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ASD

Impact of cephalad versus caudal lumbar lordosis correction on spinal shape and outcomes of complex deformity spine surgery

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Abstract

Purpose To compare the impact of lumbar lordosis correction achieved by cephalad versus caudal distribution on radiographic alignment and surgical outcomes among adult spinal deformity (ASD) patients.

Methods Patients who underwent ASD surgery with uppermost instrumented vertebrae (UIV) at or above L1, had preoperative pelvic incidence-lumbar lordosis (PI–LL) > 10°, and had full-body radiographs available were included. Eligible patients were categorized by the focus of lordosis correction: caudal (L4–S1 lordosis between 35 and 45°) and cephalad lordosis-based correction. Patient demographics, preoperative and 2 years spinopelvic alignment and PROMs, and 2 years postoperative surgical complications were compared.

Results In total, 187 (111 caudal and 76 cephalad) patients were included, with mean age of 66.2 years, 78.6% female, and mean frailty score of 3.6. Caudally-restored patients often had an upper thoracic UIV, sacrum/ilium LIV, longer length of fusion, and no lateral lumbar interbody fusion (LLIF) while cephaladly-restored patients had two or more LLIFs above L4 ($p < 0.001$). Preoperatively, there were no significant differences in radiographic alignment and PROMs between the two groups ($p > 0.02$). Two years postoperatively, caudally-restored patients had higher L1–S1 LL ($p = 0.015$) and L4–S1 LL ($p < 0.001$), and lower PI–LL ($p = 0.039$) and SVA ($p = 0.001$). In addition, they had higher SRS-22 activity ($p = 0.045$), pain ($p = 0.047$), appearance ($p = 0.046$), and total ($p = 0.016$) scores. Finally, they had lower rates of sensory deficits ($p < 0.001$), motor deficits ($p = 0.003$), implant failure ($p = 0.092$), and reoperation ($p = 0.020$).

Conclusion Caudal lordosis-based correction of spinal deformity patients was associated with higher PROMs and lower rates of neurologic deficits, implant failure, and revisions at 2 years. These findings, while subject to unmeasured confounding, indicate that great caution should be taken when considering cephalad-based correction of ASD.

Keywords Adult spinal deformity · Caudal lordosis · Lumbar lordosis · Lordotic correction · Complications · Patient outcomes

Introduction

Our understanding of optimal sagittal alignment of the spine has evolved since the invention of spinopelvic mismatch concept and data by Schwab et al. [1]. For almost two decades, PI–LL had inspired deeper dives to the regional and global alignment of the spine and its relationship to the pelvis, mainly pelvic incidence (PI) parameter.

While PI–LL of 10 degree had narrowed surgical targets in terms of magnitude of regional lordosis, recent emphasis has been placed on the appropriate distribution of lumbar lordosis. Pesenti et al. reported that the proximal lumbar spine makes a smaller contribution to total lumbar lordosis and is primarily dependent on the degree of pelvic incidence [2]. Distal lordosis, on the other hand, is often constant and inadequate restoration of distal lordosis may result in compensatory changes in the adjacent spine, ultimately contributing to the development of adjacent segment disease [3].

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In deformity correction surgery, the impact of inadequate lumbar distribution on clinical outcomes remain unclear. With recent and ever evolving surgical techniques empowering lumbar correction in the cephalad region such as direct lateral, and oblique interbody devices, it is important to understand the impact of cephalad based correction on spinal deformity outcomes [4, 5] Therefore, this study aimed to investigate two types of patients that underwent cephalad versus caudal based lordosis correction for spinal deformity and study the impact of altering the spinal shape on their 2 years clinical outcomes.

Methods

Study design

The present study was a retrospective analysis of a prospectively collected, multicenter database of ASD patients across 24 spinal deformity centers in the United States and Canada between 2008 and 2020. Institutional review board approval was obtained from all centers before data collection and informed consent was obtained from each patient included in the study.

Patient selection

Patients were included in the database if they were 18 years or older and met one of the following criteria: pelvic incidence-lumbar lordosis mismatch (PI–LL) > 25°, T1 pelvic angle (TPA) > 30°, sagittal vertical axis (SVA) > 15 cm, thoracic scoliosis > 70°, lumbar scoliosis > 50°, or global coronal malalignment > 7 cm. Patients with a history of active spinal tumor or infection and deformity secondary to trauma, neuromuscular conditions, syndromic scoliosis, and autoimmune conditions were excluded. Patients were subsequently included in the current study if they had preoperative PI–LL > 10°, postoperative uppermost instrumented vertebrae (UIV) at L1 or above, no 3-column osteotomies, and full-body radiographs available at preoperative and 2 years postoperative visits.

Data extraction

Patient demographics included age, sex, body mass index (BMI), race, Edmonton Frailty Score, and history of spine surgery. Radiographic measurements based on coronal and sagittal full-length standing films included sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI), T4–T12 thoracic kyphosis (TK), T10–L2 thoracolumbar lordosis (TL), L1–S1 lumbar lordosis (LL), PI–LL, SVA, T1PA, T9 pelvic angle (T9PA), T1 spinopelvic inclination (T1SPi), T4–T12 thoracic apex, L1–S1 lordotic apex, and UIV inclination and translation. Patient-reported outcome measures included Lumbar Stiffness Disability Index (LSDI), Oswestry Disability Index (ODI), Scoliosis Research Society 22-item (SRS-22) for activity, pain, appearance, and total scores, and Short-Form 36-item (SF-36) for physical (PCS) and mental (MCS) component scores. Surgical complications included wound, infections, neuropraxia (e.g., sensory deficit, motor deficit), implant failure (e.g., rod breakage, screw loosening), implant malposition, radiographic (e.g., adjacent segment disease, proximal junctional kyphosis [PJK], pseudoarthrosis), and reoperation.

Statistical analyses

Eligible patients were categorized into two groups according to the location of lordosis correction: caudal lordosis-based correction (L4–S1 between 35 and 45°) and cephalad lordosis-based correction. Patient demographics, preoperative and 2 years spinopelvic alignment and PROMs, and 2 years postoperative surgical complications were compared using chi-squared test for categorical variables and student's *t*-tests for quantitative variables. All statistical analyses were conducted using SPSS Statistics for Windows, Version 29.0 (Armonk, NY: IBM Corp), with statistical significance defined as $p < 0.05$.

Results

Patient characteristics

In total, 187 patients, which included 111 caudal-based and 76 cephalad-based lumbar lordosis correction patients, met the inclusion criteria (Fig. 1). The mean age was 66.2 years, 78.6% were female, and mean frailty score was 3.6, with only the percent female sex being statistically different across groups (Caudal = 87.4% vs. Cephalad = 65.8%, $p < 0.001$). Caudally-restored patients frequently had an upper thoracic UIV (36.9% vs. 15.8%, $p < 0.001$), a sacrum/ilium LIV (99.1% vs. 88.2%, $p < 0.001$), and longer length of fusion (11.1 vs. 8.9 levels, $p < 0.001$). No statistically significant different was reported in BMI, race, prior spine surgeries, and Surgical Invasiveness Index (Table 1). Caudally-restored patients had no lateral lumbar interbody fusions (LLIFs) while all cephaladly-restored patients had two or more LLIFs above L4.

Radiographic spinopelvic alignment

At baseline, with the exception of a more caudal apex of lordosis in the caudally-restored patients (L4 vs. L3–L4, $p = 0.008$), there were no significant difference in radiographic alignment between the two groups. Two years

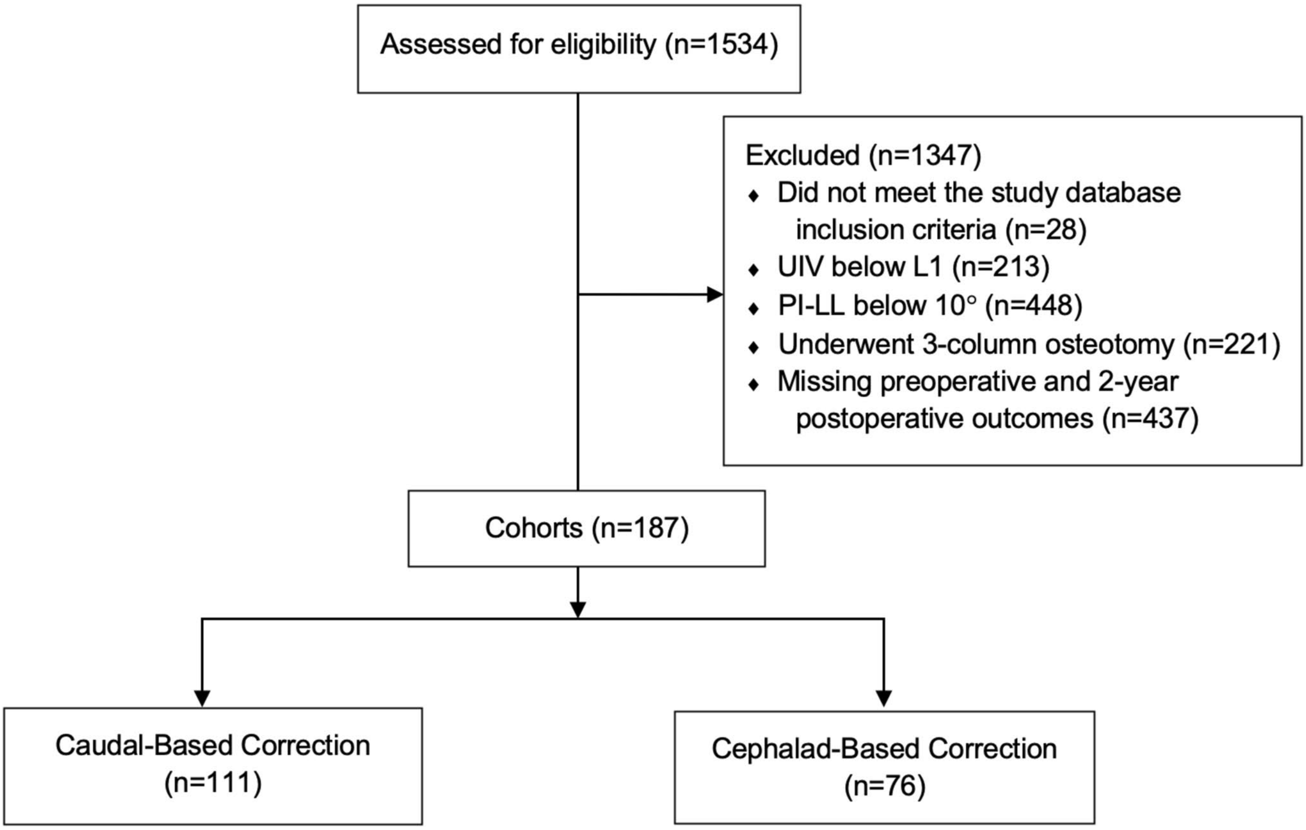

Fig. 1 Consort study flow diagram

postoperatively, caudally-restored patients had slightly higher L1–S1 LL (52.6° vs. 48.0°, $p=0.015$), resulting from a higher L4–S1 LL (36.9° vs. 32.4°, $p<0.001$), and lower PI–LL (6.0° vs. 9.9°, $p=0.039$), SVA (30.4 mm vs. 56.7 mm, $p=0.001$), T1PA (19.3° vs. 22.4°, $p=0.024$), and T9PA (10.3° vs. 12.9°, $p=0.036$). They also continued to have a more caudal apex of lordosis ($p=0.005$) (Table 2). In addition, UIV inclination and translation were comparable across groups, though caudally-restored patients had non-significantly lower UIV inclination at 6 weeks postoperatively (− 6.1° vs. − 10.6°, $p=0.057$) that became more comparable by 2 years postoperatively (− 4.5° vs. − 5.8°, $p=0.616$) (Table 3). Similarly, T10 translation above 15° was comparable across groups (31.5% vs. 34.2%, $p=0.701$), though it was predictive of PJK at 2 years postoperatively (T10 above 15° = 34.4% vs. T10 below 15° = 14.3%, $p=0.001$).

Patient-reported outcome measures

Preoperatively, there was no difference in PROMs between the two groups. Two years postoperatively, caudally-restored patients had higher SRS-22 activity (3.7 vs. 3.4, $p=0.045$), better SRS-pain (3.7 vs. 3.4, $p=0.047$), appearance (3.7 vs. 3.4, $p=0.046$), and total (3.8 vs. 3.5, $p=0.016$) scores but the groups were otherwise comparable (Table 2).

Surgical complications

Two years postoperatively, caudally-restored patients had significantly lower rates of sensory deficits (including neuropraxia) (8.1% vs. 27.6%, $p<0.001$), such as dysesthesias (6.3% vs. 21.1%, $p=0.003$) and paresthesias (6.3% vs. 22.4%, $p=0.001$), and motor deficits (11.7% vs. 28.9%, $p=0.003$). They were also non-significantly less likely to observe a decline in their lower extremity motor scores (19.8% vs. 31.6%, $p=0.067$). In addition, caudally-restored patients had non-significantly lower rates radiographic and implant-related complications (36.0% vs. 48.7%, $p=0.084$). In particular, they had non-significantly lower rates of implant failure (16.2% vs. 26.3%, $p=0.092$) resulting from significantly lower rates of screw loosening (0.0% vs. 13.2%, $p<0.001$). Finally, they had significantly lower rates of reoperation (22.5% vs. 38.2%, $p=0.020$), though reoperations due to radiographic and implant-related complications (40.0% vs. 31.0%, $p=0.492$) and PJK (60.0% vs. 75.9%, $p=0.211$) were comparable across the two groups (Table 4). Others, including wound, infectious, implant

Table 1 Baseline patient characteristics

Variable	Total (N = 187)	Caudal (N = 111)	Cephalad (N = 76)	*P*-value
Age (years)	66.2 (9.0)	65.3 (10.0)	67.6 (7.2)	0.080
Female sex	147 (78.6)	97 (87.4)	50 (65.8)	< 0.001
BMI (kg/m^2)	28.4 (5.7)	28.2 (6.0)	28.7 (5.2)	0.550
Race				0.542
Asian	5 (2.7)	3 (2.7)	2 (2.6)	
Black/African	7 (3.7)	6 (5.4)	1 (1.3)	
Hispanic	4 (2.1)	3 (2.7)	1 (1.3)	
White/Caucasian	162 (86.6)	95 (85.6)	67 (88.2)	
Other	8 (4.3)	4 (3.6)	5 (6.6)	
Edmonton frailty score	3.6 (1.4)	3.5 (1.5)	3.7 (1.3)	0.314
Prior spine surgery	102 (54.5)	62 (55.9)	40 (52.6)	0.664
Uppermost instrumented vertebrae				< 0.001
Upper thoracic	53 (28.3)	41 (36.9)	12 (15.8)	
Lower thoracic	113 (60.4)	68 (61.3)	45 (59.2)	
Proximal lumbar	21 (11.2)	2 (1.8)	19 (25.0)	
Lowermost instrumented vertebrae				< 0.001
Distal lumbar	10 (5.3)	1 (0.9)	9 (11.8)	
Sacrum/ilium	177 (94.7)	110 (99.1)	67 (88.2)	
Number of levels fused	10.2 (3.3)	11.1 (3.1)	8.9 (3.2)	< 0.001
Surgical invasiveness index	97.1 (36.2)	91.1 (35.4)	101.6 (36.3)	0.089

Variables are presented as mean (standard deviation) for continuous variables and count (frequency) for categorical variables

BMI = Body mass index

malposition-related, and radiographic complications, were also comparable.

Discussion

In this retrospective analysis of ASD patients who underwent surgical correction of their lumbar lordosis through caudal or cephalad techniques, caudal lordosis-based correction of the spinal deformity resulted in a more optimal spinal alignment and shape, with less inclination of the construct at the UIV. As a result, these patients had higher SRS-22 scores and lower surgical complications, such as sensory or motor deficits and implant failure, postoperatively. They also had lower rates of reoperation in the 2 years follow-up period, including reoperation due to PJK.

Unlike the cephalad lumbar lordosis which can vary depending on the pelvic incidence, the caudal lordosis has been shown to be nearly constant at around 35° to 45° across Roussouly types, a classification system that categorizes the morphology of lumbar lordosis by the orientation of the sacral slope [6]. The L4–S1 segments also generate the largest focal angulation throughout the entirety of the spine and make the greatest contributions to lumbar lordosis, with nearly two-thirds of the lumbar lordosis originating from the caudal spine [7]. On the other hand, cephalad lordosis is heavily dependent on pelvic incidence, with the magnitude of proximal lordosis increasing and the apex of lordosis migrating further cephalad with increasing pelvic incidence [2, 8, 9]. Because caudal lordosis is responsible for the majority of lumbar lordosis and because there is often a larger loss of lordosis in the caudal spine among patients with ASD, preoperative surgical planning frequently emphasizes correction of the lordosis in the L4–S1 region to improve sagittal alignment and associated patient-reported outcomes [10]. The present study reinforces this notion by demonstrating that caudal correction, in fact, allowed for better restoration of lumbar lordosis and PI–LL mismatch than cephalad correction. Lower SVA and higher SRS-22 scores subsequently indicates better sagittal alignment and patient-reported outcomes with caudal lordosis correction as well.

ALIF can offer powerful correction of alignment frequently exceeding 30° of lumbar lordosis, which is often beneficial in the L4–S1 spinal segments [11]. However, ALIF cage placement can be challenging in the upper lumbar spine [6, 12]. Instead, LLIFs and oblique lateral interbody fusion (OLIFs) may be used since they offer surgical access to the proximal spine and adequate correction of lumbar lordosis [13, 14]. Patients with LLIFs, especially with multiple LLIF cages, undergo significant alterations in their spinal shape resulting from a sudden and significant

Table 2 Preoperative and 2 years postoperative spinopelvic and patient-reported outcomes

Variable	Preoperative			2 Years postoperative		
	Caudal (N = 111)	Cephalad (N = 76)	*P*-value	Caudal (N = 111)	Cephalad (N = 76)	*P*-value
Spinopelvic alignment						
SS (°)	31.9 (11.3)	29.5 (10.5)	0.152	34.9 (10.1)	33.7 (7.7)	0.369
PT (°)	27.0 (7.5)	27.5 (8.4)	0.682	23.6 (8.5)	24.2 (9.6)	0.666
PI (°)	58.9 (12.4)	57.0 (11.3)	0.296	58.5 (12.5)	57.9 (11.1)	0.714
T4–T12 TK (°)	−26.3 (15.3)	−28.2 (15.6)	0.408	−43.4 (16.5)	−44.0 (14.6)	0.800
T10–L2 TL (°)	−15.9 (19.6)	−12.3 (18.8)	0.215	−9.8 (11.6)	−12.3 (12.8)	0.160
L1–S1 LL (°)	34.0 (15.7)	30.5 (16.9)	0.155	52.6 (12.2)	48.0 (13.3)	0.015
L1–L4 (°)	−0.8 (17.2)	−2.7 (17.2)	0.471	15.7 (11.7)	15.57 (12.8)	0.955
L4–S1 (°)	34.8 (11.2)	33.2 (13.8)	0.386	36.9 (5.8)	32.4 (10.3)	< 0.001
PI–LL (°)	24.9 (11.2)	26.5 (14.3)	0.398	6.0 (11.5)	9.9 (14.5)	0.039
SVA (mm)	85.3 (65.7)	83.7 (58.2)	0.867	30.4 (55.8)	56.7 (51.8)	0.001
T1PA (°)	27.2 (9.2)	27.4 (9.3)	0.881	19.3 (8.8)	22.4 (10.1)	0.024
T9PA (°)	18.2 (8.2)	17.9 (8.2)	0.794	10.3 (7.8)	12.9 (9.3)	0.036
TK Apex	T8	T8	0.937	T8	T8	0.986
LL Apex	L4	L3–L4	0.008	L3–L4	L3–L4	0.005
Patient-reported outcome measures						
LSDI	32.2 (15.0)	31.8 (12.3)	0.926	28.8 (19.6)	33.2 (16.9)	0.513
ODI	44.5 (14.7)	48.8 (14.8)	0.054	23.8 (17.5)	26.5 (19.5)	0.351
SRS-22						
Activity	2.8 (0.8)	2.8 (0.8)	0.971	3.7 (0.8)	3.4 (0.9)	0.045
Pain	2.4 (0.7)	2.3 (0.7)	0.406	3.7 (1.0)	3.4 (1.0)	0.047
Appearance	2.5 (0.7)	2.5 (0.8)	0.977	3.7 (0.9)	3.4 (0.9)	0.046
Total	2.8 (0.6)	2.8 (0.6)	0.734	3.8 (0.7)	3.5 (0.7)	0.016
SF-36						
PCS	29.2 (10.6)	27.2 (9.5)	0.185	38.9 (11.4)	36.4 (10.9)	0.172
MCS	45.8 (12.2)	46.7 (10.3)	0.621	52.5 (11.3)	51 .9 (8.7)	0.738

Variables are presented as mean (standard deviation)

SS = Sacral Slope, PT = Pelvic Tilt, PI = Pelvic Incidence, TK = Thoracic Kyphosis, TL = Thoracolumbar Lordosis, LL = Lumbar Lordosis, PI–LL = Pelvic Incidence–Lumbar Lordosis Mismatch, SVA = Sagittal Vertical Axis, T1PA = T1 Pelvic Angle, T9PA = T9 Pelvic Angle, T1SPi = T1 Spinopelvic Inclination, LSDI = Lumbar Stiffness Disability Index, ODI = Oswestry Disability Index, SRS-22 = Scoliosis Research Society 22-item, SF-36 = Short Form 36-item, PCS = Physical Component Score, MCS = Mental Component Score

Table 3 Postoperative inclination and translation of the uppermost instrumented vertebrae

Variable	Caudal (N = 111)	Cephalad (N = 76)	*P*-value
UIV inclination (°)			
6 Weeks postoperative	−6.1 (16.4)	−10.6 (15.3)	0.057
2 Years postoperative	−4.5 (17.7)	−5.8 (17.5)	0.616
UIV translation (°)			
6 Weeks postoperative	−11.4 (5.7)	−11.2 (6.5)	0.830
2 Years postoperative	−12.2 (6.4)	−10.6 (6.4)	0.081

Variables are presented as mean (standard deviation)

UIV = Uppermost Instrumented Vertebrae

increase in intervertebral disc height and segmental angulation at the operated levels [15, 16]. However, such emphasis on the cephalad lumbar spine, with undercorrection of the distal segments, can be concerning since the majority of the lumbar lordosis originates in the caudal spine [7, 17]. This was shown in the present study where a more cranial apex of lordosis, as noted in the cephalad group, was associated with worse sagittal alignment and SRS-22 scores. In addition to inadequate correction of the distal segments, they also had more posterior inclination which could make them more prone to implant or junctional failure and other surgical complications [18].

Indeed, at 2 years postoperatively, cephaladly-restored patients in the present study were significantly more prone to neuropraxia, implant failure, and reoperation, especially due to PJK. Nerve root tension and stretch-related neuropraxia

Table 4 Two-year postoperative complications

Complication	Caudal (N = 111)	Cephalad (N = 76)	*P*-value
Wound	4 (3.6)	3 (3.9)	0.903
Infection	6 (5.4)	3 (3.9)	0.647
Neuropraxia	20 (18.0)	22 (28.9)	0.079
Sensory deficit	9 (8.1)	21 (27.6)	< 0.001
Dysesthesia	7 (6.3)	16 (21.1)	0.003
Paresthesia	7 (6.3)	17 (22.4)	0.001
Motor deficit	13 (11.7)	22 (28.9)	0.003
Implant failure	18 (16.2)	20 (26.3)	0.092
Rod breakage	15 (13.4)	7 (9.2)	0.370
Screw loosening	0 (0.0)	10 (13.2)	< 0.001
Implant malposition	3 (2.7)	5 (6.6)	0.274
Radiographic	26 (23.4)	26 (34.2)	0.106
Adjacent segment disease	2 (1.8)	3 (3.9)	0.372
Proximal junctional kyphosis	24 (21.6)	15 (19.7)	0.755
Pseudoarthrosis	3 (2.7)	4 (5.3)	0.445
Reoperation	25 (22.5)	29 (38.2)	0.020

Variables are presented as count (frequency)

secondary to significant increases in the intervertebral disc height have previously been reported after interbody fusions [19, 20]. Such increases in disc heights are likely more common after the placement of multiple LLIF cages and may be responsible for the high observed rates of motor and sensory deficits among the cephaladly-restored patients. Additionally, inadequate correction of the distal segments and overcorrection of the proximal segments may further predispose them to implant strain and, subsequently, implant failure [18]. To compensate for the posterior inclination of the cephalad spine, patients may develop proximal junctional kyphosis which can require extension of fusion and reoperations [21, 22]. Careful consideration is, thus, essential when determining whether to pursue cephalad lumbar lordosis-based correction using multiple LLIFs.

The present study has several potential limitations. First, this was a retrospective cohort study and the findings may be subject to selection bias, residual confounding, and other biases inherent in observational designs. Second, treatment allocation to caudal or cephalad lordosis-based correction was not randomized but determined by surgeon preference, patient anatomy, and other clinical considerations, which may have introduced systematic differences between groups. Third, as the patients are divided by the focus of lordosis, there are inherent differences in the UIV, LIV, and number of levels fused between groups, which may introduce residual confounding and bias. Fourth, patients were not matched for the complexity of preoperative sagittal plane deformity and unmeasured confounders, such as curve rigidity, sagittal flexibility, bone mineral density, degree of degeneration at specific motion segments, or patient comorbidities not captured by the dataset, which may limit our ability to adequately compare the two different lordosis correction techniques. Fifth, while several radiographic differences between groups reached statistical significance, the clinical relevance of these findings is uncertain given the lack of clinically important magnitudes of differences in alignment parameters across various correction techniques. In addition, thresholds for clinically meaningful differences were not established a priori, which may limit the interpretation of their importance beyond statistical significance. Finally, surgeon experience may have played a role in the degree of lumbar lordosis correction achieved after cephalad or caudal techniques.

Conclusion

This investigation of ASD patients who underwent caudal or cephalad lumbar lordosis-based correction revealed that caudal lordosis-based correction of spinal deformity was associated with more optimal spinal alignment and shape, with less inclination of the of the construct at the UIV, higher PROMs, and lower rates of neurologic deficits, implant-related complications and revisions for PJK at 2 years. Given the observational nature of the study, these differences in outcomes may be influenced by confounding variables, including differential patient characteristics, surgical planning, and surgeon technique. However, these findings do suggest that great caution should be taken when considering cranial lordosis-based correction in the treatment of ASD.

Author contributions All authors read and approved the final manuscript. BGD: Study Conception, Data Analysis, Manuscript Draft—Writing; MS: Data Analysis, Manuscript Draft—Writing; RL: Data Analysis; LGL, SML, EOK, RKE, GMM, JLG, RH, PGP, TSP, KMK, HJK, CIS, JSU, PVM, JT, SB, VL and FJS: Data Contribution, Manuscript Draft—Critical Review; AHD: Manuscript Draft—Critical Review, Supervision.

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Data availability Data used for this investigation is privately collected.

Declarations

Institutional review board HCA-HealthONE Institutional Review Board. 4900 South Monaco Street, Suite 220, Denver, Colorado 80237. Approval Number: 231842–20.

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