Spine

SPINE Volume 41, Number 22, pp E1328–E1335

DEFORMITY

Development of Validated Computer-based Preoperative Predictive Model for Proximal Junction Failure (PJF) or Clinically Significant PJK With 86% Accuracy Based on 510 ASD Patients With 2-year Follow-up

Justin K. Scheer, BS,* Joseph A. Osorio, MD, PhD,† Justin S. Smith, MD, PhD,‡ Frank Schwab, MD,§ Virginie Lafage, PhD,§ Robert A. Hart, MD,¶ Shay Bess, MD,|| Breton Line, BSME,|| Bassel G. Diebo, MD,§ Themistocles S. Protopsaltis, MD,|| Amit Jain, MD,** Tamir Ailon, MD,‡ Douglas C. Burton, MD,†† Christopher I. Shaffrey, MD,‡ Eric Klineberg, MD,‡‡ and Christopher P. Ames, MD†, the International Spine Study Group

Study Design. A retrospective review of large, multicenter adult spinal deformity (ASD) database.

Objective. The aim of this study was to build a model based on baseline demographic, radiographic, and surgical factors that can predict clinically significant proximal junctional kyphosis (PJK) and proximal junctional failure (PJF).

Summary of Background Data. PJF and PJK are significant complications and it remains unclear what are the specific drivers behind the development of either. There exists no predictive model that could potentially aid in the clinical decision making for adult patients undergoing deformity correction.

Methods. Inclusion criteria: age ≥18 years, ASD, at least four levels fused. Variables included in the model were demographics, primary/revision, use of three-column osteotomy, upper-most instrumented vertebra (UIV)/lower-most instrumented vertebra (LIV) levels and UIV implant type (screw, hooks), number of levels fused, and baseline sagittal radiographs [pelvic tilt (PT), pelvic incidence and lumbar lordosis (PI-LL), thoracic kyphosis (TK), and sagittal vertical axis (SVA)]. PJK was defined as an increase from baseline of proximal junctional angle ≥20° with concomitant deterioration of at least one SRS-Schwab sagittal modifier grade from 6 weeks postop. PJF was defined as requiring revision for PJK. An ensemble of decision trees were constructed using the C5.0 algorithm with five different bootstrapped models, and internally validated *via* a 70:30 data split for training and testing. Accuracy and the area under a receiver operator characteristic curve (AUC) were calculated.

Results. Five hundred ten patients were included, with 357 for model training and 153 as testing targets (PJF: 37, PJK: 102). The overall model accuracy was 86.3% with an AUC of 0.89 indicating a good model fit. The seven strongest (importance ≥0.95) predictors were age, LIV, pre-operative SVA, UIV implant type, UIV, pre-operative PT, and pre-operative PI-LL.

Conclusion. A successful model (86% accuracy, 0.89 AUC) was built predicting either PJF or clinically significant PJK. This model can set the groundwork for preop point of care decision making, risk stratification, and need for prophylactic strategies for patients undergoing ASD surgery.

Key words: adult spinal deformity, predictive modeling, proximal junctional failure, proximal junctional kyphosis, sagittal malalignment, scoliosis.

Level of Evidence: 3

Spine 2016;41:E1328–E1335

From the *University of California, San Diego, School of Medicine, La Jolla, CA; †Department of Neurological Surgery, University of California, San Francisco, San Francisco, CA; ‡Department of Neurosurgery, University of Virginia Health System, Charlottesville, VA; §Spine Service, Hospital for Special Surgery, New York, NY; ¶Department of Orthopaedic Surgery, Oregon Health & Science University, Portland, OR; ||Department of Orthopaedic Surgery, NYU Hospital for Joint Diseases, New York, NY; **Department of Orthopaedic Surgery, Johns Hopkins University, Baltimore, MD; ††Department of Orthopaedic Surgery, University of Kansas Medical Center, Kansas City, KS; and ‡‡Department of Orthopaedic Surgery, University of California, Davis, CA.

Acknowledgment date: January 6, 2016. First revision date: February 15, 2016. Second revision date: March 21, 2016. Acceptance date: March 21, 2016.

The manuscript submitted does not contain information about medical device(s)/drug(s).

Funding for the International Spine Study Group Foundation, through which this study was conducted, is provided through research grants from DePuy Spine and individual donations.

Relevant financial activities outside the submitted work: board membership, grants, consultancy, payment lectures, stocks.

Address correspondence and reprint requests to Justin K. Scheer, BS, School of Medicine, University of California, San Diego, La Jolla, CA 92093. E-mail: jscheer@ucsd.edu

DOI: 10.1097/BRS.0000000000001598

The postoperative risks of adult spinal deformity (ASD) surgery[1–7] can be separated into the immediate peri-operative period, and the delayed complications of surgery such as proximal junctional kyphosis (PJK).[8–17] The incidence of PJK ranges from 20 to 40%[10,16,18–20] with variable impact on quality of life.[8,21–24] In addition, the clinical impact of PJK can vary from a benign radiographic finding to a severe form of PJK, termed proximal junctional failure (PJF), which may result in compromised structural integrity, neurological deficit, and the need for revision surgery.[13,25–27] Patients with PJF generally have a worse clinical course.[13,25,28]

Identifying patients before the operation that will have a successful outcome with minimal or no complications is difficult. A pre-operative, patient-specific model that can predict the likelihood of developing PJK and/or PJF does not exist. There is a strong need for such model, as this can be beneficial for both the patient and surgeon. The surgeon can plan accordingly for the operation by employing additional techniques and preventative measures at the level that is at highest risk of failure.[12] Such a targeted approach at complication avoidance, informed by preoperative data, could reduce the overall complication rate and thus decrease patient morbidity.[29]

Current predictive analytics methods allow for the creation of accurate, patient-specific, predictive models that can aid in clinical decision making. Although traditional statistical methods, including regressions, provide insight into what variables and patient characteristics might carry the highest risk, these methods are limited for use in developing patient-specific predictive models.[30] They generally use averages not accounting for individual changes or produce odds/hazard ratios for each variable. Moreover, they are bound by many assumptions and designed to test a specific hypothesis, whereas predictive analytic algorithms are designed to identify patterns in the data that allow for accurate predictions without the need for a hypothesis. As a result, when using predictive modeling, the final interpretation of the data can provide a tangible number that can be readily used when discussing the risk with a patient that is deciding to undergo an operation. The goal of this study was to create a predictive model based on baseline demographic, radiographic, and surgical factors that can predict PJF or clinically significant PJK within 2 years following surgery.

MATERIALS AND METHODS

Patient Population

This study is a retrospective review of a large ASD database. Three separate databases were combined in order to maximize the available patients for model building. The three databases included a prospective ASD database, a retrospective three-column osteotomy ASD database, and a retrospective ASD database. For all three databases, the inclusion criteria were age >18 years and presence of spinal deformity, as defined by scoliosis Cobb angle ≥20°, sagittal vertical axis (SVA) ≥5 cm, pelvic tilt (PT) ≥25°, and/or thoracic kyphosis (TK) ≥60°. Exclusion criteria for all included spinal deformity of a neuromuscular etiology and presence of active infection or malignancy. In addition to the above criteria, patients were selected if a minimum of four vertebral levels were fused and there was complete 2-year follow-up. A cohort of 510 patients was identified on the basis of the above criteria and included in the construction of the model. This form of patient selection is accepted in predictive modeling, as the goal is to produce a model that accurately predicts the target of interest for the given variables available.[30]

Data Collection, Radiographic Assessment, and HRQOL

The demographic and clinical data collected included patient age, gender, body mass index (BMI), and primary *versus* revision surgery. Surgical data collected included the presence of a three-column osteotomy (pedicle subtraction osteotomy or vertebral column resection), upper-most instrumented vertebra (UIV), UIV implant type (hooks or screws), the lower-most instrumented vertebra (LIV), and the number of posterior vertebral levels fused. The surgical variables were added with the intention that the same factors would be derived from a pre-operative surgical plan for a complete pre-operative predictive model.

Full-length free-standing lateral spine radiographs (36" cassette) at baseline, 6 weeks, 3 months, 1-year, and 2-year follow-up were analyzed using validated software[31,32] (Spineview; ENSAM, Laboratory of Biomechanics, Paris, France). All radiographic measures were performed at a central location on the basis of standard techniques[33] and included coronal Cobb angles of thoracic and lumbar curves, TK (TK, T4-T12; Cobb angle between superior endplate of T4 and inferior endplate of T12), lumbar lordosis (LL, Cobb angle between superior endplate of L1 and superior endplate of S1), SVA (offset of C7 plumbline relative to S1), PT, and the mismatch between pelvic incidence (PI) and LL (PI-LL). On the basis of the above radiographic parameters, patients were additionally stratified by the SRS-Schwab ASD classification.[34]

Patients were grouped as either having clinically significant PJK or PJF (PJK/PJF) at any postoperative time point up to 2 years postoperative or not (NONE). Clinically significant PJK was defined as an increase in the proximal junctional angle (PJA) by 20° or more compared with baseline and deterioration by at least one SRS-Schwab sagittal modifier grade from the 6 weeks postoperative time point of interest. PJA angle was measured from the inferior end plate of the UIV to the superior end plate two levels above the UIV. PJF was defined as requiring revision surgery for PJK.

Statistics and Predictive Model Construction

Continuous variables were described with the mean and standard deviation. Baseline variables were compared between the groups. Normality of data was determined using the Shapiro-Wilk test. Comparison of baseline means between the groups included Student *t* test with Tukey

TABLE 1. Means ± 1 Standard Deviation for the Demographics of all the Patients as Well as Each Group

	All Patients	PJK/PJF	NONE	*P*
Number	510	139	371	
Age	57.2 ± 13.9	63.3 ± 10.9	54.9 ± 14.2	**<0.0001***
Female: male	396:114	113:26	283:88	0.2199
BMI	27.3 ± 5.9	28.1 ± 5.4	27 ± 6	**0.0143***

*Values in bold marked with represent a statistically significant difference between the PJK/PJF and NONE groups.
NONE indicates patients who did not develop PJK or PJF over 2 years postoperative; PJF, proximal junctional failure; PJK, proximal junctional kyphosis.

Honest Significant Difference test to control for type I error or Wilcoxon summed ranked tests where appropriate. Frequency analyses for categorical variables were conducted *via* Pearson's χ^2 analysis. All statistical analyses were conducted using commercially available software (SPSS v22; IBM, Armonk, NY) and the level of significance was set at $P < 0.05$ for all tests.

For the predictive model, categories were created for UIV and LIV. UIV categories included cervical, T1-T5, T6-T9, and T10-L3. LIV categories included T11-L2, L3-L5, and sacroiliac (S1-ilium). Missing values within the database were imputated using standard techniques such as mean and median imputation.[30] Once a complete dataset was constructed, a supervised ensemble of decision trees was constructed with the target variable being binary that included (1) patients who had clinically significant PJK or PJF, as defined above, or (0) not having PJK or PJF over the 2 years postoperative. The decision tree algorithm was C5.0 and five different bootstrapped models were built.[30] Internal validation was accomplished *via* a 70 : 30 data split for training and testing the model, respectively.[30] Final overall predictions from the models were combined and chosen by voting with random selection for tied votes. Overall accuracy and the area under a receiver operator characteristic curve (AUC) were calculated as well as predictor importance as determined by the model. The model was built using commercially available software (SPSS Modeler v16; IBM, Armonk, NY).

RESULTS

Patient Population

Of the total 510 patients, 357 (70%) were used for model training and 153 (30%) were used for testing the model. The percent split was randomly determined, but it is within the acceptable splitting percent options for predictive modeling.[30] There were 139 (27.3%) targets as defined above (PJF: 37, PJK: 102) and 371 (72.7%) patients who did not meet criteria for clinically significant PJK or PJF (NONE). There were 396 (77.6%) women and 114 (22.3%) men and the mean age was 57.2 ± 13.9 years with mean BMI of 27.3 ± 5.9 kg/m^2 (Table 1). The PJK/PJF group was significantly older and had a greater mean BMI ($P < 0.05$ for both, Table 1). The PJK/PJF group had a higher proportion of patients with baseline SRS-Schwab coronal curve class of N (52.2% *vs.* 38.8%, $P < 0.05$, Table 2). The proportions of SRS-Schwab sagittal modifier grades were also significantly different between the groups with the PJK/PJF group having more patients in the + and ++ grades ($P < 0.05$, Table 2).

Surgical Data

Both groups had statistically similar proportions of patients who underwent a revision *versus* primary surgery and who had a three-column osteotomy ($P > 0.05$ for both, Table 3). The mean number of posterior levels fused was also statistically similar between groups ($P > 0.05$, Table 3). However, the PJK/PJF group had a significantly higher proportion of patients with a UIV in the thoracolumbar region (T10-L3) and a LIV in the sacroiliac region (L5-S1) ($P < 0.05$ for both, Table 3). The PJK/PJF group had a significantly higher proportion of patients with screws as the UIV implant type (as opposed to hooks) than the NONE group ($P < 0.05$, Table 3).

Radiographic Data

The PJK/PJF group had significantly greater mean baseline PT, PI-LL, and SVA than the NONE group ($P < 0.05$ for all, Table 4). Both groups had similar baseline mean TK ($P > 0.05$).

Model Results

The overall model accuracy was 86.3% with an AUC of 0.89 indicating a good model fit. The seven strongest predictors were (importance ≥0.95 as determined by the model) age, LIV, pre-operative SVA, UIV implant type, UIV, pre-operative PT, and pre-operative PI-LL (Table 5). Case examples of patients that were correctly predicted to develop PJK/PJF or not within the testing dataset are presented in Figures 1 (A–D) and 2 (A–D).

DISCUSSION

We have used a large cohort of ASD patients who underwent surgical correction to construct an accurate, internally validated, pre-operative predictive model for developing PJK or PJF over the course of 2 years postoperatively. The surgical variables were added retrospectively under the assumption that these could be part of a pre-operative surgical plan. This model sets the framework to create a website or other

TABLE 2. The Percentage of Patients for Each Grade With the Baseline SRS-Schwab Coronal Curve and Sagittal Modifier Classification for all of the Patients as well as the PJK/PJF and NONE Groups

Preop SRS-Schwab Coronal Curve	All Patients	PJK/PJF	NONE	*P*
Type N	42.5%	52.2%	38.8%	**0.0025***
Type T	4.0%	1.4%	5.0%	
Type L	32.3%	33.3%	32.0%	
Type D	21.2%	13.0%	24.2%	
Preop SRS-Schwab PT modifier				
0	29.2%	18.7%	33.2%	**0.0044***
+	35.1%	39.6%	33.4%	
++	35.7%	41.7%	33.4%	
Preop SRS-Schwab GA modifier				
0	33.8%	22.6%	38.0%	**0.0040***
+	21.8%	24.8%	20.7%	
++	44.4%	52.6%	41.3%	
Preop SRS-Schwab PI-LL modifier				
0	33.5%	25.2%	36.7%	**0.0394***
+	15.3%	15.8%	15.1%	
++	51.2%	59.0%	48.2%	

*Values in bold marked with represent a statistically significant difference between the PJK/PJF and NONE groups. See the Materials and methods section and Figure 1 for the description of the SRS-Schwab adult spinal deformity classification.

NONE indicates patients who did not develop PJK or PJF over 2 years postoperative; PJF, proximal junctional failure; PJK, proximal junctional kyphosis.

mobile (*i.e.*, tablet) application for calculating the risk of developing PJK/PJF in real-time as a point-of-care device.

The predictive modeling we used is a distinct form of analysis from traditional regression in a few different ways.[30] It involves complex algorithms that identify patterns in large data sets, which then allow for prediction of a given outcome of interest. There is no hypothesis, no control being compared, and the model relies entirely on the available data.[30] Conversely, traditional statistics are mathematical analyses used to test a hypothesis about a relationship between independent and dependent variables, and thus, appropriate controls are necessary. Furthermore, the

TABLE 3. The Number and Percentage of Patients in Category for the Surgical Variables for all the Patients, PJK/PJF Group, and the NONE Group

Surgical Data	All Patients	PJK/PJF	NONE	*P*
Number	510	139	371	
Primary: revision	200 : 310	57 : 82	143 : 228	0.6283
Mean number posterior levels fused (range)	11.8 ± 3.7	11.3 ± 3.5	11.9 ± 3.7	0.0667
3-column osteotomy	289 (56.7%)	83 (59.7%)	206 (55.5%)	0.3946
UIV levels				
Cervical	7 (1.4%)	1 (0.7%)	6 (1.6%)	**0.0085***
T1-T5	248 (48.6%)	52 (37.4%)	196 (52.8%)	
T6-T9	61 (12%)	18 (12.9%)	43 (11.6%)	
T10-L3	194 (38%)	68 (48.9%)	126 (34%)	
UIV implant types				
Hook	90 (17.6%)	14 (10.1%)	76 (20.5%)	**0.0040***
Screw	420 (82.4%)	125 (89.9%)	295 (79.5%)	
LIV levels				
T11-L2	31 (6.1%)	3 (2.2%)	28 (7.5%)	**<0.0001***
L3-L5	80 (15.7%)	10 (7.2%)	70 (18.9%)	
Sacroiliac	399 (78.2%)	126 (90.6%)	273 (73.6%)	

*Values in bold marked with represent a statistically significant difference between the PJK/PJF and NONE groups. LIV indicates lower-most instrumented vertebra; NONE, patients who did not develop PJK or PJF over 2 years postoperative; PJF, proximal junctional failure; PJK, proximal junctional kyphosis; UIV, upper-most instrumented vertebra.

TABLE 4. Mean ± 1 Standard Deviation for the Preoperative Radiographic Parameters Included in the Model for all Patients, PJK/PJF, and NONE Groups

Preop	All Patients	PJK/PJF	NONE	*P*
PT	26.4 ± 12.3	28.5 ± 9.6	25.6 ± 13.1	**0.0038***
PI-LL	20.4 ± 25.2	24.5 ± 23.3	18.8 ± 25.8	**0.0135***
TK	33.1 ± 22	33.9 ± 21.2	32.8 ± 22.3	0.6331
SVA	87.3 ± 89.5	110.2 ± 88.4	78.8 ± 88.5	**0.0006***

Values in bold marked with represent a statistically significant difference between the PJK/PJF and NONE groups. NONE, patients who did not develop PJK or PJF over 2 years postoperative; PI-LL, mismatch between pelvic incidence (PI) and lumbar lordosis (LL); PJF, proximal junctional failure; PJK, proximal junctional kyphosis; PT, pelvic tilt; SVA, sagittal vertical axis; TK, thoracic kyphosis.

appropriate statistical test must be selected for a given clinical question/hypothesis and type of data. Using the wrong statistical test can result in erroneous results. Predictive modeling is more flexible, as it relies on the available data. Assuming that one has a complete and trustworthy set of data, multiple types of models can be constructed to assess which one has the greatest utility for the aims of the model.[30] One can combine models that are similar or even different to further enhance the goals of the model.[30] When creating a model, one must balance accuracy, generalizability, and transparency.[30] A model can be very accurate yet not generalizable to other datasets or be so complicated, one does not know exactly how the model is making its predictions. It all depends on the goals of the model.

In the present study, we have constructed a predictive model using several established techniques. First, decision trees were used, which have desirable properties: they are easy to build, can handle both continuous and categorical data, can handle hundreds of variables, and can even handle missing data.[30] Second, an ensemble of five decision tree models was constructed in which the final predictions are based on the combined predictions from each of the five trees. The use of ensembles increases the accuracy of the model; however, the trade-off is a decrease in interpretability (transparency).[30] The computer makes the predictions and thus rendering the exact rules governing how the predictions are made unavailable. Third, a 70 : 30 data split was used for training and testing in order to increase the generalizability of the model. The 70% of patients used for training were randomly chosen and were used to initially create the models. Next, the remaining 30% were "run" through the models to predict whether the patients would have PJK or PJF based on the predictions from the initial 70% of the data. Those predictions were then "tested" against what actually happened in the data to produce the accuracy and AUC values reported in the results. And lastly, for each step of the training and testing stages of the model, and for each of the five decision trees, the data were bootstrapped meaning that a random sample of the data was used each time. Therefore, no model received the same set of patient data for training and for testing, which further increases the generalizability of the final model.

TABLE 5. List of all 13 Variables Used in the Model in Order of Predictor Importance

Order of Importance	Variable
1	Age
2	LIV
3	SVA
4	UIV implant type
5	UIV
6	PT
7	PI-LL
8	BMI
9	No. of levels fused
10	Gender
11	Presence of 3CO
12	TK
13	Primary *vs.* revision

Note that this list is generated in a univariate fashion. The actual variable predictor importance may vary in the model because during model deployment, the variables are considered in the context of the others as they may influence one another.

There is a paucity of predictive models in the spine literature. For the ones that do exist, most use logistic regression in order to develop a set of odds ratios for developing the outcome of interest.[35–39] Logistic regression is commonly used in prediction analysis because it is simple and very transparent.[30] Odds ratios are easy to interpret and apply. However, the limitations include the number of assumptions that must be satisfied in order to apply logistic regression; for large datasets, the *P* values become less meaningful because significance may be achieved solely on the basis of large numbers (*i.e.*, a very small difference in means may be significant but not clinically relevant), and they generally provide information on which variables are "predictors."

There are a few studies using predictive modeling techniques.[40,41] Spratt *et al.*[41] used the Chisquare Automatic Interaction Detection (CHAID) decision tree analysis to predict successful outcome following decompression for lumbar stenosis. Their model correctly classified 90.1% of successful outcomes with a positive predictive value of 85.7% and a negative predictive value of 100%.[41] However, their sample size was 32 patients and they only constructed one decision tree. Daubs *et al.*[40] also performed a decision tree analysis but used an ensemble of 50 decision

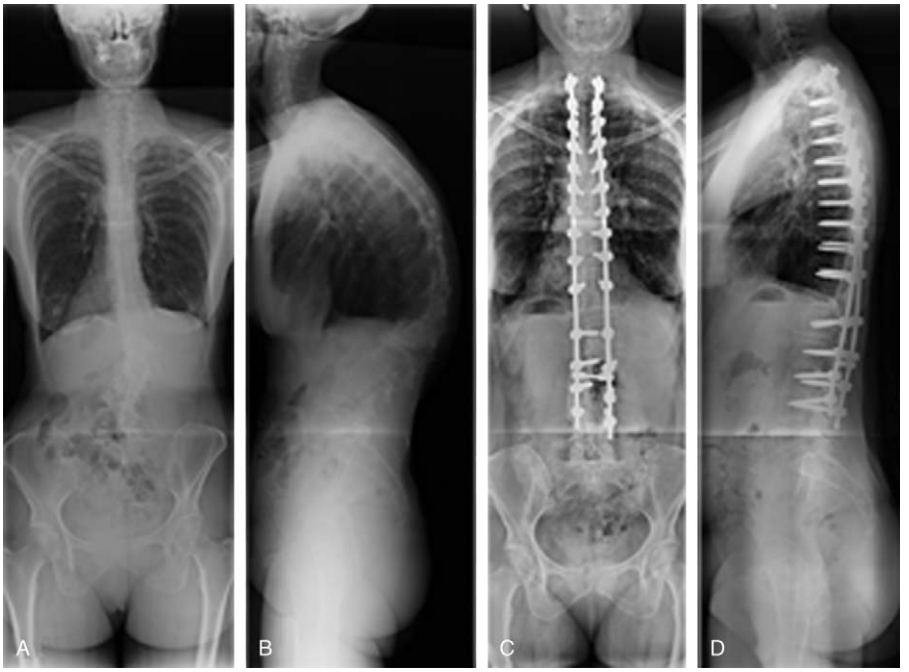

Figure 1. Case example of a patient from the testing dataset that the model correctly predicted to not develop proximal junctional failure (PJF) or clinically significant proximal junctional kyphosis (PJK) within 2 years postoperative. This patient is a 58-year-old female, and at baseline, the (**A**) anteroposterior and (**B**) lateral radiographs demonstrate both coronal and sagittal malalignment with the following measurements: Lumbar Cobb (L1-L5) = 15.2°, Thoracic kyphosis (TK; T4-T12) = 63.3°, Pelvic tilt (PT) = 14.7°, mismatch between pelvic incidence and lumbar lordosis (PI-LL) = −4.1°, Sagittal vertical axis (SVA) = 8.3 cm. At 2 years postoperative (C and **D**), she is well corrected without PJK or PJF and the following measurements: Lumbar Cobb (L1-L5) = 0.68°, PT = 9.3°, PI-LL = 4.1°, SVA = 3.6 cm. In contrast to the other case example; note the younger age, the UIV in the T1-T5 range, the use of hooks at UIV instead of screws, and the UIV in L3-L5 range (not ilium).

trees in order evaluate predictors of psychological distress in patients presenting for evaluation of a spinal disorder. Their model was 92% accurate, 92% sensitive, and 95% specific in predicting a patient's level of psychological distress using six variables for 188 patients.[40] These types of studies are only the beginning to more predictive analytics in spine surgery outcomes.

The strengths of the current study include the multicenter design and a large number of ASD patients (510) being evaluated for PJK/PJF. Furthermore, patients were enrolled from multiple surgeons comprising 11 different sites across the United States, which allows for better generalizability of the results. Another strength of this study is the complete pre-operative and 2-year follow-up of the patients. And lastly, modern predictive analytics algorithms were used

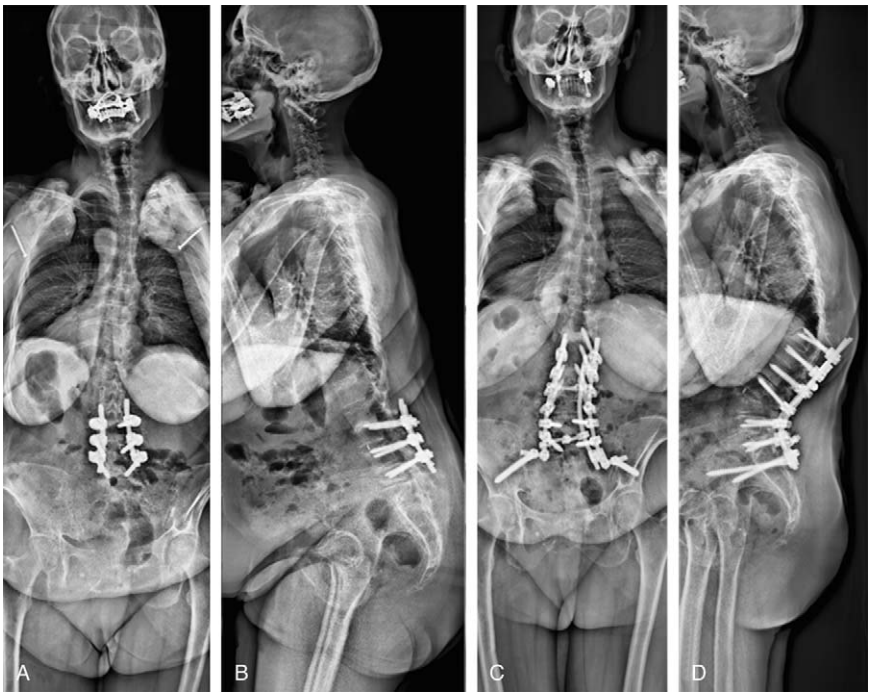

Figure 2. Case example of a patient from the testing dataset that the model correctly predicted to develop proximal junctional failure (PJF) within 2 years postoperative. The patient is a 66-year-old female and at baseline the (**A**) anteroposterior and (**B**) lateral radiographs demonstrate prior lumbar fusion and significant flatback with positive sagittal malalignment with the following measurements: Pelvic tilt (PT) = 39.1°, mismatch between pelvic incidence and lumbar lordosis (PI-LL) = 61.6°, Sagittal vertical axis (SVA) = 16.5 cm. She underwent L4 PSO and posterior fusion from T12 to ilium. At 6 months postoperative (**C** and **D**) she developed PJF with vertebral fracture at the upper-most instrumented vertebra (UIV) site of T12. The measurements were the following: PT = 33.4°, PI-LL = 1.1°, SVA = 3.4 cm, PJK angle (T10-T12) = 55.0°. In contrast to Case 1; note the greater age, the UIV in the T10-L2 range, the use of screws at UIV instead of hooks, and the LIV in sacroiliac range.

to create the model providing a patient-specific decision tree ensemble. However, the model is computer-based, and thus, the real-time deployment of the model needs to be with application or on a computer in the clinic. It can aid the surgeon in real-time by identifying the patients at risk for PJK/PJF and then the surgeon may decide to offer prevention strategies to reduce the risk.

However, there are a few limitations to this study, one of which includes the retrospective design. Another limitation is the use of only 13 variables in the model. This was the maximum number available when identifying individual patients that could complete a dataset. Ideally, there would be more demographic and surgical variables entered into the model, including patient bone mineral density. Thus, it is important to note that this model is an early version. Although this is a limitation, we feel that this model provides the initial ground work into the area of advanced predictive modeling in ASD surgery outcomes. The model can still be used clinically, and as more data are collected, the model will be continuously updated. Another limitation includes combining both PJK and PJF as the target variable of interest. These are different pathologies that may be managed in different ways. We tried to address this with the addition of PJK being "clinically significant" by having a deterioration of at least one SRS-Schwab sagittal modifier grade. If the patient is decompensating in the sagittal plane and developing PJK $>20^\circ$, we feel that this is significant and would most likely have an impact on HRQOL and/or the need for surgery. However, this information was not available given the current data set. Additional limitations include that PJK and PJF are radiographic measures of failed surgery. We are not incorporating data on how the operations are affecting recovery,[42,43] quality of life, or need for further surgery for measures outside PJK and PJF. Although this is a limitation, our experience shows that the development of PJK or PJF, and the need for corrective surgery thereafter, is one of the predominant complications of ASD surgery that most surgeons would prefer to avoid. And lastly, the model needs to be deployed on a computer given the complexity (and loss of transparency) of the model. However, the tradeoff for loss of model transparency is increased model accuracy and generalizability. Future directions will be aimed at integrating these models as a point-of-care aid in clinical decision making.

CONCLUSION

A successful model (86% accuracy, 0.89 AUC) was built predicting either PJF or clinically significant PJK. This model can set the groundwork for pre-operative point of care decision making, risk stratification, and the need for prophylactic strategies for patients undergoing ASD surgery.

➢ Key Points

- ❑ To date, no predictive model exists allowing for accurate prediction of proximal junctional kyphosis (PJK) or proximal junctional failure (PJF) following correction of adult spinal deformity (ASD).
- ❑ A successful model with 86% accuracy was constructed predicting clinically significant PJK or PJF using baseline demographics and radiographic parameters as well as surgical variables for future planning purposes.
- ❑ This is the first predictive model for PJK/PJF and can set the groundwork for a website and/or a mobile device to aid in point-of-care decision making between the surgeon and patient.

References

1. Lafage V, Schwab F, Vira S, et al. Does vertebral level of pedicle subtraction osteotomy correlate with degree of spinopelvic parameter correction? *J Neurosurg Spine* 2011;14:184–91.
2. Maier S, Smith JS, Schwab F, et al. Revision surgery after three-column osteotomy in 335 adult spinal deformity patients: inter-center variability and risk factors. *Spine (Phila Pa 1976)* 2014; [Epub ahead of print].
3. Scheer JK, Tang JA, Smith JS, et al. Reoperation rates and impact on outcome in a large, prospective, multicenter, adult spinal deformity database: clinical article. *J Neurosurg Spine* 2013;19:464–70.
4. Pichelmann MA, Lenke LG, Bridwell KH, et al. Revision rates following primary adult spinal deformity surgery: six hundred forty-three consecutive patients followed-up to twenty-two years postoperative. *Spine (Phila Pa 1976)* 2010;35:219–26.
5. Smith JS, Sansur CA, Donaldson WF 3rd, et al. Short-term morbidity and mortality associated with correction of thoracolumbar fixed sagittal plane deformity: a report from the Scoliosis Research Society Morbidity and Mortality Committee. *Spine (Phila Pa 1976)* 2011;36:958–64.
6. Daubs MD, Lenke LG, Cheh G, et al. Adult spinal deformity surgery: complications and outcomes in patients over age 60. *Spine (Phila Pa 1976)* 2007;32:2238–44.
7. Kimmell KT, Patrick Joynt HA, Schmidt T, et al. Risk modeling predicts complication rates for spinal surgery. *Spine (Phila Pa 1976)* 2015;40:1836–41.
8. 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.
9. Lau D, Clark AJ, Scheer JK, et al. Proximal junctional kyphosis and failure after spinal deformity surgery: a systematic review of the literature as a background to classification development. *Spine (Phila Pa 1976)* 2014;39:2093–102.
10. Kim HJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis results in inferior SRS pain subscores in adult deformity patients. *Spine (Phila Pa 1976)* 2013;38:896–901.
11. 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.
12. 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.
13. Hart RA, McCarthy I, Ames CP, et al. Proximal junctional kyphosis and proximal junctional failure. *Neurosurg Clin N Am* 2013;24:213–8.
14. Kim HJ, Lenke LG, Shaffrey CI, et al. Proximal junctional kyphosis as a distinct form of adjacent segment pathology after spinal deformity surgery: a systematic review. *Spine (Phila Pa 1976)* 2012;37:S144–64.

15. Mendoza-Lattes S, Ries Z, Gao Y, et al. Proximal junctional kyphosis in adult reconstructive spine surgery results from incomplete restoration of the lumbar lordosis relative to the magnitude of the thoracic kyphosis. *Iowa Orthop J* 2011;31:199–206.
16. Wang J, Zhao Y, Shen B, et al. Risk factor analysis of proximal junctional kyphosis after posterior fusion in patients with idiopathic scoliosis. *Injury* 2010;41:415–20.
17. Yagi M, King AB, Boachie-Adjei O. Incidence, risk factors, and natural course of proximal junctional kyphosis: surgical outcomes review of adult idiopathic scoliosis. Minimum 5 years of follow-up. *Spine (Phila Pa 1976)* 2012;37:1479–89.
18. Kim HJ, Yagi M, Nyugen J, et al. Combined anterior-posterior surgery is the most important risk factor for developing proximal junctional kyphosis in idiopathic scoliosis. *Clin Orthop Relat Res* 2012;470:1633–9.
19. Maruo K, Ha Y, Inoue S, et al. Predictive factors for proximal junctional kyphosis in long fusions to the sacrum in adult spinal deformity. *Spine (Phila Pa 1976)* 2013;38:E1469–76.
20. Denis F, Sun EC, Winter RB. Incidence and risk factors for proximal and distal junctional kyphosis following surgical treatment for Scheuermann kyphosis: minimum five-year follow-up. *Spine (Phila Pa 1976)* 2009;34:E729–34.
21. 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.
22. Hyun SJ, Rhim SC. Clinical outcomes and complications after pedicle subtraction osteotomy for fixed sagittal imbalance patients: a long-term follow-up data. *J Korean Neurosurg Soc* 2010;47:95–101.
23. Lee GA, Betz RR,Clements DH 3rd, et al. Proximal kyphosis after posterior spinal fusion in patients with idiopathic scoliosis. *Spine (Phila Pa 1976)* 1999;24:795–9.
24. 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.
25. 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: 875–81.
26. O'Leary PT, Bridwell KH, Lenke LG, et al. Risk factors and outcomes for catastrophic failures at the top of long pedicle screw constructs: a matched cohort analysis performed at a single center. *Spine (Phila Pa 1976)* 2009;34:2134–9.
27. Watanabe K, Lenke LG, Bridwell KH, et al. Proximal junctional vertebral fracture in adults after spinal deformity surgery using pedicle screw constructs: analysis of morphological features. *Spine (Phila Pa 1976)* 2010;35:138–45.
28. Hostin R, McCarthy I, O'Brien M, et al. Incidence, mode, and location of acute proximal junctional failures following surgical treatment for adult spinal deformity. *Spine (Phila Pa 1976)* 2013;38:1008–15.
29. Scheer JK, Fakurnejad S, Lau D, et al. Results of the 2014 SRS Survey on PJK/PJF: a report on variation of select SRS member practice patterns, treatment indications, and opinions on classification development. *Spine (Phila Pa 1976)* 2015;40:829–40.
30. Abbott D. *Applied Predictive Analytics: Principles and Techniques for the Professional Data Analyst*, 1st ed. Indianapolis, IN: John Wiley & Sons, Inc; 2014.
31. Champain S, Benchikh K, Nogier A, et al. Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. *Eur Spine J* 2006;15:982–91.
32. Rillardon L, Levassor N, Guigui P, et al. Validation of a tool to measure pelvic and spinal parameters of sagittal balance. *Rev Chir Orthop Reparatrice Appar Mot* 2003;89:218–27.
33. O'Brien MF, Kuklo TR, Blanke K, et al. *Spinal Deformity Study Group Radiographic Measurement Manual*. Medtronic Sofamor Danek: Memphis, TN; 2005.
34. Schwab F, Ungar B, Blondel B, et al. Scoliosis Research Society-Schwab adult spinal deformity classification: a validation study. *Spine (Phila Pa 1976)* 2012;37:1077–82.
35. Chen HN, Tsai YF. A predictive model for disability in patients with lumbar disc herniation. *J Orthop Sci* 2013;18:220–9.
36. Ialenti MN, Lonner BS, Verma K, et al. Predicting operative blood loss during spinal fusion for adolescent idiopathic scoliosis. *J Pediatr Orthop* 2013;33:372–6.
37. Lee MJ, Cizik AM, Hamilton D, et al. Predicting medical complications after spine surgery: a validated model using a prospective surgical registry. *Spine J* 2014;14:291–9.
38. Mathai KM, Kang JD, Donaldson WF, et al. Prediction of blood loss during surgery on the lumbar spine with the patient supported prone on the Jackson table. *Spine J* 2012;12:1103–10.
39. Tetreault LA, Kopjar B, Vaccaro A, et al. A clinical prediction model to determine outcomes in patients with cervical spondylotic myelopathy undergoing surgical treatment: data from the prospective, multi-center AOSpine North America study. *J Bone Joint Surg Am* 2013;95:1659–66.
40. Daubs MD, Hung M, Adams JR, et al. Clinical predictors of psychological distress in patients presenting for evaluation of a spinal disorder. *Spine J* 2014;14:1978–83.
41. Spratt KF, Keller TS, Szpalski M, et al. A predictive model for outcome after conservative decompression surgery for lumbar spinal stenosis. *Eur Spine J* 2004;13:14–21.
42. Scheer JK, Mundis GM, Klineberg E, et al. Recovery following adult spinal deformity surgery: the effect of complications and reoperation in 149 patients with 2-year follow-up. *Eur Spine J* 2015; [Epub ahead of print].
43. Scheer JK, Mundis GM, Klineberg E, et al. Postoperative recovery after adult spinal deformity surgery: comparative analysis of age in 149 patients during 2-year follow-up. *Spine (Phila Pa 1976)* 2015; 40:1505–15.