as well as the increasing availability and popularity of alternative techniques such as anterior column realignment (ACR) via a lateral lumbar interbody fusion approach.[23,36,37] Although 3CO procedures are associated with greater correction of ASD, there have been reports of higher complications and revision rates in these procedures, especially PJK and instrumentation failure.[36,38] The magnitude and location of correction of lumbar lordosis have been shown to be important factors in PJK development. [39] Historically, although L3 has been the most common level for lordosis restoration via PSO, emerging evidence from Lafage et al suggests that restoring lordosis in a more physiological location (i.e., L4–S1) may be protective against PJK.[40] In our cohort, we can see a small difference between the two halves in term of L4-S1 pre- to postoperative change. However, the magnitude of this difference falls within the measurement error and therefore lacks clinical significance.

Along with the change in correction strategy, there has been an increase in the use of PJK prophylaxis techniques, with 55.1% of patients in the second half having PJK prophylaxis versus 31.3% in the first half. Utilization of hooks over pedicle screws has been associated in some reports with lower proximal junctional angle.[41,42] Others have investigated the effect of spinal construct stiffness,[43] and the use of vertebral cement augmentation at the UIV or UIVþ1 has been proposed to be an effective method to prevent PJK and PJF.[44] All of these methods have been used for several years, but the literature lacks high-quality prospective studies to assess whether there is a clear benefit. In our cohort, the most apparent change in PJK prophylaxis was seen in the use of tether augmentation, as it increased from 4.4% to 26.2%. Biomechanical studies on posterior polyester tethers suggested that the posterior tethers created a more gradual transition in the range of motion and adjacent segment stress when compared with pedicle screws and transverse process hooks at the proximal levels.[45] One retrospective review found that tethers reduced the odds of PJK, as did placing the lumbar lordosis lower in the lumbar spine. These same authors looked at a short-term prospective cohort of 184 patients with 3-month follow-up, that either had no tether or a polyethylene tether with and without a crosslink to aid in tensioning. They found that tethers clinically reduced the incidence of PJK at 3 months from 45% without tether to 26.7%.[46–49] However the limitation of tether augmentation is that for it to work, other aspects of the surgery need to be well-performed, including achieving the appropriate age-adjusted alignment.[50] Line et al, in a propensity score-matched analysis of 625 ASD patients, demonstrated that the use of prophylactic surgical implants alone to prevent PJF was less effective than combining implants with avoidance of sagittal overcorrection. Patients that received no PJF implant prophylaxis and had sagittal overcorrection had the highest incidence of PJF.[51]

Overall, reports from this multicenter ASD surgery registry show a decrease in overall complication rates. From 2009 to 2016, despite an increasingly elderly, medically compromised, and obese patient population, complication rates decreased. Evolving strategies may result in improved treatment of ASD patients.[23] Our findings using the same

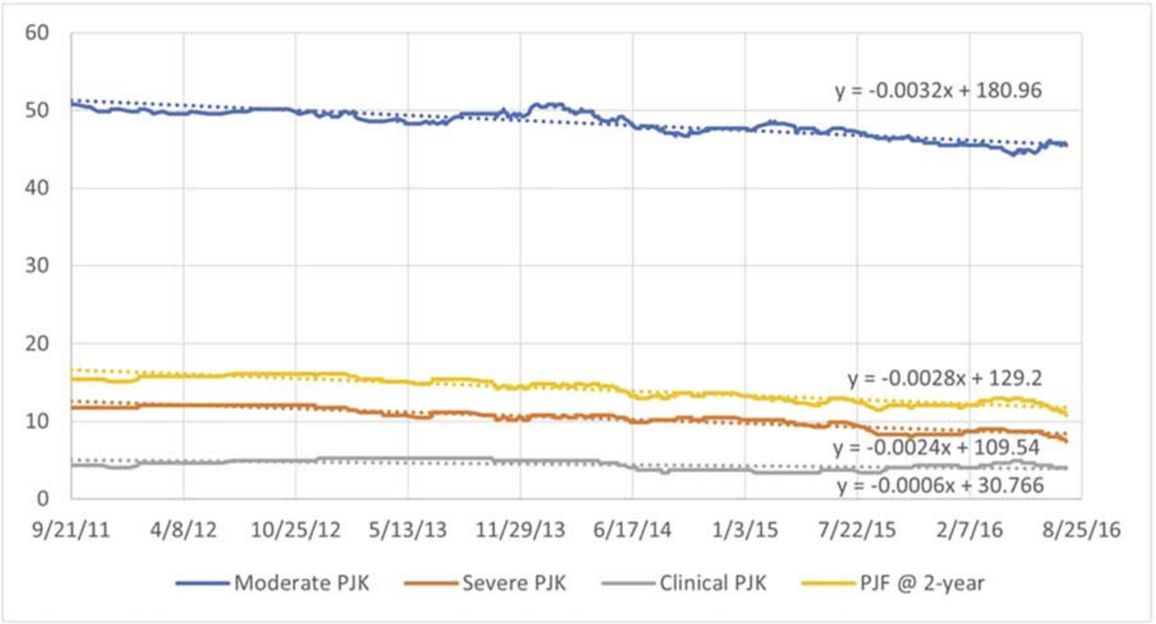

FIGURE 1. Evolution rate of moderate PJK, severe PJK, Clinical PJK, and PJF across enrolment period. PJF indicates proximal junctional failure; PJK, proximal junctional kyphosis. full color online

registry suggest that despite improvement in what we perceive as better alignment and surgical techniques, we did not find a significant decrease in proximal junctional disease, however, at the same time, the rate of this pathology at 2- year follow-up did not increase. We can hypothesize that the increase in patient complexity was balanced with an increased understanding of alignment risk factors; there was also a shift to fewer 3CO and greater ACR technique usage, and the use of more PJK prophylaxis techniques. It is worth mentioning that surgical treatment of ASD demonstrated significant improvement in patient-reported outcomes across all time enrollment periods, with noticeable better disability scores (ODI) at 2 years for patients having surgery in the second half.

This study does have limitations, including the retrospective study design. Although it is a multicenter study, there is no subanalysis of individual surgeons which might carry possible differences in volume, skills, and patient selection. Also, the examined data represent the change in multicenter data, not that of a single site. Not all sites enrolled patients across all time intervals, nor did they enroll comparable proportions of patients. Data included are limited to plain radiographic parameters as muscle quality, bone health or quantitative computed tomography were not part of the original design 10 years ago. Finally, study enrollment was not strictly done on consecutive patients, which could create a bias of enrollment with a resulting impact on evolution trends. The effect of patient selection and expertise bias is unfortunately inevitable when doing multicenter highly specialize database project.

CONCLUSION

ASD patient profile in this multicenter study group has become slightly older over the last decade which has more potential risk for junctional issues. At the same time, surgical strategy has evolved with less invasive osteotomies, better preoperative planning, and more operative PJK prophylaxis methods. Despite the observation that ASD surgery is associated with fewer overall complications, our results did not reveal a significant decrease in PJK rates. However, the balance between more complex patient characteristics and the improvement in surgical planning, intraoperative reconciliation, and prophylaxis techniques have helped to maintain the PJK rates with a slow, not statistically significant, decreasing trend. It is possible that further enrollment and longer follow-up may demonstrate significant decreases in the rates of PJK and PJF.

➢ Key Points

- ❑ The rate of PJK and PJF did not significantly decrease across the 10 years' enrollment period; it did not increase neither.
- ❑ The increase in patient risk factors (older) was probably balanced by changes in surgical strategy including preoperative optimization, distal correction, and PJK prophylaxis methods.
- ❑ Continuous enrollment and follow-up will allow further outcome analysis which may demonstrate significant decreases in the rates of PJK and PJF.

References

1. Smith JS, Kelly MP, Yanik EL, et al. Operative versus nonoperative treatment for adult symptomatic lumbar scoliosis at 5-year followup: durability of outcomes and impact of treatment-related serious adverse events. *J Neurosurgeon Spine*. 2021;35:67–79.
2. Smith JS, Lafage V, Shaffrey CI, 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;78:851–61.
3. Kelly MP, Lurie JD, Yanik EL, et al. Operative versus non-operative treatment for adult symptomatic lumbar scoliosis. *J Bone Joint Surg Am*. 2019;101:338–52.
4. Kim YJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis in adolescent idiopathic scoliosis following segmental posterior spinal instrumentation and fusion: minimum 5-year follow-up. *Spine (Phyla Pa 1976)*. 2005:2045–50.
5. Kim HJ, Lenke LG, Shaffrey CI, et al. Proximal junctional kyphosis as a distinct form of adjacent segment pathology after spinal deformity surgery. *Spine (Phila Pa 1976)*. 2012;37(22 suppl):S144–64.
6. Faundez AA, Richards J, Maxy P, et al. 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):139–48.
7. Glattes RC, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. *Spine (Phila Pa 1976)*. 2005;30:1643–9.
8. Bridwell KH, Lenke LG, Cho SK, et al. Proximal junctional kyphosis in primary adult deformity surgery: evaluation of 20 degrees as a critical angle. *Neurosurgery*. 2013;72:899–906.
9. Hostin R, McCarthy I, O'Brien M, et al. Incidence, mode, and location of acute proximal junctional failures after surgical treatment of adult spinal deformity. *Spine (Phila Pa 1976)*. 2013;38:1008–15.
10. Lafage R, Schwab FJ, Bess S, et al. Redefining radiographic thresholds for junctional kyphosis pathologies. *Spine J*. 2015;15: S216.
11. Lee J-H, Kim J-U, Jang J-S, et al. Analysis of the incidence and risk factors for the progression of proximal junctional kyphosis following surgical treatment for lumbar degenerative kyphosis: minimum 2-year follow-up. *Br J Neurosurg*. 2014;28:252–8.
12. Lapp MA, Bridwell KH, Lenke LG, et al. Long-term complications in adult spinal deformity patients having combined surgery a comparison of primary to revision patients. *Spine (Phila Pa 1976)*. 2001;26:973–83.
13. Hassanzadeh H, Gupta S, Jain A, et al. Type of anchor at the proximal fusion level has a significant effect on the incidence of proximal junctional kyphosis and outcome in adults after long posterior spinal fusion. *Spine Deform*. 2016;1:299–305.
14. Hart R, McCarthy I, O'brien M, et al. Identification of decision criteria for revision surgery among patients with proximal junctional failure after surgical treatment of spinal deformity. *Spine (Phila Pa 1976)*. 2013;38:E1223–7.
15. Kim YJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum five-year follow-up. *Spine (Phila Pa 1976)*. 2008;33:2045–50.
16. Safaee MM, Dalle Ore CL, Zygourakis CC, et al. The unreimbursed costs of preventing revision surgery in adult spinal deformity: analysis of cost-effectiveness of proximal junctional failure prevention with ligament augmentation. *Neurosurg Focus*. 2018;44:1–7.
17. Kim HJ, Bridwell KH, Lenke LG, et al. Patients with proximal junctional kyphosis requiring revision surgery have higher post-operative lumbar lordosis and larger sagittal balance corrections. *Spine (Phila Pa 1976)*. 2014;39:E576–80.
18. Schwab FJ, Lafage R, Glassman SD, et al. Age-adjusted alignment AQ5 goals have the potential to reduce proximal junctional kyphosis. *North American Spine Society*. Elsevier Inc; 2015;15:S137.
19. Cammarata M, Aubin CE, Wang X, et al. Biomechanical risk factors for proximal junctional kyphosis: a detailed numerical analysis of surgical instrumentation variables. *Spine (Phila Pa 1976*. 2014;39:E500–7.
20. Nordin P, van der Linden W. Volume of procedures and risk of recurrence after repair of groin hernia: national register study. *BMJ*. 2008;336:934–7.
21. Birkmeyer J, Stukel T. Surgeon volume and operative mortality in the United States. *N Engl J Med* . 2003:2117–7. Published online http://www.nejm.org/doi/full/10.1056/nejmsa035205.
22. Luft HS, Bunker JP, Enthoven AC. Should operations be regionalized? *N Engl J Med*. 1979;301:1364–9.
23. Daniels, AH, Reid, DBCC, Tran SN, et al. Evolution in surgical approach, complications, and outcomes in an adult spinal deformity surgery multicenter study group patient population. *Spine Deform*. 2019;7:481–8.
24. Champain S, Benchikh K, Nogier A, et al. Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. *Eur Spine J*. 2006;15:982–1.
25. Schwab F, Ungar B, Blondel B, et al. SRS-Schwab Adult Spinal Deformity Classification: a validation study. *Spine (Phila Pa 1976)*. 2011;37:1077–82.
26. Smith MW, Annis P, Lawrence BD, et al. Early proximal junctional failure in patients with preoperative sagittal imbalance. *Evid Based Spine Care J*. 2013;4:163–4.
27. Ha Y, Maruo K, Racine L, 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;19:360–9.
28. Cho SK, Bridwell KH, Lenke LG, et al. Major complications in revision adult deformity surgery: risk factors and clinical outcomes with 2- to 7-year follow-up. *Spine (Phila Pa 1976)*. 2012;37:489–500.
29. Yagi M, King AB, Boachie-Adjei O. Incidence, risk factors, and natural course of proximal junctional kyphosis. *Spine (Phila Pa 1976)*. 2012;37:1479–89.
30. Kim YJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum five-year follow-up. *Spine (Phila Pa 1976)*. 2008;33:2179–84.
31. Liu F-YY, Wang T, Yang S-DD, et al. Incidence and risk factors for proximal junctional kyphosis: a meta-analysis. *Eur Spine J*. 2016;25:2376–83.
32. Miller EK, Lenke LG, Neuman BJ, et al. External validation of the adult spinal deformity (asd) frailty index (asd-fi) in the scoli-risk-1 patient database. *Spine (Phila Pa 1976)*. 2018;43:1426–31.
33. Reid, DBCC, Daniels, AH, Ailon. T, et al. Frailty and health-related quality of life improvement following adult spinal deformity surgery. *World Neurosurg*. 2018;112:e548–54.
34. 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:E60–8.
35. Sheikh Alshabab B, Gupta MC, Lafage R, et al. Does achieving global spinal alignment lead to higher patient satisfaction and lower disability in adult spinal deformity? *Spine (Phila Pa 1976)*. 2021;46:1105–10.
36. Maier SP, Smith JS, Schwab FJ, et al. Revision surgery after 3-column osteotomy in 335 patients with adult spinal deformity intercenter variability and risk factors. *Spine (Phila Pa 1976)*. 2014;39:881–5.
37. Mundis GM, Turner JD, Kabirian N, et al. Anterior column realignment has similar results to pedicle subtraction osteotomy in treating adults with sagittal plane deformity. *World Neurosurg*. 2017;105:249–56.
38. Smith JS, Shaffrey CI, Klineberg E, et al. Complication rates associated with 3-column osteotomy in 82 adult spinal deformity patients: retrospective review of a prospectively collected multicenter consecutive series with 2-year follow-up. *J Neurosurg Spine*. 2017;27:444–57.
39. Park S-HS-J, Lee C-S, Chung S-S, et al. Different risk factors of proximal junctional kyphosis and proximal junctional failure following long instrumented fusion to the sacrum for adult spinal deformity: survivorship analysis of 160 patients. *Neurosurgery*. 2017;80:279–86.
40. Lafage R, Obeid I, Liabaud B, et al. Location of correction within the lumbar spine impacts acute adjacent-segment kyphosis. *J Neurosurg Spine*. 2019;30:69–77.

41. Metzger MF, Robinson ST, Svet MT, et al. Biomechanical analysis of the proximal adjacent segment after multilevel instrumentation of the thoracic spine: Do hooks ease the transition? *Glob Spine J*. 2016;6:335–43.
42. Matsumura A, Namikawa T, Kato M, et al. Effect of different types of upper instrumented vertebrae instruments on proximal junctional kyphosis following adult spinal deformity surgery: pedicle screw versus transverse process hook. *Asian Spine J*. 2018;12:622–31.
43. Han S, Hyun S-JJ, Kim K-JJ, et al. Rod stiffness as a risk factor of proximal junctional kyphosis after adult spinal deformity surgery: comparative study between cobalt chrome multiple-rod constructs and titanium alloy two-rod constructs. *Spine J*. 2017;17:962–8.
44. Hart RA, Prendergast MA, Roberts WG, et al. Proximal junctional acute collapse cranial to multi-level lumbar fusion: a cost analysis of prophylactic vertebral augmentation. *Spine J*. 2008;8:875–1.
45. Bess S, Harris JE, Turner AWL, et al. The effect of posterior polyester tethers on the biomechanics of proximal junctional kyphosis: a finite element analysis. *J Neurosurg Spine*. 2016;26:125–33.
46. Buell TJ, Buchholz AL, Quinn JC, et al. A pilot study on posterior polyethylene tethers to prevent proximal junctional kyphosis after multilevel spinal instrumentation for adult spinal deformity. *Oper Neurosurg*. 2019;16:256–66.
47. Buell TJ, Chen C-JJ, Quinn JC, et al. Alignment risk factors for proximal junctional kyphosis and the effect of lower thoracic junctional tethers for adult spinal deformity. *World Neurosurg*. 2019;121:e96–103.
48. Daniels AH, Patel SA, Reid DBC, et al. Proximal junctional failure prevention in adult spinal deformity surgery utilizing interlaminar fixation constructs. *Orthop Rev (Pavia)*. 2019;11:66–9.
49. Buell TJ, Bess S, Xu M, et al. Optimal tether configurations and preload tensioning to prevent proximal junctional kyphosis: a finite element analysis. *J Neurosurg Spine*. 2019;30:574–84.
50. Lafage R, Schwab F, Glassman S, et al. Age-adjusted alignment goals have the potential to reduce PJK. *Spine (Phila Pa 1976)*. 2017;42:1275–82.
51. Line BG, Bess S, Lafage R, et al. Effective prevention of proximal junctional failure in adult spinal deformity surgery requires a combination of surgical implant prophylaxis and avoidance of sagittal alignment overcorrection. *Spine (Phila Pa 1976)*. 2020;45: 258–67.