Location of correction within the lumbar spine impacts acute adjacent-segment kyphosis

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OBJECTIVE The surgical correction of adult spinal deformity (ASD) often involves modifying lumbar lordosis (LL) to restore ideal sagittal alignment. However, corrections that include large changes in LL increase the risk for development of proximal junctional kyphosis (PJK). Little is known about the impact of cranial versus caudal correction in the lumbar spine on the occurrence of PJK. The goal of this study was to investigate the impact of the location of the correction on acute PJK development.

METHODS This study was a retrospective review of a prospective multicenter database. Surgically treated ASD patients with early follow-up evaluations (6 weeks) and fusions of the full lumbosacral spine were included. Radiographic parameters analyzed included the classic spinopelvic parameters (pelvic incidence [PI], pelvic tilt [PT], PI–LL, and sagittal vertical axis [SVA]) and segmental correction. Using Glattes' criteria, patients were stratified into PJK and noPJK groups and propensity matched by age and regional lumbar correction (Δ PI–LL). Radiographic parameters and segmental correction were compared between PJK and noPJK patients using independent t-tests.

RESULTS After propensity matching, 312 of 483 patients were included in the analysis (mean age 64 years, 76% women, 40% with PJK). There were no significant differences between PJK and noPJK patients at baseline or postoperatively, or between changes in alignment, with the exception of thoracic kyphosis (TK) and Δ TK. PJK patients had a decrease in segmental lordosis at L4–L5–S1 (-0.6° vs 1.6° , $p = 0.025$), and larger increases in segmental correction at cranial levels L1–L2–L3 (9.9° vs 7.1°), T12–L1–L2 (7.3° vs 5.4°), and T11–T12–L1 (2.9° vs 0.7°) (all $p < 0.05$).

CONCLUSIONS Although achievement of an optimal sagittal alignment is the goal of realignment surgery, dramatic lumbar corrections appear to increase the risk of PJK. This study was the first to demonstrate that patients who developed PJK underwent kyphotic changes in the L4–S1 segments while restoring LL at more cranial levels (T12–L3). These findings suggest that restoring lordosis at lower lumbar levels may result in a decreased risk of developing PJK.

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KEYWORDS adult spinal deformity; proximal junctional kyphosis; lumbar correction; segmental change; lumbar fusion; overcorrection

ADULT spinal deformity (ASD) is an increasingly recognized source of pain and disability in our aging population. Increased ASD severity, characterized by a flattening of lumbar lordosis (LL)¹ as well as an anterior trunk inclination,²³ corresponds to worsened

patient-reported health-related quality-of-life (HRQOL) scores.^{9,23}

When the severity of ASD starts to negatively impact patients' lives and livelihoods, symptomatic and definitive treatment should be identified and pursued. Fortunately, the

ABBREVIATIONS ASD = adult spinal deformity; FH = femoral head; HRQOL = health-related quality of life; LIV = lower instrumented vertebra; LL = lumbar lordosis; PI = pelvic incidence; PJK = proximal junctional kyphosis; PT = pelvic tilt; SVA = sagittal vertical axis; TK = thoracic kyphosis; TPA = T1–pelvic angle; UIV = upper instrumented vertebra.

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majority of symptomatic ASD patients can be sufficiently managed initially using nonoperative treatment. However, for those with severe pain or disability, or those who are not responding to conservative treatment, the symptoms may warrant surgical treatment. Smith et al. reported that ASD patients who underwent nonoperative treatment were less likely to improve at the 1-year follow-up than surgically treated patients.³⁵ With a surgical approach, direct decompression of the neural elements, a known pain generator, is critical in providing a satisfactory improvement in patient HRQOL scores. Additionally, when possible, spinopelvic alignment should be restored, because extensive evidence has been reported supporting the significant correlation between sagittal profile restoration and improved HRQOL.^{1,32}

Several operative techniques have successfully reached similar clinical outcomes for ASD patients. A recent study by Park et al. demonstrated similar clinical improvement between circumferential minimally invasive surgery and minimally invasive lateral interbody fusion with open posterior instrumented fusion.²⁷ The combined anterior and posterior approach was also reported to be as effective as the posterior-only approach in ASD patients.¹¹ For ASD patients requiring aggressive corrections, 3-column osteotomies have revealed promising results.^{5,7} However, despite satisfactory outcomes, revisions following correction surgery continue to occur. Among all complications requiring revision surgery, adjacent segmental pathologies, e.g., proximal junctional kyphosis (PJK), are among the most common and critical pathologies.^{2,11}

Risk factors predicting adjacent segmental pathology following ASD correction surgery have attracted considerable interest. Early in 1994, Lowe and Kasten recognized that overcorrection (> 50%) may lead to consequential kyphotic deformity.²⁴ This theory was reaffirmed by recent studies demonstrating that changes in LL > 30°, large postoperative LLs, or large corrections of the sagittal vertical axis (SVA) may all lead to the occurrence of PJK.^{16,25} As previous studies have highlighted the importance of appropriately correcting LL, a thorough understanding of lumbar regional and segmental profiles may, therefore, benefit the surgical decision-making process.

To achieve the goal of properly restoring LL, the natural shape of the lumbar region and its associated factors should be examined. Pelvic incidence (PI), the presentation of pelvic morphology, has been demonstrated as a fundamental determinant of LL. In addition to caudal factors, LL was also recently found to adapt to cranial alignment (large and rigid thoracic kyphosis [TK]).³⁴ For optimal restoration of lordosis, both regional and segmental alignment should be recognized. According to previous efforts regarding the natural shape of LL, 60% of the overall LL is located in the L4–S1 motion segment.^{8,12} Roussouly et al., therefore, proposed 4 lumbar types based on the pelvic morphology and the location of the apex of LL.³¹ In clinical applications, however, the importance of restoring segmental LL has not been illustrated. In this study we sought to analyze the location of the correction in the lumbar area following realignment ASD surgery and to compare the lumbar correction between patients with and without signs of radiographic PJK.

Methods

Patient Population

This study was a retrospective review of a prospective multicenter database of patients with ASD. After IRB approval at each of the 11 participating sites across the US, patients were enrolled in this database if they met the following criteria: age > 18 years and spinal deformity confirmed by at least one of the following measures: scoliosis Cobb angle > 20°, SVA > 5 cm, pelvic tilt (PT) > 25°, and TK > 60°. For this specific study, only patients treated surgically with a fusion extending from the pelvis (sacrum or ilium) to at least L1 were included.

Data Collection and Radiographic Parameters

Demographics (e.g., age, sex, and BMI) and surgical parameters (e.g., upper and lower instrumented vertebrae [UIV and LIV], and number of levels fused) were collected.

Full-length, freestanding lateral and anteroposterior spine radiographs were collected preoperatively and postoperatively. Identification and mapping of various anatomical landmarks were performed using validated software (SpineView, ENSAM Laboratory of Biomechanics³) at a central location. Using this spatial data, the parameters of interest were then calculated using MATLAB (MATLAB 2015b, MathWorks). The radiographic parameters included the following classic spinopelvic parameters: PT, PI, LL between S1 and L1 (LL), mismatch between PI and LL (PI–LL), TK between T4 and T12 (TK), SVA, and T1–pelvic angle (TPA).²⁹ In addition, the segmental alignment—the relative position of a vertebra with respect to the location of its 2 adjacent vertebrae—was calculated at each level (Fig. 1).^{19,38} Changes in alignment were evaluated by subtracting the preoperative alignment from the postoperative alignment. A negative change in alignment was defined as a kyphotic change and/or an anterior progression.

Radiographic PJK was defined using the following criteria described by Glattes et al.:¹⁰ a kyphotic angle > 10° between UIV and 2 levels above UIV and a kyphotic change > 10° from the baseline between UIV and 2 levels above UIV.

Statistical Analysis

The collected demographic, surgical, and radiographic data were described and analyzed at baseline and immediate postoperative follow-up. Changes in radiographic alignment were also investigated, including a preoperative to postoperative analysis of sagittal alignment and the rate of radiographic PJK.

Patients were stratified into 5 groups based on the preoperative to postoperative degree of change in LL: decrease in LL (kyphotic change > 5°), stable (change between –5° and 5°), 5°–15° increase (lordotic change of 5°–15°), 15°–25° increase (lordotic change of 15°–25°), and more than 25° increase (lordotic change > 25°). The segmental change at each level was described for each stratified change in LL group and then compared using ANOVA.

To mitigate the influence of confounding variables on

FIG. 1. Segmental change between 2 adjacent segments using L3-L2-L1 as an example. The change was calculated by subtracting the angle between L1-L2 and L2-L3 preoperatively (Pre) (black line vs light gray line) from L1-L2 and L2-L3 postoperatively (Post). If the difference is negative, the segmental change is kyphotic, otherwise it is a lordotic change.

analyzing factors surrounding the development of PJK, patients with a radiographic PJK were matched to postoperative patients without radiographic PJK (noPJK group) by age, preoperative TPA (measurement of the preoperative global deformity), and change in LL using a propensity score.^{18,39} This matching was performed by use of logistical regression and stratification to obtain 2 groups of equal numbers of patients without significant differences in age, preoperative alignment, or total correction within the lumbar spine. Global and segmental changes in sagittal alignment were then compared between PJK and noPJK patients using a paired t-test. Finally, substratified groups based on the location of the UIV (lower thoracic, UIV between L1 and T8; upper thoracic, UIV between T7 and T1) were also analyzed in a similar way.

Results

Patient Population

The study population included 483 patients, 78% of whom were women. The mean age was 62.7 ± 9.9 years, the mean BMI was 28.1 ± 5.7 kg/m², and the mean follow-up period was 6.9 ± 3 weeks.

Patients had a mean number of 11.9 ± 3.6 levels fused, ranging from 6 to 18. Further analysis revealed that the UIV location was T10 for 32.9% ($n = 159$), T4 for 18.8% ($n = 91$), T3 for 14.7% ($n = 71$), and T11 for 11.2% ($n = 54$) of the cases. The majority of patients received fusion to the ilium (95.4%); only a few underwent fusions ending inferiorly at the sacrum (22 cases).

Postoperatively, patients experienced significant improvements in every sagittal parameter from baseline; PI-LL decreased from $21.2^\circ \pm 19.2^\circ$ to $1.5^\circ \pm 13.7^\circ$, PT decreased from $26.1^\circ \pm 10.1^\circ$ to $20.1^\circ \pm 9.8^\circ$, and SVA decreased from 8.5 cm to 2.5 cm (all $p < 0.001$). The mean

TABLE 1. Pre- and postoperative sagittal alignment and pre- to postoperative comparison

Parameter	Preop	Postop	p Value
PI ($^\circ$)	55.4 ± 12.4	55.3 ± 12.2	0.105
PT ($^\circ$)	26.1 ± 10.1	20.1 ± 9.8	<0.001
Lumbar mismatch, PI-LL ($^\circ$)	21.2 ± 19.2	1.5 ± 13.7	<0.001
TK, T4-T12 ($^\circ$)	-31.1 ± 18.2	-42.3 ± 15.2	<0.001
SVA (mm)	85 ± 73	25 ± 48	<0.001
TPA ($^\circ$)	26.2 ± 12.1	16 ± 9.8	<0.001

Every sagittal parameter (mean $\pm$ SD) significantly decreased from preoperatively to postoperatively.

pre- and postoperative sagittal alignment values are summarized in Table 1. The rate of postoperative radiographic PJK was 40% ($n = 193$).

Comparing Segmental Change by LL Group

Stratifying the 483 patients by the pre- to postoperative changes in LL resulted in the following distribution: 27 patients in the $\Delta LL < -5^\circ$ group, 66 patients in the $-5^\circ < \Delta LL < 5^\circ$ group, 103 patients in the $5^\circ < \Delta LL < 15^\circ$ group, 125 patients in the $15^\circ < \Delta LL < 25^\circ$ group, and 162 patients in the $\Delta LL > 25^\circ$ group.

The mean value for each segmental change in each group was computed. A graphical representation of these changes within the lumbar and thoracolumbar regions illustrates the distribution of the pre- to postoperative degree of segmental changes in each ΔLL group at each vertebral level (Fig. 2). Most of the correction was performed within the upper part of the lumbar region (L3 to L1).

Propensity Match

Propensity-matched noPJK and PJK groups consisted of 156 patients each. By design, patients with and without radiographic PJK had similar ages (noPJK 63.9 ± 9.5 vs PJK 64.0 ± 9.0 years, $p = 0.919$), preoperative TPA ($26.7^\circ \pm 11.7^\circ$ vs $26.7^\circ \pm 12.9^\circ$, $p = 1$), and similar corrections of LL (ΔLL : $21.6^\circ \pm 15.9^\circ$ vs $21.0^\circ \pm 15.9^\circ$, $p = 0.726$; Fig. 3). In addition, no significant differences between the two groups in terms of changes in sagittal alignment were noted (ΔPT : $-7.2^\circ \pm 8.4^\circ$ vs $-5.9^\circ \pm 7.6^\circ$, $p = 0.146$; ΔSVA : -62 mm ± 65 mm vs -67 mm ± 70 mm, $p = 0.465$; Table 2).

Segmental change analysis in the PJK and noPJK groups revealed significant differences at several levels. PJK patients displayed significantly smaller lordotic changes at the lowest lumbar level (S1, L5, L4: -0.6° vs 1.6° , $p = 0.025$) but significantly greater lordotic changes at the upper lumbar and thoracolumbar levels (L3-L2-L1: 9.9° vs 7.1° ; L2-L1-T12: 7.3° vs 5.4° ; L1-T12-T11: 2.9° vs 0.7° ; all $p < 0.05$). In addition, PJK patients experienced a greater kyphotic change than noPJK patients at two distinct levels (Fig. 4). These two levels of greater kyphotic change were associated with the two most common UIV positions.

Stratification by UIV position demonstrated that PJK patients had a more kyphotic change at the UIV level (by design) with a lordotic change higher on the lumbar spine.

FIG. 2. Segmental change (in degrees) within the lumbar spine according to LL correction group. No significant difference was found in segmental change at the lower part of the lordosis (FH-S1-L5) or at the thoracolumbar junction (L1-T12-T11). FH = femoral head. Figure is available in color online only.

FIG. 3. Distribution of age (in years), preoperative TPA (in degrees), and change (in degrees) in LL between PJK and noPJK after a propensity match. yo = years old. Figure is available in color online only.

TABLE 2. Comparing PJK versus noPJK groups after propensity matching

Parameter	NoPJK (n = 156)	PJK (n = 156)	p Value
Age (yrs)	63.9 ± 9.5	64.0 ± 9.0	0.919
ΔPT (°)	-7.2 ± 8.4	-5.9 ± 7.6	0.146
ΔLL (°)	21.6 ± 15.9	21.0 ± 15.9	0.726
ΔPI-LL (°)	-21.7 ± 15.7	-21.3 ± 16.5	0.830
ΔTK (°)	-11.4 ± 11.5	-12.8 ± 17.9	0.416
ΔSVA (mm)	-62 ± 65	-67 ± 70	0.465
ΔTPA (°)	-11.3 ± 9.73	-10.9 ± 10.6	0.760

No significant differences in change (Δ) in alignment between PJK and noPJK were noted. Data in each group are given as mean ± SD.

Lower Thoracic UIV

PJK patients had a significantly larger lordotic change in the upper lumbar segments than did noPJK patients (L3-L2-L1: $6.3^\circ \pm 7.5^\circ$ vs $9.7^\circ \pm 9.3^\circ$, $p = 0.011$; L2-L1-

T12: $3.6^\circ \pm 5.7^\circ$ vs $6.1^\circ \pm 6.8^\circ$, $p = 0.011$; L1-T12-T11: $-1.0^\circ \pm 4.6^\circ$ vs $1.1^\circ \pm 6.2^\circ$, $p = 0.017$; Fig. 5).

Upper Thoracic UIV

Similarly, PJK patients experienced significantly larger lordotic changes in the thoracolumbar levels and greater kyphotic changes in the UIV area compared to noPJK patients (Fig. 5). Interestingly, PJK patients also experienced a kyphotic change at the lowest lumbar level (S1-L5-L4: -1.7° vs 1.5° , $p = 0.028$).

Discussion

The importance of restoring regional LL has been recognized by the spine community; however, the way in which segmental LL influences adjacent alignment is frequently overlooked. This novel study focused on both regional and segmental correction of LL in ASD patients, showing that PJK may be associated with the location of LL correction. After matching patients by age and degree

FIG. 4. Comparison of segmental changes (in degrees) between PJK and noPJK. PJK patients experienced a significantly larger lordotic change in the upper part of the lumbar spine and a significantly more kyphotic change at the 2 UIV areas (T10 and T4). An asterisk denotes a significant difference between PJK and noPJK patients ($p < 0.05$). Figure is available in color online only.

FIG. 5. Comparison of the segmental correction (in degrees) between PJK and noPJK after substratification by UIV position. PJK patients experienced a larger lordotic change in the proximal lumbar levels (correction) associated with a kyphotic change at the UIV area (PJK). An asterisk denotes a significant difference between PJK and noPJK patients ($p < 0.05$). Figure is available in color online only.

of PI–LL correction, a comparison between PJK and non-PJK patients revealed significantly more lordosis correction at both the upper level of LL and the UIV area in PJK patients. To eliminate the impact of UIV location, patients were stratified into lower thoracic and higher thoracic UIV subgroups, and the comparison between PJK and non-PJK patients within subgroups showed similar results, demonstrating the importance of appropriate proximal and distal LL correction.

The necessity of LL correction has been well described over the last 30 years. Recently, after general recognition of the importance of sagittal spinal alignment, PI–LL modifiers in the SRS-Schwab ASD classification³³ demonstrated a correlation to HRQOL. Thus, failing to restore normal PI–LL leads to unfavorable clinical outcomes,^{20,23,26} e.g., constant pain and disability, mechanical implant failure, PJK, and even preventive revision surgery. Therefore, adequate correction is of utmost importance in the surgical treatment of ASD patients; both over- and undercorrection of LL may cause suboptimal consequences. According to Glassman et al., the undercorrection of LL will lead to suboptimal alignment and decreased HRQOL.⁹ Similarly, Rothenfluh et al. addressed the occurrence of adjacent segmental degeneration following undercorrection of LL with biomechanical proof, confirming at the same time the

10° threshold for PI–LL regarding the risk of adjacent segmental degeneration.³⁰ Overcorrection of LL, on the other hand, also causes unfavorable clinical outcomes such as PJK and implant failure.^{21,36}

Radiographic PJK has been receiving increased attention by the spine community over the past several years. In some extreme cases, revision surgery is required for severe or progressive PJK generating severe pain, disability, and/or neurological complications. The occurrence of PJK is a multifactorial problem with numerous ongoing studies aiming at revealing its predictors. The overcorrection of LL has been documented as one of the best predictors of developing PJK. Maruo et al. proposed that a change in LL of more than 30° is a risk factor for PJK.²⁵ This result was echoed by a study by Kim et al. that identified both larger postoperative LLs and larger SVA corrections as risk factors.¹⁷ A similar conclusion was also drawn by Yagi et al., proposing a large SVA change as a predictor for PJK.³⁹ Recently, Lafage et al. provided additional evidence for the overcorrection theory with a virtual model, indicating that PJK was a reciprocal change from an overambitious correction threshold.²¹

However, all previous studies investigated the pre- and postoperative change in global alignment. In the current study, the proximal segmental correction of LL was asso-

ciated with the occurrence of PJK, which has not yet been reported. Greater correction in the upper lumbar section predisposed patients to develop PJK, independent of the location of UIV. As found by previous studies,^{8,12} the upper lumbar section only contributed to less than 40% of total lordosis. Considering that the total LL correction was matched between PJK and noPJK patients, a more aggressive correction of upper LL level resulted in an “unnatural” lordosis and a relative overcorrection in the proximal lumbar section (or thoracolumbar region) associated with an undercorrection of the caudal LL. As a reciprocal adaptation, radiographic PJK may, therefore, occur to compensate for the regional overcorrection.

Instead of restoring the caudal LL—which accounts for 60% of total LL in the normal population—a kyphotic change or no change in lordosis at the most caudal level (femoral head [FH]–S1–L5 change) was observed. In addition, PJK patients showed significantly more caudal kyphotic changes at S1–L5–L4. In patients undergoing 3-column osteotomies, the lumbar spine is pushed forward when closing the osteotomy site; this forces the caudal levels to be relatively kyphotic with respect to the osteotomy level, creating a compensatory reverse curve. Therefore, a smaller caudal lordotic change represents a greater cranial lordotic correction in a given total LL correction. Following this explanation, we also found that most of the correction happened between the upper segments of the lumbar region (L4–L3–L2 and L3–L2–L1), probably because L3 is the most common level for a 3-column osteotomy.⁶ According to Roussouly’s classification, the apex of LL is not always the same for all subjects.³¹ Nevertheless, the lumbar apex of ASD patients after a 3-column osteotomy would be the osteotomy level and may, therefore, differ from the natural lumbar apex.

The current study showed that overcorrection at the upper lumbar level predisposed patients to PJK occurrence following ASD correction surgery, emphasizing the importance of proper LL restoration. Previous efforts toward guiding LL restoration have been widely recognized, e.g., ideal PI–LL mismatch within 10°. However, the use of criteria such as these needs to evolve as our understanding of sagittal alignment improves. Recent work by Inami et al. demonstrated the necessity of determining if PI is extremely large or extremely small so that the PI–LL could be restored accordingly.¹⁵ Moreover, the impact of age on sagittal alignment should also be considered during surgical planning, as demonstrated by Lafage et al.²² According to the current data, LL restoration should be performed based on both the patient’s PI and segmental lordosis, allowing a more tailored management of ASD that accounts for pelvic morphology and the natural shape of the spine, and an overcorrection in the proximal LL cannot compensate for a loss of lordosis in the caudal portion of the lumbar spine.

The limitations of the current study are mainly in its retrospective study design and the lack of integrating HRQOL data due to early follow-up. Another limitation due to the retrospective design is the absence of bone mineral density in the analysis. Several studies demonstrated the impact of bone quality on PJK incidence, and further investigation is needed to delineate the impact of bone mineral density on the alignment and, eventually, on the

development of PJK.^{4,14,39} In addition, PJK was analyzed using the radiographic criteria; in clinical practice, clinical and symptomatic PJK is less prevalent than radiographic PJK. Finally, this study assessed the rate of radiographic PJK in early follow-up. While our results probably underestimated the true 2-year PJK rate, it is also well documented that the majority of PJK happens within the first few months following the surgical procedure.^{13,28,37}

Conclusions

Restoration of correct alignment in patients with ASD is crucial in achieving an optimal balance and clinical outcomes postoperatively. In addition to the reestablishment of harmony between regional curvatures, the correction of LL should agree with the natural shape of a patient’s spine, ultimately avoiding not only unfavorable changes at the upper end of the construct, but also hypercorrection in the proximal segment, which does not compensate for hypercorrection in the distal segment of LL.

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