Spine

SPINE Volume 46, Number 9, pp 559–566

CERVICAL SPINE

Predictors of Superior Recovery Kinetics in Adult Cervical Deformity Correction

An Analysis Using a Novel Area Under the Curve Methodology

Katherine E. Pierce, BS,[a] Peter G. Passias, MD,[a] Avery E. Brown, BS,[a] Cole A. Bortz, BA,[a] Haddy Alas, MD,[a] Renaud Lafage, MS,[b] Virginie Lafage, PhD,[b] Christopher Ames, MD,[c] Douglas C Burton, MD,[d] Robert Hart, MD,[e] Kojo Hamilton, MD,[f] Jeffrey Gum, MD,[g] Justin Scheer, MD,[c] Alan Daniels, MD,[h] Shay Bess, MD,[i] Alex Soroceanu, MD,[j] Eric Klineberg, MD,[k] Christopher Shaffrey, MD,[l] Breton Line, BS,[i] Frank A. Schwab, MD,[b] and Justin S. Smith, MD, PhD[m], on behalf of the International Spine Study Group (ISSG)[i]

Study Design. Retrospective review of a prospective database.

Objective. The aim of this study was to identify demographic, surgical, and radiographic factors that predict superior recovery kinetics following cervical deformity (CD) corrective surgery.

Summary of Background Data. Analyses of CD corrective surgery use area under the curve (AUC) to assess health-related quality of life (HRQL) metrics throughout recovery.

Methods. Outcome measures were baseline (BL) to 1-year (1Y) health-related quality of life (HRQL) (Neck Disability Index [NDI]). CD criteria were C2-7 Cobb angle >10°, coronal Cobb angle >10°, C2-C7 sagittal vertical axis (cSVA) >4 cm, TS-CL >10°, or chin-brow vertical angle >25°. AUC normalization divided BL and postoperative outcomes by BL. Normalized scores (*y* axis) were plotted against follow-up (*x* axis). AUC was calculated and divided by cumulative follow-up length to determine overall, time-adjusted recovery (Integrated Health State [IHS]). IHS NDI was stratified by quartile, uppermost 25% being ''Superior" Recovery Kinetics (SRK) *versus* ''Normal" Recovery Kinetics (NRK). BL demographic, clinical, and surgical information predicted SRK using generalized linear modeling.

Results. Ninety-eight patients included (62 ± 10 years, 28 ± 6 kg/m^2, 65% females, Charlson Comorbidity Index: 0.95), 6% smokers, 31% smoking history. Surgical approach was: combined (33%), posterior (49%), anterior (18%). Posterior levels fused: 8.7, anterior: 3.6, estimated blood loss: 915.9ccs, operative time: 495 minutes. Ames BL classification: cSVA (53.2% minor deformity, 46.8% moderate), TS-CL (9.8% minor, 4.3% moderate, 85.9% marked), horizontal gaze (27.4% minor, 46.6% moderate, 26% marked). Relative to BL NDI (Mean: 47), normalized NDI decreased at 3 months (0.9 ± 0.5, $P = 0.260$) and 1Y (0.78 ± 0.41, $P < 0.001$). NDI IHS correlated with age ($P = 0.011$), sex ($P = 0.042$), anterior approach ($P = 0.042$), posterior approach ($P = 0.042$). Greater BL pelvic tilt (PT) (SRK: 25.6°, NRK: 17°, $P = 0.002$), pelvic incidence-lumbar lordosis (PI-LL) (SRK: 8.4°, NRK: −2.8°, $P = 0.009$), and anterior approach (SRK: 34.8%, NRK: 13.3%; $P = 0.020$) correlated with SRK. 69.4% met MCID for NDI (<Δ−15) and 63.3% met substantial clinical benefit for NDI (<Δ−10); 100% of SRK met both MCID and substantial clinical benefit. The predictive model for SRK included (AUC = 88.1%): BL visual analog scale (VAS) EuroQol five-dimensional descriptive system (EQ5D) (odds rario [OR] 0.96, 95% confidence interval [CI]: 0.92–0.99), BL swallow sleep score (OR: 1.04, 95% CI: 1.01–1.06), BL PT (OR: 1.12, 95% CI: 1.03–1.22), BL modified Japanese Orthopedic Association scale (mJOA) (OR: 1.5, 95% CI: 1.07–2.16), BL T4-T12, BL T10-L2, BL T12-S1, and BL L1-S1.

From the [a]Departments of Orthopedic and Neurologic Surgery, NYU Langone Orthopedic Hospital; New York Spine Institute, New York, NY; [b]Department of Orthopedics, Hospital for Special Surgery, New York, NY; [c]Department of Neurological Surgery, University of California, San Francisco, San Francisco, CA; [d]Department of Orthopedic Surgery, University of Kansas Medical Center, Kansas City, KS; [e]Department of Orthopedic Surgery, Swedish Neuroscience Institute, Seattle, WA; [f]Department of Neurological Surgery, University of Pittsburgh School of Medicine, Pittsburgh, PA; [g]Norton Leatherman Spine Center, Louisville, KY; [h]Department of Orthopedic Surgery, Warren Alpert School of Medicine, Brown University, Providence, RI; [i]Rocky Mountain Scoliosis and Spine, Denver, CO; [j]Department of Orthopedic Surgery, University of Calgary, Calgary, AB, Canada; [k]Department of Orthopedic Surgery, University of California, Davis, Davis, CA; [l]Departments of Neurosurgery and Orthopedic Surgery, Duke University Medical Center, Durham, NC; and [m]Department of Neurosurgery, University of Virginia, Charlottesville, VA.

Acknowledgment date: April 30, 2020. First revision date: June 30, 2020. Acceptance date: August 6, 2020.

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

The International Spine Study Group (ISSG) is funded through research grants from DePuy Synthes and individual donations.

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

Address correspondence and reprint requests to Peter G. Passias, MD, New York Spine Institute, Division of Spinal Surgery, Departments of Orthopedic and Neurological Surgery, NYU Langone Medical Center, Orthopedic Hospital—NYU School of Medicine, 301 East 17th St, New York, NY 10003; E-mail: Peter.Passias@nyumc.org

DOI: 10.1097/BRS.0000000000003971

Conclusion. Superior recovery kinetics following CD surgery was predicted with high accuracy using BL patient-reported (VAS EQ5D, swallow sleep, mJOA) and radiographic factors (PT, TK, T10-L2, T12-S1, L1-S1). Awareness of these factors can improve decision-making and reduce postoperative neck disability.

Key words: AUC, CD, cervical deformity, recovery kinetics, spine surgery, superior.
Level of Evidence: 3
Spine 2021;46:559–566

Cervical deformity (CD) surgical correction is warranted for patients who present with debilitating disability, neurologic compromise, progressive deformity, and major patient-reported neck pain.[1–3] CD correction is technically demanding and is associated with high complication rates; therefore, preoperative risk assessment and evaluation is critical.[4,5] Previous studies have shown how baseline (BL) radiographic global and cervical alignment parameters, comorbidities and frailty status can influence postoperative outcomes and quality of life.[6,7] As surgeons continually develop a greater understanding of how a candidate may fare postoperatively, the interest to predict patients that recover well after CD surgical correction using BL factors is growing.

Postoperative positive recovery can be exhibited by lack of complications or improved sagittal alignment, but more recently, a successful outcome is greatly defined by patient perspective. Novel analyses of clinical or patient-reported outcomes following CD corrective surgery use an area-under-the-curve (AUC) method to assess health-related quality of life (HRQL) metrics throughout the surgical recovery process.[8,9] This methodology was established by Liu *et al*, allowing for comparison of dissimilar patients across varying follow-up time points.[10] The proposed method normalizes HRQL follow-up scores relative to BL scores, and plot the resulting scores against follow-up time points. An AUC is computed, divided by the total overall follow-up time period, to quantify patient recovery trajectory in one final number.

With this novel methodology, and the emergent concept of predictive analytics, prediction of superior recovery kinetics (SRK), or those who displayed the best patient-reported recovery patterns, in a CD population was investigated. The aim of this study was to predict SRK after CD corrective surgery using predictive modeling incorporating demographic, clinical, and surgical predictive factors.

METHODS

Data Source

This study is a retrospective review of a prospective, multicenter International Spine Study Group (ISSG) database of CD patients enrolled from 2013 to 2018. Patients were enrolled at 13 participating centers around the United States. All patients were enrolled into an Institutional Review Board-approved protocol by each site and informed patient consent was obtained before patient enrollment. The ISSG database inclusion criteria were patients older than 18 years presenting with radiographic evidence of CD. This was defined by the presence of at least one of the following on BL imaging: cervical kyphosis (C2-C7 Cobb angle $>10^\circ$), cervical scoliosis (C2-C7 coronal Cobb angle $<10^\circ$), C2-C7 sagittal vertical axis (cSVA) >40 mm, or chin-brow vertical angle (CBVA) $>25^\circ$. Exclusion criteria from the database included patients with spinal deformity of neuromuscular etiology, presence of active infection or malignancy. Included in the present study were surgical CD patients with available HRQL) data at BL, 3-months (3M) postoperative and 1-year postoperative (1Y).

Data Collection and Radiographic Assessment

Patient demographic and clinical data included patient age, gender, body mass index (BMI), Charlson Comorbidity Index (CCI). Operative and complication data collected included operative time, surgical approach, number of levels fused, and length of hospital stay (LOS). Standardized HRQLs were collected preoperatively and at 3M and 1Y follow-up time points. HRQL questionnaire analyzed was the Neck Disability Index (NDI), but other patient-reported outcome follow-up assessments included EuroQol five-dimensional descriptive system (EQ5D), modified Japanese Orthopedic Association scale (mJOA), and Swallow dysfunction scores.

Full-length free-standing lateral spine radiographs were used to assess included patients at BL and follow-up intervals. Radiographic were analyzed with SpineView (ENSAM, Laboratory of Biomechanics, Paris, France) software according to the literature.[11–13] Cervical radiographic parameters assessed included cervical sagittal vertical axis (cSVA: C2 plumbline offset from the posterosuperior corner of C7), T1 slope minus CL (TS-CL: mismatch between T1 slope and cervical curvature), McGregor slope (McGS: angle between the line from the posterosuperior aspect of the hard palate to the caudal portion of the opisthion and the horizontal). Global parameters investigated included pelvic tilt (PT), T4-T12 angle (thoracic kyphosis [TK]), T10-L2 angle, T12-S1 angle, and L1-S1 angle.

Development of the Normalized Integrated Health State

Normalized HRQLs (NDI) were developed and analyzed allowing for the calculation of an Integrated Health State (IHS) with validated AUC methodology.[8–10,14]

All reported BL and postoperative (3M and 1Y) values for each NDI outcome score were divided by the corresponding BL score for each patient. This developed normalized NDI scores, amounting to values greater than, equal to, or less than 1, depending on the improvement or deterioration (relative to BL) of the patient-reported neck disability. These normalized HRQL scores were plotted on the y-axis against the duration of follow-up on the x-axis (in months, beginning with BL). After all follow-up points were connected, and the change in x and y from one follow-up interval to the next created trapezoidal shapes. Each trapezoidal area was calculated and summed together to create a total follow-up length area. Total area was divided by the cumulative follow-up time (52 weeks for patients with complete 1-year data). A single value, the IHS score, was obtained representing a patient's overall time-adjusted neck disability recovery.

Lower NDI IHS scores indicated a better outcome. IHS NDI scores were stratified by quartile, the uppermost (the quartile of lowest IHS scores) categorized as having "Superior" Recovery Kinetics (SRK), compared to the remaining three-fourths, or "Normal" Recovery Kinetics (NRK).

Statistical Analysis

Statistical analysis was performed using SPSS software (version 21.0 IBM, Armonk, NY) and R-statistical package (www.r-project.org). Descriptive analyses assessed demographic, clinical, surgical, and complication-related data. Frequency analysis evaluated categorical variables with χ^2 analysis determining significant variance of expected *versus* observed values. Comparison of means from BL to 3M and 1Y postoperative follow-up visits utilized paired samples t tests or Wilcoxon rank-sum tests, as appropriate. All analyses were two-sided and the level of significance was set to $P < 0.05$.

BL demographic, clinical, and surgical information was used to predict SRK in the CD cohort using stepwise forward regression modeling with Akaike's Information Criterion (AIC) to select which variables should be included. With each additional variable in the stepwise process, the corresponding AIC was significantly lowered, statistically improving the model. To build the formal prediction model, a traditional "bootstrap" approach was used, combining the use of bootstrap resampling with automated variable selection methods.[15] Modeling the probability of being in the "SRK" outcome, odds ratio (OR) was estimated for each predictor, together with the 95% confidence interval (CI) and P value. Random forest analysis generated 20,000 Conditional Inference Trees to determine cutoff values of the variables included in the formal predictive model, this was accomplished through iteration of multivariate regression equations.

RESULTS

Overall Cohort Patient Characteristics

Ninety-eight CD patients met inclusion criteria, with complete BL, 3M and 1Y follow-up data. Mean patient age was 62 ± 10years, mean BMI of 28 ± 6 kg/m^2, with 65% of the cohort as female. According to the Ames CD classification system at BL, 53.2% were categorized with minor and 46.8% moderate deformity for cSVA, whereas 9.8% of patients were minor, 4.3% moderate, 85.9% marked deformity for TS-CL, and 27.4% minor, 46.6% moderate, 26% marked for horizontal gaze. By approach, these CD patients underwent more posterior-only (49%), compared to anterior (18%) and combined approaches (33%). Average total levels fused was 7.8 (posterior: 8.7; anterior: 3.6). The estimated blood loss (EBL) for the cohort was 915.9 ccs with a total operative time of 495 minutes.

Standard and Normalized HRQL Analysis

When assessing standard NDI scores at BL, 3M, and 1Y, average cohort scores decreased from BL to 1Y (BL: 47, 3M: 41.6, 1Y: 36.4). 69.4% of patients met MCID for NDI, defined as an improvement in >15 points, and 63.3% met substantial clinical benefit for NDI, improvement by >10. HRQL scores were then normalized against the preoperative visit. The normalized postoperative NDI scores showed a decrease in disability at 3M (0.9 ± 0.5, $P = 0.260$) and a further decrease at 1Y postop (0.78 ± 0.41, $P < 0.001$) compared to BL. These normalized NDI scores showed significant patient improvement in neck disability from BL to 1Y overall (<0.001).

Integrated Health State

The average IHS score, from the trapezoidal areas divided by total follow-up, for the cohort was 0.89 ± 0.37. Pearson correlations between overall IHS NDI scores and basic BL demographic and surgical factors demonstrated correlation with age ($P = 0.011$), sex ($P = 0.042$), anterior surgical approach ($P = 0.042$), posterior surgical approach ($P = 0.042$). The IHS NDI scores were stratified by quartile, where the top quarter (SRK: lowest IHS scores) included 23 patients, and the remaining patients (NRK: highest IHS scores) consisted of 75. Mean IHS score for SRK was 0.44 ± 0.11, whereas NRK was 1.03 ± 0.31; $P < 0.001$ (Figure 1).

BL Demographics, Surgical Details, and Complications between NRK and SRK

Age, sex, BMI, race, CCI, and smoking status were similar between the SRK and NRK recovery groups ($P > 0.05$). Comparison of surgical details exhibited that SRK patients underwent significantly more procedures with anterior approach (SRK: 34.8%, NRK: 13.3%; $P = 0.020$) and had a greater EBL (SRK: 1331.4 *vs.* NRK: 734.1 ccs; $P = 0.050$). Complication comparison found no significant differences between the two patient-reported recovery groups ($P > 0.05$) (Table 1).

Sagittal Alignment Parameters Between NRK and SRK

Stratifying the cohort by Ames CD severity at BL, no significant difference was found for cSVA or horizontal gaze modifiers ($P > 0.05$). SRK patients were categorized with the moderate Ames TS-CL modifier significantly more than the NRK recovery group (SRK: 13% *vs.* NRK: 1.4%; $P = 0.013$). In regards to the BL mJOA modifier, SRK patients were categorized significantly more with mild (SRK: 68.2% *vs.* NRK: 25.4; $P < 0.001$) and NRK patients with moderate BL myelopathy severity (SRK: 13.6% *vs.* NRK: 44.8%; $P = 0.016$) (Table 2).

At BL, patients within the SRK recovery group had significantly greater mean PI-LL (SRK: 8.4° *vs.* NRK:

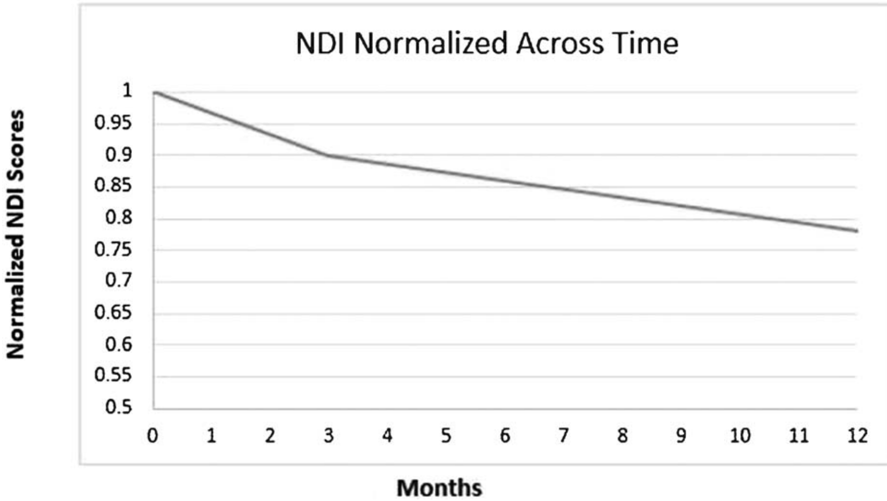

Figure 1. Area Graph representation of normalized HRQL scores for cervical deformity patients up to 1 year.

TABLE 1. Demographics, Surgical Details, and Complications Between SRK and NRK Recovery Groups

	SRK	NRK	*P*
Demographics			
Age, y	60.8	61.9	0.665
Sex (female)	70%	64%	0.600
BMI, kg/m^2	28.8	27.5	0.408
Race			0.729
White	90.5%	91.5%	
Black	4.8%	5.6%	
Other	4.8%	2.8%	
CCI	0.65	1.04	0.236
Smoker (yes)	4%	7%	0.679
Surgical details			
Anterior only approach	34.8%	13.3%	**0.020**
Posterior only approach	34.8%	53.3%	0.122
Combined approach	30.4%	33.3%	0.798
Decompression	43.5%	54.7%	0.353
Osteotomy	43.5%	58.7%	0.204
Total Levels Fused	6.72	8.11	0.147
Operative time, min	531.7	478.9	0.595
EBL, ccs	1331.4	734.1	**0.050**
LOS	4.52	6.24	0.096
Complications			
Any complication	60.9%	65.3%	0.700
Major	21.7%	21.3%	0.967
Minor	26.1%	29.3%	0.766
Operative	5.3%	5.3%	0.990
Cardiopulmonary	5.3%	9.3%	0.575
Infection	10.5%	6.7%	0.572
Radiographic	0%	10.7%	0.140
Dysphagia	10.5%	9.3%	0.876
Dysphonia	0%	2.7%	0.477
Gastrointestinal	0%	4%	0.381
Neurological	26.3%	25.3%	0.931

BMI indicates body mass index; CCI, Charlson Comorbidity Index; EBL, estimated blood loss; LOS, length of hospital stay; NRK, Normal Recovery Kinetics; SRK, Superior Recovery Kinetics.

TABLE 2. Baseline Ames CD Classification Between SRK and NRK Recovery Groups

	SRK	NRK	*P*
BL C2-C7 SVA			0.910
Ames Low Modifier	52.2%	53.5%	0.901
Ames Moderate Modifier	47.8%	46.5%	0.750
Ames High Modifier	—	—	—
BL TS-CL			0.062
Ames Low Modifier	8.7%	10.1%	0.927
Ames Moderate Modifier	13%	1.4%	**0.013**
Ames High Modifier	78.3%	88.4%	0.747
BL Horizontal Gaze			0.280
Ames Low Modifier	16.7%	30.9%	0.321
Ames Moderate Modifier	44.4%	47.3%	0.992
Ames High Modifier	38.9%	21.8%	0.128
BL mJOA			**0.003**
Ames None Modifier	4.5%	10.4%	0.450
Ames Mild Modifier	68.2%	25.4%	**<0.001**
Ames Moderate Modifier	13.6%	44.8%	**0.016**
Ames High Modifier	13.6%	19.4%	0.631

BL, baseline; NRK, Normal Recovery Kinetics; SRK, Superior Recovery Kinetics; mJOA, modified Japanese Orthopedic Association scale; SVA, sagittal vertical axis.

−2.8°, $P = 0.009$), PT (SRK: 25.6° *vs.* NRK: 17°, $P = 0.002$), T12-S1 angle (SRK: −42.7° *vs.* NRK: −53.1°, $P = 0.023$), and L1-S1 angle (SRK: −45.7° *vs.* NRK: −55.2°, $P = 0.032$) alignment values. At 3M (SRK: 26.3° *vs.* NRK: 18.8°, $P = 0.009$) and 1Y (SRK: 25° *vs.* NRK: 17.9°, $P = 0.015$), PT remained significantly larger in the SRK group compared to NRK. At BL and 1Y T1 spinopelvic inclination angle was significantly for the SRK group (both $P < 0.05$). C2-C7 cervical lordosis, TS-CL, cSVA, T1 Slope, and C7-S1 SVA parameters were not significant between SRK and NRK groups at BL, 3M, and 1Y (all $P > 0.05$) (Table 3).

Predictors of Superior Recovery Kinetics

Superior recovery kinetics post- CD corrective surgery can be predicted using high accuracy (AUC = 88.1%) using clinical and radiographic predictors with the following combination of BL factors (Table 4): EQ5D Visual Analog Scale (VAS) (odds ratio [OR]: 0.96, 95% confidence interval [CI]: 0.92–0.99), Swallow Sleep score (OR: 1.04, 95% CI: 1.02–1.06), mJOA (OR: 1.52, 95% CI: 1.07–2.16), PT (OR: 1.12, 95% CI: 1.03–1.22), T4-T12 angle (OR: 1.10, 95% CI: 1.03–1.18), T10-L2 angle (OR: 0.90, 95% CI: 0.83–0.98), T12-S1 angle (OR: 1.23, 95% CI: 1.00–1.52), and L1-S1 angle (OR: 0.83, 95% CI: 0.68–1.01).

SRK Predictor Cut-offs

Random forest analysis followed by conditional inference tree analysis generated statistically significant cut-offs for top patient-reported and alignment predictors from the predictive model for SRK. Overall, radiographic-related were the top category of predictors: PT >13.7°, TK <42.9,° T10-L2 < −6.9°, T12-S1 >−58.6°, L1-S1 >−62.1°. The clinical predictor cut-offs included in the model were as follows: EQ5D VAS score of <40, swallow sleep score of >63, and mJOA score of >14.

DISCUSSION

The interest surrounding the clinical recovery trajectory of operative CD patients has been growing within the surgical spine literature. Recovery course after CD surgeries are poorly reported, due to the heterogeneity of cases and complexities of etiology.[1] In this study we aimed to capture superior recovery process using BL, 3M, and 1Y NDI scores in a retrospective case series of CD patients. With the utilization of the Liu *et al*'s method, we were able to quantify a "superior" recovery pattern (accounting for neck-related disability) for postoperative CD patients.[10] This IHS methodology of patient-reported score regulation provided an effective stage for the use of predictive analytics to generate a patient-derived model to predict superior clinical recovery by 1Y.

The predictive modeling employed traditional stepwise regression analysis involving complex algorithms that identify patterns in large data sets, allowing for the prediction of a given outcome of interest, in this case SRK.[7,16] This "bootstrap" approach relies on the available data, balancing accuracy, generalizability, and transparency.[15] The decision trees were used to establish clinically relevant cut-offs representing the sequence of chance events and decisions over time.[17]

In demographic analysis, age, sex, BMI, and CCI did not significantly impact having superior recovery kinetics.[18] When assessing postoperative complications between NRK and SRK patients, there were no significant differences. Other studies note that patient satisfaction, by way of HRQL assessment, is unrepresented by postoperative complications after corrective adult spinal deformity surgery.[19,20] This known lack of correlation (which future

TABLE 3. Baseline, 3-month and 1-year Sagittal Radiographic Parameters Between SRK and NRK Recovery Groups

Sagittal Radiographic Parameters	SRK	NRK	*P*
Baseline			
BL cervical lordosis (C2-C7)	−11	−3.7	0.178
BL TS-CL	36.8	35.9	0.851
BL cSVA	47	45.9	0.864
BL T1-Slope	26.7	31.5	0.270
BL C7-S1 SVA	−16.2	−3.7	0.449
BL PI-LL	8.4	−2.8	**0.009**
BL PT	25.6	17	**0.002**
BL T4-T12	34.1	40.8	0.088
BL T10-L2	−11.8	−6.3	0.088
BL T12-S1	−42.7	−53.1	**0.023**
BL L1-S1	−45.7	−55.2	**0.032**
BL T1 Spino Pelvic Inclination	−9.0	−6.0	**0.040**
3 −mo			
M3 Cervical Lordosis (C2-C7)	5.7	9.7	0.362
M3 TS-CL	24.3	26.6	0.575
M3 cSVA	37.6	38.3	0.895
M3 T1-Slope	30.9	36.3	0.250
M3 C7-S1 SVA	10.4	26.7	0.418
M3 PI-LL	7.8	1.3	0.137
M3 PT	26.3	18.8	**0.009**
M3 T4-T12	42.3	43.3	0.811
M3 T10-L2	−12.7	−10.4	0.537
M3 T12-S1	44.1	49.1	0.260
M3 L1-S1	47.9	51.9	0.335
M3 T1 spino pelvic inclination	−7.1	−3.9	0.067
1-Year			
Y1 Cervical Lordosis (C2-C7)	7.8	8.3	0.895
Y1 TS-CL	23.6	27.4	0.215
Y1 cSVA	39.3	39.5	0.979
Y1 T1-Slope	31.4	35.5	0.281
Y1 C7-S1 SVA	−0.31	24.5	0.145
Y1 PI-LL	6.2	0.55	0.220
Y1 PT	25	17.9	**0.015**
Y1 T4-T12	40.2	42.8	0.533
Y1 T10-L2	−14.7	−10.3	0.270
Y1 T12-S1	44.3	50.1	0.198
Y1 L1-S1	47.6	53.1	0.219
Y1 T1 spino pelvic inclination	−7.9	−3.4	**0.005**

BL indicates baselineNRK; cSVA, C2-C7 sagittal vertical axis, Normal Recovery Kinetics; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SRK, Superior Recovery Kinetics.

studies should investigate in a CD-only population) between patient-reported outcome and postoperative physical assessment, in addition to the general comorbid or high-risk nature of our cohort (older aged, high BMI, at least one comorbidity), lack of clear demographic predictors, and postoperative complication differences results.

Superior recovery kinetics following CD corrective surgery was predicted with high accuracy (AUC = 88.1%) using a combination of clinical and radiographic factors. Our model with respective decision tree cut-offs of clinical variables indicated that worse BL EQ5D VAS scores (<40), better Swallow Sleep scores (>63), and better mJOA scores (>14) were predictors of superior neck disability recovery. Radiographic predictors included increased malalignment of BL PT (>13.7°), whereas lower sagittal malalignment in terms of TK (<42.9°), T10-L2 angle (<−6.9°), and lumbar lordosis (LL) (T12-S1: >−58.6°; L1-S1: >−62.1°).

TABLE 4. Final Model of BL Factors Predictive "Superior" Recovery Kinetics Following Cervical Deformity Corrective Surgery

Model With All Factors	OR	Lower CI	Upper CI	*P*
BL EQ5D VAS	0.955	0.918	0.994	0.024
BL Swallow Sleep Score	1.037	1.011	1.064	0.005
BL mJOA	1.522	1.070	2.163	0.019
BL pelvic tilt	1.120	1.025	1.222	0.011
BL T4-T12	1.101	1.028	1.179	0.006
BL T10-L2	0.903	0.832	0.980	0.015
BL T12-S1	1.234	1.000	1.521	0.049
BL L1-S1	0.829	0.678	1.013	0.067
AUC	**0.8810**			

AUC indicates area under the curve; BL, baseline; EQ5D, EuroQol five-dimensional descriptive system; mJOA, modified Japanese Orthopedic Association scale; VAS, Visual Analog Scale.

Of the clinical predictors included in the predictive model, EQ5D VAS scores record the patient's self-rated health on a vertical visual analogue scale, a single number from 0 to 100.[21] This predictor demonstrated that patients who rate their BL "health state" as poor have superior room for improvement to recover in their overall outlook on health. From BL to 1Y, SRK patients' EQ5D VAS scores vastly improved, with averaged 60.7 at BL to 79.7 at 1Y. The literature reports that these responses may be influenced by personal, non-health-related contextual factors, and to a large part patient anxiety/depression status, but similar rates of depression comorbidity were seen between recovery groups ($P = 0.845$).[21] Greater BL mJOA scores were the strongest predictor for SRK (OR: 1.522), or decreased myelopathy severity, and is consistent with the literature.[22] Moderate to severe functional impairment at BL, including disruption of sleep from functionality of swallowing, from greater degree of injury or more substantial degenerative pathology, increases risk for poor postoperative outcomes and overall recovery trajectory.

SRK and NRK patients had similar radiographic display of BL CD as defined by the Ames classification system, was well as comparable cervical alignment parameters from BL to 1Y.[2] Interestingly, global sagittal alignment parameters did influence the recovery trajectory of neck disability for these CD patients. Specifically, increased PT and decreased TK and LL were found as predictors for this superior neck disability recovery. This signifies the interdependence of the spinal regions.[4] Lafage *et al*[23] demonstrated the relationship between pelvic retroversion and spinal malalignment with clinical outcomes measured by the Oswestry Disability Index and SF-12 Physical Component Score. In the presence of sagittal malalignment, such as our predictors of decreased of LL and TK at BL, the objective of the spine is to keep a balanced standing posture. One way to compensate for a positive shift is pelvic retroversion to maintain global alignment.[24,25] This increased compensation at BL ultimately impacts HRQL assessment, including the cervical spinal pain/disability (BL NDI), which was reported worse for the SRK group (43.1) compared to the NRK group (48.2). This allows for greater room for recovery in relation to the patients' low BL quality of life.

Our study is not without limitations. The required follow-up time points for our analyses caused the sample sizes to become relatively small, which may not completely reflect the true postoperative courses of these CD patients. Also, the normalization of HRQL scores at BL only controls for BL severity score, allowing for superior assessment of postoperative HRQL changes. Additionally, although the multicenter methodology used for database correction increases the generalizability of our findings, the data analyzed for the purposes of this study may be skewed toward more complex cases. A limitation of the predictive model is that many variables are assigned to predict relatively few patients. It is possible that the model may suffer from overfitting, and as a result may not be generalizable to other patients. A larger sample size may help to address this issue.

CONCLUSION

SRK following CD surgery was predicted with high accuracy using a combination of BL patient-reported factors (VAS EQ5D, swallow sleep, and mJOA scores) and radiographic factors (PT, TK, T10-L2, T12-S1, L1-S1). Patients and health care providers should be aware of these factors to improve surgical decision-making, in an effort to reduce postop neck disability.

➢ Key Points

- ❑ With a novel AUC methodology, and the emergent concept of predictive analytics, prediction of SRK, or those who displayed the best patient-reported recovery patterns, in a CD population was investigated.
- ❑ The lowest quartile of neck disability index IHS scores were classified as superior recovery.
- ❑ Superior recovery kinetics following CD surgery was predicted with high accuracy using a combination of BL patient-reported factors (VAS EQ5D, swallow

sleep, and mJOA scores) and radiographic factors (PT, TK, T10-L2, T12-S1, L1-S1).

- Patients and health care providers should be aware of these factors to improve surgical decision-making, in an effort to reduce postop neck disability.

References

1. Chi JH, Tay B, Stahl D, et al. Complex deformities of the cervical spine. *Neurosurg Clin N Am* 2007;18:295–304.
2. Ames CP, Smith JS, Eastlack R, et al. Reliability assessment of a novel cervical spine deformity classification system. *J Neurosurg Spine* 2015;23:673–83.
3. Grob D, Frauenfelder H, Mannion AF. The association between cervical spine curvature and neck pain. *Eur Spine J* 2007;16: 669–78.
4. Scheer JK, Tang JA, Smith JS, et al. Cervical spine alignment, sagittal deformity, and clinical implications: a review. *J Neurosurg Spine* 2013;19:141–59.
5. Ebersold MJ, Pare MC, Quast LM. Surgical treatment for cervical spondylitic myelopathy. *J Neurosurg* 1995;82:745–51.
6. Miller EK, Ailon T, Neuman BJ, et al. Assessment of a novel adult cervical deformity frailty index as a component of preoperative risk stratification. *World Neurosurg* 2018;109:e800–6.
7. Passias PG, Oh C, Horn SR, et al. Predicting the occurrence of complications following corrective cervical deformity surgery: analysis of a prospective multicenter database using predictive analytics. *Spine J* 2018;59:155–61.
8. Segreto FA, Lafage V, Lafage R, et al. Recovery kinetics: comparison of patients undergoing primary or revision procedures for adult cervical deformity using a novel area under the curve methodology. *Neurosurgery* 2019;85:E40–51.
9. Passias PG, Jalai CM, Lafage V, et al. Recovery kinetics of radiographic and implant-related revision patients following adult spinal deformity surgery. *Neurosurgery* 2018;83:700–8.
10. Liu S, Tetreault L, Fehlings MG, et al. Novel method using baseline normalization and area under the curve to evaluate differences in outcome between treatment groups and application to patients with cervical spondylotic myelopathy undergoing anterior versus posterior surgery. *Spine (Phila Pa 1976)* 2015;40:E1299–304.
11. 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.
12. 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.
13. O'Brien MF, Kuklo TRTR, Blanke KM, Lenke LG. Spinal Deformity Study Group Radiographic Measurement Manual. 2005. Available at: http://www.oref.org/docs/default-source/default-document-library/sdsg-radiographic-measuremnt-manual.pdf?sfvrsn=2.
14. Ames CP, Scheer JK, Mundis GM, et al. The Effect of Patient Age on Recovery Kinetics in 149 Adult Spinal Deformity Patients with 2-year Follow-up: A Novel Area Under the Curve Analysis. In: Scoliosis Research Society (SRS); September 10-13. Vol 36. Anchorage, Alaska; 2014.
15. Austin PC, Tu JV. Bootstrap methods for developing predictive models. *Am Stat* 2004;58:131–7.
16. Scheer JK, Osorio JA, Smith JS, et al. Development of validated computer based pre-operative predictive model for proximal junction failure (PJF) or clinically significant PJK with 86% accuracy based on 510 ASD patients with 2-year follow-up. *Spine (Phila Pa 1976)* 2016;41:E1328–35.
17. McAnany SJ, Anwar MAF, Qureshi SA. Decision analytic modeling in spinal surgery: a methodologic overview with review of current published literature. *Spine J* 2015;15:2254–70.
18. Passias PG, Vasquez-Montes D, Poorman GW, et al. Predictive model for distal junctional kyphosis after cervical deformity surgery. *Spine J* 2018;18:2187–94.
19. Hamilton DK, Kong C, Hiratzka J, et al. Patient satisfaction after adult spinal deformity surgery does not strongly correlate with health-related quality of life scores, radiographic parameters or occurrence of complications. *Spine (Phila Pa 1976)* 2016;42:1.
20. Glassman SD, Bridwell KH, Shaffrey CI, et al. Health-related quality of life scores underestimate the impact of major complications in lumbar degenerative scoliosis surgery. *Spine Deform* 2018;6:67–71.
21. Feng Y, Parkin D, Devlin NJ. Assessing the performance of the EQ-VAS in the NHS PROMs programme. *Qual Life Res* 2014;23: 977–89.
22. Tetreault L, Kopjar B, Nouri A, et al. The modified Japanese Orthopaedic Association scale: establishing criteria for mild, moderate and severe impairment in patients with degenerative cervical myelopathy. *Eur Spine J* 2017;26:78–84.
23. Lafage V, Schwab F, Patel A, et al. Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. *Spine (Phila Pa 1976)* 2009;34:E599–606.
24. Ramchandran S, Protopsaltis TS, Sciubba D, et al. Prospective multi-centric evaluation of upper cervical and infra-cervical sagittal compensatory alignment in patients with adult cervical deformity. *Eur spine J* 2018;27:416–25.
25. Protopsaltis T, Schwab F, Bronsard N, et al. TheT1 pelvic angle, a novel radiographic measure of global sagittal deformity, accounts for both spinal inclination and pelvic tilt and correlates with health-related quality of life. *J Bone Joint Surg Am* 2014;96: 1631–40.