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CLINICAL ARTICLE

Calibration of a comprehensive predictive model for the development of proximal junctional kyphosis and failure in adult spinal deformity patients with consideration of contemporary goals and techniques

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OBJECTIVE The objective of this study was to calibrate an updated predictive model incorporating novel clinical, radiographic, and prophylactic measures to assess the risk of proximal junctional kyphosis (PJK) and failure (PJF).

METHODS Operative patients with adult spinal deformity (ASD) and baseline and 2-year postoperative data were included. PJK was defined as ≥ 10° in sagittal Cobb angle between the inferior uppermost instrumented vertebra (UIV) endplate and superior endplate of the UIV + 2 vertebrae. PJF was radiographically defined as a proximal junctional sagittal Cobb angle ≥ 15° with the presence of structural failure and/or mechanical instability, or PJK with reoperation. Backstep conditional binary supervised learning models assessed baseline demographic, clinical, and surgical information to predict the occurrence of PJK and PJF. Internal cross validation of the model was performed via a 70%/30% cohort split. Conditional inference tree analysis determined thresholds at an alpha level of 0.05.

ABBREVIATIONS ASD = adult spinal deformity; AUC = area under the ROC curve; CCI = Charlson Comorbidity Index; EBL = estimated blood loss; GAP = global alignment and proportion; HRQOL = health-related quality of life; LIV = lowermost instrumented vertebra; mASD-FI = modified ASD Frailty Index; OR = odds ratio; PI-LL = pelvic incidence minus lumbar lordosis; PJF = proximal junctional failure; PJK = proximal junctional kyphosis; PT = pelvic tilt; ROC = receiver operating characteristic; SAAS = sagittal age-adjusted score; SRS = Scoliosis Research Society; SVA = sagittal vertical axis; TPA = T1 pelvic angle; TS-CL = T1 slope minus cervical lordosis; UIV = uppermost instrumented vertebra.

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RESULTS Seven hundred seventy-nine patients with ASD (mean 59.87 ± 14.24 years, 78% female, mean BMI 27.78 ± 6.02 kg/m^2, mean Charlson Comorbidity Index 1.74 ± 1.71) were included. PJK developed in 50.2% of patients, and 10.5% developed PJF by their last recorded visit. The six most significant demographic, radiographic, surgical, and postoperative predictors of PJK/PJF were baseline age ≥ 74 years, baseline sagittal age-adjusted score (SAAS) T1 pelvic angle modifier > 1, baseline SAAS pelvic tilt modifier > 0, levels fused > 10, nonuse of prophylaxis measures, and 6-week SAAS pelvic incidence minus lumbar lordosis modifier > 1 (all $p < 0.015$). Overall, the model was deemed significant ($p < 0.001$), and internally validated receiver operating characteristic analysis returned an area under the curve of 0.923, indicating robust model fit.

CONCLUSIONS PJK and PJF remain critical concerns in ASD surgery, and efforts to reduce the occurrence of PJK and PJF have resulted in the development of novel prophylactic techniques and enhanced clinical and radiographic selection criteria. This study demonstrates a validated model incorporating such techniques that may allow for the prediction of clinically significant PJK and PJF, and thus assist in optimizing patient selection, enhancing intraoperative decision making, and reducing postoperative complications in ASD surgery.

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KEYWORDS adult spinal deformity; ASD; proximal junctional kyphosis; PJK; proximal junctional failure; PJF; predictive model

Proximal junctional kyphosis (PJK) and failure (PJF) are two of the most prevalent challenges that disrupt the durability of an adult spinal deformity (ASD) correction.[1–4] Radiographic definitions of PJK are numerous, although often-cited metrics include proximal junctional sagittal Cobb angle ≥ 10° and at least 10° greater than the preoperative measurement for one or two levels proximal (cephalad) to the uppermost instrumented vertebra (UIV; UIV + 1 or 2 levels) postoperatively.[5] PJK may be associated with increased pain and disability, and is a frequent cause of revision.[6–8] Upon progression to revision, or an increase of the proximal junctional angle ≥ 15° with the presence of structural failure and mechanical instability, PJK is then often redefined as PJF.[5]

With advancements in knowledge and technology, however, such as minimally invasive techniques, robotic and navigational assistance, novel adaptive alignment criteria, and prophylaxis techniques, rates of PJK and PJF have fallen in recent years.[9] Segreto et al. reported that between 2009 and 2017, the annual incidence of PJK was approximately 69.4%, yet the annual incidence of acute PJK decreased from 53.7% in 2012 to 31.6% in 2017.[10] Despite these trends, the economic burden of PJK and PJF remains significant. In their single-center analysis, Theologis et al. reported that direct costs of PJF revision equaled $3.2 million (US dollars).[11]

Thus, identifying risk factors for PJK and PJF have come to the forefront of the spine literature. Previous studies have demonstrated that common risk factors such as advanced age, increased BMI, and osteoporosis increased the risk for PJK and PJF development.[12] Early predictive models by Scheer et al. found that further incorporation of preoperative radiographic measures such as sagittal vertical axis (SVA), pelvic tilt (PT), and pelvic incidence minus lumbar lordosis (PI-LL) contributed to a robust model predicting PJK/PJF.[13] Yet, the rise of novel alignment schema such as the sagittal age-adjusted score (SAAS) system by Lafage et al. has revealed an increased ability to individually predict PJK, but the incorporation and weighted impact of such variables has not yet been assessed via predictive modeling.[14]

This study aimed to assess the effects of improvements in surgical technique, ASD classification, and patient selection on the rates of PJK following surgical cervical spine deformity intervention through longitudinal analysis. Using multicenter data from 2009 to 2018, the authors aimed to incorporate novel techniques and alignment systems to develop an updated model predictive of PJK and PJF.

Methods

Data Source and Study Design

We conducted a retrospective analysis of a prospectively collected, multicenter database containing patients with ASD enrolled at 13 participating centers from 2009 to 2018. IRB approval was obtained at each participating enrollment site and all patients provided informed consent. Patients enrolled in the database were older than 18 years, had a plan to undergo surgical correction, and met at least one of the following radiographic criteria for ASD: coronal Cobb angle ≥ 20°, SVA ≥ 50 mm, PT ≥ 25°, and/or thoracic kyphosis > 60°. Patients whose spinal deformity had a neuromuscular etiology and those with active infections or malignancy were excluded from the database. All data collected at the participating sites were subject to rigorous quality control and have been extensively utilized in the peer-reviewed literature.[12,15,16] Patients included in the present study required operative ASD treatment with complete radiographic and health-related quality-of-life (HRQOL) data preoperatively and at 6 weeks and 2 years postoperatively. Patients with a UIV above T1 or lowermost instrumented vertebra (LIV) above L1 were excluded from analysis.

Data Collection and Radiographic Assessment

Standardized data collection forms tracked patient demographics, surgical parameters, and comorbidities beginning at the initial presentation. HRQOL metrics collected at baseline and multiple follow-up time points included the Short-Form 36-Item Health Survey, Oswestry Disability Index, and Scoliosis Research Society-22 revised.[17–19]

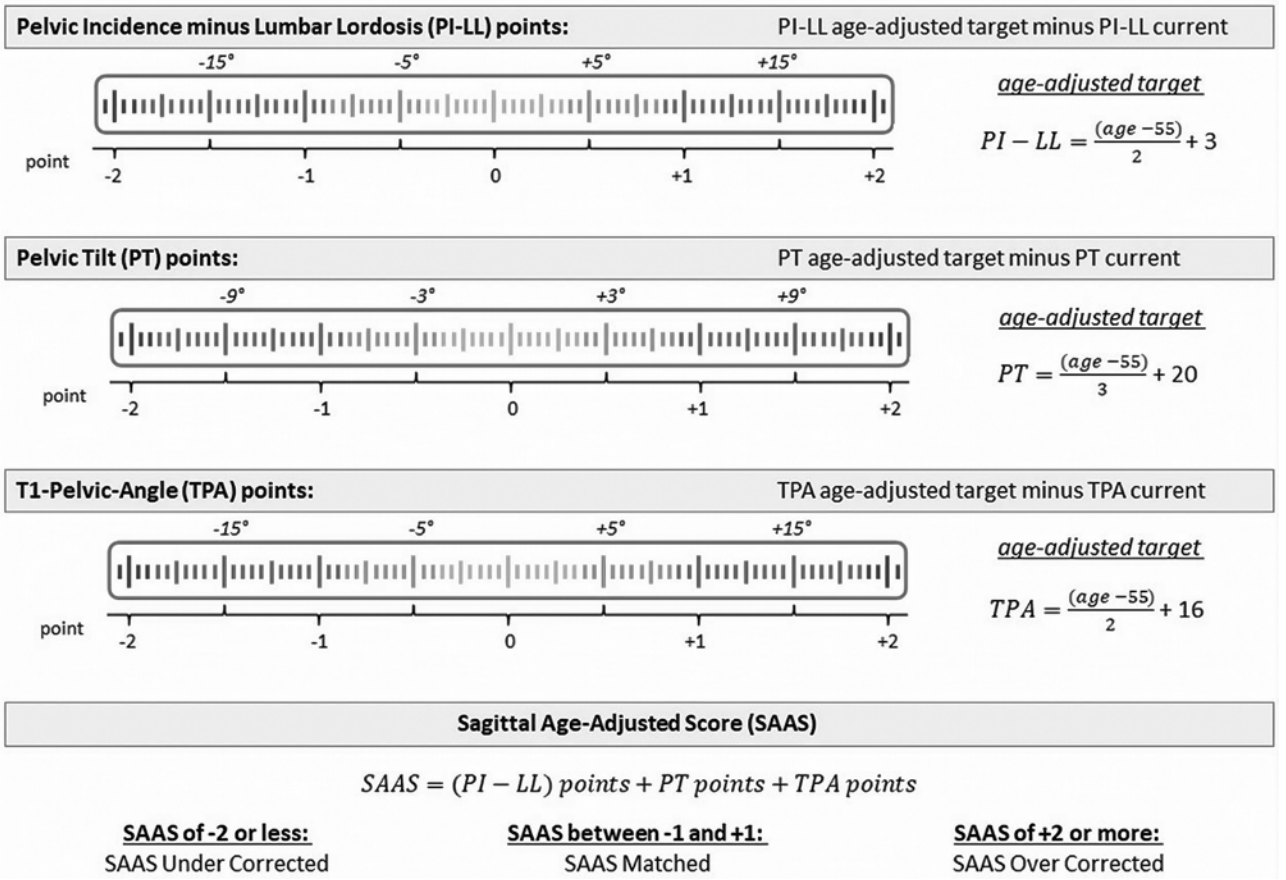


FIG. 1. SAAS calculation and parameters.

Frailty was calculated in a linear and categorical manner according to the established modified ASD Frailty Index (mASD-FI).[20]

Full-length free-standing lateral spine radiographs were used to assess radiographic parameters at baseline and follow-up intervals. All images were analyzed using SpineView (ENSAM, Laboratory of Biomechanics).[21] Spinopelvic radiographic parameters assessed included PT (the angle formed by a vertical line originating from the midpoint of the femoral head and a line running from the midpoint of the femoral head to the midpoint of the upper endplate of S1), PI-LL, and the SVA (C7 plumb line relative to the posterosuperior corner of S1).[22]

Measures of Radiographic Alignment

Deformity severity was assessed using the Scoliosis Research Society (SRS)–Schwab ASD classification system, which involves three established modifiers of PT, PI-LL, and SVA, each stratified into three tiers of severity: 0 (nonpathologic), + (moderate deformity), and ++ (marked deformity).[23] Roussouly classification of sagittal spinal shape was also used and classified patients by their theoretical and current Roussouly types as previously published. Patients were considered a match if their theoretical and current Roussouly types were the same, or a mismatch if the types differed.[24] Age-adjusted alignment targets and SAAS (Fig. 1) for sagittal correction were assessed using previously published formulas established by Lafage et al.[14,25]

PJK and PJF

Clinically significant PJK was defined as ≥ 10° in sagittal Cobb angle between the inferior UIV endplate and the superior endplate of UIV + 2 vertebrae.[26] PJF was defined as subsequent revision surgery for PJK or a proximal junctional sagittal Cobb angle ≥ 15° with or without evidence of vertebral body fracture, implant fracture or displacement, or disruption of the osseoligamentous complex.[3] PJK/PJF prophylaxis was considered to be utilization of cement augmentation, transverse process hooks, vertebral body tethers, percutaneous screw fixation, or one or more combinations thereof (hybrid measures).[27]

Statistical Analysis

Means comparison via independent-samples Student t-test and chi-square distribution analysis provided an initial comparison of baseline and postoperative factors in patients with and without evidence of PJK/PJF. Baseline demographic, clinical, radiographic, and surgical variables were then used to predict the occurrence of PJK or PJF by last recorded follow-up using backstep binary

TABLE 1. Baseline demographic factor comparison of patients with and without PJK/PJF

Parameter	Mean	SD	p Value
Age, yrs			**<0.001**
No PJK/PJF	58.83	15.48	
PJK/PJF	65.41	8.47	
BMI, kg/m^2			0.375
No PJK/PJF	27.98	6.14	
PJK/PJF	28.15	4.72	
Prior spine surgery, %			0.291
No PJK/PJF	51.00	0.50	
PJK/PJF	54.00	0.50	
Baseline arthritis, %			**0.001**
No PJK/PJF	38.00	0.49	
PJK/PJF	54.00	0.50	
Baseline depression, %			**0.045**
No PJK/PJF	21.00	0.41	
PJK/PJF	32.00	0.47	
Baseline CCI			0.118
No PJK/PJF	1.68	1.69	
PJK/PJF	1.97	1.62	
mASD-FI			**0.002**
No PJK/PJF	7.17	4.93	
PJK/PJF	8.82	5.49	

Boldface type indicates statistical significance.

logistic regression analysis. Internal cross validation of the supervised model was performed to assess for model generalizability using a 70%/30% training-to-testing distribution. Area under the receiver operating characteristic (ROC) curve (AUC) was used to assess sensitivity and specificity of the predictive model. Conditional inference tree analysis then determined thresholds of significant predictive factors for the development of PJK/PJF at an alpha level of 0.05. An odds ratio (OR) > 1.0 represented increased likelihood of PJK or PJF.

Results

Patient Demographics

There were 1495 patients eligible with baseline data, and 779 patients (52.11%) with 2-year postoperative data were included. The mean (± SD) age of the cohort was 59.87 ± 14.24 years; 78% were female. At baseline, the cohort mean BMI was 27.78 ± 6.02 kg/m^2 and the mean Charlson Comorbidity Index (CCI) was 1.74 ± 1.71. According to the mASD-FI, 46.6% of patients were classified as not frail, 37.0% as frail, and 16.3% as severely frail. Univariate analysis revealed that patients who developed PJK or PJF were significantly older (65.41 vs 58.83 years, $p < 0.001$) and were more likely to have a baseline diagnosis of arthritis ($p = 0.001$), depression ($p = 0.045$), and lung disease ($p = 0.040$). Patients with PJK/PJF also had higher mean mASD-FI scores ($p = 0.002$) than patients who did not have PJK/PJF by last recorded visit (Table 1).

Radiographic Overview

At 2 years postoperatively, 57.3% of the cohort (n = 446) had at least 1 age-adjusted match, with 27.0% (n = 120) matched on PT, 22.7% (n = 101) matched on PI-LL, and 30.7% (n = 137) matched on SVA. By SAAS parameters, mean offset by PI-LL was –11.91° ± 20.25°, by PT was –2.69° ± 10.17°, and by T1 pelvic angle (TPA) was –5.10° ± 12.31°. Overall, 22.5% of patients were considered matched on SAAS at baseline. Patients who would later develop PJK or PJF were more likely to present with greater degrees of offset by PT ($p = 0.009$) and TPA ($p = 0.011$) and were more likely to be considered undercorrected per SAAS scoring (61.22% vs 49.18%, $p = 0.026$).

Surgical Overview

In terms of surgical characteristics, the mean number of levels fused was 11.6 ± 4.1, the mean estimated blood loss (EBL) was 1848.23 ± 1487.14 ml, and the mean operative time was 446.89 ± 176.61 minutes. Sixty-seven percent of patients (n = 522) underwent osteotomy of Schwab grade 3 or higher during index surgery and 18.51% of patients underwent 3-column osteotomy. By surgical approach, 65% of patients (n = 506) underwent posterior-only and 35% (n = 273) underwent combined surgery. Patients with a UIV of T10 or below were significantly more likely to develop PJK or PJF by last follow-up ($p < 0.001$), as were patients with LIV at the sacrum ($p < 0.001$). Detailed surgical comparisons are presented in Table 2.

Postoperative Radiographic Analysis

At 2 years postoperatively, 64.1% of patients demonstrated improvement in at least 1 SRS-Schwab modifier. Furthermore, 48.0% of patients were considered matched by Roussouly thresholds, and 40.7% patients were considered to have met age-adjusted metrics. However, per SAAS criteria, only 23.9% of patients were considered matched, with 21.6% of patients considered undercorrected.

Adjusting for baseline age, CCI, and levels fused, patients who developed PJK or PJF were significantly more likely to demonstrate greater 6-week SAAS offset by PI-LL (< 0.001) and PT (< 0.001) and were less likely to be proportioned by 6-week global alignment and proportion (GAP) score, although not significantly ($p = 0.08$). Detailed 6-week radiographic parameter comparison analysis of patients who developed PJK or PJF is presented in Table 3.

PJK and PJF Rates and Predictors

PJK of any severity developed in 50.2% of patients (n = 471) and 10.5% (n = 82) developed PJF according to their last recorded visit. Of these patients, 6.4% developed radiographic PJF by the 6-week time point. Backstep conditional regression analysis revealed that significant risk modulators for PJK/PJF were age, osteoporosis, arthritis, baseline lower-extremity paresthesia, mASD-FI categorization, baseline T1 slope minus cervical lordosis (TS-CL), PI-LL, SAAS modifiers, baseline maximal kyphosis at the thoracic apex, levels fused, UIV, and PJK prophylaxis techniques (cement, hooks, percutaneous screw fixation, or hybrid measures [hybrid]; rod diameter; and rod composition [all $p < 0.05$]).

TABLE 2. Surgical factor comparison in patients with and without PJK/PJF

Parameter	Mean	SD	p Value
EBL, ml			**0.001**
No PJK/PJF	1531.64	1507.40	
PJK/PJF	2057.78	1477.80	
Op time, mins			**0.006**
No PJK/PJF	406.81	180.95	
PJK/PJF	460.20	159.97	
Levels fused			**<0.001**
No PJK/PJF	9.45	4.75	
PJK/PJF	12.60	3.66	
Anterior-only approach, %			0.337
No PJK/PJF	0.93	0.10	
PJK/PJF	0.00	0.00	
Posterior-only approach, %			**0.008**
No PJK/PJF	63.86	0.48	
PJK/PJF	75.51	0.43	
Combined approach, %			**0.026**
No PJK/PJF	35.20	0.48	
PJK/PJF	24.49	0.43	
3-column osteotomy, %			0.127
No PJK/PJF	16.49	0.37	
PJK/PJF	23.47	0.43	
PJK prophylaxis			
Cement, %			0.071
No PJK/PJF	7.31	0.26	
PJK/PJF	15.71	0.37	
Hooks, %			**0.023**
No PJK/PJF	19.75	0.40	
PJK/PJF	10.61	0.31	
Tether, %			0.296
No PJK/PJF	17.88	0.38	
PJK/PJF	23.38	0.43	
Hybrid, %			**<0.001**
No PJK/PJF	7.04	0.26	
PJK/PJF	0.00	0.00	
Percutaneous fixation, %			**<0.001**
No PJK/PJF	25.76	0.44	
PJK/PJF	4.84	0.22	
Sacral fixation, %			**<0.001**
No PJK/PJF	62.64	0.48	
PJK/PJF	93.88	0.24	

Boldface type indicates statistical significance.

TABLE 3. Six-week postoperative radiographic parameter comparison of patients with and without PJK/PJF

Parameter	Mean	SD	p Value
TS-CL			0.427
No PJK/PJF	19.91	11.05	
PJK/PJF	20.90	11.43	
C2 SS			0.274
No PJK/PJF	18.03	11.44	
PJK/PJF	19.45	11.92	
C7–S1 SVA			**0.041**
No PJK/PJF	31.96	48.91	
PJK/PJF	21.01	46.33	
TPA			0.429
No PJK/PJF	16.75	9.43	
PJK/PJF	15.78	11.35	
S1 SS			**0.008**
No PJK/PJF	37.10	10.48	
PJK/PJF	34.01	11.30	
PT			0.486
No PJK/PJF	19.94	9.65	
PJK/PJF	20.80	11.39	
PI			0.130
No PJK/PJF	57.06	13.59	
PJK/PJF	54.80	13.21	
PI-LL			**<0.001**
No PJK/PJF	4.75	13.35	
PJK/PJF	−2.29	14.61	

SS = sacral slope.
Boldface type indicates statistical significance.

Predictor Thresholds and Model Assessment

The six most significant demographic, radiographic, surgical, and postoperative predictors of PJK/PJF were baseline age ≥ 74 years (OR 1.06, 95% CI 1.014–1.107, p = 0.005), baseline SAAS TPA modifier ≥ 1 (OR 0.352, 95% CI 0.169–0.733, p = 0.004), baseline SAAS PT modifier ≥ 0 (OR 0.547, 95% CI 0.344–0.870, p = 0.008), levels fused > 10 (OR 1.139, 95% CI 1.022–1.269, p = 0.015), use of prophylaxis (OR 0.122, 95% CI 0.040–0.372, p < 0.001), and 6-week SAAS PI-LL modifier > 1 (OR 3.604, 95% CI 1.840–7.061, p < 0.001; Table 4). Overall, the predictive model was deemed significant (p < 0.001), and internally validated ROC analysis returned an AUC of 0.923, indicating robust model fit (Fig. 2). In a subset of patients with fusion to the pelvis, ROC analysis also returned a robust AUC of 89.5%.

Discussion

The present study aimed to utilize supervised logistic regression analytics to construct a predictive model for the development of PJK or PJF after ASD corrective surgery. Although predictive models have been described in prior literature, the present model is the first of its kind to incorporate novel prophylactic measures for PJK/PJF, as well as the most up-to-date alignment schema available to assess the risk of postoperative junctional failure most accurately, with a robust final AUC of 92.3%.

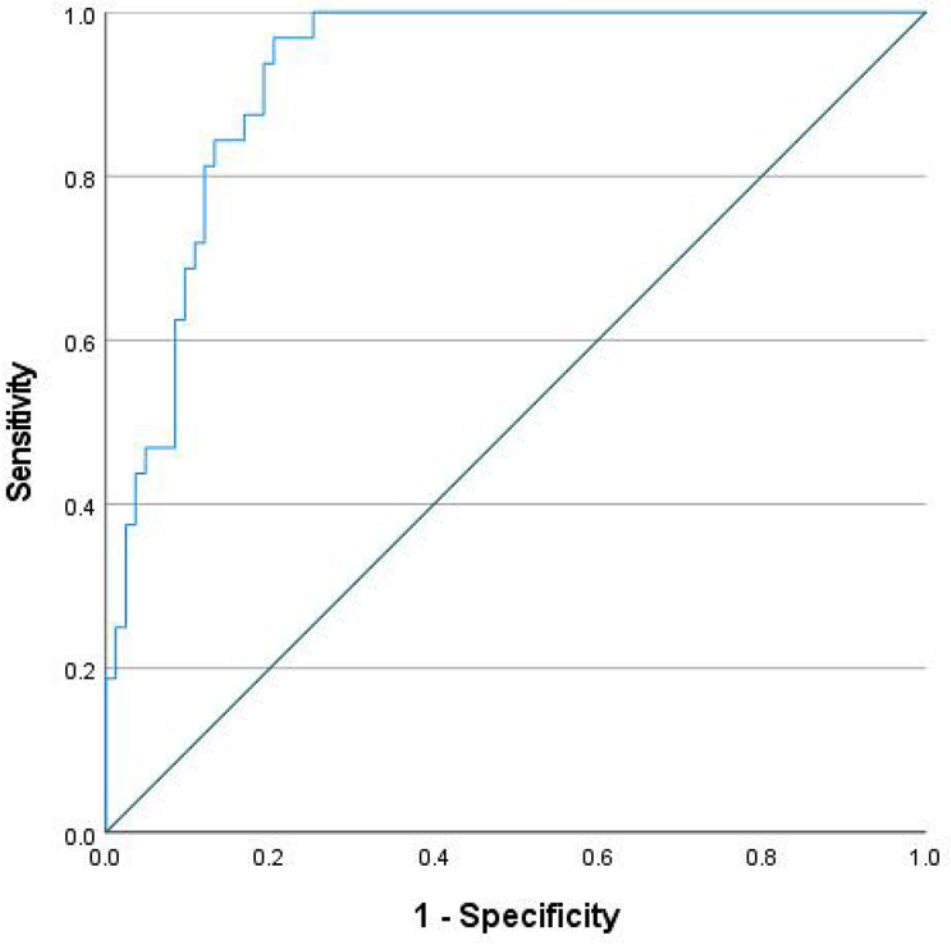
In contrast to previous attempts at modeling the risk of PJK or PJF, our study utilized a supervised predictive analysis approach with the aim of increasing the transpar-

TABLE 4. Top six predictive factors for development of PJK or PJF

Predictive Factor	OR*	95% CI	p Value
Baseline age ≥74 yrs	1.06	1.014–1.107	**0.005**
Baseline SAAS TPA modifier ≥1	0.352	0.169–0.733	**0.004**
Baseline SAAS PT modifier ≥0	0.547	0.344–0.870	**0.008**
Levels fused >10	1.139	1.022–1.269	**0.015**
Use of any prophylaxis	0.122	0.040–0.372	**<0.001**
6-wk SAAS PI-LL modifier >1	3.604	1.840–7.061	**<0.001**

Boldface type indicates statistical significance.
* An OR < 1 indicates a protective factor, whereas an OR > 1 indicates an elevated risk of PJK/PJF.

ency of factors studied. While a random forest ensemble-driven methodology was considered, Janitza and Hornung reported that random forest models may increase out-of-bag error in binary applications and can thus overestimate target outcomes.[28] In the context of medical or surgical applications, it is necessary to mitigate such errors. For example, overestimating the risk of PJF and suggesting greater prophylactic measures or increased surgical correction beyond what is clinically indicated may result in adverse outcomes associated with increased surgical invasiveness, as well as potentially inflate the cost burden for both patients and institutions.[29,30] By increasing the trans-



Area Under the Curve

Test Result Variable(s): Predicted probability

Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
.923	.024	.000	.876	.969

a. Under the nonparametric assumption

b. Null hypothesis: true area = 0.5

FIG. 2. ROC curve (AUC = 92.3%). Sig. = significance; Std. = standard. Figure is available in color online only.

parency and interpretability of the modeling technique used, we believe the present model is more generalizable and applicable to the clinical setting. However, it should be noted that since their inception in 2001, random forest models and associated statistical software continue to improve in balancing predictive versus explanatory goals of use.[31]

Through the use of validated techniques used such as logistic regression and conditional inference tree analysis of parameter relationships and variable thresholds, the predictive model presented in this study reveals the increasing utility of novel alignment schema to predict PJK and PJF. Although SRS-Schwab criteria, age-adjusted, and GAP metrics were assessed within the model, our findings indicate that the hybrid successor to such systems (the SAAS) may provide the best radiographic indicator of whether patients develop junctional degeneration or failure at follow-up. Perhaps counterintuitively, the six strongest predictors of PJK/PJF include baseline TPA and PT markers > 0 (matched). However, in their original study, Lafage et al. noted that patients considered with a modifier between –1 and 1 are considered matched. Thus, such patients may see a lower risk of PJK or PJF due to less global malalignment. In contrast, the strongest predictor was the 6-week PI-LL modifier > 1 (i.e., overcorrected), which supports prior findings that overcorrection is associated with the development of severe PJK by 2 years.[14] Likewise, increased age and decreased levels fused are consistent with the findings of previous calibration efforts by Yagi et al.[32] Although not included in the final model, the unadjusted comparison did demonstrate an increased incidence of PJK or PJF in patients with fusion to the pelvis. Such results are contentious but supported by the findings of Inoue et al.,[33] who reported up to a 37% incidence of mechanical failure in sacral fusions, as well as those of Decker et al.,[34] who identified a UIV between T9 and T12 as a risk factor for PJK in long fusions with sacral fixation.

Beyond the novel radiographic schema included in the present model, a strong protective factor against the development of PJK and PJF was prophylactic measures such as cementing, hooks, tethers, percutaneous fixation, or hybrid measures. Our findings therefore provide some support for the soft-landing theory as described by Cazzulino et al.,[37] who found that using transverse process hooks resulted in more than 53% of their 39-patient cohort demonstrating a < 10° proximal junctional angle change by 2 years. Previous literature assessing the cost-effectiveness of overall prophylaxis suggests substantially lower costs associated with reoperation and disability, i.e., $399,948 versus $514,228 per quality-adjusted life year gained in patients treated with and without prophylaxis, respectively.[35] Despite such findings, Vercoulen et al. noted in their review of the current literature on the subject that further high-quality randomized trials must be performed to assess the utility of PJK/PJF prophylaxis.[36]

Limitations of the Study

We acknowledge several potential limitations to the present study. First, the multicenter nature of this analysis inherently increases the heterogeneity of approach, technique, and geographical or institutional variance of materials or equipment. For instance, novel prophylactic measures were not uniformly utilized across study sites due to availability, institutional approval, or surgeon preference. Furthermore, surgical planning and incorporation of alignment schema used in this regard may not be equal. Although the use of a large multicenter cohort and adjusted analysis minimizes the risk of bias, we believe further validation should be performed to assess generalizability of the predictive model presented using both national and single-center data. Statistically, the 70%/30% training-versus-testing split aimed to address these limitations via internal validation, but longer recorded follow-up with more granular complication data may be advantageous. Lastly, the relatively low mean CCI score may not reflect the disease burden for patients most at risk for suffering PJK or PJF. However, the CCI was originally paired to mortality risk at 1 year, not junctional failure, and the mean score may reflect improving contemporary patient selection criteria on the part of surgeons and medical teams. Furthermore, no significant differences were observed in CCI at baseline in patients who suffered PJK or PJF versus those who did not in this analysis. We acknowledge the importance of incorporating bone density measurements in future predictive models, such as the use of Hounsfield units. Although we were unable to utilize these due to limitations of the database used, we hope to incorporate such modalities in future study.

Despite these limitations, we believe the present study retains merit in its transparent inclusion and calibration criteria and incorporation of the most contemporary surgical and radiographic techniques available, and may provide a scaffold for transition into an integrated point-of-care system that spine surgeons can use to accurately assess the risk of PJK/PJF for their patients. By doing so, the disability and cost detriments of such complications may be prevented.

Conclusions

PJK and PJF remain critical concerns in ASD surgery and efforts to reduce the occurrence of PJK/PJF have resulted in the development of novel prophylactic techniques and enhanced clinical and radiographic selection criteria. This study demonstrates a validated model incorporating such techniques with a robust model AUC of 92.3%, allowing for the prediction of clinically significant PJK and PJF. Our model can assist surgeons and institutions in optimizing patient selection, enhancing intraoperative decision-making, and reducing postoperative complications in ASD surgery.

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