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DEFORMITY

Predicting the Magnitude of Distal Junctional Kyphosis Following Cervical Deformity Correction

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Study Design. Retrospective review of a cervical deformity database.

Objective. This study aimed to develop a model that can predict the postoperative distal junctional kyphosis angle (DJKA) using preoperative and postoperative radiographic measurements.

Summary of Background Data. Distal junctional kyphosis (DJK) is a complication following cervical deformity correction that can reduce of patient quality of life and functional status. Although researchers have identified the risk factors for DJK, no model has been proposed to predict the magnitude of DJK.

Materials and Methods. The DJKA was defined as the Cobb angle from the lower instrumented vertebra (LIV) to LIV-2 with traditional DJK having a DJKA change $>10°$. Models were trained using 66.6% of the randomly selected patients and validated in the remaining 33.3%. Preoperative and postoperative radiographic parameters associated with DJK were identified and ranked using a conditional variable importance table. Linear regression models were developed using the factors most strongly associated with postoperative DJKA.

Results. A total of 131 patients were included with a mean follow-up duration of 14 ± 8 months. The mean postoperative DJKA was $14.6 \pm 14°$ and occurred in 35% of the patients. No significant differences between the training and validation cohort were observed. The variables most associated with postoperative DJK were: preoperative DJKA (DJKApre), postoperative C2–LIV, and change in cervical lordosis (ΔCL). The model identified the following equation as predictive of DJKA: DJKA = 9.365+(0.123×ΔCL)−(0.315×ΔC2–LIV)−(0.054×DJKApre). The predicted and actual postoperative DJKA values were highly correlated ($R=0.871$, $R^2=0.759$, $P<0.001$).

Conclusions. The variables that most increased the DJKA were the preoperative DJKA, postoperative alignment within the construct, and change in cervical lordosis. Future studies can build upon the model developed to be applied in a clinical setting when planning for cervical deformity correction.

Key words: distal junctional kyphosis, DJK, cervical deformity, sagittal spine deformity

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Over the past decades, it has been established that adult spinal deformities are associated with pain and disability[1–5] and that malalignment of the cervical spine is similarly linked to poor health-related quality of life.[6–12] Patients with cervical deformity have been shown to have a substantial disability, comparable to the lowest quartile of debilitating chronic diseases such as blindness, emphysema, renal failure, and stroke.[8] The most common type of cervical deformity is kyphosis, and if left untreated, it can progress to the point where not only vision is compromised but also breathing and swallowing.[13]

Recent advancements in cervical deformity surgery have allowed surgeons to more effectively correct deformities and restore natural cervical lordosis. Although studies have shown that adequate realignment can significantly improve health-related quality of life, loss of correction is common.[14–17] Distal junctional kyphosis (DJK) is a serious, but frequent complication following cervical deformity surgery with rates reported up to 38%.[18] In the literature, DJK is generally characterized by alignment loss at two levels distal to the lower instrumented vertebra (LIV). The development of DJK can lead to loss of alignment deterioration, worsening disability, and revision surgery.[19,20]

Researchers have identified several risk factors for the development of DJK. Many these studies focus on non-modifiable risk factors, such as preoperative cervical alignment.[20] Currently, there are no methods by which

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surgeons can predict the magnitude of DJK after surgery. This study aimed to develop a model to accurately predict the postoperative DJKA in patients with cervical deformity using preoperative and intraoperative radiographic measurements. A reliable and easy-to-use formula would enable surgeons to predict postoperative DJK based on the corrections achieved intraoperatively.

MATERIALS AND METHODS

Study Population

This was a retrospective review of a multicenter database of patients with operative cervical deformity enrolled from 2013 to 2018. All participating centers obtained institutional review board approval prior to patient enrollment, and all participating patients provided consent. Inclusion criteria consisted of operative cervical deformity patients aged 18 years and above with clinical and radiographic data available at baseline and at any postoperative interval. The cervical deformity was defined as the presence of at least one of the following on baseline radiographs: cervical kyphosis (C2–C7 Cobb angle > 10°), cervical scoliosis (C2–C7 coronal Cobb angle > 10°), C2–C7 sagittal vertical axis (cSVA) > 40 mm, or chin-brow vertical angle (CBVA) > 25°. Patients were excluded from the database if they were under 18 years of age, were pregnant, or had evidence of spinal neoplasm or infection. Patients with a history of spinal fusion extending below the L4 level were excluded from the analysis. All patients had a minimum of three months of follow-up postoperatively.

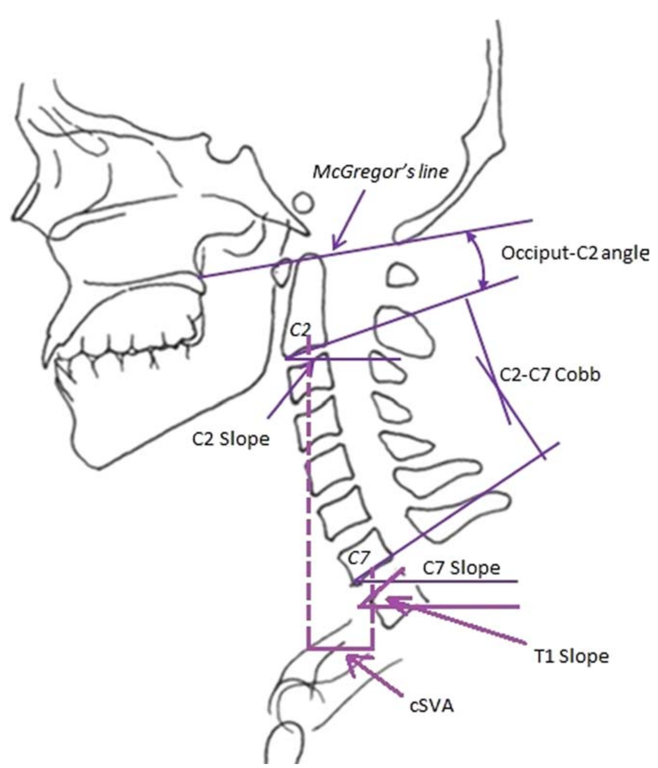

Figure 1. Diagram illustrating the cervical alignment parameters measured in this study. cSVA indicates C2–C7 sagittal vertical axis. full color online

Data Collection and Radiographic Assessment

Demographic and clinical data collected included patient age, sex, body mass index, and Charlson Comorbidity Index. Perioperative data was collected following surgery, including surgical approach, osteotomy utilization, number of levels fused, upper instrumented vertebra, LIV, complications, reoperations, and indication(s) for reoperation.

Full-length (36-inch cassette) and anterior-posterior and lateral radiographs were obtained at baseline and at each postoperative interval (three months, six months, one year, and two years) from patients in a free-standing posture with neutral cervical flexion. Each image was deidentified and sent securely to a central location. All radiographs were analyzed at a central location using a validated software[21–23] (SpineView; ENSAM, Laboratory of Biomechanics). Each image was measured based on standard techniques and verified by two independent researchers, who were not surgeons, to avoid implicit bias. These measurements were not shared with the surgeon involved.[22]

The cervical radiographic parameters of interest included C2–C7 cervical lordosis (CL), cervical sagittal vertical axis (cSVA), C2 slope, T1 slope, T1 slope minus cervical lordosis (TS–CL), McGregor's slope (McGS), and chin-brow vertical angle (CBVA) (Figure 1).

Thoracolumbar, spinopelvic, and global alignment parameters were also collected, including lumbar lordosis (LL), thoracic kyphosis (TK), C7–S1 sagittal vertical axis (SVA), T1 pelvic angle (TPA), pelvic tilt (PT), pelvic incidence (PI), and the difference between PI and LL (PI-LL) (Figure 2).

The C2–LIV tilt is a measure of alignment within the fusion construct (in-construct alignment) and was used in this study to assess the correction achieved intraoperatively. The C2–LIV tilt was defined as the angle between a line from the centroid of C2 to the centroid of the LIV body and a line parallel to the posterior body of the LIV (Figure 3). All measurements, their abbreviation, and definition can be seen in the Supplemental Digital Content Table 1, http://links.lww.com/BRS/B946.

Distal Junctional Kyphosis

The distal junctional kyphosis angle (DJKA) was defined as the angle measured from the superior endplate of the LIV to the inferior endplate of vertebra 2 levels caudal to the LIV. Traditional distal junctional kyphosis (tDJK) was defined as a kyphotic change > 10° of the DJKA angle preoperatively to postoperatively, and severe distal junctional kyphosis (sDJK) was defined as a kyphotic change > 20° (Figure 4)

Model Development

Random forest analysis was first performed using the R statistical software package (version 3.2.4; R Foundation for Statistical Computing) to identify radiographic parameters associated with postoperative DJKA that could be measured preoperatively and intraoperatively in 84 (66.6%) patient cohort. These parameters were ranked according to

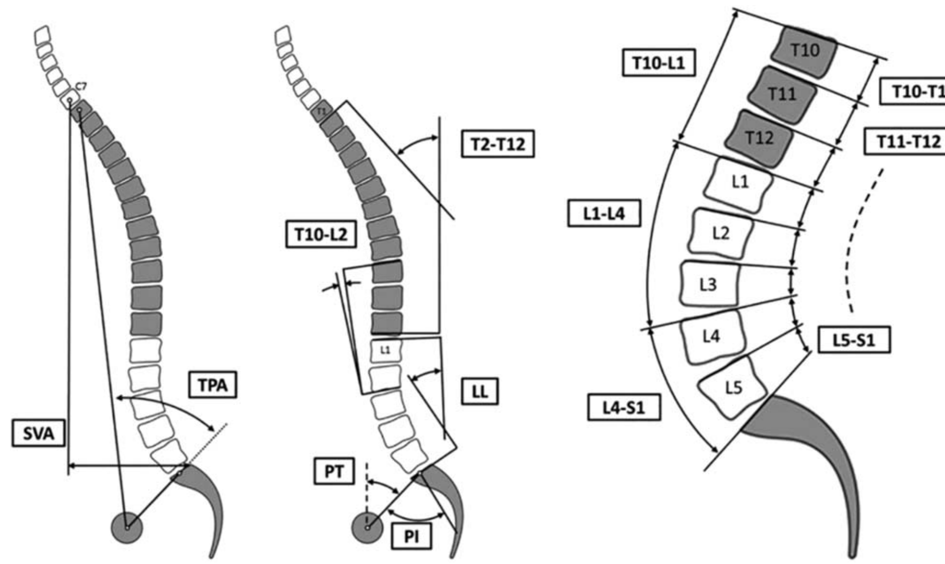

Figure 2. Radiographic parameters collected for this study including global parameters, regional parameters, and segmental parameters.

the strength of association with the DJKA using a variable importance table, generated per conditional permutation importance defined by the "varimp" function within the R "party" package. Using the top factors identified in the variable importance table as independent variables, multivariate linear regression was used to construct a model predicting the postoperative DJKA. Randomization of cohorts was insured with the use of a random number generating function in the R package "randomizeR" with the development of a training cohort (66.6%) and validation cohort (33.3%).

Model Validation

The formula generated from the regression analysis within the training subset was applied to the remaining 33.3% of the patients to predict the development of postoperative DJK. The formula predicted tDJK and sDJK if the difference between the predicted postoperative DJKA and the actual preoperative DJKA was > 10° or 20°, respectively. The ability of the model to correctly predict tDJK and sDJK was assessed in the validation subset and in the entire study cohort.

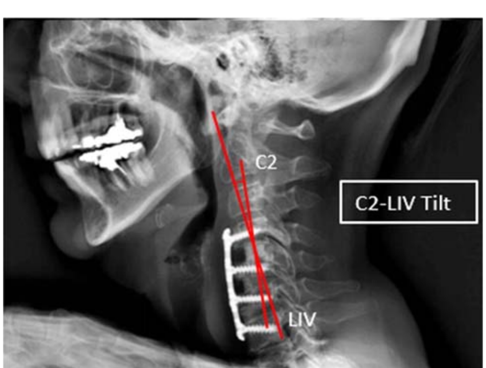

Figure 3. Lateral cervical radiograph illustrating C2–LIV tilt, which is a measure of alignment within the fusion construct. It is measured as the angle between a line from the centroid of C2 to the LIV centroid and a line parallel to the posterior vertebral body of the LIV. LIV indicates lower instrumented vertebra. full color online

Statistical Analysis

Patient demographics and baseline cervical alignment were summarized using descriptive statistics. The training and validation subsets were compared using independent-sample *t* tests and χ^2 tests where appropriate. The median absolute error and Interquartile ranges were calculated to determine the absolute differences between actual and predicted postoperative DJKA. The sensitivity, specificity, and negative and positive predictive values (NPV and PPV, respectively) for tDJK and sDJK were also calculated. (Fig. 5) Descriptive statistics, linear regression analysis, and all validation calculations were performed using SPSS (v21.0, Armonk, NY, USA) with statistical significance was set to *P* value <0.05.

RESULTS

Study Participants and Patient Characteristics

There were 159 eligible cervical deformity patients. In 28 patients were excluded because they either had a fusion caudal to L4 or did not have both preoperative and postoperative DJKA recorded. The remaining 131 patients were included in the analysis. The study population was 62.2% female with a mean age of 60.6 ± 10.3 years, and body mass index of 29.6 ± 8.1 kg/m^2. T2 was the most common LIV (20.6%), and 44% of the patients had a fusion caudal to T2. The mean follow-up duration was 14 ± 8 months. Following randomization, the model training subset included 84 (66.6%) of patients and the validation subset included 47 (33.3%) of patients. Baseline patient characteristics and cervical alignment did not differ between the training and validation subsets (Table 1).

TABLE 1. Demographics, Baseline Alignment, and Postoperative Distal Junctional Kyphosis

	Mean ± SD			
Variables	**Validation (n = 47)**	**Training (n = 84)**	**All patients (N = 131)**	***P*†**
Demographics and surgical characteristics				
Age (y)	58.95 ± 9.94	61.46 ± 10.45	60.56 ± 10.30	> 0.05
Sex (female) (%)	65.9	59.5	61.8	> 0.05
BMI (kg/m^2)	28.91 ± 7.79	29.90 ± 8.31	29.56 ± 8.11	> 0.05
Levels fused	6.91 ± 4.07	8.10 ± 4.07	7.66 ± 4.10	> 0.05
CCI	0.97 ± 1.27	0.96 ± 1.41	0.96 ± 1.3	> 0.05
Anterior approach (%)	17.1	17.0	17.1	> 0.05
Posterior approach (%)	48.8	55.3	51.2	> 0.05
Combined anterior and posterior approach (%)	27.7	34.1	31.8	> 0.05
Intraoperative osteotomy (%)	51.2	46.8	49.6	> 0.05
Baseline alignment				
TPA (°)	8.99 ± 9.93	15.75 ± 13.36	13.42 ± 12.66	**0.005**
SVA (mm)	−8.11 ± 56.11	9.73 ± 76.22	3.64 ± 70.28	> 0.05
CL (°)	−7.07 ± 23.8	−6.8 ± 19.62	−6.9 ± 21.1	> 0.05
cSVA (mm)	36.07 ± 18.05	38.62 ± 19.99	37.72 ± 19.28	> 0.05
TS–CL (°)	35.85 ± 20.76	37.66 ± 17.84	37.02 ± 18.85	> 0.05
T1S (°)	28.74 ± 17.71	30.94 ± 14.5	30.17 ± 15.67	> 0.05
C2–LIV tilt (°)	0.03 ± 10.32	−0.02 ± 6.44	0.00 ± 8.05	> 0.05
DJK				
Baseline DJKA (°)	4.68 ± 11.2	5.53 ± 12.23	5.23 ± 11.84	> 0.05
Postoperative DJKA (°)	12.09 ± 13.03	15.91 ± 14.59	14.7 ± 13.57	> 0.05
DJKA change (°)	8.46 ± 6.38	9.83 ± 12.61	9.47 ± 11.01	> 0.05
tDJK (ΔDJKA ≥ 10°) [n (%)]	15 (34.1)	33 (40.7)	48 (38.4)	> 0.05
sDJK (ΔDJKA ≥ 20°) [n (%)]	3 (6.8)	10 (12.3)	13 (10.4)	> 0.05

Values are reported for all patients and stratified by validation or training subset.

BMI indicates body mass index; CCI, Charlson Comorbidity Index; CL, C2–C7 lordosis; cSVA, C2–C7 sagittal vertical axis; ΔDJKA, preoperative to postoperative change in distal junctional kyphosis angle; DJKA, distal junctional kyphosis angle; LIV, lower instrumented vertebra; sDJK, severe distal junctional kyphosis; SVA, C7 sagittal vertical axis; T1S, T1 slope; tDJK, traditional distal junctional kyphosis; TPA, T1 pelvic angle; TS−CL, T1 slope minus cervical lordosis.

P values are reported for comparisons between training and validation groups.

†P < 0.05 indicate significant differences between the validation and training subsets. Significant differences are indicated in bold font.

Distal Junctional Kyphosis

The average DJKA change in the entire cohort was 9.47 ± 11.01°. Postoperatively, 35.1% (n = 44) of the patients developed tDJK, and 10.7% (n = 14) developed sDJK. T2 was the most common vertebrae for the development of tDJK (20.1%), T3 (13.6%), then T4 (9.1%), and T5 (9.1%). As far as sDJK, T10 was the most affected vertebrae (27.3%) followed by T3 (18.2%) and L2 (18.2%).

There were no difference in the prevalence of tDJK and sDJK between the training and validation groups. During the follow-up period, 15 patients underwent revision surgery, five of whom required revision for DJK. Other reasons for reoperation included: three for Infection, five for stenosis necessitating additional direct decompression, one exchange of hardware at the ilium, and one traumatic burst fracture.

Model Development

From the training subset (n = 84), the radiographic parameters most associated with postoperative DJKA, in increasing order of importance, were preoperative to postoperative change in C2–C7 lordosis (ΔCL), postcorrection C2–LIV tilt (C2–LIV$_{post}$), and preoperative DJKA (DJKA$_{pre}$).

Linear regression was used to generate the following formula for predicting postoperative DJKA (DJKA$_{post}$). $DJKA_{post} = 9.365 + 0.315\times(C2\text{–}LIV_{post}) + 0.504\times(DJKA_{pre}) + 0.123\times(\Delta CL)$. This model was significant and accounted for 37% of the variability in postoperative DJKA ($r = 0.609$, $r^2_{adj} = 0.370$, $P < 0.001$).

This formula demonstrates that a larger postoperative DJKA is associated with worse postoperative in-construct alignment (↑C2–LIV tilt), greater correction of CL (↑ΔCL), and a larger preoperative DJKA. No violations of linearity,

Figure 4. Preoperative (left) and one-year postoperative (right) lateral radiographs depicting a patient with severe distal junctional kyphosis (sDJK). The distal junctional kyphosis angle (DJKA) is the Cobb angle measured from the superior endplate of the lower instrumented vertebra (LIV) to the inferior endplate of the vertebra 2 levels caudal to the LIV. Traditional distal junctional kyphosis (tDJK) is defined as a kyphotic change >10° of the DJKA, preoperatively to postoperatively; sDJK is a kyphotic change >20°.

		Actual		
		DJK	No DJK	**Se= a/(a + c)**
Predicted	DJK	*a*	*b*	**Sp= d/(b + d)**
	No DJK	*c*	*d*	**PPV= a/(a + b)**
				NPV= d/(c + d)

Figure 5. Calculations used to validate the formula predicting postoperative distal junctional kyphosis. Cells *a* and *d* represent cases where the formula correctly predicted postoperative DJK. Cells *b* and *c* represent incorrect predictions. DJK indicates distal junctional kyphosis; NPV, negative predictive value; PPV, positive predictive value; Se, sensitivity; Sp, specificity.

homoscedasticity, normality, or observation independence were observed.

Model Validation

In the validation subset (n = 47), the model accounted for 75.9% of the variability in the postoperative DJKA (R = 0.871, R^2_{adj} = 0.759, $P < 0.001$). The median absolute error between the predicted and actual postoperative DJKA was 6.22° (interquartile range: –1.71 to 14.15). The sensitivity, specificity, PPV, NPV, accuracy, and F1 score of this formula for predicting tDJK were 66.7%, 56.7%, 50.0%, 72.3%, 60.6%, and 57.7%, respectively (Supplementary Digital Content, Table 2, http://links.lww.com/BRS/B947). The sensitivity, specificity, PPV, NPV, and accuracy of this formula for predicting sDJK were 16.7%, 94.3%, 28.6%, 89.1%, and 84.8%, respectively.

DISCUSSION

In the present study, we analyzed radiographic and clinical data from 131 patients with operative cervical deformity to develop a formula that predicts postoperative DJK based on preoperative alignment and the correction achieved intraoperatively.

In cervical deformity surgery, adequate correction of deformity and maintenance of long-term correction are critical to achieving optimal patient outcomes. Tang *et al*[12] determined that a postoperative cSVA of >4 cm following realignment was associated with worse disability. Protopsaltis *et al*[24] found that at one year postoperatively, 46% of patients had a cSVA > 4 cm, and 65% had a TS–CL > 20°. In that study, postoperative DJK surgery was the most significant predictor of failed realignment and increased the risk of revision surgery. In a 2018 study by Passias *et al*,[20] risk factors for DJK were identified, the most significant being excessive thoracic kyphosis and worse baseline cervical alignment. Similarly, Koller *et al*[13] cited baseline alignment as the strongest risk factor for DJK because patients with worse baseline alignment tended to have residual deformities postoperatively. While results from these studies can help surgeons risk-stratify patients, it is critical for surgeons to also have a means by which they can actively decrease a patient's risk of developing DJK.

Previous studies have proposed targets for postoperative cervical alignment; however, these targets were based on parameters measured from standing radiographs.[12] In the present study, we assessed intraoperative correction using C2–LIV tilt, which is a measure of alignment within the fusion construct. Unlike alignment measures, such as cSVA and T1S, C2–LIV tilt does not require a reference frame and can therefore be measured using images obtained intraoperatively. Although we used postoperative C2–LIV tilt as a surrogate for intraoperative alignment, it is a measure of alignment within the fusion construct and not affected by the development of postoperative DJK.

During our study's follow-up period, 35% of the patients developed DJK > 10°, which is consistent with prior studies that reported rates between 24% and 38%.[19,20,24] This study also found that 10.7% of patients met the criteria for sDJK (DJK > 20°), which is similar to the sDJK rate of 9.8% reported by Protopsaltis *et al*.[19] Of the 15 patients who required revision surgery, only five were due to DJK.

Studies have demonstrated that patients who develop proximal junctional kyphosis (PJK) tend to have worse preoperative alignment and undergo significantly greater corrections than patients without PJK.[25,26] Following the introduction of age-specific alignment goals in adult spinal deformity surgery, overcorrection has also been found to be a risk factor for PJK.[27] In cervical deformity surgery, the relationship between correction magnitude and postoperative outcomes is poorly understood.

We initially planned to predict postoperative DJK by using only measurements obtained intraoperatively. However, the results from the conditional inference tree analysis

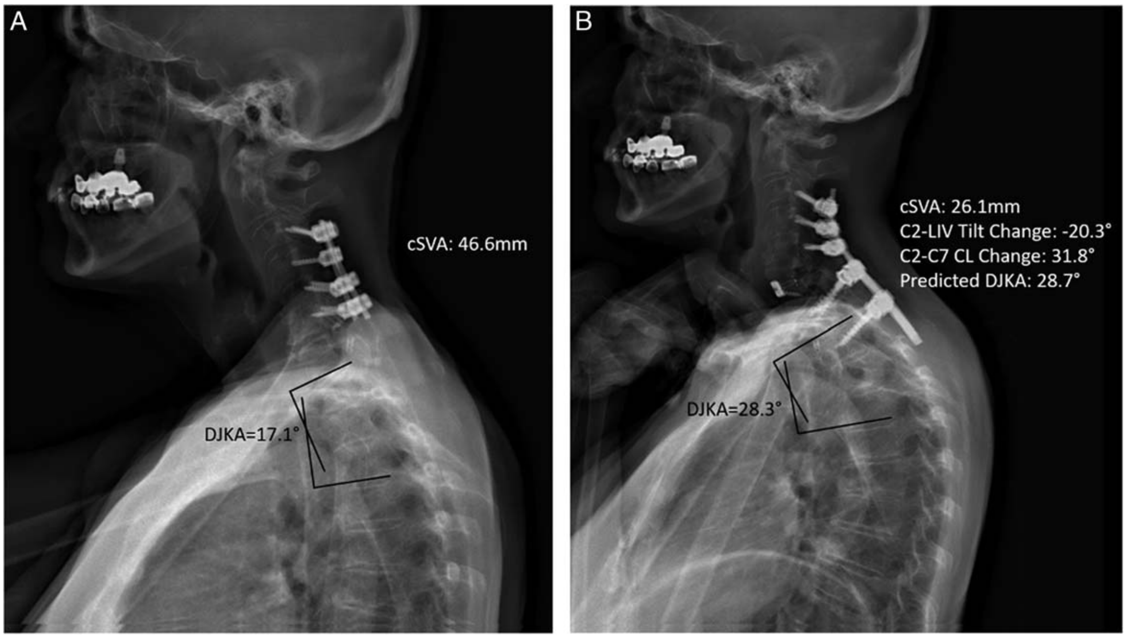

Figure 6. Lateral radiographs of a 71-year-old female preoperatively (A) and three months postoperatively (B). Based on the preoperative DJKA, C2–LIV tilt, and C2–C7 lordosis change, the model predicted a postoperative DJKA = 28.7°. The actual postoperative DJKA was 28.3°. DJKA indicates distal junctional kyphosis angle; LIV, lower instrumented vertebra.

demonstrated that preoperative DJKA was a significant determinant of whether a patient would develop DJK. Therefore, it was essential to include this in our model. This finding underscores the importance of selecting an LIV in the relatively neutral or lordotic region of the spine. The formula proposed in this study shows that postoperative DJKA is associated with a larger preoperative DJKA, worse in-construct alignment postoperatively (larger postoperative C2–LIV tilt), and greater correction of cervical lordosis (↑CL). A case example is shown in Figure 6.

The predicted and actual DJKA values were highly correlated ($r = 0.871$, $r^2_{adj} = 0.759$, $P < 0.001$) in the validation subset. The predicted change in the DJKA was calculated as the difference between the predicted postoperative DJKA and actual preoperative DJKA. Our model was more sensitive for tDJK (sensitivity = 66.7%%, specificity = 56.7%), with a greater NPV than PPV (NPV = 72.3%, PPV = 50.0%). For sDJK, the model was 16.7% sensitive and 94.3% specific, with 89.1% NPV and 2.6% PPV. However, it is important to note that only 13 cases of sDJK have been reported.

Although this is an initial step in the development of a model that can predict incidence of DJK after cervical spine surgery, there are several means on immediate practical application. The most conservative application of the model would be to calculate the predicted DJKA and if high, use this to inform counseling and shared decision making following surgery. Due to the model's high specificity for severe DJK, it has immense utility in its ability to rule out the possibility of this complication. As a surgeon becomes more familiar with the model through increased use, they may also elect to revise the surgical plan, or their envisioned surgical construct, to reduce likelihood of the development of DJK in select patients.

The strengths of this study include its multicenter design, standardized data collection, and the use of random forest plots to identify the variables to be included in our equation for predicting DJKA. Limitations include the retrospective nature of the study, subjecting the data and analysis to the potential for confounding by selection and indication. There may also be issues with the surveillance period and restricted clinical variation in the cohort. Additional prospective studies are required to validate this formula clinically, as well as in the intraoperative setting. Another potential criticism is the relative simplicity of the formula given the complex nature of DJK and several risk factors that have been previously identified. However, we felt that for a formula to be clinically useful, especially intraoperatively, it must not only be accurate but also easy to use.

CONCLUSIONS

Distal junctional kyphosis is a serious but relatively common following complication of surgical correction of cervical deformities. In this study, random forest analysis and linear regression were used to develop a formula that predicts the DJKA following cervical deformity surgery. In order of importance, the variables that increased postoperative DJKA were preoperative DJKA, postoperative in-construct alignment, and the magnitude of cervical lordosis correction. This study is unique in that it not only identifies risk factors for DJK, but also provides a foundation for the development of a tool that can be used to reduce the incidence of DJK.

This remains an initial work that explores factors associated with the development of DJK. Though further investigation and validation in a larger population are necessary, we believe there is the prospect for immediate application for our formula in a clinical context.

➢ Key Points

- ❑ Mean postoperative DJKA was 14.6 ± 14°. DJK occurred in 35% of patients, while sDJK occurred in 11%.
- ❑ Using preoperative and postoperative measurements, surgeons can reliably predict the magnitude of DJK after correction.
- ❑ Our model identified the following equation as predictive of DJKA: DJKA = 9.365+(0.123×ΔCL) −(0.315×ΔC2–LIV)−(0.054×DJKApre), (R = 0.871, R^2 = 0.759, P < 0.001).
- ❑ Variables that most increased the DJKA were: preoperative DJKA, postoperative alignment within the construct, and change in cervical lordosis.
- ❑ The model was more sensitive for tDJK (sensitivity = 66.7%%, specificity = 56.7%, NPV = 72.3%, PPV = 50%). For sDJK, the model was 16.7% sensitive and 94.3% specific, with 89.1% NPV and 2.6% PPV.

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