Original Article

Radiographic benefit of incorporating the inflection between the cervical and thoracic curves in fusion constructs for surgical cervical deformity patients

ABSTRACT

Purpose: The aim is to assess the relationship between cervicothoracic inflection point and baseline disability, as well as the relationship between clinical outcomes and pre- to postoperative changes in inflection point.

Methods: Cervical deformity (CD) patients with baseline and 3-month (3M) postoperative radiographic, clinical, and inflection data were grouped by region of inflection point: C6 or above, C6-C7 to C7-T1, T1, or below. Inflection was defined as: Distal-most level where cervical lordosis (CL) changes to thoracic kyphosis (TK). Differences in alignment and patient factors across pre- and postoperative inflection point groups were assessed, as were outcomes by the inclusion of inflection in the CD-corrective fusion construct.

Results: A total of 108 patients were included. Preoperative inflection breakdown: C6 or above (42%), C6-C7 to C7-T1 (44%), T1 or below (15%). Surgery was associated with a caudal migration of inflection by 3M: C6 or above (8%), C6-C7 to C7-T1 (58%), T1 or below (33%). For patients with preoperative inflection T1 or below, the inclusion of inflection in the fusion construct was associated with improvements in horizontal gaze (McGregor's Slope included: 11.3 vs. not included: 1.6 , $P = 0.038$). The inclusion of preoperative inflection in fusion was associated with the superior cervical sagittal vertical axis (cSVA) changes for C6-C7 to C7-T1 patients (5.2 mm vs. 3.2 mm, $P = 0.018$). The location of postoperative inflection was associated with variation in 3M alignment: Inflection C6 or above was associated with less Pelvic Tilt (PT), PT and a trend of larger cSVA. Location of inflection or inclusion in fusion was not associated with reoperation or distal junctional kyphosis.

Conclusions: Incorporating the inflection point between CL and TK in the fusion construct was associated with superior restoration of cervical alignment and horizontal gaze for surgical CD patients.

Keywords: Cervical deformity, cervicothoracic junction, inflection, outcomes, surgery

INTRODUCTION

The cervical spine serves as a crucial column of support responsible for transmitting the weight of the cranium. Critical in establishing the harmonious sagittal balance of the cervical spine is the cervicothoracic junction.[1] As the cervicothoracic junction serves as a transition point between the flexible cervical spine and the rigid thoracic spine, it is thought to be a biomechanically important site in bearing axial weight from the head.[2,3]

To date, few studies have investigated the inflection point between cervical lordosis (CL) and thoracic kyphosis (TK),

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particularly in the context of cervical deformity (CD). One radiographic survey of 172 lateral spinal radiographs from nondeformed patients suggests that the natural inflection point between the cervical and thoracic curves is near T3 and that an age-related cranial shift in the cervicothoracic inflection point may be normal.[4] Cranial migration of the cervicothoracic inflection point may be associated with an anterior shift in cervical sagittal alignment, resulting in increased shear stress at the cervicothoracic transition. It remains unclear, however, whether a relationship exists between cervicothoracic inflection point, sagittal alignment, or neck disability for patients diagnosed with CD.

The present study aims to assess the relationship between cervicothoracic inflection point, sagittal alignment, and neck disability for surgical CD patients. Specifically, as CD-corrective surgery is associated with significant pre- to postoperative changes in cervical sagittal alignment, this study seeks to investigate whether operative intervention is associated with similar changes in cervicothoracic inflection point and whether including inflection point in the fusion construct is associated with superior clinical or radiographic outcomes.

MATERIALS AND METHODS

Study design
This study analyzes a database of consecutive CD patients >18 years old prospectively enrolled at 13 spine centers across the United States. All patients presented for surgical evaluation of CD, defined from baseline radiographs as cervical kyphosis (C2-C7 sagittal Cobb angle >10°), cervical

scoliosis (C2-C7 coronal Cobb angle >10°), C2-C7 sagittal vertical axis (cSVA) >4 cm or chin-brow vertical angle >25°. Patients with active tumors, infection, or deformity of neuromuscular etiology were excluded from the database.

Data collection and radiographic assessment
Standardized forms collected patient demographic and comorbidity (including Charlson Comorbidity Index score) information.[5] Patient frailty was assessed using the previously published modified CD frailty index.[6] The following validated health-related quality of life (HRQL) measures were administered to patients at baseline and follow-up intervals: Numeric Rating Scales for Neck and Back Pain, Neck Disability Index (NDI), and the 5-dimension, 3-level EuroQol questionnaire.[7,8] The modified Japanese Orthopaedic Association (mJOA) was also administered as a measure of cervical myelopathy severity.[9]

Standing anterior-posterior and lateral long-cassette radiographs and corresponding cervical radiographs were analyzed using validated software (Spine view, ENSAM Laboratory of Biomechanics, Paris, France) as previously published.[10-12] Long cassette radiographs were used to assess global alignment through the SVA (horizontal distance from C7 plumbline relative to the posterosuperior corner of S1). Regional alignment parameters assessed were pelvic tilt (PT), pelvic incidence (PI), TK, lumbar lordosis (LL), CL, cSVA, and T1 slope [Figure 1]. Upper-cervical alignment parameters included C0-C2 sagittal Cobb angle (C0-C2), C2 slope, and McGregor's slope (McGS; a validated measure of horizontal gaze).[13] Mismatches between T1 slope and CL (TS-CL), and PI and LL (PI-LL) were calculated as measures of harmonious cervical and thoracolumbar alignment, respectively. The cervicothoracic inflection point was identified numerically as the level where CL changes to TK. For patients with multiple inflection points, the distal-most was included in the analysis.

Statistical analysis
This study hypothesizes that there is a relationship between cervicothoracic inflection points and outcomes following CD-corrective surgery. Only patients with available radiographic, HRQL, and cervicothoracic inflection point data at pre- and 3-month (3M) postoperative study intervals were retained for the analysis. Descriptive analyses summarized demographic, clinical, and radiographic variables. Pre- to postoperative changes in alignment were assessed with paired samples *t*-tests. Patients were grouped by region of postoperative cervicothoracic inflection point: C6 or above, C6-C7 to C7-T1, and T1 or below. Differences in demographic, clinical, surgical, and radiographic variables were assessed across patient groups using analysis of variance for continuous variables and Chi-squared tests for categorical variables. Secondary analysis

grouped patients by the inclusion of postoperative inflection points in the fusion construct. Independent samples *t*-tests compared patients whose inflection points were included in the fusion construct to patients whose inflection points were not for differences in clinical and radiographic variables. Pearson bivariate correlation assessed the relationship between pre-to postoperative changes in an inflection point, alignment, and clinical outcomes. All analyses were conducted with SPSS software (version 23.0, IBM, Armonk, New York). All statistical tests were two-tailed; $P < 0.05$ were considered statistically significant.

RESULTS

Cohort overview
Overall, 108 patients met inclusion criteria and were included in the analysis. Table 1 provides a demographic, surgical, and radiographic description of the overall cohort. By Ames Classification descriptor, 55.7% of patients had "cervical" deformity drivers, 26.4% had "cervicothoracic," 11.3% had "thoracic" and 6.6% had "coronal." At baseline, patients presented with moderate horizontal gaze disruption (McGS: 4.4°±13.6) and moderate-to-severe cervical malalignment, as assessed by TS-CL (37.6°±18.5) and cSVA (47.0 mm ± 25.7). At 3M postop, the overall cohort showed significant improvement in cervical alignment: cSVA (37.3 mm ± 18.9), TS-CL (26.8°±13.2), McGS (-2.0°±8.2, all $P < 0.001$), as well as distal alignment: TK (-40.3°±15.7 to-43.0°±15.5, $P = 0.013$).

Cohort breakdown by the inflection point
Preoperatively, the overall breakdown by inflection point was: C6 or above (42%), C6-C7 to C7-T1 (44%), T1 or below (15%). There was significant variation in inflection point across Ames descriptor groups, with the majority of "cervical" patients

having inflection points from C6-C7 to C7-T1, the majority of "cervicothoracic" patients having inflection points C6 or above, and the majority of "thoracic" patients having inflection points T1 or below [Table 2, $P = 0.002$].

Radiographic assessment by inflection point
Overall, CD-corrective surgery was associated with a caudal migration of cervicothoracic inflection by 3M postop: C6 or above (8%), C6-C7 to C7-T1 (58%), T1 or below (33%). Figure 2 shows the breakdown of postoperative inflection point by preoperative inflection point groups–of note, the majority of patients with preoperative inflection

Table 1: Preoperative demographic, surgical, and radiographic overview of the included cervical deformity cohort (*n*=108)

|	Mean (± Standard Deviation) or Frequency (%)
Demographics	
Age (years)	61.2±10.5
Body Mass Index (kg/m²)	29.2±7.7
Sex (% female)	66.4%
Surgical Factors	
Levels fused	8.3±4.5
Posterior-only surgical approach	52.8%
Anterior-only surgical approach	15.7%
Combined surgical approach	31.5%
Any osteotomy	55.6%
Smith Petersen osteotomy	18.5%
Pedicle subtraction osteotomy	16.7%
Vertebral column resection	6.0%
Sagittal Radiographic Alignment	
PT (°)	19.7±11.0
PI-LL (°)	1.0±17.0
SVA (mm)	3.7±68.0
TK (°)	-40.3±15.7
CL (°)	-5.0±20.8
TS-CL (°)	37.6±18.5
cSVA (mm)	47.0±25.7
C0-C2 sagittal Cobb (°)	33.3±11.3
McGregor's Slope (°)	4.4±13.6
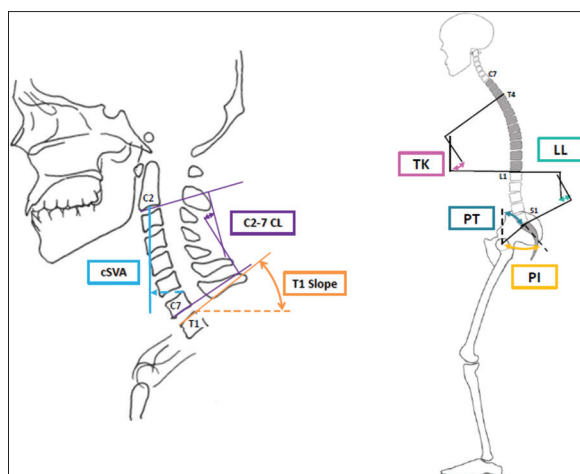
Figure 1: Schematic demonstrating common cervical sagittal alignment parameters (C2-C7 cervical lordosis [CL], C2-C7 sagittal vertical axis [cSVA], T1 slope) and regional alignment paramters (T4-T12 thoracic kyphosis [TK], L1-S1 lumbar lordosis [LL], pelvic tilt [PT], pelvic incidence [PI])
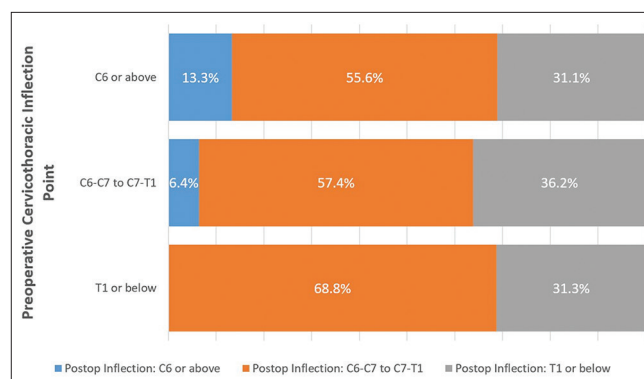

Figure 2: A breakdown of postoperative inflection point by preoperative inflection point groups

points C6 or above showed caudal migration of inflection point to C6-C7/C7-T1 (55.6%), while the majority of patients with preoperative inflection points T1 or below showed cranial migration of inflection point to C6-C7/C7-T1 (68.8%).

Across postop inflection point groups, there were no differences in preopertive alignment for upper-cervical, cervical, or global alignment parameters, though those with postop inflection C6 or above showed significantly less pelvic retroversion (PT) and a trend of larger cSVA [Table 3]. Following surgery, inflection points C6 or above were associated with a greater deformity in cSVA and CL. Postop inflection groups did not differ in pre-to postop alignment changes for any radiographic parameters (all *P* > 0.05).

Demographic and surgical assessment by the cervicothoracic inflection point

There were no differences in baseline demographics, frailty, or comorbidity burden across postop inflection point groups [Table 4]. There was no difference in fusion length across inflection point groups, though osteotomy was associated with higher rates of postoperative cervicothoracic inflection above T1.

Clinical assessment by inflection point

There were no differences across preoperative inflection point groups in baseline HRQL scores (all *P* > 0.1). Although patients with postoperative inflection points T1 or below showed significantly lower levels of preoperative back pain, there were no significant differences across inflection point groups in clinical outcomes at 3M postop [Table 5]. There was a trend of superior postop NDI (*P* = 0.078) and back pain (*P* = 0.054) outcomes for patients with inflection points T1 or below. Pre-to postoperative changes in clinical outcomes did not differ across inflection groups (all *P* > 0.05). The length of inpatient stay similarly did not differ across inflection groups (*P* = 0.890).

Table 2: Breakdown of baseline cervicothoracic inflection point location (C6 or above, C6-C7 to C7-T1, T1 or below) across patients stratified by Ames cervical deformity types

Ames Descriptor Group	C6 or above (*n*=9)	C6-C7 to C7-T1 (*n*=63)	T1 or below (*n*=36)	*p*
Cervical	35.6%	52.5%	11.9%	
Cervicothoracic	64.3%	25.0%	10.7%	
Thoracic	33.3%	25.0%	41.7%	0.002
Coronal	0.0%	85.7%	14.3%	

Table 3: Comparison of baseline (BL) and 3-month postoperative (3M) sagittal alignment across patients grouped by location of postoperative inflection point (C6 or above, C6-C7 to C7-T1, T1 or below)

		C6 or above (*n*=9)	C6-C7 to C7-T1 (*n*=63)	T1 or below (*n*=36)	*p*
Sagittal Alignment					
PT (°)	BL	8.1±12.6	21.6±9.3	19.1±12.0	*P=0.002
	3M	11.0±12.4	22.3±9.1	20.5±12.0	*P=0.011
PI-LL (°)	BL	-11.1±26.4	1.9±14.0	2.4±18.3	P=0.081
	3M	-6.9±22.3	5.4±13.3	3.6 ±20.0	P=0.119
SVA (mm)	BL	-12.8±55.3	-2.4±65.7	18.4±73.8	P=0.267
	3M	-16.1±44.6	32.2±69.4	32.8±72.0	P=0.133
TK (°)	BL	-35.2±21.1	-40.1±15.3	-41.9±15.2	P=0.520
	3M	-36.7±20.4	-43.7±14.0	-43.3±16.9	P=0.439
cSVA (mm)	BL	57.8±17.5	49.9±24.4	38.9±28.4	P=0.066
	3M	52.7±11.8	41.9±17.5	29.7±19.0	*P<0.001
CL (°)	BL	-9.8±15.4	-2.4±22.5	-8.2±18.9	P=0.353
	3M	-1.9±15.0	10.6±16.4	4.5±14.8	*P=0.040
TS-CL (°)	BL	39.7±17.5	38.3±24.4	38.9±28.4	P=0.796
	3M	29.0±13.4	28.4±13.0	25.6±15.9	P=0.617
C0-C2 sagittal Cobb (°)	BL	36.8±9.6	32.0±11.6	35.0±11.0	P=0.369
	3M	32.4±9.5	27.0±10.7	27.0±10.8	P=0.350
McGregor's Slope (°)	BL	6.4±13.0	6.0±14.5	0.7±11.5	P=0.244
	3M	-0.8±9.2	-2.1±8.5	-3.5±8.1	P=0.623
C2 slope (°)	BL	42.8±18.4	38.6±20.6	35.9±17.5	P=0.599
	3M	31.7±13.0	26.2±13.0	23.9±14.3	P=0.303

Bolded and asterisked values indicate statistical significance to *p*<0.05.

Table 4: Comparison of demographic and surgical factors across patients grouped by postoperative location of inflection point (C6 or above, C6-C7 to C7-T1, T1 or below)

	C6 or above (n=9)	C6-C7 to C7-T1 (n=63)	T1 or below (n=36)	p
Demographics				
Age (years)	64.1±10.2	61.4±9.9	60.1±11.7	P=0.572
BMI (kg/m²)	30.3±7.2	29.0±7.3	29.1±8.7	P=0.889
Sex (% female)	33%	67%	74%	P=0.068
Charlson Comorbidity Index (CCI score)	1.22±1.09	0.89±1.19	1.35±1.76	P=0.319
Frailty (mCD-FI score)	0.34±0.14	0.29±0.14	0.31±0.14	P=0.473
Surgical Factors				
Number of levels fused	8.8±4.7	8.8±4.9	7.2±3.6	P=0.305
Any Posterior Osteotomy (%)	56%	65%	39%	*P=0.041
Smith Petersen Osteotomy (%)	22.2%	19.0%	16.7%	P=0.916
Pedicle Subtraction Osteotomy (%)	33.3%	19.0%	8.3%	P=0.145
Vertebral Column Resection (%)	0.0%	7.9%	2.8%	P=0.419

Bolded and asterisked values indicate statistical significance to *p*<0.05

Table 5: Comparison of health-related quality of life scores at both baseline (BL) and 3-month postoperative (3M) intervals across patients grouped by location of postoperative inflection point (C6 or above, C6-C7 to C7-T1, T1 or below)

		C6 or above (n=9)	C6-C7 to C7-T1 (n=63)	T1 or below (n=36)	p
Clinical Outcome Assessment					
Numeric Rating Scale - Back Pain	BL	6.0±2.6	5.9±2.9	4.3±3.3	*P=0.042
	3M	5.6±2.7	5.5±3.1	3.9±3.4	P=0.054
Numeric Rating Scale - Neck Pain	BL	7.4±1.1	7.0±2.5	6.7±2.5	P=0.688
	3M	5.3±2.1	4.6±3.0	3.4±2.7	P=0.078
Neck Disability Index score	BL	47.8±23.7	48.1±17.5	47.6±17.5	P=0.992
	3M	50.7±15.3	44.2±21.6	41.2±16.9	P=0.417
mJOA score	BL	13.4±3.4	13.4±2.7	13.9±2.8	P=0.992
	3M	13.1±2.4	14.2±2.8	14.3±2.8	P=0.267
EQ-5D score	BL	0.72±0.06	0.74±0.06	0.73±0.07	P=0.801
	3M	0.71±0.05	0.76±0.08	0.76±0.07	P=0.890

Bolded and asterisked values indicate statistical significance to *p*<0.05

Outcomes by the inclusion of inflection point in fusion

Overall, 77.8% of patients had their preoperative inflection points included in the fusion construct. Following surgery, 75.9% of patients had inflection points within the fusion construct. Overall, the inclusion of preoperative inflection point in the fusion construct was not associated with differences in postop distal alignment or compensatory global alignment (all $P > 0.05$); however, for patients with preop inflection points T1 or below, the inclusion of inflection point in the fusion construct was associated with significant pre-to postop improvements in horizontal gaze (McGS of included:-11.3° vs. not included: 1.6°, $P = 0.038$). Similarly, for patients with preoperative inflection points from C6-C7 to C7-T1, inclusion of inflection point in fusion was associated with superior pre-to postop cSVA changes [−5.2 mm vs. 3.2 mm, $P = 0.018$, Figure 3]. Including preoperative inflection point in fusion was not associated with superior pre-to postoperative HRQL or mJOA changes, both overall and by the level of inflection point (all $P > 0.05$).

Patients with postoperative inflection points included in the fusion construct showed superior pre-to postop
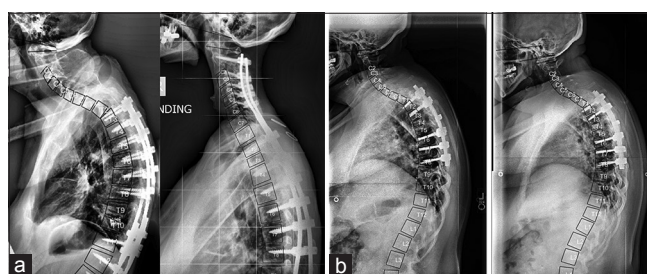

Figure 3: Preoperative (left) and 3-month postoperative (right) case examples of patients with preoperative inflection points C6-C7 to C7-T1. (a) a patient with a preoperative cervicothoracic inflection point at C7-T1 that was included in the fusion construct. This patient's cervical sagittal vertical axis consequently improved from 59.2 mm at baseline to 35.0 mm at 3-months. (b) Shows a patient with a preoperative cervicothoracic inflection point at C7-T1 that was not included in the fusion construct. This patient's cervical sagittal vertical axis consequently deteriorated from 63.8 mm at baseline to 72.5 mm at 3-months

changes in horizontal gaze (McGS: −8.3° vs. not included: −2.3°, $P = 0.008$), TS-CL (−12.6° vs. −5.3°, $P = 0.025$), and cSVA (−12.9 mm vs. −1.9 mm, $P = 0.007$). Including postop inflection point in fusion was not associated with superior pre-to postoperative HRQL or mJOA changes (all $P > 0.05$). Caudal pre-to postoperative change in inflection point

correlated with kyphotic pre-to post-operative changes in CL ($r = 0.237$, $P = 0.026$), but greater reductions in cSVA ($r = -0.254$, $P = 0.017$), C2 slope ($r = -0.200$, $P = 0.040$), and C0-C2 Cobb ($r = -0.227$, $P = 0.037$).

Neither location of postoperative inflection point nor the inclusion of pre-operative inflection point in the fusion construct were associated with reoperation ($P = 0.526$) or distal junctional kyphosis (DJK) development ($P = 0.353$) by 3M postoperative.

DISCUSSION

Previous research makes clear that the evaluation and treatment of CD requires a thorough understanding of the relationship between the cervical, thoracic, and lumbar curves.[14] Although there is wide variation in the cervical curvature of healthy individuals, asymptomatic subjects typically present with lordotic cervical alignment,[15] as this configuration can resist large compressive loads, effectively minimizing the stress on vertebral body endplates.[16,17] In the cervicothoracic region, transition from the lordotic cervical spine to the kyphotic thoracic spine results in appreciable levels of mechanical stress – as a result, the cervicothoracic junction plays an important role in the biomechanics of CD. Despite this biomechanical importance, relatively few studies in the CD literature have investigated the relationship between cervicothoracic inflection point, sagittal alignment, and neck disability. This study showed that for patients undergoing CD-corrective surgery, there was little relationship between the location of the postoperative cervicothoracic inflection point, alignment outcomes, or clinical outcomes. Incorporating the postoperative inflection point in the fusion construct, however, was associated with superior restoration of cervical alignment and horizontal gaze.

Previous research has used the spatial relationship between vertebral bodies to describe variations in sagittal spinal alignment. For example, Roussouly and Nnadi identified the thoracolumbar inflection point-or the point at which the orientation of the thoracolumbar vertebral bodies change-as a key attribute that can be used to delineate four different types of normal spinal curvatures.[18] In addition to describing variation in sagittal spinal shape among healthy adults, this method of classification has also been used to describe variations in alignment among patients diagnosed with adult spinal deformity.[19] Recent research highlights a relationship between these different spine types and clinical outcomes following lumbar disc arthroplasty, suggesting that variation in the inflection point between spinal curves could be an important consideration in indicating patients for surgery.[20]

Although classification systems exist in the literature to describe the sagittal profiles of patients with different types of CD, these frameworks do not incorporate assessments of the cervicothoracic inflection point.[21] The results of this study show significant variations in sagittal alignment across inflection point groups, suggesting a potential rationale for modifying existing CD classification systems to incorporate inflection point.

The results of this study also show that for some CD patients, inclusion of preoperative inflection point in the fusion construct is associated with superior postoperative radiographic outcomes. Specifically, for CD patients with preoperative inflection points T1 or below, the inclusion of inflection point in the fusion construct is associated with superior improvements in the horizontal gaze. For patients with preoperative inflection from C6-C7 to C7-T1, inclusion of inflection point in the fusion construct is also associated with superior cSVA changes. These results are comparable to previous research showing that for CD patients with cervicothoracic drivers of deformity, inclusion of the deformity driver in surgery may be associated with relaxation of lumbopelvic compensation.[22] Importantly, however, whereas previous research shows that including the deformity driver in surgery may be associated with distal changes in alignment, this study shows that including the cervicothoracic inflection point in surgery may be associated with superior changes in cervical alignment and horizontal gaze—both key goals of CD-corrective surgery. These results suggest that the cervicothoracic inflection point may be an important factor to consider in the surgical planning process, though further research is necessary to determine the rate of overlap between inflection point and primary deformity driver.

Guidelines for selecting the appropriate caudal "end level" in long-segment posterior cervical fusion vary across the literature. The consequences of end level selection can be dramatic, with previous research highlighting a potential connection between the inappropriate selection of the lower-most instrumented vertebrae and incidence of DJK.[23] A number of studies suggest that ending posterior fusion constructs at C7 (as opposed to T1) results in inferior postoperative cervical sagittal alignment, and is associated with an increased rate of surgical revision.[24,25] Our study did not show a difference in the rate of DJK between patients whose cervicothoracic inflection points were included in surgery and patients whose inflection points were not; however, it did show superior postoperative alignment outcomes for those with inflection points included in the fusion construct. These results indicate that the cervicothoracic inflection point may warrant additional

consideration by the surgeon when deciding the optimal lower-most instrumented vertebrae for patients undergoing CD-corrective surgery.

This study appreciates a number of limitations, including a limited sample size and a retrospective study design. A particularly important limitation of this study was the inclusion of a heterogeneous population of CD patients. Although including patients form 13 surgical centers provides our analysis with increased generalizability and a patient population representative of CD in the United States, it also results in a patient population with many different types of CD. For example, per the radiographic definition of CD used in this study, some patients may have presented with severe cervical kyphosis (C2-C7 sagittal Cobb angle >10°), while others may have presented with cervical hyperlordosis and severe cSVA deformity (>4 cm). These different types of deformity may be associated with substantial differences in treatment strategy, which in turn may influence radiographic outcomes.

CONCLUSION

Surgery to correct CD was associated with caudal migration of the inflection point between CL and TK. For patients with preoperative inflection points at T1 or below, the inclusion of the inflection point in the fusion construct was associated with significant improvements in the horizontal gaze. Similarly, for patients with preoperative inflection points from C6-C7 to C7-T1, inclusion of inflection point in fusion was associated with superior changes in cervical sagittal alignment. The location of the postoperative inflection point was also associated with variation in postoperative cervical and distal alignment. These findings suggest that the assessment of CD may warrant additional consideration of the cervicothoracic inflection point, particularly as it relates to the appropriate "end level" selection of the CD-corrective fusion construct.

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Conflicts of interest
There are no conflicts of interest

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