Original Article

Predictive model for achieving good clinical and radiographic outcomes at one-year following surgical correction of adult cervical deformity

ABSTRACT

Background: For cervical deformity (CD) surgery, goals include realignment, improved patient quality of life, and improved clinical outcomes. There is limited research identifying patients most likely to achieve all three.

Objective: The objective is to create a model predicting good 1-year postoperative realignment, quality of life, and clinical outcomes following CD surgery using baseline demographic, clinical, and radiographic factors.

Methods: Retrospective review of a multicenter CD database. CD patients were defined as having one of the following radiographic criteria: Cervical sagittal vertical axis (cSVA) >4 cm, cervical kyphosis/scoliosis >10° or chin-brow vertical angle >25°. The outcome assessed was whether a patient achieved both a good radiographic and clinical outcome. The primary analysis was stepwise regression models which generated a dataset-specific prediction model for achieving a good radiographic and clinical outcome. Model internal validation was achieved by bootstrapping and calculating the area under the curve (AUC) of the final model with 95% confidence intervals.

Results: Seventy-three CD patients were included (61.8 years, 58.9% F). The final model predicting the achievement of a good overall outcome (radiographic and clinical) yielded an AUC of 73.5% and included the following baseline demographic, clinical, and radiographic factors: mild-moderate myelopathy (Modified Japanese Orthopedic Association >12), no pedicle subtraction osteotomy, no prior cervical spine surgery, posterior lowest instrumented vertebra (LIV) at T1 or above, thoracic kyphosis >33° , T1 slope <16 and cSVA <20 mm.

Conclusions: Achievement of a positive outcome in radiographic and clinical outcomes following surgical correction of CD can be predicted with high accuracy using a combination of demographic, clinical, radiographic, and surgical factors, with the top factors being baseline cSVA <20 mm, no prior cervical surgery, and posterior LIV at T1 or above.

Keywords: Cervical deformity, clinical outcomes, predictive modeling, radiographic alignment, surgical correction

Peter Gust Passias, Samantha R. Horn, Cheongeun Oh, Gregory W. Poorman, Cole Bortz, Frank Segreto, Renaud Lafage[1], Bassel Diebo[2], Justin K. Scheer[3], Justin S. Smith[4], Christopher I. Shaffrey[5], Robert Eastlack[6], Daniel M. Sciubba[7], Themistocles Protopsaltis, Han Jo Kim[1], Robert A. Hart[8], Virginie Lafage[1], Christopher P. Ames[3], International Spine Study Group

Department of Orthopaedic and Neurologic Surgery, NYU Langone Medical Center, New York Spine Institute, [1]Department of Orthopaedic Surgery, Hospital for Special Surgery, New York, [2]Department of Orthopaedic Surgery, SUNY Downstate Medical Center, Brooklyn, NY, [3]Department of Neurological Surgery, University of California, San Francisco, San Francisco, CA, [4]Department of Neurosurgery, University of Virginia Medical Center, Charlottesville, VA, [5]Department of Neurosurgery, Duke University Medical Center, Durham, NC, [7]Department of Neurosurgery, Johns Hopkins Medical Center, Baltimore, MD, [6]Department of Orthopaedic Surgery, Scripps Clinic, La Jolla, CA, [8]Department of Orthopaedic Surgery, Swedish Medical Center, Seattle, WA, USA

Address for correspondence: Dr. Peter Gust Passias, Departments of Orthopaedic and Neurologic Surgery, New York Spine Institute, NYU Langone Medical Center – NYU Langone Orthopedic Hospital, 301 East 17th Street, New York, NY, 10003, USA.
E-mail: peter.passias@nyumc.org

Submitted: 23-Mar-21 **Accepted:** 28-Jul-21
Published: 08-Sep-21

How to cite this article: Passias PG, Horn SR, Oh C, Poorman GW, Bortz C, Segreto F, *et al*. Predictive model for achieving good clinical and radiographic outcomes at one-year following surgical correction of adult cervical deformity. J Craniovert Jun Spine 2021;12:228-35.

Access this article online	
	Quick Response Code
Website: www.jcvjs.com	
DOI: 10.4103/jcvjs.jcvjs_40_21	

INTRODUCTION

Cervical deformity (CD) encompasses a complex group of disorders with a wide range of etiologies, including inflammatory arthroplasty, spondylosis, trauma, and others.[1] Although uncommon, CD can be debilitating and can result in severe disability and pain related to progressive neurologic impairment. Unlike for thoracolumbar deformities, there is less consensus and granularity for CD in regards to optimal treatment approaches, managements, and outcome assessments.[2-5] With recent advances in CD correction techniques and improvements in understanding of regional sagittal alignment in the cervical spine with respect to global alignment, a new classification system of CD was developed by Ames-ISSG *et al*. to characterize the apex of the deformity as well as incorporate radiographic and outcome modifiers.[3] This classification system characterized CD patients based on the apex of the deformity, as well as the severity of modifiers: Cervical sagittal vertical axis (cSVA), horizontal gaze, TS-CL, myelopathy (mJOA score), and SRS-Schwab modifiers.

Progressive cervical kyphosis leads to spinal cord compression and resulting neurologic impairment. As the spinal cord becomes tethered and bends around the kyphotic regions of the spine, it causes increased intramedullary pressure and neuronal loss and potential demyelination of the spinal cord.[6] When the spinal cord experiences increased elongation because of dynamic motion including flexion of the spine and increased stretching because of the deformity, the strain is heightened and can lead to myelopathy.[6-9] CD surgical correction has led to improvements in radiographic alignment and patient reported outcome metrics for pain, disability and neurologic and myelopathy improvement.[3,10]

The use of predictive analytics in spine surgery outcomes allows surgeons to identify patient-specific predictors of the outcome of interest. As both surgeons and their patients are invested and interested in positive outcomes following surgery, isolating relevant factors that are predictive of a good outcome are of utmost importance. Recently, one study developed a statistical model to predict poor postoperative surgical outcomes following thoracolumbar deformity corrective surgery.[11] This model included radiographic and surgical predictors of a poor outcome, but did not incorporate patient-reported outcome metrics in the model. Improvements in functional outcomes following CD surgery are understudied in the literature. With a recent definition of the minimum clinically important difference (MCID) for the mJOA in a cervical spondylotic myelopathy population,[12] clinical assessments of patient-reported outcomes using mJOA improvements can be used in conjunction with the assessments of radiographic alignment improvements.

The aim of this study was to develop a predictive model of good radiographic and clinical outcomes following CD corrective surgery. Identifying factors that are predictive of a good outcome can aid in preoperative counseling and decision-making.

METHODS

Data source

This study is a retrospective review of a prospectively-collected database of CD patients enrolled from 13 sites within the United States. Internal Review Board approval was obtained at each participating site prior to study initiation and informed consent was given by each included patient. Inclusion criteria for the database were patients ages ≥18 years, and radiographic evidence of CD at baseline assessment, defined as the presence of at least 1 of the following: cervical kyphosis (C2–C7 Cobb angle >10°), cervical scoliosis (C2–C7 coronal Cobb angle >10°), C2–C7 sagittal vertical axis (cSVA) >4 cm, or chin-brow vertical angle (CBVA) >25°. Patients with active tumors or infections were excluded from the study.

Data collection

Demographic and clinical data collected included patient age, sex, body mass index (BMI), prior cervical surgery, and Charlson comorbidity index (CCI). Surgical data collected included operative time, estimated blood loss, surgical approach, off-label use of bone morphogenetic protein 2, osteotomy use and number of osteotomies, levels fused, and instrumentation used.

Patients were evaluated using full-length free-standing lateral spine radiographs (36” long-cassette) at baseline and 1 year postoperative follow-up visit. Radiographs were analyzed using dedicated and validated software (SpineView®; ENSAM, Laboratory of Biomechanics, Paris, France) at a single center with standard techniques.[13-15] Measured cervical spine parameters included cSVA (offset from the C2 plumbline and the posterosuperior corner of C7), C2–C7 lordosis (CL: Cobb angle between C2 inferior endplate and C7 inferior endplate), T1 slope minus CL (TS-CL: mismatch between T1 slope and cervical lordosis), and CBVA (angle subtended between the vertical line and the line from the brow to the chin). Measured spinopelvic parameters [Figure 1] included: sagittal vertical axis (SVA: C7 plumb line relative to the posterior-superior corner of S1), pelvic incidence minus lumbar lordosis (PI-LL: mismatch between pelvic incidence and lumbar lordosis), and pelvic tilt (PT: angle between the vertical and the line through the sacral midpoint to the center of the two femoral heads).

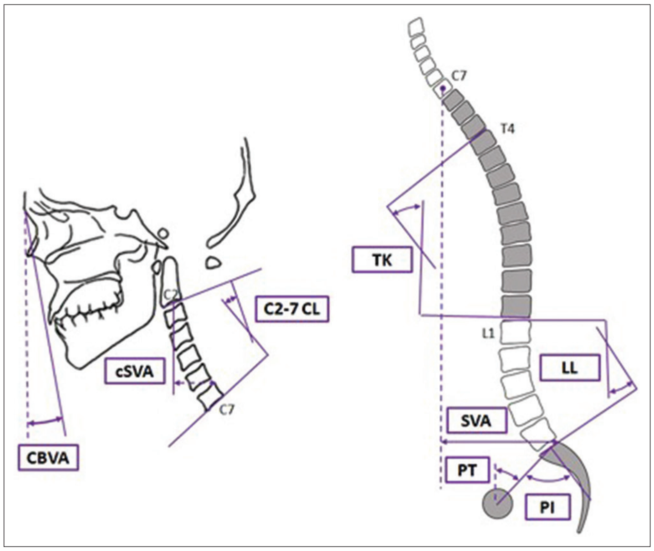

Figure 1: Schematic of the measured sagittal alignment parameters for the cervical (left) and global spinopelvic (right) spinal regions. cSVA - Cervical sagittal vertical axis, C2–C7 CL - Cervical lordosis, CBVA - Chin-brow vertical angle, TK - Thoracic kyphosis, LL - Lumbar lordosis, SVA - Sagittal vertical axis, PT - Pelvic tilt, PI - Pelvic incidence

Achievement of "Good" radiographic and clinical outcomes

Patients were evaluated using the Ames-CD classification system's radiographic modifiers (cSVA, CBVA, TS-CL, and SVA from the Schwab classification system).[3] Alignment modifiers are graded from 0 (normal) to 2 (markedly abnormal/severe). A good radiographic outcome was achieved if patients did not have any "severe" Ames modifier grades at 1-year. We also assessed patients' radiographic outcomes on the basis of having at least two non-"severe" radiographic Ames modifiers at 1-year. A positive improvement in patient-reported health-related quality of life outcome was achieved if (1) a patient improved in modified Japanese Orthopedic Association (mJOA) score or (2) a patient reached the MCID for the mJOA questionnaire at 1-year postoperative. The favorable outcome for the modeling was assessed by whether a patient achieved both a good radiographic and clinical outcome.

Statistical analysis

The characteristics of subjects including demographics were first summarized using descriptive statistics in mean ± standard deviation for continuous variables or % (counts) for categorical variables. In investigating an association of predictors with outcomes, the prediction model was fitted using a non-linear mixed model featuring a logistic model in which the subject was considered as a random factor to account for more than one outcome for the same patient. We first evaluated the association of the outcome with variables in a univariate manner. Then, all variables were evaluated in one multivariate model to control for confounding effects. All variables with $P < 0.05$ for the bivariate association with outcome were considered for initial inclusion in the multivariate model, but only those which remained significant to $P < 0.05$ were retained in the final model. To establish a final prediction model, a series of prediction models were built by sequentially adding predictors from the ranked list and a final model was chosen based on the model with the lowest Akaike information criterion. Internal validation of the prediction model was performed by calculating area under the curve (AUC) of the corresponding final prediction model by drawing the receiver operating characteristic. This process was repeated 1000 times and each time a resample of the validation data was used, and in this way, the distribution of the AUCs was obtained. The mean and 95% CI of the AUC was then estimated. Results are reported as coefficient with odds ratios with 95% confidence intervals. Two-sided $P < 0.05$ was considered statistically significant. All analyses were carried out using SPSS software (version 21.0, IBM, Armonk, New York). R statistical software package (R, version 2.12.2, R Development Core Team). Unless otherwise noted, analyses used mixed-effects models (package lme4: Bates, Maechler and Bolker 2011) in R 2.14.2 (R Development Core Team 2012).

RESULTS

Patient demographics

Seventy-three CD patients were included in the study. The most common diagnoses for these patients were degenerative kyphosis, iatrogenic kyphosis, and cervical stenosis. Demographic details are available in Table 1.

Surgical details

The average levels fused was 7.57 levels, with an estimated blood loss of 891 cc and average operative time of 361 min [Table 1]. The breakdown of surgical approaches was as follows: 17.8% anterior-only, 47.9% posterior-only, and 34.3% combined approach.

Preoperative and 1-year postoperative radiographic alignment

At baseline, the average cSVA was 46.2 mm, TS-CL was 36.7°, thoracic kyphosis was 40.2°, global SVA was 8.28 mm, and PI-LL was 1.33° [Table 2]. Broken down by Ames modifiers, 4.1% of patients had a cSVA modifier Grade 2 ("severe"), 27.1% had a severe horizontal gaze modifier, 83.6% had a severe TS-CL modifier, and 8.3% had a global SVA modifier [Table 3].

From baseline to 1-year postoperative, patients improved in all cervical parameters including, TS-CL, cervical lordosis, cSVA, C2–T3 angle, C2 slope, with the exception of C2–T3 SVA [Table 2].

Health-related quality of life scores

At baseline, the average Neck Disability Index score was 48.6

Table 1: Demographics and surgical details for cervical deformity patients

Demographic variable	Frequency or mean
Age (years)	61.81±10.67
BMI (kg/m^2)	29.47±8.13
CCI	0.63±0.936
Gender (female) (%)	43 (58.9)
Prior cervical surgery (%)	27 (38.0)
History of smoking (%)	20 (29.0)
Ambulatory status (percentage walking without any aid)	56 (76.7)
Diabetes (%)	12 (16.4)
Osteoporosis (%)	8 (11.0)
Surgical variables	
Levels fused	7.57±3.62
Estimated blood loss (cc)	891.59±915.78
Operative time (min)	361.29±233.05
BMP-2 use (%)	28 (38.9)
Surgical approach (%)	
Anterior only	13 (17.8)
Posterior only	35 (47.9)
Combined	25 (34.3)
Posterior LIV	T4
Osteotomy use (%)	
Partial facet	3 (5.0)
Complete facet	1 (1.7)
Smith-peterson osteotomy	14 (19.2)
Opening wedge	1 (3.8)
Closing wedge	12 (16.4)
Vertebral column resection	3 (4.1)
Transition rods (%)	18 (24.7)

BMI - Body mass index; CCI - Charlson comorbidity index; BMP-2 - Bone morphogenetic protein 2; LIV - Lowest instrumented vertebra

Table 2: Baseline and 1-year postoperative radiographic measurements

Radiographic parameter	Baseline	Postoperative	*P*
PT (°)	19.39±11.06	18.21±10.32	0.118
PI-LL (°)	1.33±16.29	1.31±15.33	0.987
C7-S1 SVA (mm)	8.28±75.34	26.33±63.9	0.002*
C2–S1 SVA (mm)	48.98±82.37	64.01±72.93	0.022*
T4-T12 TK (°)	−40.21±16.39	−44.17±15.59	0.001*
T1PA (°)	13.87±11.65	14.68±10.26	0.199
CTPA (°)	4.83±2.7	4.38±1.87	0.024*
T1 slope (°)	31.77±17.48	37.17±14.23	<0.001*
TS-CL (°)	36.74±19.36	27.42±13.18	<0.001*
C2-C7 CL (°)	−6.32±21.35	8.28±16.14	<0.001*
C2-C7 SVA (mm)	46.21±23.91	41.34±16.51	0.018*
C2-T3 (°)	−16.03±20.4	0.07±16.43	<0.001*
C2-T3 SVA (mm)	78.82±39.45	77.73±27.17	0.663
C2 slope (°)	38.71±19.62	28.36±13.47	<0.001*
C1 slope (°)	1.92±18.21	−7.09±13.42	<0.001*
C0 slope (°)	−1.27±14.37	−7.23±9.88	0.002*
C0-C2 angle (°)	33.49±12.05	28.34±11.12	0.001*

*C7-S1 SVA (mm) 8.28±75.34 26.33±63.9 0.002. PT - Pelvic tilt; PI-LL - Pelvic incidence minus lumbar lordosis; SVA - Sagittal vertical axis; TK - Thoracic kyphosis; T1PA - T1 pelvic angle; CTPA - Cervical-thoracic pelvic angle; TS-CL - T1 slope minus cervical lordosis

out of 100, EQ-5D was 0.73, and mJOA was 13.6 [Table 4]. Using the Ames mJOA modifier grade, 10.6% of patients had no myelopathy (mJOA score of 18), 27.3% of patients had mild myelopathy (mJOA score 15–17), 40.9% of patients had moderate myelopathy (mJOA score 12–14), and 21.2% had severe myelopathy. 35.6% of patients improved in mJOA, with 20.5% of patients reaching mJOA MCID.

Predicting a good clinical and radiographic outcome

The following baseline demographic, clinical, and radiographic factors were included in initial models predicting a good overall outcome following CD surgery: gender, CCI, osteoporosis, Ames type driver, prior history of cervical spine surgery, pedicle subtraction osteotomy (PSO) osteotomy use, baseline mJOA score, baseline cSVA, T2–T12 kyphosis, T1 slope, C2 slope, maximum kyphosis value, T1SPi, C2SPi, baseline neurologic weakness, and presence of neurologic symptoms. In using a liberal definition of a good clinical and radiographic outcome, the highest AUC achieved was 0.848, however this model did not contain clinically relevant predictors. We sought to use more stringent definitions of a good overall outcome in combination with more clinically relevant parameters [Table 5]. The best overall outcome was predicted using Model 1 (no severe Ames radiographic modifiers and reaching 1Y MCID for mJOA). Model 2 was a slight variation on this first model that still required a patient to not have any severe radiographic alignment parameters but the clinical definition of a good outcome was loosened slightly so that a patient had to improve in mJOA from pre- to postoperative but did not necessarily need to meet MCID. Model 3 had a strict definition of the clinical outcome (must meet mJOA MCID) but a slightly more relaxed radiographic outcome and Model 4 had the most liberal definitions of the final models chosen, with patients still having one severe radiographic parameter and only improving but not reaching MCID for mJOA.

All four models had lack of PSO use and no prior cervical spine surgery as predictors of a good overall outcome. For both models that required patients to not have any severe radiographic parameters (Models 1 and 2), a mean baseline mJOA score >12, baseline T2-T12 thoracic kyphosis >32.6°, and baseline cSVA <20.2 mm predicted a good overall outcome. Both models where patients still had one severe radiographic parameter (Models 3 and 4) had the same T2-T12 thoracic kyphosis cutoffs and similar mJOA score cutoffs (>15 for Model 3 and >16 for Model 4). All models except Model 2 had a posterior lowest instrumented vertebra (LIV) at T1 or above as a significant predictor of a good outcome, whereas for Model 2 the cutoff was T2 or above for a good outcome. The cutoff for cSVA being predictive of a good

Table 3: Distribution of ames and schwab modifier grades at baseline and 1-year postoperatively as well as the percentage of patients without a severe modifier grade at 1-year

Modifier grade	Baseline (%)	1-year postoperative (%)	Nonsevere modifier grade at 1-year (%)
cSVA			
0	34.2	35.2	98.6
1	61.6	63.4	
2	4.1	1.4	
Horizontal gaze			
0	32.2	26.1	76.9
1	40.7	50.8	
2	27.1	23.1	
TS-CL			
0	9.6	15.5	28.2
1	6.8	12.7	
2	83.6	71.8	
mJOA			
0	10.6	15.9	81
1	27.3	28.6	
2	40.9	36.5	
3	21.2	19.0	
Global SVA			
0	65.3	63.9	86.1
1	26.4	22.2	
2	8.3	13.9	

SVA - Sagittal vertical axis; mJOA - Modified Japanese Orthopedic Association; TS-CL - T1 slope minus cervical lordosis; cSVA - C2-C7 sagittal vertical axis

Table 4: Pre- and post-operative values for health-related quality of life metrics assessed

	Baseline	1-year postoperative	*P*	Percentage improved (%)	Percentage met MCID (%)
mJOA	13.63±2.55	13.98±2.88	0.282	26 (35.6)	15 (20.5)
NDI	48.58±17.30	36.97±19.85	<0.001*	57 (78.1)	29 (39.7)
EQ-5D	0.73±0.06	0.78±0.07	<0.001*	45 (61.6)	13 (17.8)

These include the mJOA, NDI and EQ-5D questionnaires. The percentage of patients who improved from baseline to 1-year postoperative and the percentage of patients who reached the MCID for each metric were also reported. NDI - Neck disability index; EQ-5D - Euro-qol five dimensions; MCID - Minimum clinically important difference; mJOA - Modified Japanese Orthopedic Association

outcome was the same for Models 1, 2, and 4 (<20.2 mm) and for Model 3 it was 23.9 mm.

Case examples

Figure 2 presents a case of a 53-year-old female patient with a BMI of 21.9 kg/m^2 who underwent CD surgery from C2–T2 with no pedicle subtraction osteotomy performed. At baseline, cSVA was 27.7 mm, TS-CL was 30.5°, and horizontal gaze was 3.3°. 1-year postoperatively, cSVA was 20.2 mm, TS-CL was 20.4°, and horizontal gaze was 3.4°. This patient had a baseline mJOA score of 12 and postoperative score of 15, thus meeting 1-year MCID for mJOA. This patient achieved a good overall outcome as defined by the most strict definition of Model 1.

Figure 3 presents a case of a 52-year-old female patient with a BMI of 24.3 kg/m^2 who underwent CD surgery from C2 to T2 with no pedicle subtraction osteotomy performed. At baseline, cSVA was 2.7 mm, TS-CL was 15.6°, and horizontal gaze was 2.9°. One-year postoperatively, cSVA was 18.9 mm, TS-CL was 31.3°, and horizontal gaze was 8.9°. This patient had a baseline mJOA score of 12 and postoperative score of 13, thus slightly improving in mJOA but not reaching MCID. This patient achieved a good overall outcome as defined by the more loosely defined definition of Model 4.

DISCUSSION

As the field of CD corrective surgery continues to progress, the importance of being able to identify patient factors that are predictive of a good outcome in terms of radiographic alignment and clinical improvements is heightened. In this study, we created four predictive models with variations in the definition of a good clinical and radiographic outcome that used baseline clinical, demographic, and surgical factors to predict this good overall outcome.

As both surgeons and their patients are invested and interested in positive outcomes following surgery, isolating relevant factors that are predictive of a good outcome are

Table 5: Description of the four Models utilized to assess postoperative outcomes

Significant predictor	OR (LCI-UCI)/*P*			
	Model 1 No severe radiographic modifiers and met mJOA MCID	Model 2 No severe radiographic modifiers and improved in mJOA	Model 3 At least two nonsevere radiographic modifiers and met mJOA MCID	Model 4 At least two nonsevere radiographic modifiers and improved in mJOA
(a) Significant predictors of the final outcome for all four final models included in the analysis				
1. PSO use	0.372 (0.073-1.906)/0.236	0.555 (0.170-1.817)/0.331	1.066 (0.442-2.566)/0.887	1.107 (0.460-2.663)/0.821
2. Baseline mJOA score	0.870 (0.718-1.054)/0.155	0.883 (0.758-1.029)/0.111	1.004 (0.884-1.141)/0.948	0.985 (0.867-1.120)/0.819
3. Posterior LIV	0.924 (0.778-1.096)/0.363	0.982 (0.868-1.112)/0.779	1.042 (0.946-1.149)/0.405	1.063 (0.962-1.174)/0.229
4. Prior history of cervical spine surgery	0.480 (0.145-1.583)/0.228	0.711 (0.295-1.715)/0.448	0.864 (0.435-1.716)/0.676	0.956 (0.485-1.882)/0.895
5. Baseline T2-T12 kyphosis	1.047 (1.017-1.078)/0.002	1.028 (1.005-1.051)/0.015	1.020 (1.002-1.039)/0.029	1.017 (1.000-1.035)/0.054
6. Baseline T1 slope	0.953 (0.921-0.986)/0.005	0.970 (0.946-0.995)/0.017	0.972 (0.952-0.992)/0.007	0.975 (0.955-0.994)/0.012
7. Baseline cSVA	0.958 (0.933-0.983)/0.001	0.974 (0.954-0.996)/0.018	0.977 (0.958-0.995)/0.014	0.981 (0.963-1.000)/0.047
AUC with 95% CI by bootstrapping	0.735 (0.4987-0.7649)	0.706 (0.4982-0.7516)	0.678 (0.4652-0.7254)	0.694 (0.5106-0.7463)
Cutoffs for all variables	**Model 1 No severe radiographic modifiers and met mJOA MCID**	**Model 2 No severe radiographic modifiers and improved in mJOA**	**Model 3 At least two nonsevere radiographic modifiers and met mJOA MCID**	**Model 4 At least two nonsevere radiographic modifiers and improved in mJOA**
(b) Cutoff values at which each variable is a significant predictor of the outcome predicted by each of the four models				
1. PSO use	No	No	No	No
2. Baseline mJOA score	>12	>12	>15	>16
3. Posterior LIV	T1 or above	T2 or above	T1 or above	T1 or above
4. Prior history of cervical spine surgery	No	No	No	No
5. Baseline T2-T12 kyphosis (°)	>32.6	>32.6	>33.1	>33.1
6. Baseline T1 slope (°)	<16.0	<21.3	<22.2	<20.2
7. Baseline cSVA (mm)	<20.2	<20.2	<23.9	<20.2

MCID - Minimum clinically important difference; mJOA - Modified Japanese Orthopedic Association; LIV - Lowest instrumented vertebra; cSVA - C2-C7 sagittal vertical axis; CI - Confidence interval; LCI - Lower confidence interval; UPI - Upper confidence interval, PSO - : Pedicle subtraction osteotomy

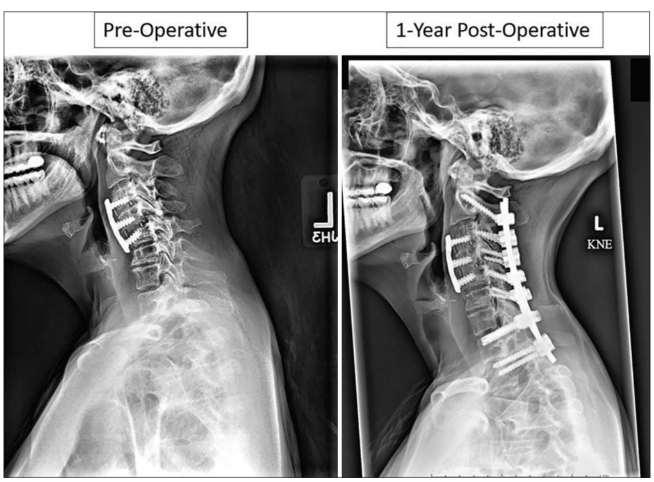

Figure 2: Lateral cervical radiographs of pre- and 1-year postoperative for a case example of a cervical deformity patient who achieved a good overall outcome as defined by Model 1. This patient is a 53-year-old female with a body mass index of 21.9 kg/m² who underwent cervical deformity corrective surgery from C2 to T2 with no pedicle subtraction osteotomy performed. At baseline, cSVA was 27.7 mm, TS-CL was 30.5°, and horizontal gaze was 3.3°. 1-year postoperatively, cSVA was 20.2 mm, TS-CL was 20.4°, and horizontal gaze was 3.4°. This patient had a baseline mJOA score of 12 and postoperative score of 15, thus meeting 1-year minimum clinically important difference for mJOA. cSVA - Cervical sagittal vertical axis

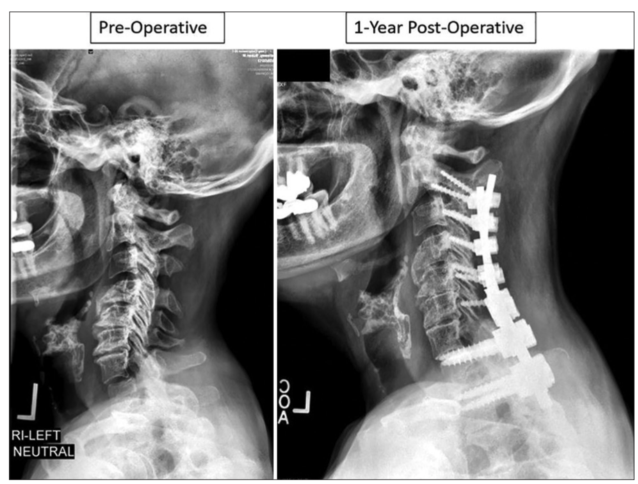

Figure 3: Lateral cervical radiographs of pre- and 1-year postoperative for a case example of a patient who achieved a good overall outcome as defined by Model 4. This patient is a 52-year-old female with a body mass index of 24.3 kg/m² who underwent cervical deformity corrective surgery from C2 to T2 with no pedicle subtraction osteotomy performed. At baseline, cSVA was 2.7 mm, TS-CL was 15.6°, and horizontal gaze was 2.9°. 1-year postoperatively, cSVA was 18.9 mm, TS-CL was 31.3°, and horizontal gaze was 8.9°. This patient had a baseline mJOA score of 12 and postoperative score of 13, thus slightly improving in mJOA but not reaching minimum clinically important difference. cSVA - Cervical sagittal vertical axis

of utmost importance. Predictive analytics in spine surgery outcomes allows surgeons to identify patient-specific predictors of the outcome of interest. Recent work has looked at predicting outcomes in spine surgery and specifically for adult spinal deformity.[11,16] Traditional statistics are hypothesis driven and sometimes-needed assumptions often do not make the findings generalizable. By using predictive analytics to aid in clinically-relevant decision making, patient-specific pre-operative and surgical factors can be used to assess outcomes following CD surgery. Since neither clinical nor radiographic outcomes correlate strongly with outcomes following CD surgery, we sought to incorporate both factors into one predictive model in an attempt to predict the strongest and most reliable outcome possible.[17,18]

The fact that we were unable to achieve an AUC greater than 85% even when utilizing a liberal definition of a good outcome and incorporating factors that were not as clinically relevant speaks to the fact that radiographic and clinical outcomes do not display a linear relationship and that a much more complex interaction of these factors is at play. Previous studies of CD patients mirror this concept, with low correlations seen between radiographic and clinical outcomes.[18] Previous reports have shown that baseline mJOA score is predictive of postoperative outcomes in cervical spondylotic myelopathy patients, and similar results have also been shown in a recent study looking at predicting outcomes after CD surgery.[11,19] Few studies have reported the relationship between radiographic parameters in the cervical spine and health-related quality of life metrics.[20,21] One study reported no significant relationship between segmental kyphosis and clinical outcomes and another found that overall cervical alignment did not correlate with outcomes despite correlated segmental changes.[21,22] This speaks to the fact that varied combinations of clinical and radiographic good outcomes needs to be used to assess CD patients.

We sought to use more stringent definitions of a good overall outcome in combination with more clinically relevant parameters to assess these CD patients. As previously noted, radiographic and clinical outcomes following CD surgery are not linearly correlated and thus we aimed to test variations on a good outcome to find the best fit for this population.[18] The MCID for mJOA in a CD-specific population has yet to be developed, but related literature for other cervical spine pathologies were used in this study, given that many deformity patients in this study also presented with cervical myelopathy.[23] The best overall outcome was Model 1, where a patient had no severe radiographic modifiers at 1-year and reached MCID for mJOA and milder baseline deformity and more severe myelopathy predicted this good outcome. When we combine these outcomes into one model, where we are predicting both a good radiographic and clinical outcome, we found that milder baseline deformity and severe myelopathy treated with fusions not extending beyond T1 or T2 were predictive of the best overall outcome.

The variability of cutoff values for predictability of the seven factors included in each of the four final predictive models is of interest. The fact that a posterior LIV cutoff of T1 or above for three of the four models suggests that shorter constructs that do not extend far into the thoracolumbar spine are predictive of good overall outcomes. This can be explained in part by the fact that a shorter construct is most likely being performed on a less severe CD and thus the achievement of a good radiographic outcome is more attainable. The variation in baseline mJOA scores that were predictive of a good overall outcome suggest a relationship between radiographic and clinical outcomes, since patients in the first two models (with more strict requirements for radiographic alignment) allowed for a lower threshold at which mJOA was predictive of a good outcome (score >12), whereas for patients who could still have one severe radiographic parameter postoperatively, patients needed to have a higher mJOA score to achieve a good outcome.

Limitations

We appreciate several limitations. First, the retrospective nature of this study might contribute to surgeon and site variation and bias. The limited follow-up and relatively low sample size of this cohort limits our findings, though sets a framework for future studies that can incorporate a larger cohort of patients followed for a longer period. Metrics for assessing CD are subject to ceiling effects and are for the most part not deformity-specific or even cervical specific. In particular, the MCID used in this analysis, while previously published for a cervical population, is not strictly deformity-specific. The lack of consensus of a good outcome following CD corrective surgery means that the definitions of a good outcome defined here many not be applicable to all CD patients outside of this cohort.

CONCLUSIONS

Achievement of a positive outcome in radiographic and clinical outcomes following surgical correction of CD can be predicted with high accuracy using a combination of demographic, clinical, radiographic, and surgical factors, with the top factors being baseline cSVA <20 mm, no prior cervical surgery, and posterior LIV at T1 or above. With the combination of factors, we found that milder CD also presenting with more severe baseline myelopathy is the most ideal combination to predict a good outcome. Further study is needed however to identify predictors of a good overall outcome in a more severely deformed population. Preoperative assessment of patients' overall characteristics can help counsel patients and increase the chance of the patient improving in radiographic and clinical factors and achieving a good outcome after surgery.

Financial support and sponsorship

The International Spine Study Group is funded through research grants from DePuy Synthes and individual donations, and supported the current work.

Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Smith JS, Lafage V, Schwab FJ, Shaffrey CI, Protopsaltis T, Klineberg E, *et al.* Prevalence and type of cervical deformity among 470 adults with thoracolumbar deformity. Spine (Phila Pa 1976) 2014;39:E1001-9.
2. Smith JS, Klineberg E, Shaffrey CI, Lafage V, Schwab FJ, Protopsaltis T, *et al.* Assessment of surgical treatment strategies for moderate to severe cervical spinal deformity reveals marked variation in approaches, osteotomies, and fusion levels. World Neurosurg 2016;91:228-37.
3. Ames CP, Smith JS, Eastlack R, Blaskiewicz DJ, Shaffrey CI, Schwab F, *et al.* Reliability assessment of a novel cervical spine deformity classification system. J Neurosurg Spine 2015;23:673-83.
4. Passias PG, Soroceanu A, Smith J, Boniello A, Yang S, Scheer JK, *et al.* Postoperative cervical deformity in 215 thoracolumbar patients with adult spinal deformity: Prevalence, risk factors, and impact on patient-reported outcome and satisfaction at 2-year follow-up. Spine (Phila Pa 1976) 2015;40:283-91.
5. Fountas KN, Kapsalaki EZ, Nikolakakos LG, Smisson HF, Johnston KW, Grigorian AA, *et al.* Anterior cervical discectomy and fusion associated complications. Spine (Phila Pa 1976) 2007;32:2310-7.
6. Dickson RA. The aetiology of spinal deformities. Lancet 1988;1:1151-5.
7. Uchida K, Nakajima H, Sato R, Yayama T, Mwaka ES, Kobayashi S, *et al.* Cervical spondylotic myelopathy associated with kyphosis or sagittal sigmoid alignment: Outcome after anterior or posterior decompression. J Neurosurg Spine 2009;11:521-8.
8. Albert TJ, Vacarro A. Postlaminectomy kyphosis. Spine (Phila Pa 1976) 1998;23:2738-45.
9. Masini M, Maranhão V. Experimental determination of the effect of progressive sharp-angle spinal deformity on the spinal cord. Eur Spine J 1997;6:89-92.
10. Passias PG, Horn SR, Bortz CA, Ramachandran S, Burton DC, Protopsaltis T, *et al.* The relationship between improvements in myelopathy and sagittal realignment in cervical deformity surgery outcomes. Spine (Phila Pa 1976) 2018;43:1117-24.
11. Passias PG, Oh C, Jalai CM, Worley N, Lafage R, Scheer JK, *et al.* Predictive model for cervical alignment and malalignment following surgical correction of adult spinal deformity. Spine (Phila Pa 1976) 2016;41:E1096-103.
12. Tetreault LA, Côté P, Kopjar B, Arnold P, Fehlings MG, AOSpine North America and International Clinical Trial Research Network. A clinical prediction model to assess surgical outcome in patients with cervical spondylotic myelopathy: Internal and external validations using the prospective multicenter AOSpine North American and international datasets of 743 patients. Spine J 2015;15:388-97.
13. Champain S, Benchikh K, Nogier A, Mazel C, Guise JD, Skalli W. Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. Eur Spine J 2006;15:982-91.
14. Rillardon L, Levassor N, Guigui P, Wodecki P, Cardinne L, Templier A, *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.
15. O'Brien MF, Kuklo TR, Blanke KM, Lenke LG. Spinal Deformity Study Group Radiographic Measurement Manual; 2005. Available from: http://www.oref.org/docs/default-source/default-document-library/sdsg-radiographic-measuremnt-manual.pdf?sfvrsn=2. [Last accessed 2018 Feb 02].
16. Osorio JA, Scheer JK, Ames CP. Predictive modeling of complications. Curr Rev Musculoskelet Med 2016;9:333-7.
17. Passias PG, Oh C, Jalai CM, Poorman GW, Lafage R, Diebo BG, *et al*. Predictive model for patient-reported outcomes scores following cervical spine deformity surgical correction. Spine J 2016;16:S307-8.
18. Passias PG, Lavery J, Horn SR, Oh C, Ramchandran S, Burton DC, *et al*. Evaluating cervical deformity corrective surgery outcomes at one-year using current patient derived and functional measures: Are they adequate? Spine J 2016;17:S242.
19. Nouri A, Tetreault L, Zamorano JJ, Dalzell K, Davis AM, Mikulis D, *et al.* Role of magnetic resonance imaging in predicting surgical outcome in patients with cervical spondylotic myelopathy. Spine (Phila Pa 1976) 2015;40:171-8.
20. Tang JA, Scheer JK, Smith JS, Deviren V, Bess S, Hart RA, *et al.* The impact of standing regional cervical sagittal alignment on outcomes in posterior cervical fusion surgery. Neurosurgery 2015;76 Suppl 1:S14-21.
21. Scheer JK, Tang JA, Smith JS, Acosta FL Jr., Protopsaltis TS, Blondel B, *et al.* Cervical spine alignment, sagittal deformity, and clinical implications: A review. J Neurosurg Spine 2013;19:141-59.
22. Jagannathan J, Shaffrey CI, Oskouian RJ, Dumont AS, Herrold C, Sansur CA, *et al.* Radiographic and clinical outcomes following single-level anterior cervical discectomy and allograft fusion without plate placement or cervical collar. J Neurosurg Spine 2008;8:420-8.
23. Tetreault L, Kopjar B, Côté P, Arnold P, Fehlings MG. A clinical prediction rule for functional outcomes in patients undergoing surgery for degenerative cervical myelopathy: Analysis of an International Prospective Multicenter Data Set of 757 Subjects. J Bone Joint Surg Am 2015;97:2038-46.