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Establishment of an Individualized Distal Junctional Kyphosis Risk Index following the Surgical Treatment of Adult Cervical Deformities

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Study Design. A retrospective review of a multicenter comprehensive cervical deformity (CD) database.

Objective. To develop a novel risk index specific to each patient to aid in patient counseling and surgical planning to minimize postop distal junctional kyphosis (DJK) occurrence.

Background. DJK is a radiographic finding identified after patients undergo instrumented spinal fusions which can result in sagittal spinal deformity, pain and disability, and potentially neurological compromise. DJK is considered multifactorial in nature and there is a lack of consensus on the true etiology of DJK.

Materials and Methods. CD patients with baseline (BL) and at least one-year postoperative radiographic follow-up were included. A patient-specific DJK score was created through use of unstandardized Beta weights of a multivariate regression model predicting DJK (end of fusion construct to the second distal vertebra change in this angle by <−10° from BL to postop).

Results. A total of 110 CD patients included (61 yr, 66.4% females, 28.8 kg/m^2). In all, 31.8% of these patients developed DJK (16.1% three males, 11.4% six males, 62.9% one-year). At BL, DJK patients were more frail and underwent combined approach more (both $P<0.05$). Multivariate model regression analysis identified individualized scores through creation of a DJK equation. −0.55+0.009 (BL inclination)−0.078 (preinflection)+5.9×10^{-5} (BL lowest instrumented vertebra angle) + 0.43 (combine approach)−0.002 (BL TS-CL)−0.002 (BL pelvic tilt)−0.031 (BL C2-C7) + 0.02 (ΔT4–T12)+ 0.63 (osteoporosis)−0.03 (anterior approach)−0.036 (frail)−0.032 (3 column osteotomy). This equation has a 77.8% accuracy of predicting DJK. A score ≥81 predicted DJK with an accuracy of 89.3%. The BL reference equation correlated with two year outcomes of Numeric Rating Scales of Back percentage ($P=0.003$), reoperation ($P=0.04$), and minimal clinically importance differences for 5-dimension EuroQol questionnaire ($P=0.04$).

Conclusions. This study proposes a novel risk index of DJK development that focuses on potentially modifiable surgical factors as well as established patient-related and radiographic determinants. The reference model created demonstrated strong correlations with relevant two-year outcome measures, including axial pain-related symptoms, occurrence of related reoperations, and the achievement of minimal clinically importance differences for 5-dimension EuroQol questionnaire.

Key words: cervical deformity (CD), distal junctional kyphosis (DJK), pelvic incidence, predictive model, surgical factors, radiographic parameters

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Each institution obtained approval from their local Institutional Review Board to enroll patients in the prospective database. Informed consent was obtained from each patient before enrollment.

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The cervical spine has distinct biomechanical functions that enable it to optimize horizontal gaze, maintain physiological head and neck movement, and support vital neurovascular structures. The complexity of the cervical segment makes it susceptible to a variety of alignment pathologies, often leading to adverse effects on a person's overall functioning and health-related quality of life (HRQL). The heterogeneous nature of adult cervical deformity (CD) has prompted the development of the Ames classification system, with the overall goal of restoring cervical sagittal alignment; however, despite favorable short-term clinical outcomes observed after CD-corrective surgery, long-term durability remains a challenge with revision rates frequently exceeding 20%.[1–4]

Distal junctional kyphosis (DJK), defined as a loss of alignment 1 or 2 levels distal to the lowest instrumented vertebra (LIV), is a growing concern for both surgeons and patients. The incidence of DJK ranges from 12% to 24%, with etiologies that include fixation failure, adjacent level fracture, and spondylolisthesis.[5–7] These may, in turn, lead to pain, radiculopathy, myelopathy, and deformity.[8] Few studies have investigated the risk factors that may predict the occurrence of DJK following CD-corrective surgery. Previous work suggests that certain clinical and maladaptive characteristics, including neurologic comorbidities and preoperative T1-slope, sagittal vertical axis (SVA), cervical lordosis (CL), and cervical kyphosis strongly predict DJK at specific cut-off points.[7] Other studies have identified that undergoing a three-column osteotomy or undergoing a combined approach significantly impacts the development of DJK.[6]

Although these independent risk factors may aid in clinical decision-making, a unified index encompassing not only patient-related and deformity-specific parameters but also factors describing surgical intervention is lacking. This study presents a novel index based on distal construct factors, surgical variables, and radiographic alignment that aims to both predict the occurrence of DJK in a CD cohort and aid in patient risk assessment at baseline (BL) and early follow-up.

MATERIALS AND METHODS

Study Design

This study utilizes a database of consecutive, prospectively enrolled CD patients above 18 years of age from 13 spine centers across the continental United States. All patients presented for surgical evaluation of CD, which was defined radiographically as cervical kyphosis (C2-C7 sagittal Cobb angle $>10°$), cervical scoliosis (C2-C7 coronal Cobb angle $>10°$), C2-C7 SVA >4 cm, or chin-brow vertical angle $>25°$. Patients included in this specific study had BL and one-year radiographic and HRQL data. Database exclusion criteria included patients with active tumors, infection, or deformity of neuromuscular etiology.

Data Collection and Radiographic Assessment

HRQL was assessed at BL and one year using validated HRQL forms, including Neck Disability Index (NDI), Numeric Rating Scales (NRS) for Neck and Back Pain, and the 5-dimension EuroQol questionnaire (EQ-5D) and the EQ-5D Visual Analog Score (VAS).[9,10] Cervical myelopathy was also assessed via the modified Japanese Orthopaedic Association (mJOA) form.[11] Radiographic data were identified through the use of long-cassette, full-standing anterior-posterior and lateral radiographs. These radiographic parameters were analyzed using validated software (Spineview, ENSAM Laboratory of Biomechanics, Paris, France) as previously published. Global alignment via the SVA (horizontal distance from C7 plumb line relative to the poster superior corner of S1). Regional alignment parameters assessed were pelvic tilt (PT), pelvic incidence (PI), thoracic kyphosis (TK), lumbar lordosis (LL), CL, and C2-C7 SVA. Upper-cervical alignment parameters included C0-C2 sagittal Cobb angle (C0-C2), C2 slope, and McGregor slope (a validated measure of horizontal gaze).[12] Mismatches between T1 slope and CL (TS-CL), and PI and LL (PI-LL) were calculated as measures of harmonious cervical and thoracolumbar alignment, respectively.[12] The cervicothoracic inflection point was identified numerically as the level where CL changes to TK. For patients with multiple inflection points, the distal-most was included in the analysis. Inclination angle was identified by the angle between a plumb line and a straight line from the first thoracic vertebra to the first sacral vertebra (Figure 1).

Assessment of DJK

DJK was defined radiographically via the Cobb angle method as a $>10°$ kyphosis between the superior endplate of the LIV and the inferior endplate of the second distal vertebra (LIV-2), in addition to a preoperative to postoperative change in DJK angle (DJKA) $>10°$.

Statistical Analysis

BL demographics and surgical characteristics were first summarized using descriptive statistics in mean ± SD for continuous variables or % (counts) for categorical variables. Variables identified to be clinically meaningful to the development of DJK were classified into three groups: (1) distal construct factors, (2) surgical variables, and (3) radiographic variables. Each variable in these categories was first assessed through the use of bivariate logistic regression to identify the association with the outcome of interest. Following bivariate analysis, statistically significant variables were entered into the multivariable model. To ensure that the number of individuals was adequate for the number of predictors, a minimum of 10 events for each covariate were included in all of the models.[13] Selected models' prediction performance was evaluated by the use of discrimination and calibration powers. Model discrimination was evaluated with area under the curve (AUC). The calibration was evaluated with a decile-decile plot of the observed and predicted outcomes. To calculate

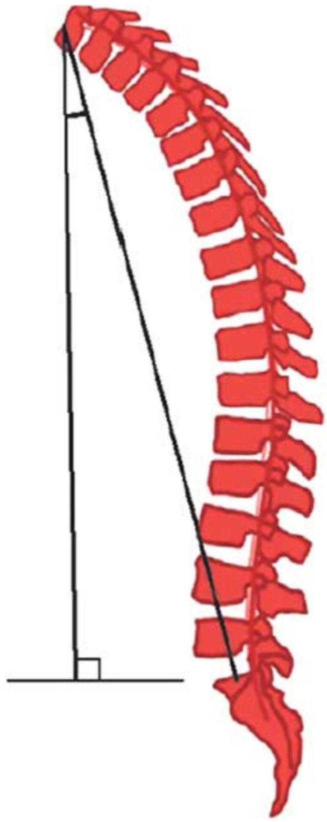

FIGURE 1. Depiction of the inclination angle as measured on a lateral radiograph. full color online

the calibration intercept and slope parameters, a linear regression model was fitted with the deciles of the observed outcome as the dependent variable and the deciles of the predicted outcome as the independent variable. The Hosmer-Lemeshow goodness-of-fit test was used to compare the expected and observed number of outcomes. All statistical procedures were performed using R (www.R-project.org). Calibration of the final model was assessed using Regression Modeling Strategies (RMS) package in R statistical software.

DJK Score Development

The variables identified from the predictive models were utilized to generate a utility that predicts the development of DJK, consisting of preoperative variables relating to surgical approach, BL alignment, and other construct factors. The scoring system was employed by using beta weights for each individual variable identified through multivariable regression.

RESULTS

Cohort Overview

A total of 110 consecutive patients with CD met inclusion criteria. Average levels fused was 7.5 ± 3.6, average age 61.5 ± 9.8 years, 66.4% female, and average body mass index 28.8 ± 7.7 kg/m^2. In all, 18.2% of the 110 patients received an anterior approach, while 46.4% received a posterior approach. The most common upper-most instrumented vertebra was C2 (min: C1, max: T3) and the most common lower-most instrumented vertebra was T3 (min: C6, max: L2).Radiographically, patients presented at BL with a mean PT = 23.4°, PI minus LL (PI–LL) = 0.23°, TK = –47.5°, C2-C7 SVA = 45.5°, TS-CL = 38.08°, and a McGregor slope = 4.17°.

DJK Occurrence

Of the 110 patients, 31.8% developed DJK postoperatively (20.0% within 6 mo, 45.7% within 1 yr, and 34.3% within 2 yr). DJK patients did not differ from those that did not develop DJK based on demographics, as shown in Table 1. HRQL outcomes for NDI, mJOA, EQ-5D, EQ-5D-VAS, and NSR-Back and Neck scores were similar among the groups at BL (all $P > 0.05$). Surgical characteristics such as estimated blood loss, operative time, and average level of instrumented fusion were all similar between the two groups. However, those that developed DJK had less posterior-only approaches than those that did not develop DJK (31.4% *vs.* 53.3%; $P = 0.032$). By BL radiographic data, DJK patients had a significantly more lordotic thoracolumbar spine identified by T10-L2 (–4.4 *vs.* –9.8) and a greater SVA C2-C7 (52.8 *vs.* 42.0; all $P < 0.05$; Table 1).

DJK Postoperative Alignment and Outcomes

By one-year there were no differences between DJK and no DJK in terms of HRQL outcomes. However, DJK patients trended toward a greater self-reported NDI (42.13 *vs.* 34.3; $P = 0.08$). By alignment at one year postop, DJK patients had greater C2SS (65.4 *vs.* 56.5), C2T3 (31.9 *vs.* 24.4), C2S1 (46.7 *vs.* 37.9), and a more kyphotic C2-C7 (–4.8 *vs.* 0.95; all $P < 0.05$; Table 2). By two years, DJK patients had a reciprocal increase in SVA C7-S1 (–6.4 to 3.9), C2-T3 (–23.1 to –4.2), and sagittal balance as measured by T1-SS (24.4–39.4; all $P < 0.05$).

Preoperative Predictive Model

A combination of distal construct factors, radiographic factors, and BL surgical factors were used for multivariate analysis to reflect the created model's predictability in relation to DJK development. Table 3 displays the selected factors with their associated odds ratio. The radiographic parameters that the model selected were BL TS-CL, C2-C7, TK, and PT. The distal construct factors used were LIV angle, inclination angle, and inflection point. The surgical factors were combined approach, anterior approach, three column osteotomy, osteoporosis, and patient frailty. The selected model with the highest reliability and precision was selected. Even though the final model was not well calibrated using the Hosmer-Lemeshow goodness-of-fit test ($\chi^2 = 13.5$, $P = 0.0945$; Figure 2). The area under the receiver operating characteristic curve was 0.778 (SE = 0.025, confidence interval = 0.833–0.930), indicating that the final model has a good discriminative ability. From this, a preoperative equation was created and utilized, as shown in Figure 3.

TABLE 1. Baseline Differences Between DJK and No DJK Patients

	DJK	No DJK	*P*
Basic demographics			
Age (yr)	60.57 ± 10.1	61.9 ± 9.8	> 0.05
BMI (kg/m^2)	30.5 ± 9.6	28.0 ± 6.5	
Charlson Comorbidity Index (CCI)	1.07 ± 1.36	0.9 ± 1.2	
Surgical characteristics			
Estimated blood loss (mL)	864.1 ± 718.8	807.7 ± 907.0	> 0.05
Operative time (minutes)	506.6 ± 170.8	542.2 ± 279.3	
No. levels fused	8.21 ± 3.7	7.4 ± 3.6	
Posterior approach	31.4%	53.3%	0.032
Anterior approach	14.3%	20.0%	> 0.05
UIV	C3	C3	
LIV	T3	T3	
Radiographic alignment			
L1-S1	54.1	52.8	> 0.05
PI-LL	1.1	−0.2	
TK	−46.2	−48.3	
C2T3	−22.1	−15.7	
C2SS	42.0	36.4	
C2S1	33.9	45.7	
SVA C2-C7	52.8	42.0	0.04
T10-L2	−4.4	−9.9	0.04
TS-CL	41.3	36.5	> 0.05
McGregor slope	5.0	3.1	
Inflection point			
C6 or above	55.6%	36.8%	
C6-C7 to C7-T1	33.3%	43.9%	
T1 or below	11.1%	19.3%	
Inclination angle	38.5	30.3	

BMI indicates body mass index; DJK, distal junctional kyphosis; LIV, lowest instrumented vertebra; SVA, sagittal vertical axis; TK, thoracic kyphosis; TS-CL, T1 slope cervical lordosis; UIV, upper-instrumented vertebra.

TABLE 2. Outcomes at One Year Postoperatively

	DJK	No DJK	*P*
Radiographic alignment			
L1-S1	52.4	51.4	> 0.05
PI-LL	2.8	1.1	> 0.05
TK	−55.8	−50.1	> 0.05
C2T3	−4.8	0.95	0.008
C2SS	31.9	24.4	0.01
C2S1	65.4	56.5	0.04
SVA C2-C7	46.7	37.9	0.01
T10-L2	−10.9	−11.7	> 0.05
TS-CL	32.2	27.6	0.075
McGregor slope	0.91	−1.4	> 0.05

DJK indicates distal junctional kyphosis; LIV, lowest instrumented vertebra; LL, lumbar lordosis; PI, pelvic incidence; SVA, sagittal vertical axis; TK, thoracic kyphosis; TS-CL, T1 slope cervical lordosis.

TABLE 3. Baseline Predictive Model

	Coefficient
Intercept	-5.03×10^{-1}
TS-CL	-2.6×10^{-2}
C2-C7	-3.14×10^{-2}
Osteoporosis	6.33×10^{-1}
TK (T4-T12)	-2.31×10^{-2}
LIV angle	5.98×10^{-5}
Inclination angle	9.12×10^{-3}
PT	-2.04×10^{-3}
Combined approach	4.30×10^{-1}
Anterior only approach	-3.07×10^{-1}
Frail	-3.6×10^{-1}
Inflection point	-7.86×10^{-1}
Three column osteotomy	-3.2×10^{-1}
AUC = 77.8%	

AUC indicates area under the curve; BMI, body mass index; DJK, distal junctional kyphosis; LIV, lowest instrumented vertebra; PT, pelvic tilt; TK, thoracic kyphosis; TS-CL, T1 slope cervical lordosis.

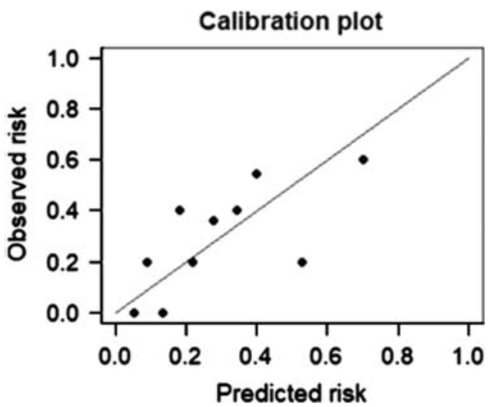

FIGURE 2. Hosmer-Lemeshow goodness-of-fit plot.

Case Examples

Figure 4 presents a 67-year-old frail female with a flatneck deformity and a history of osteoporosis. At BL (Figure 4A) the patient had a TS-CL of 81.1°, T4-T12 of –28.4°, inclination angle of 132.3°, PT 32.8°, LIV angle –9.5°, and C2-C7 –52.5°. Surgically, the patient received a combined approach. Utilizing the BL scoring equation, the patient had an 81.1% probability of developing DJK postoperatively. The patient developed mild DJK at three months postop, as shown in Figure 4B.

Figure 5 presents a 50-year-old nonfrail male with no history of osteoporosis. At BL (Figure 5A) the patient had a TS-CL of 21.1°, T4-T12 of –32.1°, PT 13.0°, LIV angle 9.3°, and C2-C7 –7.0°. The patient underwent posterior-only approach. Utilizing the BL scoring equation, the patient had an 47.4% probability of developing DJK postoperatively. The patient did not develop any DJK postoperatively (Figure 5, B).

DISCUSSION

DJK development continues to be a significant concern after CD-corrective surgery. Limited studies have investigated the specific preoperative factors that may predict the occurrence of DJK. A lack of a comprehensive understanding surrounding DJK prompts further investigation into the various contributing BL and procedural factors. Proper models of risk stratification at various treatment points are important for patient counseling and for surgical decision-making in CD surgery.[14] Therefore, we sought to develop a validated tool that can assess a patient's likelihood of developing DJK based on a combination of surgical, radiographic, and distal construct factors in a CD cohort.

The rate of DJK development in our study cohort was 31.8%. DJK most commonly occurred within one year of index surgery. These findings are similar to other studies reporting that up to 80% of patients typically develop proximal junctional kyphosis within 18 months of CD-corrective surgery.[15,16] In our study, BL demographic factors such as age, sex, and Charlson Comorbidity Index did not increase the risk of developing DJK. Interestingly, HRQL outcomes were also similar among both DJK and non-DJK patient cohorts. Regarding surgical characteristics, patients who developed DJK had significantly less posterior-only approaches than those that did not develop DJK. Previous studies have also indicated that a combined approach was a significant factor in predicting DJK.[6,7] The DJK cohort had significantly higher BL regional malalignment as measured by SVA C2-C7 (52.8 *vs*. 42.0 mm) as well as increased lordosis in the thoracolumbar spine as measured by T10-L2 (–4.4 *vs*. –9.8°). These measurements are reflective of sagittal malignment as is well established in the literature.

$$\textit{Estimate of } P(y=1 \mid x_1,\ldots x_p) = 1/(1+e^{-(a+\sum_k b_k x_k)})$$

FIGURE 3. Preoperative equation to assess a patient's risk of distal junctional kyphosis development.

FIGURE 4. Lateral preoperative (A) and one-year posteroperative (B) radiographs of a 67-year-old patient who had a 81.1% probability of developing distal junctional kyphosis postoperatively by the novel risk index.

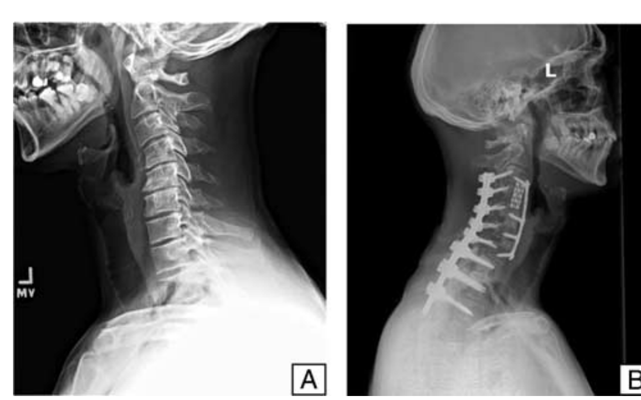

FIGURE 5. Lateral preoperative (A) and one-year posteroperative (B) radiographs of a 50-year-old patient who had a 47.4% probability of developing distal junctional kyphosis postoperatively by the novel risk index.

Although understudied in the literature, several reports have identified factors which have the potential to reduce the incidence of proximal junctional kyphosis such as terminal rod contouring, hook fixation, ligament augmentation, fusion construct length, metal flexibility, and less destruction of soft tissue at the upper-instrumented vertebra.[17] Certain radiographic factors such as C2-T1 tilt, C2-C7 lordosis, T1 slope minus CL, SVA C2-C7, and C4 tilt have also been identified to significantly affect the occurrence of DJK postoperatively. Specifically, combined approaches and usage of Smith Peterson osteotomy have the biggest effect for this outcome. Other such studies have reported a greater number of levels fused, higher grade osteotomies, and the use of posterior transition rods as having a significant effect on the development of DJK *versus* those who did not.[18] These findings are in line with some of the factors we used in the creation of our own risk stratification tool.

At one year postoperatively, DJK patients reported greater values in NDI (42.13 *vs*. 34.3), indicating severe functional disability in these patients. Regarding radiographic alignment at one year postoperatively, DJK patients had greater C2SS (65.4 *vs*. 56.5°), C2T3 (31.9 *vs*. 24.4°), C2S1 (46.7 *vs*. 37.9°), and a more kyphotic C2-C7 (–4.8 *vs*. 0.95°). By two years, DJK patients had a reciprocal increases in SVA C7-S1 (–6.4 to 3.9), C2-T3 (–23.1 to –4.2), and sagittal balance as measured by T1-SS (24.4–39.4). These values are reflective of progressively worsening long-term sagittal malignment over a two-year follow-up period.

The BL predictive model consisted of preoperative factors relating to surgical approach, BL alignment, and distal construct factors. Utilizing the factors in our predictive model, we were able to validate that these factors can predict DJK occurrence with high predictability and high accuracy, as seen with the preoperative model's AUC (77.8%). Upon validating the utility of these factors, we were able to create an equation that adequately describes a patient's likelihood of developing DJK. Inclination angle was the strongest predictor of DJK in this model. Moreover, surgery using a combined approach also had a sizeable effect on DJK, in line with previous studies.[6,7] The presence of osteoporosis was additionally predictive of DJK in this model. This is in line with previous studies, as poor bone quality is often cited as an important factor contributing to junctional kyphosis.[19–21] Lastly, the level of LIV was shown to play an important role in contributing to DJK. This is also mirrored by previous studies demonstrating that the choice of the LIV may increase susceptibility to developing DJK.[8,22]

On the basis of the factors included in our predictive, we propose that the risk of developing distal junctional kyphosis following CD correction may be minimized if surgeons consider several preoperative factors. First, patients with pronounced cervical kyphosis at BL as well as more pronounced thoracolumbar deformity, should be flagged as potentially having a higher risk of postoperative DJK. Second, bone quality as indicated by preoperative diagnoses, including osteopenia or osteoporosis, should be assessed. Third, the benefits of utilizing a combined approach and low *versus* high-grade osteotomy should be weighed carefully against the risk of DJK.

We appreciate several limitations to our study. First, the retrospective nature of this study likely introduces selection, indication and expertise bias which cannot be controlled for and potentially confound results. The prospect of clustering at the provider level can also not be quantified or controlled for. There was also a relatively small cohort of CD patients that developed DJK. As a result, the findings and resultant predictive tool should be viewed as exploratory, and further refinement and validation may be needed in other populations before the true clinical validity and utility can be determined. Nevertheless, the data utilized in this study is derived from the largest repository of CD patients available and therefore represents the best possibility of accuracy thus far. The CD cohort included in our analysis also presented with severe BL sagittal malalignment and were elderly. This patient cohort along with the possibility of overfitting the predictive models, may limit the generalizability of study findings to other populations with different socioclinical characteristics and BL risk for DJK. Second, there was no control group of CD patients who underwent nonoperative treatment, which potentially limits conclusions drawn in regard to outcomes. We do plan future work with a larger sample size and external data source, through which we will be able to externally validate these determinations.

CONCLUSIONS

We observed a 31.8% incidence of DJK in our CD cohort. Based on our predictive model, we found that specific radiologic, surgical, and distal construct factors played a pivotal role in predicting the occurrence of DJK with high predictability and high accuracy (AUC 77.8%). Predictive variables of significance included inclination angle, combined approach, osteoporosis, and level of LIV. This model provides a foundation for preoperative, patient-specific surgical planning for CD patients and provides insight into the factors that may be predictive of DJK, thus mitigating poor outcomes.

➢ Key Points

- ❑ Inclination angle was the strongest predictor of DJK in our predictive model.
- ❑ Surgery using a combined approach also had a sizeable effect on DJK, in line with previous studies.[6,7] The presence of osteoporosis was additionally predictive of DJK in this model as well as the LIV.

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