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Clinical Study

Recovery kinetics following spinal deformity correction: a comparison of isolated cervical, thoracolumbar, and combined deformity morphometries

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ABSTRACT

BACKGROUND CONTEXT: The postoperative recovery patterns of cervical deformity patients, thoracolumbar deformity patients, and patients with combined cervical and thoracolumbar deformities, all relative to one another, is not well understood. Clear objective benchmarks are needed to quantitatively define a "good" versus a "bad" postoperative recovery across multiple follow-up visits, varying deformity types, and guide expectations.

PURPOSE: To objectively define and compare the complete 2-year postoperative recovery process among operative cervical only, thoracolumbar only, and combined deformity patients using area-under-the-curve (AUC) methodology.

STUDY DESIGN/SETTING: Retrospective review of 2 prospective, multicenter adult cervical and spinal deformity databases.

PATIENT SAMPLE: One hundred seventy spinal deformity patients.

OUTCOME MEASURES: Common health-related quality of life (HRQOL) assessments across both databases included the EuroQol 5-Dimension Questionnaire and Numeric Rating Scale (NRS) back pain assessment. In order to compare disability improvements, the Neck Disability Index (NDI) and the Oswestry Disability Index (ODI) were merged into one outcome variable, the ODI-NDI. Both assessments are gauged on the same scale, with minimal question deviation. Sagittal Radiographic Alignment was also assessed at pre- and all postoperative time points.

METHODS: Operative deformity patients >18 years old with baseline (BL) to 2-year HRQOLs were included. Patients were stratified by cervical only (C), thoracolumbar only (T), and combined deformities (CT). HRQOL and radiographic outcomes were compared within and between deformity groups. AUC normalization generated normalized HRQOL scores at BL and all follow-up intervals (6 weeks, 3 months, 1 year, and 2 year). Normalized scores were plotted against follow-up time interval. AUC was calculated for each follow-up interval, and total area was divided by cumulative follow-up length, determining overall, time-adjusted HRQOL recovery (Integrated Health State, IHS). Multiple linear regression models determined significant predictors of HRQOL discrepancies among deformity groups.

RESULTS: One hundred seventy patients were included (27 C, 27 T, and 116 CT). Age, BMI, sex, smoking status, osteoporosis, depression, and BL HRQOL scores were similar among groups (p >.05). T and CT patients had higher comorbidity severities (CCI: C 0.696, T 1.815, CT 1.699, p = .020). Posterior surgical approaches were most common (62.9%) followed by combined (28.8%) and anterior (6.5%). Standard HRQOL analysis found no significant differences among groups until 1-year follow-up, where C patients exhibited comparatively greater NRS back pain (4.88 vs. 3.65 vs. 3.28, p = .028). NRS Back pain differences between groups subsided by 2-years (p>.05). Despite C patients exhibiting significantly faster ODI-NDI minimal clinically important difference (MCID) achievement (33.3% vs. 0% vs. 23.0%, p < .001), all deformity groups exhibited similar ODI-NDI MCID achievement by 2-years (51.9% vs. 59.3% vs. 62.9%, p = 0.563). After HRQOL normalization, similar results were observed relative to the standard analysis (1-year NRS Back: C 1.17 vs. T 0.50 vs. CT 0.51, p < .001; 2-year NRS Back: 1.20 vs. 0.51 vs. 0.69, p = .060). C patients exhibited a worse NRS back normalized IHS (C 1.18 vs. T 0.58 vs. CT 0.63, p = .004), indicating C patients were in a greater state of postoperative back pain for a longer amount of time. Linear regression models determined postoperative distal junctional kyphosis (adjusted beta: 0.207, p = .039) and osteoporosis (adjusted beta: 0.269, p = .007) as the strongest predictors of a poor NRS back IHS (model summary: $R^2 = 0.177$, p = .039).

CONCLUSIONS: Despite C patients exhibiting a quicker rate of MCID disability (ODI-NDI) improvement, they exhibited a poorer overall recovery of back pain with worse NRS back scores compared with BL status and other deformity groups. Postoperative distal junctional kyphosis and osteoporosis were identified as primary drivers of a poor postoperative NRS back IHS. Utilization of the IHS, a single number adjusting for all postoperative HRQOL visits, in conjunction with predictive modelling may pose as an improved method of gauging the effect of surgical details and complications on a patient's entire recovery process.

Keywords: Adult spine deformity; Cervical deformity; Distal junctional kyphosis; HRQOL; Proximal junctional kyphosis; Recovery kinetics

Introduction

Spinal deformity patients can present with varying morphometry located in the cervical and thoracolumbar spinal regions [1−5]. Given the significant impact to quality of life associated with spinal deformity, current treatment methods are aimed at alleviating pain, improving health-related quality of life (HRQOL), and operative correction of deformity in cases of severe pain, disability, and neurologic compromise [6,7].

HRQOL instruments such as the Oswestry Disability Index (ODI), Numeric Rating Scale (NRS) for Back and Neck Pain, and the EuroQOL 5-Dimensions (EQ5D) Questionnaire are used to standardize the evaluation of spinal deformity patients before and after treatment interventions and among multiple follow-up visits [8−11]. Traditional methods of HRQOL analysis include the comparison of mean cohort scores between treatment groups, baseline, and follow-up visits. While standard analysis of HRQOL metrics remains one of the most commonplace methodologies used in clinical articles, several recent reports have accentuated significant limitations associated with standard HRQOL analysis [12−16]. Variations in scale among HRQOL scores may result in statistically significant differences among baseline and follow-up scores that bear no clinical relevance, which has resulted in the creation and utilization of the minimal clinically important difference (MCID) concept in order to identify clinically relevant HRQOL changes [17−19]. However, a patient's attainment of MCID only accounts for a discrete time point during the follow-up period, offering little use when assessing a patient's entire postoperative recovery process [20]. Furthermore, baseline patient variability may diminish the ability to significantly detect HRQOL fluctuations throughout the postoperative recovery process among varying treatment groups. In order to more accurately assess a patient's postoperative recovery process, as well as reduce patient and HRQOL scale variability that can bias statistical tests, Liu et al. have proposed an area-under-the-curve (AUC) analysis in which baseline and follow-up HRQOL scores are normalized before being graphically plotted and computing the AUC [15].

Clear, objective, and minimally biased benchmarks are needed to determine what constitutes a "good" versus a "bad" recovery process across multiple follow-up visits and varying deformity types. This study made it a priority to objectively define and compare the complete 2-year postoperative recovery process among operative cervical only, thoracolumbar only, and combined cervical and thoracolumbar deformity patients using AUC. Rates of achieving MCID at each postoperative follow-up time point were assessed and compared among deformity groups as well.

Methods

Study design

This study is a retrospective review of 2 prospective multicenter databases. One database captured data on adult cervical deformity patients, and the other captured data on adult spinal deformity (ASD) patients localized to the thoracic or lumbar spine.

Data source

Subjects were consecutively enrolled from 13 participating centers throughout the United States. Internal Review Board approval was obtained at each participating site before study initiation. Informed patient consent was acquired from each patient, before database and study enrollment. Inclusion criteria for the cervical deformity database consisted of patients ≥18 years of age and radiographic evidence of cervical deformity at baseline assessment, defined as the presence of cervical kyphosis (C2−7 Cobb angle >10°), cervical scoliosis (C2−7 coronal Cobb angle >10°), C2−7 sagittal vertical axis (cSVA) >4 cm, or a chin-brow vertical angle (CBVA) >25°. Similarly, inclusion criteria for the ASD database consisted of patients ≥18 years old, seeking operative management for ASD. ASD is defined radiographically in this database as Coronal Cobb angle ≥20°, SVA≥5 cm, pelvic tilt ≥25°, or thoracic kyphosis >60°. Exclusion criteria for both databases included spinal deformity with a neuromuscular etiology, presence of active infection, or malignancy.

Data collection

Common metrics collected among both databases were used in this study. Demographic data included patient age, gender, body mass index (BMI), race, and Charlson Comorbidity Index (CCI). Operative details included surgical approach, operative timing, estimated blood loss, levels fused, upper instrumented vertebra (UIV), lower instrumented vertebral (LIV), hospital length of stay, and complication occurrence (overall, major, intraoperative, infection, neurologic, instrumentation, radiographic [Proximal/Distal Junctional Kyphosis (PJK/DJK): defined as ≥10° of the sagittal cobb angle between the inferior endplate of the UIV and the superior endplate of the vertebral body position 2 vertebra above the UIV for PJK, and ≥10° between the superior endplate of the LIV and the inferior endplate of the vertebral body position 2 vertebra below the LIV]. HRQOL assessments used were the EQ5D total score, the NRS back pain assessment (NRS-Back), and the Neck Disability Index (NDI) or ODI.

Collected imaging included full-length free-standing lateral spine radiographs (36 in. cassette) at the baseline, 3-months, 1-year and 2-year postoperative follow-up visits. Severity of deformity was assessed utilizing sagittal radiographic parameters of interest, highlighted within the Ames-ISSG and SRS-Schwab deformity classification systems [21,22]. Measured cervical spine parameters included cervical SVA (cSVA: offset from the C2 plumbline and the postero-superior corner of C7), C2−C7 sagittal cobb angle (Cobb angle between C2 inferior endplate and C7 inferior endplate, positive values indicate lordosis, negative values indicate kyphosis), T1 slope minus CL (TS-CL: mismatch between T1 slope and cervical lordosis), and T1 slope. Spinopelvic parameters included: (SVA: C7 plumb line relative to the posterosuperior corner of S1), pelvic incidence minus lumbar lordosis (PI-LL: mismatch between pelvic incidence and lumbar lordosis), pelvic tilt (PT: angle between the vertical and the line through the sacral midpoint to the center of the 2 femoral heads), and T1 pelvic angle (T1PA: the angle subtended by a line from the femoral heads to the center of the T1 vertebra, and a line from the femoral heads to the center of the sacral endplate).

Study inclusion criteria and patient stratification

Patients with complete baseline, early (6 weeks to 3 months), 1-year and 2-year follow-up HRQOL and radiographic data were included for analysis, representing 60% of our total database. Patients were then stratified into 3 separate cohorts based upon deformity type. Deformity cohorts consisted of patients with cervical deformity only, thoracolumbar deformity only, and patients with combined cervical and thoracolumbar deformity. Cervical deformity only was defined as patients meeting cervical deformity database radiographic criteria, and not meeting ASD database radiographic criteria. Thoracolumbar deformity only was defined as meeting ASD database radiographic criteria, and not meeting cervical deformity database radiographic criteria. Patients meeting both cervical deformity database radiographic criteria and ASD database radiographic criteria were defined as "combined."

Statistical analysis

Statistical analysis was performed using SPSS software (version 21.0, IBM, Armonk, 134 New York). Normality of data was determined using the Shapiro-Wilk test. Demographic, surgical, radiographic, and HRQOL metrics were compared among deformity groups utilizing chi-square tests with post hoc analysis for categorical variables, and analysis of variance (ANOVA) or the Kruskal-Wallis test for continuous variables. ANOVA and Kruskal-Wallis analyses were followed by Tukey's Honest Significant Difference test or the Wilcoxon Signed-Ranks post hoc tests to assess individual group differences and attempt to control for type I error. ANOVA with repeated measures was used to assess significant temporal changes for continuous variables (ie, HRQOLs) among multiple follow-up visits within each deformity group. Multiple linear regression models identified significant predictors of HRQOL discrepancies among deformity groups. All analyses were 2-sided, and the level of significance was set to $p < .05$.

Within the assessment of HRQOLs in this analysis, it is important to note that the cervical deformity database collected the NDI questionnaire, while the ASD database collected the ODI questionnaire. To reduce missing data and maintain adequate statistical power when comparing recovery patterns among deformity groups, being that the NDI and ODI are similar assessments and scored on an equivalent scale, the NDI and ODI were considered equivalent metrics and merged into one variable (ODI-NDI).

Development of MCID and normalized integrated health state scores

MCIDs for ODI (12.8), NDI (7.5), and NRS Back (2.4) were calculated using previously validated reports for lumbar spine surgery, adult cervical deformity, and chronic low back pain patients [23−25]. To the best of our knowledge, EQ5D MCID has not been validated for spinal deformity or back pain populations.

Normalized HRQOLs were developed and analyzed, permitting the calculation of an integrated health state using the following validated AUC methodology [13−16]. All reported preoperative and postoperative (6-week or 3-month, 1-year, and 2-year) values for each outcome measure were divided by the corresponding preoperative score for each patient. The resulting preoperative normalized HRQOL score for all patients was therefore 1, with any follow-up normalized HRQOL scores being >1, equal to 1, or < 1, depending on whether the patient improved or deteriorated relative to baseline. Normalized HRQOL scores were then plotted on an area graph, with the x-axis representing time (in months, starting at the preoperative interval) and the y-axis representing normalized HRQOL scores (Fig. 1). A line was formed, connecting HRQOL values across all time-points for a single patient. This line generated trapezoidal shapes, corresponding to the Δx and Δy from one follow-up interval to the next. The area of each trapezoid was calculated, and the areas of each trapezoid were summed together to obtain the total follow-up length area. The total area was then divided by the cumulative follow-up time (24 months) to obtain a reasonably sized, single value representing a patient's entire recovery timeline (ie, Integrated Health State, IHS) for a given outcome metric. The following integrated health state equations are shown in the Fig. 1 legend.

Regarding IHS values for varying outcome metrics, lower NRS Back and ODI-NDI Integrated Health State Scores indicate a better outcome (better recovery process), and higher EQ5D Integrated Health State Scores indicated a better outcome (better recovery process). IHS means were compared across deformity groups utilizing parametric and nonparametric tests as appropriate.

Results

Demographics

One hundred-seventy operative spinal deformity patients met inclusion criteria. The cervical deformity group consisted of 27 patients, the thoracolumbar deformity group consisted of 27 patients, and the combined deformity group consisted of 116 patients. Despite no significant differences between age (60.98 vs. 61.63 vs. 62.30, p = .852), sex (Female: 70.4% vs. 77.8% vs. 73.2%, p = .821), BMI (27.9

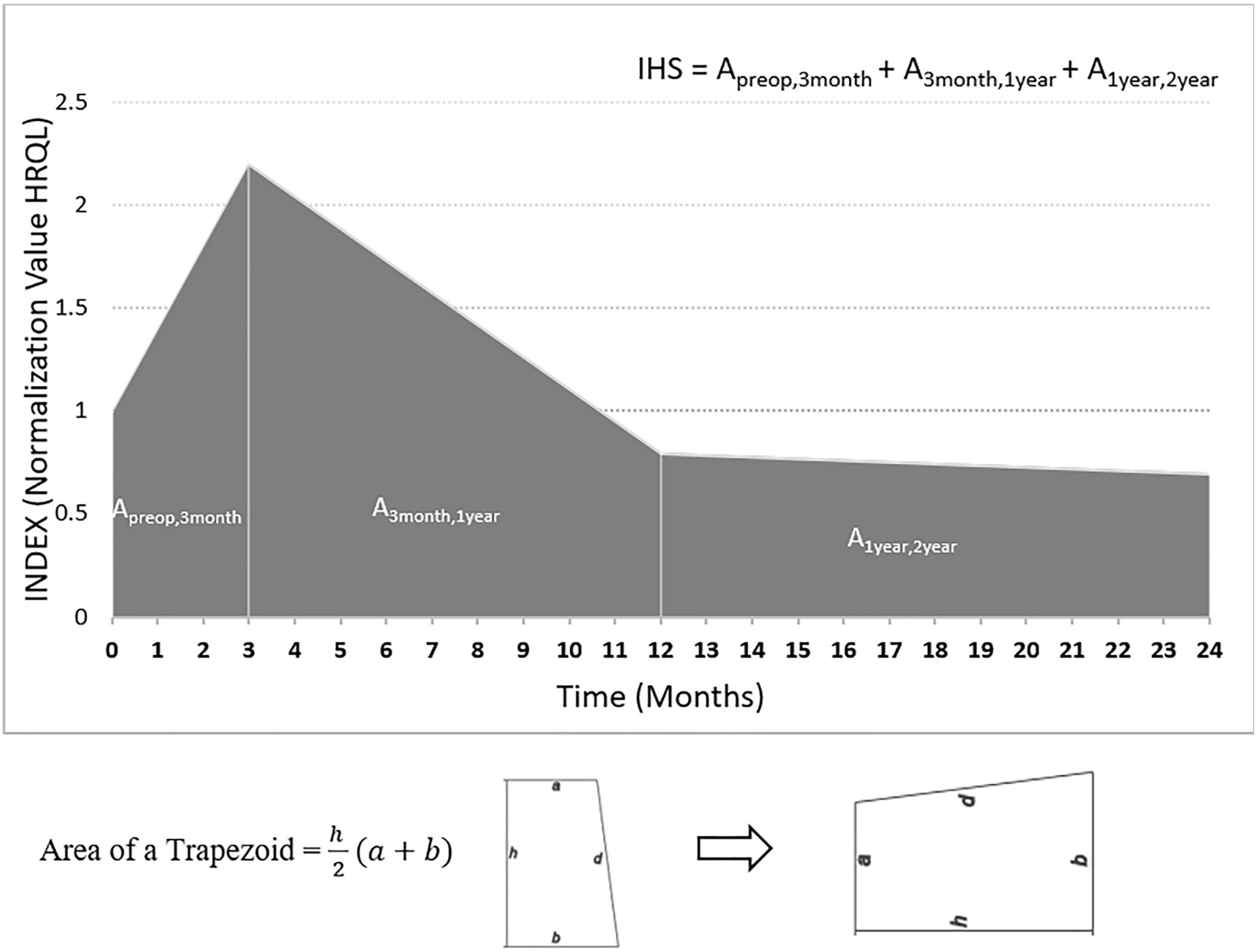

Fig. 1. Area graph representation of normalized HRQOL scores and the integrated health state calculation. The change in time was calculated as months, and is represents the "height" or "h" of the trapezoid, when calculating the area of each trapezoid: area of a trapezoid = $\frac{h}{2}(a+b)$. The "y" values represent a given normalized HRQOL value at each respective time point, and represent a+b within the trapezoid area equation. The equations used for each patient was the following:

Area of a trapezoid = $\frac{h}{2}(a+b)$

Integrated Health State Equations = $\frac{\frac{3\,\text{months}}{2}(y_{\text{preop}}+y_{3\,\text{month}})+\frac{9\,\text{months}}{2}(y_{3\,\text{month}}+y_{1\,\text{year}})+\frac{12\,\text{months}}{2}(y_{1\,\text{month}}+y_{2\,\text{year}})}{24\,\text{months}}$

$\frac{\frac{6\,\text{weeks}}{2}(y_{\text{preop}}+y_{6\,\text{weeks}})+\frac{10.5\,\text{months}}{2}(y_{6\,\text{weeks}}+y_{1\,\text{year}})+\frac{12\,\text{months}}{2}(y_{1\,\text{month}}+y_{2\,\text{year}})}{24\,\text{months}}$

vs. 27.8 vs. 28.6, p = .854), smoking status (7.4% vs. 3.7% vs. 1.8%, p = .305), osteoporosis (18.5% vs. 7.4% vs. 19.8%, p = .310), or depression (29.6% vs 33.3% vs. 32.8%, p = .946) were observed between deformity groups, thoracolumbar and combined deformity patients presented with an increased comorbidity severity (CCI: 0.696 vs. 1.815 vs. 1.70, p = .020; Table 1).

Table 1
Demographics of cervical, thoracolumbar, and combined deformity patients

	Cervical	Thoracolumbar	Combined	P value
Sample Size	27	27	116	
Age	60.98	61.63	62.3	.852
Gender (female)	70.4%	77.8%	73.2%	.821
BMI	27.93	27.91	28.55	.854
CCI	0.696	1.815	1.70	**.020**
Smoking status	7.4%	3.7%	1.8%	.305
Osteoporosis	18.5%	7.4%	19.8%	.310
Depression	29.6%	33.3%	32.8%	.946

BMI, body mass index; CCI, Charlson comorbidity index. Bolded values indicate statistical significance to $p < 0.05$.

Operative details

Overall surgical approach rates were 62.9% posterior only, 28.8% combined, and 6.5% anterior only. The most prevalent approaches used among cervical deformity patients were combined approaches (63.0%), anterior (18.5%) only, and posterior only (18.5%) approaches. The most prevalent approaches used among thoracolumbar patients were posterior only approaches (77.8%) and combined approaches (22.2%). The posterior only approach was also the most common approach used for combined

Table 2
Operative and postoperative complication details of cervical, thoracolumbar, and combined deformity patients

	Cervical	Thoracolumbar	Combined	P value
Approach				
Anterior	18.5%	0%	5.2%	**<.001**
Posterior	18.5%	77.8%	69.8%	
Combined	63.0%	22.2%	25.0%	
Levels fused	7.4	12.1	9.7	**<.001**
UIV	C2−C3	Bimodal: T4,T8	Trimodal: C2-C4, T4, T10	**<.001**
LIV	C7−T3	Ilium	Bimodal: T2-T3, Ilium	**<.001**
Operative Time (min)	568.1	429.0	414.0	**.027**
Estimated Blood Loss (ccs)	735.4	1789.9	1096.2	**.003**
Length of Stay	5.6	7.2	8.5	.173
Complication Rate	77.8%	70.4%	66.4%	.982
Major	22.2%	33.3%	27.6%	.084
Intraoperative	25.9%	18.5%	21.6%	.945
Major	7.4%	7.4%	7.8%	.214
Infection	3.7%	11.1%	6.9%	.564
Instrumentation	3.7%	14.8%	11.2%	.667
Neurologic	25.9%	18.5%	14.7%	.201
PJK				
Early	3.7%	51.9%	50.9%	**<.001**
1Y	0.0%	55.6%	50.9%	**<.001**
2Y	3.7%	59.3%	44.8%	**<.001**
DJK				
Early	33.3%	0.0%	6.9%	**<.001**
1Y	37.0%	0.0%	11.2%	**<.001**
2Y	37.0%	0.0%	6.9%	**<.001**

UIV, upper instrumented vertebra; LIV, lower instrumented vertebra; PJK, proximal junctional kyphosis; DJK, distal junctional kyphosis. Bolded values indicate statistical significance to $p < 0.05$.

deformity patients (69.8%), followed by combined approaches (25.0%) and anterior only approaches (5.2%).

Thoracolumbar deformity patients had the longest construct lengths (12.1 levels fused) relative to combined deformity (9.7) and cervical deformity (7.4) patients ($p < .001$). The average UIV and LIV placements for each deformity group is as follows: Cervical (UIV: C2−C3, LIV: C7−T3), Thoracolumbar (UIV: T4, T8, LIV: Illium), Combined (UIV: C2−C3, T4, T10 LIV: T2−T3, Illium), $p < .001$. Thoracolumbar patients also exhibited the largest blood loss (1789.9ccs) relative to combined (1096.2ccs) and cervical (735.4ccs) deformity patients ($p = .003$). Cervical patients underwent the longest operations (568.1 vs. 429.0 vs. 414.0, $p = .027$). Inpatient length of stay was similar among all deformity groups (5.6 vs. 7.2 vs. 8.5, $p = .173$; Table 2).

Postoperative complications

Overall complication rates were similar among all deformity groups (77.8% vs. 70.4% vs. 66.4%, $p = .982$), as well as prevalence of major complications (22.2% vs. 33.3% vs. 27.6%, $p = .084$), intraoperative complications (25.9% vs. 18.5% vs. 21.6%, $p = .945$), infection (3.7% vs. 11.1% vs. 6.9%, $p = .564$), instrumentation (3.7% vs 14.8% vs. 11.2%, $p = .667$), and neurologic (25.9% vs. 18.5% vs. 14.7%, $p = .201$) complications. By 3-month follow-up, while only 3.7% of cervical deformity patients developed PJK, 51.9% of thoracolumbar and 50.9% of combined patients had developed PJK ($p < .001$). These rates remained relatively stable through 2-year follow-up ($p>.05$). By 3-month follow-up, while only 6.9% of combined patients and 0% of thoracolumbar patients developed DJK, 33.3% of cervical patients had developed DJK ($p < .001$). DJK rates also remained stable through 2-year follow-up ($p>.05$; Table 2).

Sagittal radiographic alignment comparison

At baseline, cervical deformity patients presented with kyphotic cervical alignment (C2−C7 Sagittal Cobb Angle: −10.1°) and severe cSVA (39.5 mm) and TS-CL (33.4°) malalignment. Thoracolumbar deformity patients presented with severe C7-S1 SVA (65.7 mm) and PI-LL (23.0°) malalignment. Combined deformity patients presented with severe C7-S1 SVA (65.5 mm), severe pelvic tilt (24.7°), moderate cSVA (32.5 mm), and TS−CL (21.7°) malalignment. C7-S1 SVA, PI-LL, Pelvic Tilt, T1-Slope, T1-Slope minus Cervical Lordosis (TS−CL), and C2−C7 Sagittal Cobb Angle all significantly varied among deformity groups ($p < .05$).

Immediately following operative correction, cervical, thoracolumbar, and combined patients exhibited similar PI-LL, PT, cSVA, and TS−CL correction ($p>.05$). Thoracolumbar patient remained mildly malaligned regarding C7-S1 SVA in comparison to cervical and combined patients (−4.5 vs. 51.8

Table 3
Pre- and postoperative sagittal radiographic alignment parameters

	Cervical	Thoracolumbar	Combined	p value
Baseline SVA	−29.5	65.7	65.5	**<.001**
Early SVA	−4.5	51.8	36.8	**.004**
1Y SVA	0.3	42.1	35.7	**.021**
2Y SVA	8.3	31.8	35.4	.170
Baseline PILL	−9.22	23.0	15.5	**<.001**
Early PILL	−3.0	1.5	2.5	.330
1Y PILL	−5.1	1.1	4.5	**.037**
2Y PILL	−6.5	2.0	4.1	**.042**
Baseline PT	13.3	21.7	24.7	**<.001**
Early PT	17.5	15.7	20.1	.111
1Y PT	14.9	18.3	22.0	**.003**
2Y PT	16.5	20.2	21.8	.134
Baseline cSVA	39.5	21.0	32.5	.059
Early cSVA	29.3	30.9	30.0	.948
1Y cSVA	33.8	33.1	32.6	.943
2Y cSVA	36.8	34.3	31.0	.369
Baseline T1-Slope	23.8	25.9	33.3	**.002**
Early T1-Slope	27.5	30.3	35.2	**.026**
Y1 T1-Slope	29.4	31.1	36.7	**.023**
Y2 T1-Slope	33.4	29.3	37.1	**.040**
Baseline TS−CL	33.4	10.9	21.7	**.001**
Early TS−CL	20.2	20.2	18.2	.656
Y1 TS−CL	21.3	20.2	19.9	.890
Y2 TS−CL	25.2	25.2	20.7	.191
Baseline C2−C7 sagittal cobb angle	−10.1	4.9	11.5	**<.001**
Early C2−C7 sagittal cobb angle	7.5	8.7	16.5	**.007**
Y1 C2−C7 sagittal cobb angle	8.2	11.0	16.8	**.016**
Y2 C2−C7 sagittal cobb angle	9.7	4.1	15.8	**.001**

SVA, sagittal vertical axis; PILL, pelvic incidence minus lumbar lordosis; PT, pelvic tilt; cSVA, cervical sagittal vertical axis; TS−CL, T1-slope minus cervical lordosis. Bolded values indicate statistical significance to $p < 0.05$.

vs. 36.8, p = .004), while combined deformity patients exhibited a significantly greater T1-Slope (27.5 vs. 30.3 vs. 35.2, p = .026) and lordotic cervical spine curvature (7.5 vs. 8.7 vs. 16.5, p = .007).

Despite thoracolumbar patients exhibiting significant SVA improvement, achievement of neutral SVA alignment, and similar SVA alignment in comparison to cervical and combined deformity patients by 2-year follow-up (8.3 vs. 31.8 vs. 35.4 p = .170), all other alignment trends were maintained through 2-year follow-up (Table 3).

Clinical outcomes comparison

Standard HRQOL analysis found no significant differences among baseline ODI-NDI (49.26 vs. 45.41 vs. 46.48, p = .648) and EQ5D (0.75 vs. 0.75 vs. 0.74, p = .938) scores between deformity groups. Thoracolumbar deformity patients trended towards statistical significance in regards to exhibiting the greatest NRS Back pain scores (5.96 vs. 7.52 vs. 6.89, p = .052). Following operative intervention, ODI-NDI, EQ5D, and NRS Back pain scores were similar among all deformity groups (p>.05) until 1-year follow-up, where cervical deformity patients exhibited significant greater NRS Back pain in comparison to thoracolumbar and combined deformity patients (4.88 vs 3.65 vs. 3.28, p = .028). While cervical deformity patients still exhibited the greatest back pain by 2-year follow-up, differences among deformity groups were no longer significant (5.19 vs. 3.67 vs. 3.70, p = .068).

Normalized HRQOL analysis found similar results to the standard HRQOL analysis. No significant HRQOL differences were observed among deformity groups until 1-year follow-up. By 1-year postoperative, cervical deformity patients exhibited the greatest NRS back pain scores (1.17 vs. 0.50 vs. 0.51, p < .001). By 2-year follow-up, while cervical deformity patients still exhibited the greatest back pain, differences among deformity groups were no longer significant (1.20 vs. 0.51 vs. 0.69, p = .060). Cervical deformity patients also exhibited a significantly worse NRS Back Normalized Integrated Health State in comparison to thoracolumbar and combined deformity patients (1.18 vs 0.58 vs. 0.63, p = .004; Figs. 2−4, Table 4).

Regarding rates of MCID achievement, while cervical deformity patients achieved the highest rates of ODI-NDI MCID by 3-month follow-up (33.3% vs. 0% vs. 23.0%, p < .001), cervical, thoracolumbar, and combined deformity patients exhibited similar ODI-NDI MCID rates by 2-year follow-up (51.9% vs. 59.3% vs. 62.9%, p = .563). While all deformity groups met similar NRS Back MCID rates by 3-month follow-up (66.7% vs. 65.2% vs. 51.0%, p = .564),

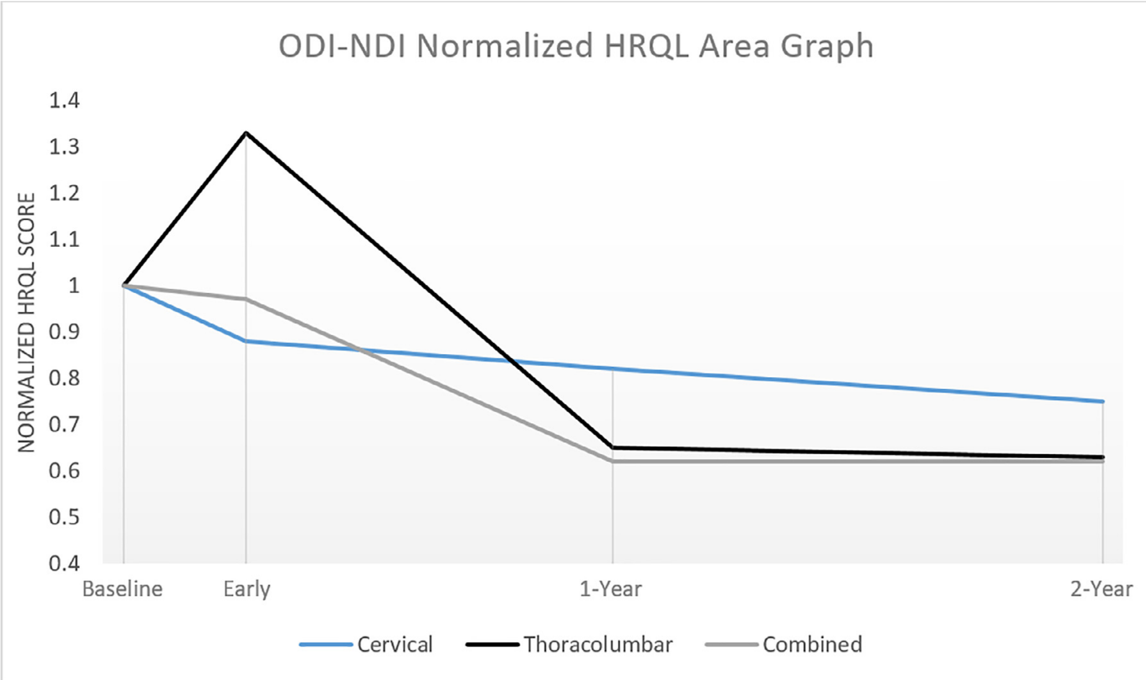

Fig. 2. Area graph representation of normalized ODI-NDI HRQOL scores for cervical, thoracolumbar, and combined deformity patients. y axis represents normalized HRQOL values, x axis represents time.

cervical patients progressively developed additional back pain throughout the postoperative recovery period, resulting in significant lower MCID rates by 2-year follow-up (40.7% vs. 77.8% vs. 64.7%, p = .015) in comparison to thoracolumbar and combined deformity patients (Table 5).

Regression analysis

Multiple linear regression model was used to determine predictors of elevated 2-year follow-up NRS Back pain scores, as well as integrated health state NRS Back pain

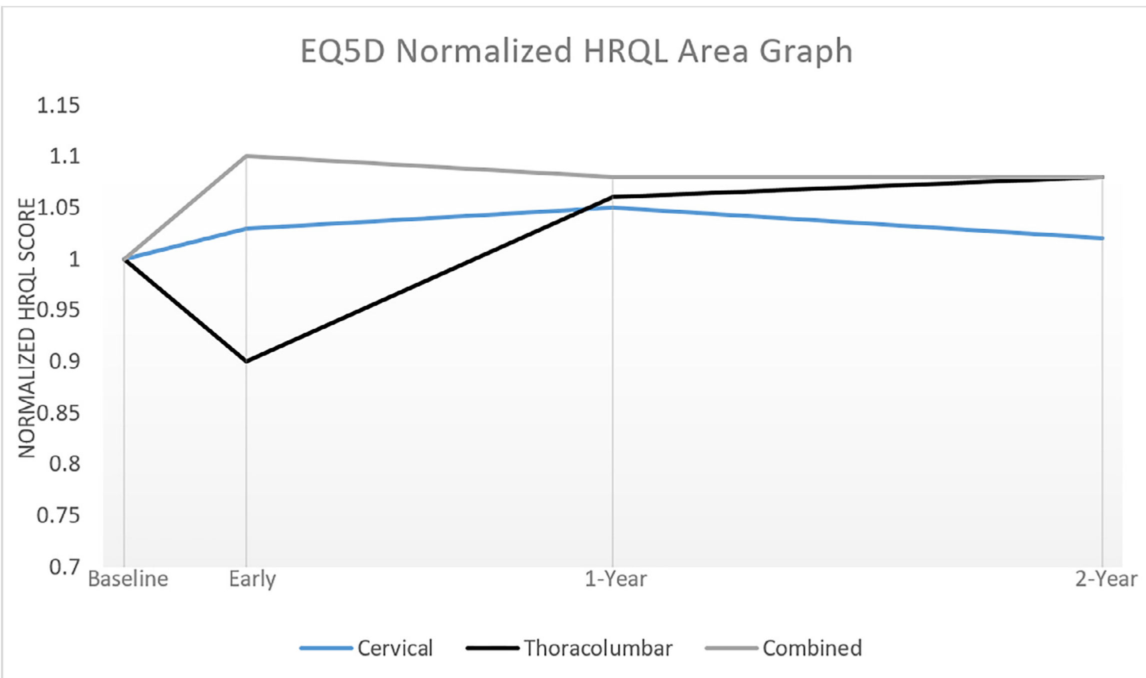

Fig. 3. Area graph representation of normalized EQ5D HRQOL scores for cervical, thoracolumbar, and combined deformity patients. y axis represents normalized HRQOL values, x axis represents time.

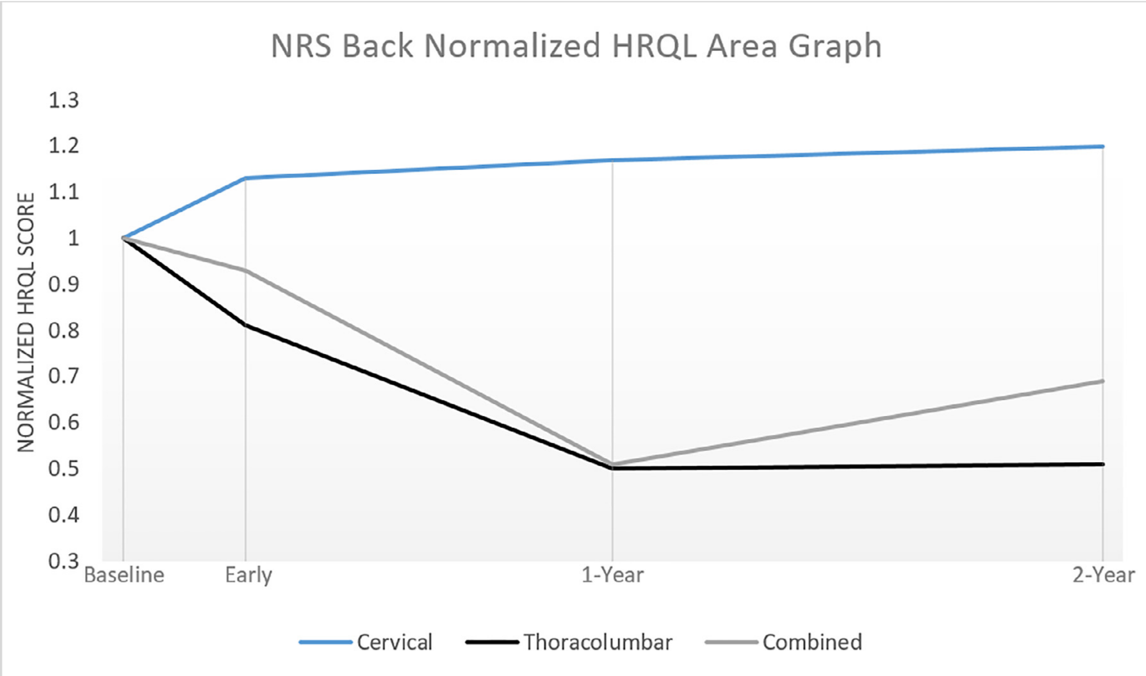

Fig. 4. Area graph representation of normalized NRS back HRQOL scores for cervical, thoracolumbar, and combined deformity patients. y axis represents normalized HRQOL values, x axis represents time.

Table 4
Standard, normalized, and integrated health state HRQL outcome comparisons

	Cervical	Thoracolumbar	Combined	p value
Standard HRQL Analysis				
Baseline ODINDI	49.26	45.41	46.48	.648
Early ODINDI	42.39	48.00	43.87	.737
1Y ODINDI	38.69	31.70	28.75	.067
2Y ODINDI	36.79	29.91	29.76	.294
Baseline EQ5D	0.75	0.75	0.74	.938
Early EQ5D	0.77	0.67	0.74	.591
1Y EQ5D	0.78	0.78	0.80	.507
2Y EQ5D	0.76	0.80	0.80	.204
Baseline NRS back	5.96	7.52	6.89	.052
Early NRS back	4.56	4.61	5.39	.278
1Y NRS back	4.88	3.64	3.28	**.028**
2Y NRS back	5.19	3.67	3.70	.068
Normalized HRQL analysis				
Baseline ODINDI	1	1	1	1
Early ODINDI	0.88	1.33	0.97	.623
1Y ODINDI	0.82	0.65	0.62	.083
2Y ODINDI	0.75	0.63	0.62	.344
Baseline EQ5D	1	1	1	1
Early EQ5D	1.03	0.90	1.1	.327
1Y EQ5D	1.05	1.06	1.08	.450
2Y EQ5D	1.02	1.08	1.08	.153
Baseline NRS back	1	1	1	1
Early NRS back	1.13	0.81	0.93	.893
1Y NRS back	1.17	0.50	0.51	**<.001**
2Y NRS back	1.20	0.51	0.69	.060
Normalized Integrated Health State				
ODINDI	0.83	0.79	0.67	.131
EQ5D	1.03	0.96	1.08	.114
NRS back	1.18	0.58	0.63	**.004**

ODI, Oswestry disability index; NDI, neck disability index; EQ5D, Euroqol 5 dimensions questionnaire; NRS, numeric rating scale. Bolded values indicate statistical significance to $p < 0.05$.

scores. Independent predictors entered into the model included presence of DJK at 2-year follow-up, BMI, levels fused, age, gender, osteoporosis, 2-year C7-S1 SVA, and 2-year T1SS. Age (Adjusted Beta: −0.165, p = .007), Osteoporosis (Adjusted Beta: 0.219, p = .021), and 2-year DJK presence (Adjusted Beta: 0.167, p = .068) were the strongest predictors of elevated 2-year NRS Back pain scores (Model Summary: R^2 = 0.182, p = .004). 3-month DJK presence (Adjusted Beta: 0.207, p = .039) and Osteoporosis (Adjusted Beta: 0.269, p = .007) were also predictive of elevated integrated health state NRS Back pain scores (Model Summary: R^2 = 0.177, p = .039; Table 6).

Discussion

Clear, objective benchmarks are needed to determine expectations in what constitutes a "good" versus a "bad" recovery process across multiple follow-up visits and varying spinal deformity morphometries. This study made it a priority to objectively define and compare the complete 2-year postoperative recovery process among operative cervical only, thoracolumbar only, and combined cervical and thoracolumbar deformity patients using AUC methodology. Whereas static analysis of outcomes typically reports absolute improvement or deterioration in clinical outcomes between 2 discrete time points, normalized AUC analysis used in this study provides an extended outcome evaluation over the entire recovery process. Clinically, the AUC analysis in this study assesses the disability recovery state, or the level of disability a patient experiences over the course of the entire recovery process. To the best of our

Table 5
Prevalence of MCID achievement among varying deformity morphometries

Prevalence of MCID achievement				
	Cervical	Thoracolumbar	Combined	p value
Early ODINDI	33.3%	0.00%	23.0%	**<.001**
1Y ODINDI	42.3%	65.4%	62.5%	.138
2Y ODINDI	51.9%	59.3%	62.9%	.563
Early NRS back	66.7%	65.2%	51.0%	.564
1Y NRS back	34.6%	84.0%	70.8%	**<.001**
2Y NRS back	40.7%	77.8%	64.7%	**.015**

ODI, Oswestry disability index; NDI, neck disability index; NRS, numeric rating scale. Bolded values indicate statistical significance to $p < 0.05$.

knowledge, this is the first study using AUC methodology to provide direct objective postoperative recovery comparisons among patients with varying spinal deformity morphometries.

Our study found that of cervical, thoracolumbar, and combined deformity patients with similar baseline demographics (exception: CCI) and HRQOL scores, cervical deformity patients were significantly more likely to achieve ODI-NDI MCID within the early postoperative period compared with thoracolumbar and combined patients. Despite this notion, by 2-year follow-up, all deformity types showed similar rates of ODI-NDI MCID achievement. Although intuitive due to the less invasive procedures performed on cervical deformity patients, the utilization of MCID increases clinical applicability of these findings, and sets expectations for threshold MCID achievements across multiple follow-up points. A fallback from the utilization of MCID is that the scalar component of an HRQOL is lost, losing the ability granularly track a patients postoperative recovery process. Furthermore, MCID is only validated to capture a patient's improvement, and fails to capture HRQOL deterioration [12]. Therefore, the utilization of the normalized AUC (ie, Integrated Health State) methodology proposed by Liu et al., which minimizes baseline patient HRQOL variability, more greatly captures HRQOL improvement and deterioration while retaining the scalar HRQOL component lost with MCID. This effectively may provide a more clinically relevant assessment of postoperative outcomes and the postoperative recovery process.

AUC analyses are relatively common in the radiology literature, especially in the context of receiver operating characteristic (ROC) analyses. However, their use in the surgical spine literature is somewhat sparse. It is important to note that although similar to the AUC value calculated in ROC analyses, the AUC value we derived in our analysis is not the same. In a ROC curve, the AUC serves as a measure of accuracy for models discriminating between patients in "diseased" and "non-diseased" states, or the probability that a randomly chosen "diseased" patient is accurately characterized as compared with a "non-diseased" patient [26]. Unlike ROC analyses, in our study, the AUC does not represent a probability between 0.5 and 1; instead, the normalized AUC value (integrated health state) serves as an outcome assessment tool for comparing patient groups, representing the level of pain or disability patients experience throughout the recovery process.

Within our analysis, while all deformity types showed postoperative ODI-NDI and EQ5D improvement and similar normalized integrated health state scores, cervical deformity patients exhibited a significantly worse NRS Back integrated health state score following surgery, compared with other deformity types. This indicates that cervical

Table 6
Multiple regression analysis determining predictors of increased 2-year and Integrated Health State (IHS) NRS back pain among all patients

Dependent variable: 2-year NRS back score					
Independent predictors	Adjusted beta	[Beta confidence interval]	p value	Model R^2	Model p value
Y2 DJK	0.167	−0.12 to 3.21	**.068**	0.182	**.004**
BMI	0.050	−0.06 to 0.10	.607		
Levels Fused	−0.101	−0.19 to 0.06	.270		
Age	−0.164	−0.12 to −0.02	**.007**		
Gender	−0.144	−2.26 to 0.25	.116		
Osteoporosis	0.219	0.27 to 3.21	**.021**		
Y2 C7-S1 SVA	0.069	−0.01 to 0.02	.533		
Y2 T1-Slope	0.146	−0.01 to 0.08	.164		
Dependent variable: IHS NRS back score					
Independent predictors	Adjusted beta	[Beta confidence interval]	p value	Model R^2	Model p value
3M DJK	0.207	0.23 to 2.08	**.039**	0.177	**.039**
BMI	0.042	0.02 to 0.85	.661		
Levels Fused	−0.073	−0.24 to 0.02	.425		
Age	−0.107	−0.04 to 0.02	.262		
Gender	−0.088	−0.02 to 0.00	.384		
Osteoporosis	0.269	−0.39 to 0.150	**.007**		
3M C7-S1 SVA	0.067	−0.00 to 0.00	.562		
3M T1-Slope	0.031	−0.01 to 0.01	.772		

DJK, distal junctional kyphosis; BMI, body mass index; SVA, sagittal vertical axis. Bolded values indicate statistical significance to $p < 0.05$.

deformity patients were in a greater state of postoperative back pain, for a significantly longer amount of time. Multiple linear regression models were used to identify drivers of worse integrated health state NRS back pain and 2-year NRS back pain among the entire cohort, determining DJK, Age, and Osteoporosis to be the strongest predictors. Despite that junctional spinal disorders are recognized as one of the greatest challenges in spinal deformity surgery, there is a relatively sparse amount of literature dedicated to the subject. Of the data that is available, very little correlations have been found between clinical symptoms and radiographic junctional disorders [27]. Furthermore, controversy surrounding the effect of junctional kyphosis on clinical outcomes has made the development of management guidelines a challenge for physicians and researchers alike, with minimal guidelines existing for PJK through the Hart-ISSG classification system [28], and no existing systems in place for DJK. Previous studies investigating the effect of PJK on clinical outcomes in adolescent and adult scoliosis patients have found no difference is scoliosis research society questionnaire scores among PJK and non-PJK patients [29−31]. Other studies by Kim et al. have described the potential fallbacks to the SRS questionnaire and identified PJK patients to have a significant higher rate of postoperative upper back pain [32,33]. Despite controversy surrounding the clinical effect of PJK, very few studies have investigated the associations between DJK and clinical HRQOL assessments. A recent study by Passias et al. reported no differences among baseline HRQOL assessments in cervical deformity patients who did and did not experience DJK [34]. To the best of our knowledge, this is the first study to determine DJK as a driver of NRS Back pain scores among spinal deformity patients. Furthermore, the utility of the Integrated Health State is exemplified in this study, in that by integrating the entire postoperative recovery process into 1 number, we can more readily isolate factors that can influence a patient's entire postoperative recovery process. As we see within our analysis, DJK development at 3-months was a significant predictor of a longer, more painful recovery process in cervical deformity patients.

Despite the successes of this analysis, and the generalizability of these results due to the multicenter design, this study is not without limitations. A primary limitation is that within this study, the cervical and thoracolumbar deformity groups are limited by relatively small sample sizes (n = 27). The AUC methodology used in the present study requires complete outcome data for all follow-up time points, which limits the number of patients meeting inclusion criteria, as full follow-up is often difficult to obtain. Furthermore, the AUC methodology in this study assumes a linear recovery between follow-up intervals, which may not be the case for many patients. Clinical data from more follow-up intervals are necessary to better gauge patient recovery patterns. Additionally, baseline normalized HRQOL values all start at 1, which sacrifices fluctuations in baseline HRQOL values for a greater sensitivity of postoperative HRQOL changes and group comparisons. While this does not affect the nature of our findings, normalized HRQOL values should not be mistaken as an equal or matched starting point. Furthermore, this analysis was only able to investigate the postoperative recovery process using the ODI-NDI, EQ5D, and NRS Back clinical outcomes assessments. In light of high postoperative PJK rates associated with thoracolumbar and combined deformity patients, additional neurologic and pain assessments (such as the modified Japanese Orthopaedic Association or NRS Neck pain assessments) may be warranted for a thorough and complete assessment of the postoperative recovery process among all spinal deformity patients.

Conclusion

This study objectively defined and compare the complete 2-year postoperative recovery process among operative cervical only, thoracolumbar only, and combined cervical and thoracolumbar deformity patients, using AUC methodology to minimize analytical bias. Our study found that of deformity patients with similar baseline demographics and HRQOL scores, cervical deformity patients were more likely to achieve ODI-NDI MCID within the early postoperative period compared with thoracolumbar and combined patients. Despite this notion, by 2-year follow-up, all deformity types showed similar rates of ODI-NDI MCID achievement. Furthermore, while all deformity types showed similar and improved postoperative ODI-NDI and EQ5D recovery processes, cervical deformity patients exhibited a worse NRS Back pain recovery process, indicating that cervical deformity patients were in a greater state of postoperative back pain for longer amount of time. Multiple linear regression models identified postoperative DJK and preoperative osteoporosis as the strongest predictors of a worse NRS Back pain recovery process and overall scores. Utilization of the integrated health state in conjunction with predictive modelling may pose as an innovative and improved method of gauging the effect surgical details and complications on a patient's entire recovery process.

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