The impact of baseline cervical malalignment on the development of proximal junctional kyphosis following surgical correction of thoracolumbar adult spinal deformity

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OBJECTIVE The objective of this study was to identify the effect of baseline cervical deformity (CD) on proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) in patients with adult spinal deformity (ASD).

METHODS This study was a retrospective analysis of a prospectively collected, multicenter database comprising ASD patients enrolled at 13 participating centers from 2009 to 2018. Included were ASD patients aged > 18 years with concurrent CD (C2–7 kyphosis < −15°, T1S minus cervical lordosis > 35°, C2–7 sagittal vertical axis > 4 cm, chin-brow vertical angle > 25°, McGregor's slope > 20°, or C2–T1 kyphosis > 15° across any three vertebrae) who underwent surgery. Patients were grouped according to four deformity classification schemes: Ames and Passias CD modifiers, sagittal morphotypes as described by Kim et al., and the head versus trunk balance system proposed by Mizutani et al. Mean comparison tests and multivariable binary logistic regression analyses were performed to assess the impact of these deformity classifications on PJK and PJF rates up to 3 years following surgery.

RESULTS A total of 712 patients with concurrent ASD and CD met the inclusion criteria (mean age 61.7 years, 71% female, mean BMI 28.2 kg/m^2, and mean Charlson Comorbidity Index 1.90) and underwent surgery (mean number of levels fused 10.1, mean estimated blood loss 1542 mL, and mean operative time 365 minutes; 70% underwent osteoto-

ABBREVIATIONS ASD = adult spinal deformity; CBVA = chin-brow vertical angle; CD = cervical deformity; cSVA = C2–7 sagittal vertical axis; FD = focal deformity; FND = flat neck deformity; LL = lumbar lordosis; PI = pelvic incidence; PI-LL = pelvic incidence–lumbar lordosis mismatch; PJF = proximal junctional failure; PJK = proximal junctional kyphosis; PT = pelvic tilt; SRS = Scoliosis Research Society; T1S = T1 slope; TS1-CL = T1S minus cervical lordosis; UIV = upper instrumented vertebra.

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my). By approach, 59% of the patients underwent a posterior-only approach and 41% underwent a combined approach. Overall, 277 patients (39.1%) had PJK by 1 year postoperatively, and an additional 189 patients (26.7%) developed PJK by 3 years postoperatively. Overall, 65 patients (9.2%) had PJF by 3 years postoperatively. Patients classified as having a cervicothoracic deformity morphotype had higher rates of early PJK than flat neck deformity and cervicothoracic deformity patients ($p = 0.020$). Compared with the head-balanced patients, trunk-balanced patients had higher rates of PJK and PJF (both $p < 0.05$). Examining Ames modifier severity showed that patients with moderate and severe deformity by the horizontal gaze modifier had higher rates of PJK ($p < 0.001$).

CONCLUSIONS In patients with concurrent cervical and thoracolumbar deformities undergoing isolated thoracolumbar correction, the use of CD classifications allows for preoperative assessment of the potential for PJK and PJF that may aid in determining the correction of extending fusion levels.

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KEYWORDS adult spinal deformity; cervical deformity; spine; clinical outcomes; proximal junctional kyphosis; PJK; proximal junctional failure; PJF; lumbar; thoracic

Adult spinal deformity (ASD) and adult cervical deformity (CD) are complex disease states that can pathologically alter one's upright standing posture and horizontal gaze. Both conditions may be associated with substantial pain and functional impairment.[1–3] There is a high degree of concurrence, with rates of cervical malalignment reported to be as high as 53% in ASD patients.[4] This may be explained by both reciprocal changes in the cervical region that occur to compensate for thoracolumbar deformities and postsurgical changes after correction of thoracolumbar malalignment.[5]

Corrective surgery of both cervical and thoracolumbar deformities may involve multilevel fusion, osteotomy, and decompression to restore sagittal and/or coronal alignment to a more ideal position. Despite recent advancements in surgical planning and techniques, ASD correction carries a notable risk of complications and other adverse events. Specifically, mechanical complications like proximal junctional kyphosis (PJK) and proximal junctional failure (PJF) are of ongoing concern, with numerous studies reporting rates between 20% and 40%.[6–9]

At this time, the impact of concurrent cervical and thoracolumbar deformities on the eventual development of PJK and PJF after isolated surgical intervention remains underexplored. We sought to identify the effect of baseline cervical malalignment on the development of PJK and PJF in patients undergoing ASD correction. Because the exact radiographic definition of CD remains disputed, we examined cervical malalignment as defined by four separate classification schemes: both the Ames and Passias CD classifications, the sagittal morphotypes described by Kim et al., and the head versus trunk balance system of global alignment proposed by Mizutani et al.[19–21,27] We hypothesized that the presence of CD, as defined by any of these schemas, would increase the likelihood for PJK and PJF following ASD surgery.

Methods

Data Source

This study was a retrospective analysis of a prospectively collected, multicenter database comprising ASD patients enrolled at 13 participating centers from 2009 to 2018. Approval from the institutional review board of each participating site was obtained, and all patients provided informed consent prior to enrollment. The inclusion and exclusion criteria for this prospective registry, how patients were recruited, data collection, and integrity assessment have been described in full in other works.[10–12] The data collected in this registry have previously been successfully used to study clinical aspects of ASD surgery as well as issues specific to health policy.[10–13]

Study Design

The inclusion criteria of the present study required ASD patients with concurrent CD who underwent surgery. CD was defined radiographically as at least one of the following being met: C2–7 sagittal kyphosis > 15°, T1 slope (T1S) minus cervical lordosis (TS1-CL) > 35°, C2–7 sagittal vertical axis (cSVA) > 40 mm, chin-brow vertical angle (CBVA) > 25°, McGregor's slope > 20°, and segmental cervical kyphosis > 15° across any three vertebrae between C2 and T1. Patients with an upper instrumented vertebra (UIV) above T1 or with preoperative PJK were excluded. All included patients had complete radiographic and health-related quality-of-life data preoperatively and up to 3 years postoperatively.

Data Collection and Radiographic Assessment

Standardized data collection forms tracked patient demographics, surgical parameters, and comorbidities beginning at the initial presentation. Health-related quality-of-life metrics collected at baseline and at follow-up included the SF-36, Oswestry Disability Index, and Scoliosis Research Society (SRS)–22 revised questionnaire.

Full-length free-standing lateral spine radiographs were used to assess radiographic parameters at baseline and follow-up intervals. SpineView (ENSAM, Laboratory of Biomechanics) was used to assess all images.[14–16] Assessment of radiographic parameters included pelvic incidence–lumbar lordosis mismatch (PI-LL), pelvic tilt (PT), and sagittal vertical axis (SVA).[17]

Deformity Classification

Preoperative thoracolumbar deformity severity at baseline was assessed using the SRS-Schwab classification. This system accounts for three modifiers (PT, PI-LL, and SVA), with each being stratified into three tiers of severity: 0 for nonpathologic, + for moderate deformity, and ++ for marked deformity.[18]

Preoperative CD severity was assessed using four dis-

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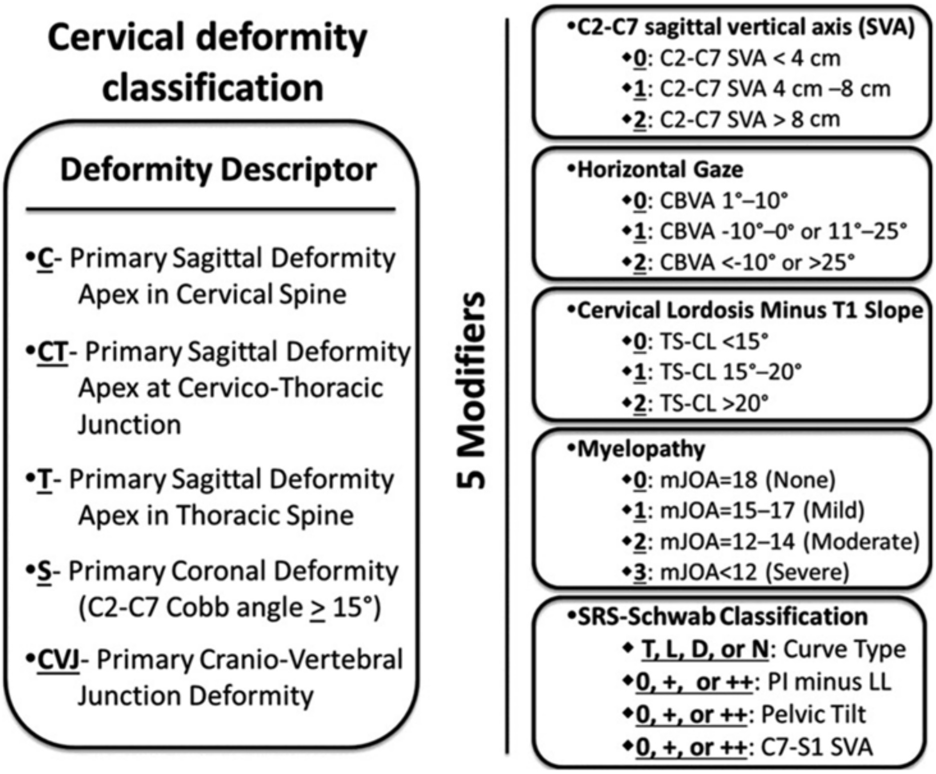

FIG. 1. The Ames classification system for CD consists of a deformity descriptor and five modifiers. Reproduced from Ames et al. *J Neurosurg Spine.* 2015;23(12):673-683.[19] © AANS, published with permission.

tinct classification systems: the Ames and Passias CD classifications, the sagittal morphotypes described by Kim et al., and the head versus trunk balance system of global alignment proposed by Mizutani et al.[19–21,27] The Ames CD classification consists of a CD descriptor that identifies the apex of the deformity, and five modifiers (Fig. 1).[19] Patients were assigned a CD descriptor based on radiographic review and were stratified by deformity severity for each of the five modifiers. The Passias modified CD classification system[20] was used to stratify patients by deformity severity for each of the radiographic modifiers.

A sagittal morphotype as described by Kim et al. was assigned by analyzing the preoperative T1S, C2–7 Cobb angle, cSVA, maximum focal kyphosis, and TS1-CL.[27] The radiographic parameters for the flat neck deformity (FND) were T1S < 29°, cSVA > 40 mm, and neutral minus extension C2–7 > 10°. The radiographic cutoffs for a focal deformity (FD) morphotype were T1S < 29°, cSVA > 40 mm, maximum focal kyphosis < –5°, and TS1-CL < 22°. A cervicothoracic deformity morphotype was defined as T1S > 40° and neutral minus extension C2–7 > –10°. Last, patients were categorized as head balanced or trunk balanced based on a description of global alignment by Mizutani et al.[21] Those with lumbar lordosis (LL) > pelvic incidence (PI), negative SVA, and T1S < 20° were considered head balanced. Patients were considered trunk balanced if they had a positive SVA, PI > LL, and T1S > 20°.

All patients were classified by Ames and Passias criteria. Patients who did not match the exact categories set forth by the Kim et al. sagittal morphotypes or the Mizutani et al.[21,27] head versus trunk balance system were not assigned a grade within these subgroups.

Classifying PJK and PJF

PJK was defined based on previously published values of a PJK angle < –10° and a difference in PJK angle < –10°.[22] PJF was defined using the criteria of a PJK angle < –28° and a difference in PJK angle < –22°.[22]

Statistical Analysis

Frequency distributions and summary statistics were calculated for all demographic, clinical, surgical, and radiographic variables. The occurrence of PJK and PJF was assessed by 1 year postoperatively (early follow-up) and between 1 and 3 years postoperatively (late follow-up). The differences in PJK and PJF occurrence were assessed by CD classification using cross-tabulations and Pearson chi-square tests. Multivariable binary logistic regression analysis was performed to determine the impact of the four CD classification systems on PJK and PJF occurrence. Statistical analysis was conducted using the IBM SPSS Statistics for Windows software (version 28.0.1, IBM Corp.), with statistical test significance set at $p < 0.05$.

Results

Cohort Overview

A total of 708 ASD patients with concurrent CD met

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TABLE 1. Mean preoperative radiographic parameters for 708 patients with concurrent ASD and CD

Radiographic Parameter	Mean at Baseline
Sacral slope, °	31.7
PT, °	24.2
PI, °	56.0
LL, °	39.7
PI-LL, °	16.3
T4–12 thoracic kyphosis, °	37.2
SVA, mm	75.5
T1S, °	34.0
C2–7 lordosis, °	14.4
TS1-CL, °	19.5
C2 slope, °	17.5
CBVA, °	4.3
McGregor's slope, °	–2.5

TABLE 2. Preoperative CD classification by sagittal morphotype and head-trunk balance in 708 patients with concurrent ASD and CD

	Count	% of Cohort
Sagittal morphotype		
FND	18	2.5
FD	10	1.4
Cervicothoracic deformity	206	29.1
None	474	66.9
Head-trunk balance		
Head balanced	14	2.0
Trunk balanced	474	66.9
None	220	31.1

the inclusion criteria. The mean age in this cohort was 61.7 ± 14.6 years, 71% of patients were female, the mean BMI was 28.2 ± 5.9 kg/m^2, and the mean Charlson Comorbidity Index was 1.90 ± 1.73. The mean number of levels fused was 10.1 ± 4.5, the mean estimated blood loss was 1542 ± 1382 mL, and the mean operative time was 365 ± 133 minutes. By approach, 59% of the patients underwent a posterior-only approach and 41% underwent a combined approach. Nearly 70% of the patients had an osteotomy as part of their index procedure. In terms of baseline comorbidities, 18.8% of the patients (n = 133) had a history of osteoporosis. The total cohort follow-up rates were 98.4% at 1 year, 89.3% at 2 years, and 70.6% at 3 years. The median follow-up duration was 2.4 years (range 1–4 years).

The mean radiographic parameters at baseline are reported in Table 1. SRS-Schwab modifier assessment at baseline depicted deformity severity with the following distribution: 35.9% nonpathologic, 20.8% moderate deformity, and 43.2% marked deformity for PI-LL; 32.3% nonpathologic, 32.7% moderate deformity, and 35.0% marked deformity for SVA; and 34.5% nonpathologic, 38.5% moderate deformity, and 27.0% marked deformity for PT.

CD Classifications

Preoperative CD severity was assessed using four previously established classification systems: the Ames and Passias CD classifications, the Kim et al.[27] sagittal morphotypes, and the Mizutani et al.[21] head versus trunk balance system. By preoperative Ames CD modifiers, the following proportion of the cohort was categorized as having severe deformity: 0% cSVA, 45.6% TS1-CL, 43.8% SVA, and 4.8% horizontal gaze. By preoperative Passias CD modifiers, the following proportion of the cohort was categorized as having severe deformity: 3.1% McGregor's slope, 3.1% TS1-CL, 3.9% C2–7 cervical lordosis, 1.4% C2–T3 angle, and 1.7% C2 slope. The distribution of these CD classifications is reported in Tables 2 and 3. Using the three sagittal morphotypes adapted from Virk et al. (FND, FD, and cervicothoracic deformity), we identified radiographic thresholds.[23] By preoperative morphotype, 19 patients (2.7%) were classified as having FND, 10 (1.4%) as having FD, and 207 (29.2%) as having cervicothoracic deformity. Patients were classified into head- and trunk-balanced groups by three major parameters: SVA, PI-LL, and T1S. Fourteen patients (2.0%) were categorized as head balanced, while 477 (67.4%) were considered trunk balanced.

PJK Prophylaxis

A total of 346 patients (48.7%) received PJK prophylaxis as part of their index procedure. Thirty-eight patients underwent cement augmentation, 71 had hook placement at the UIV, 106 underwent tether placement at the UIV, 19 patients had a hybrid construct, and 112 patients underwent a minimally invasive posterior fusion.

PJK and PJF Occurrence

Overall, 277 patients (39.1%) developed PJK by 1 year postoperatively (early PJK), and 189 patients (26.7%) developed PJK by 3 years postoperatively (late PJK). Sixty-five patients (9.2%) had PJF by the 3-year follow-up. Examination of PJK and PJF occurrence by sagittal morphotype revealed that patients who were classified as having the cervicothoracic deformity morphotype had higher rates of early PJK than the patients classified as having an FND or FD (cervicothoracic deformity: 41.1% vs FND or FD: 20.7%, p = 0.020). Compared with head-balanced patients, those categorized as trunk-balanced patients had higher rates of PJK (46.5% vs 21.4%, p = 0.048) and PJF (10.1% vs 0.0%, p < 0.001) by 3 years postoperatively. Assessment of Ames modifier severity showed that patients with moderate and severe deformity by the horizontal gaze modifier had higher rates of PJK (59.3% vs 41.3%, p < 0.001) by 3 years postoperatively.

Multivariable binary logistic regression identified the cervicothoracic deformity morphotype as an independent predictor of early PJK when adjusting for PJK prophylaxis (OR 2.9, 95% CI 1.1–7.4; p = 0.031). In a multivariable binary logistic regression analysis controlling for age, UIV, and PJK prophylaxis, the following were independent predictors of developing PJK by 3 years postoperatively: preoperatively trunk balanced versus head balanced (OR 4.6, 95% CI 1.1–19.7; p = 0.042) and moderate or severe defor-

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TABLE 3. Ames and Passias CD modifiers in 708 patients with concurrent ASD and CD

	Nonpathologic (0)		Moderate Deformity (+)		Severe Deformity (++)	
	Count	% of Cohort	Count	% of Cohort	Count	% of Cohort
Ames modifiers						
cSVA	461	65.1	247	34.9	0	0
TS1-CL	277	39.1	108	15.3	323	45.6
SVA	229	32.3	169	23.9	310	43.8
Horizontal gaze	21	3.0	101	14.3	34	4.8
Passias modifiers						
McGregor's slope*	73	10.3	69	9.7	22	3.1
TS1-CL	499	70.5	191	27.0	22	3.1
C2–7	557	78.7	127	17.9	28	3.9
C2–T3	682	96.3	20	2.8	10	1.4
C2 slope	610	86.2	90	12.7	12	1.7

* Not all patients (548 [77.0%]) had a preoperative measurement.

mity by the Ames horizontal gaze modifier preoperatively (OR 1.7, 95% CI 1.2–2.6; p = 0.008).

Multivariable backstep regression for early PJK controlling for age, sex, BMI, Charlson Comorbidity Index, osteoporosis, smoking status, baseline deformity (SVA, PT, PI-LL, C7-PL, TS1-CL, C2 slope, cSVA), deformity correction, levels fused, and invasiveness found age, PT difference, and invasiveness to be significant risk factors (age: OR 1.062, 95% CI 1.031–1.095 [p < 0.001]; PT correction: OR 1.061, 95% CI 1.007–1.117 [p = 0.026]; invasiveness index: OR 1.019, 95% CI 1.005–1.032 [p = 0.005]) (Table 4). Using the above analysis, we found prophylaxis use; baseline PT, PI, PI-LL, and cSVA; and correction amount in PT, PI-LL, and SVA to be significant for developing late PJK (Table 5).

Case Example

A 62-year-old patient presented with loss of LL and coronal deformity with baseline CD. The patient underwent fusion to the upper thoracic region with sustained CD postoperatively (Fig. 2). Ten months postoperatively, the patient presented with PJF with chin-to-chest syndrome and subsequently underwent extension of fusion to the upper cervical region (Fig. 3).

Discussion

This investigation sought to evaluate the effect of baseline CD on PJK and PJF development in ASD patients. Corrective surgery for these patients has been proven clinically effective in terms of physical improvement and quality of life.[24,25] Increased kyphosis of the proximal segment to the upper instrumented vertebra following operative treatment has been a major area of interest because of its incidence and associated symptoms.[26] Little has been studied about the impact of concurrent adult CD and ASD on the postoperative incidence of PJK and PJF. Several classification systems of adult CD have been published, and we sought to determine which deformity types were associated with postoperative PJK and PJF.

An advantage of our study is its multicenter, multisurgeon collaboration with the ability to account for trends in surgical advancements and patient-reported outcomes over the course of the enrollment period, from 2009 to 2018. The 13-center multinational database comprising regional, demographic, and socioeconomic variation represented by our cohort supports that our findings are likely to be externally validated and are representative of the

TABLE 4. Early PJK multivariable analysis controlling for confounders

	OR	95% CI for Exp(B) Lower Limit	Upper Limit	p Value
Prophylaxis	0.499	0.234	1.063	0.072
Baseline age	1.062	1.031	1.095	<0.001
Baseline plumb line C7–S1 SVA	0.993	0.985	1.001	0.073
Corrected PT	1.061	1.007	1.117	0.026
ISSG invasiveness index	1.019	1.005	1.032	0.005

ISSG = International Spine Study Group.

TABLE 5. Late PJK multivariable analysis controlling for confounders

	OR	95% CI for Exp(B) Lower Limit	Upper Limit	p Value
Prophylaxis	0.407	0.181	0.913	0.029
Baseline PT	1.219	1.113	1.335	<0.001
Baseline PI	0.943	0.905	0.982	0.005
Baseline PI-LL	0.922	0.876	0.969	0.002
Baseline plumbline C2–7	0.966	0.939	0.994	0.017
Corrected PT	1.160	1.060	1.269	0.001
Corrected PI-LL	0.901	0.844	0.961	0.002
Corrected plumbline C7–S1 SVA	1.010	0.999	1.021	0.075

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FIG. 2. Preoperative posteroanterior (*left* in each panel) and lateral (*right* in each panel) radiographs from case example of 62-year-old patient presenting with loss of lumbar lordosis and coronal deformity with baseline cervical deformity.

overall experience with ASD surgery over the last decade. For patients with concurrent cervical and thoracolumbar deformities undergoing isolated thoracolumbar correction, we found that prior cervical classification systems can assist with preoperative PJK and PJF risk assessment. The cervicothoracic deformity morphotype, defined as a very large T1S with compensatory hyperlordosis of the cervical spine, was associated with increased odds of postoperative PJK.[27] Little has been studied about this association, but it has been stated that the operative goals for these patients should focus on correcting the deformity driver leading to the high T1S.[23] Previously, these authors asked if this group of patients are at increased risk of PJK, and our analysis found such an association.[23] However, further study is warranted to determine the ideal upper and lower instrumented vertebrae as well as identifying patient-specific deformities leading to a high T1S and the compensating cervical hyperlordosis.

FIG. 3. Ten-month postoperative posteroanterior (*left*) and lateral (*right*) radiographs from case example depicting chin-to-chest syndrome with patient undergoing subsequent extension of fusion to upper cervical region.

Another significant finding in our study was the association of trunk-balanced patients with the occurrence of PJK. Patients were considered trunk balanced if they had a positive SVA, PI > LL, and T1S > 20°. In a study conducted by Scheer et al., a predictive model for PJK/PJF included preoperative SVA, and it was the most important radiographic parameter in the model.[28] Additionally, several ASD alignment schemas aimed to minimize postoperative PJK have included PI-LL as an alignment goal parameter.[29] With the goal of preventing postoperative PJK, it is imperative to consider those with a higher degree of baseline deformity, particularly SVA and PI-LL, as high-risk individuals, and further prospective study is required to marginalize the risks associated with these patients. Although the sample size may limit the effect because of the small number of patients being classified as head balanced, addressing patients by their variations in sagittal balance can allow for superior outcomes following spinal fusion.[30]

Horizontal gaze, measured as the CBVA, is defined as the angle subtended between a line drawn from the patient's chin to brow and a vertical line, with this parameter's consideration in realignment being associated with favorable outcomes following correction of spinal deformity.[31–33] It was a significant predictor of postoperative PJK in our study when classified as moderate or severe deformity using the Ames CD modifiers.[19] Because of the association of horizontal gaze with functionality and quality of life, as well as the increased odds of PJK following

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ASD correction in our study, a CBVA < 1° or > 10° should be concurrently addressed in an ASD patient.

These results are important for surgeons for their preoperative planning and risk assessment. With the regions of the spine being directly interlinked, malalignment in one region can lead to compensatory changes in another area of the spine or lower extremities.[34] This is especially important when addressing co-occurring adult CD and ASD diagnoses. The particular focus to address the thoracolumbar deformity may be because of the presenting complaint of the patient. Low-back pain may supersede co-occurring or nonsymptomatic neck pain, or the surgeon may elect to work caudally with the intention of the proximal deformity correcting on its own. This study helps identify another risk factor for PJK occurrence, which not only helps in preoperative risk stratification but also may provide certain thresholds to treat patients differently. For example, tethering and other prophylactic measures could be used in high-risk patients. Cervical or thoracolumbar deformity should be treated first or concurrently.[35]

We acknowledge several potential shortcomings associated with this effort. Although we accrued many patients over the course of 10 years from different centers and surgeons, there remains the potential for selection and expertise bias, as well as patient clustering, to confound results. Furthermore, given the study design, there is also the prospect of a surveillance bias, and we cannot ensure that all possible outcomes and events during postsurgical care for ASD are adequately represented in this cohort. The methodological approaches may be prone to overoptimistic modeling, and as such, results should be viewed as hypothesis generating rather than prescriptive at this time. Although derived from broad clinical experience across 13 centers, we cannot be certain that the outcomes and associations presented here are fully translatable, and the findings may not be uniformly applicable to all healthcare contexts, especially those that are dramatically different from the centers contributing cases to the International Spine Study Group registry. The findings our study and how they will perform in larger, more diverse patient cohorts from elsewhere in North America and across the globe remain an important aspect of further research.

Conclusions

Concurrent cervical and thoracolumbar deformities in patients undergoing isolated thoracolumbar correction are more susceptible to complications such as PJK in certain CD morphotype classifications. Specifically, patients with the cervicothoracic deformity morphotype, trunk-balanced patients, and those with a higher degree of horizontal gaze deformity are at higher risk of developing PJK following ASD correction. Surgeons considering ASD correction in patients with these characteristics might give additional consideration to simultaneous or staged treatment of the CD in addition to the thoracolumbar curvature.

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