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In the Relationship Between Change in Kyphosis and Change in Lordosis: Which Drives Which?

Bryan Ang, BS[1,2], Renaud Lafage, MS[1], Jonathan Charles Elysée, MS[1], Tejbir S. Pannu, MD[1], Mathieu Bannwarth, MD[1,3], Brandon B. Carlson, MD[1,4], Frank J. Schwab, MD[1], Han Jo Kim, MD[1], and Virginie Lafage, PhD[1]

Abstract

Study Design: Retrospective single-center study.

Objective: Investigate the effect of posterior instrumentation on the relationship between lordosis and kyphosis.

Methods: Surgically treated patients with a minimum of 6 months of follow-up were analyzed. Asymptomatic volunteers served to show the normal anatomical relationship between thoracic and lumbar curves. Patients were stratified based on postoperative instrumentation: "Thoracic Fusion" = complete fusion of thoracic spine; "Lumbar Fusion" = complete fusion of lumbar spine; and "Complete Fusion" = fusion from sacrum to at least T5. Bivariate correlations and regression analysis were used to evaluate the relationship between change in thoracic kyphosis (ΔTK) and change in spinopelvic mismatch (ΔPI-LL; pelvic incidence-lumbar lordosis) before and after fusion. Analyses were repeated in "Lumbar Fusion" patients with flexible preoperative thoracic spines.

Results: For asymptomatic volunteers, the natural anatomical relationship between TK and LL was found to be TK = 41% of LL ($r = 0.425$, $P < .001$). A total of 153 of 167 adult spinal deformity patients were included (62 years old, 26.7 kg/m^2, 78% female). Mean follow-up was 11.5 ± 6.8 months. "Thoracic Fusion" group showed no alteration in the natural relationship between TK and LL (ΔTK = 39% ΔPI-LL), whereas "Lumbar Fusion" group had a reduction in reciprocal change (ΔTK = 34% ΔPI-LL) although a subanalysis of patients in the "Lumbar Fusion" group with flexible thoracic spines showed a marked compensation in reciprocal change with (ΔTK = 58% ΔPI-LL).

Conclusion: The relationship between ΔTK and ΔPI-LL is dependent on level instrumented. "Thoracic Fusion" drives change in LL while this relationship is affected by TK's natural stiffness in "Lumbar Fusion" patients.

Keywords
lumbar lordosis, thoracic kyphosis, reciprocal change, thoracic fusion, lumbar fusion, flexibility

Introduction

Proper alignment of the spine in humans, with its characteristic S-shape formed by the interplay between cervical, thoracic, and lumbar curves, is critical for function in everyday life. There has been increasing recognition of the relationship between lordosis and kyphosis in achieving sagittal alignment.[1-5] This emphasis on spinopelvic harmony was first outlined by Jean Dubousset, whose idea of the "conus of balance" described the specific standing spinal alignment that allowed for the body to remain balanced with minimal muscle action.[6] As such, the interwoven nature between these 2 curves suggests that alterations in one portion of the spine may lead to unintended changes at another site.

Despite advancement in adult spinal deformity (ASD) knowledge over the past decade, a large proportion of the patients remain misaligned postoperatively. An analysis by Moal et al of ASD patients who underwent surgical correction revealed that on the basis of sagittal vertical axis (SVA), 11%

[1] Hospital for Special Surgery, New York, NY, USA
[2] Weill Cornell Medicine Medical School, New York, NY, USA
[3] CHU de Reims, Reims, France
[4] University of Kansas Medical Center, Kansas City, KS, USA

Corresponding Author:
Renaud Lafage, 525 E 71st St, Belaire 4E, New York, NY 10021, USA.
Email: renaud.lafage@gmail.com

of patients with normal preoperative SVA deteriorated postoperatively, while as a whole, 27% of surgically treated ASD patients met the SVA deformity threshold postoperatively.[4]

One reason for this postoperative malalignment could be due to reciprocal changes of the unfused spinal segments following surgery. Many studies have demonstrated how unfavorable reciprocal changes in the unfused portion of the spine prevent the achievement of optimal postoperative global spinal alignment.[7,8] Though some degree of reciprocal change is expected after surgery, the extent of the change remains difficult for surgeons to predict because reciprocal change depends on a myriad of factors including age, body mass index, and extent of spinal fusion. As such, predictions of postoperative spinal alignment by spine surgeons using clinical judgement alone has been shown to be rather imprecise.[9] This tendency for the unfused sagittal spinal segments to spontaneously change following the correction of a fused region has also been demonstrated in patients with Scheuermann's kyphosis, lumbar degenerative kyphosis, and degenerative flatback syndrome.[10-12] More important, these reciprocal changes can lead to the development of proximal junctional kyphosis, a serious postoperative complication that can cause significant pain and ambulatory difficulties and has been associated with a 10% revision surgery rate.[13] Thus, reciprocal change clearly has a significant role in achieving postoperative global spinal alignment and needs to be accounted for during preoperative planning due to its ultimate effects on surgical outcomes.

One aspect of the spine that may affect reciprocal change is the presence of a rib cage in the thoracic spine. Previous studies have demonstrated that the rib cage makes the thoracic spine naturally stiffer than the lumbar.[14,15] No study to date has ever investigated how this increased stiffness of the thoracic spine due to the rib cage can affect reciprocal changes in the spine after posterior spinal fusion surgery. Thus, the objectives of this study are (1) to better understand the drivers of reciprocal changes in the unfused spinal segments based on the location of spinal fusion following ASD corrective surgeries and (2) to investigate how the degree of reciprocal change in thoracic kyphosis affects proximal junctional kyphosis.

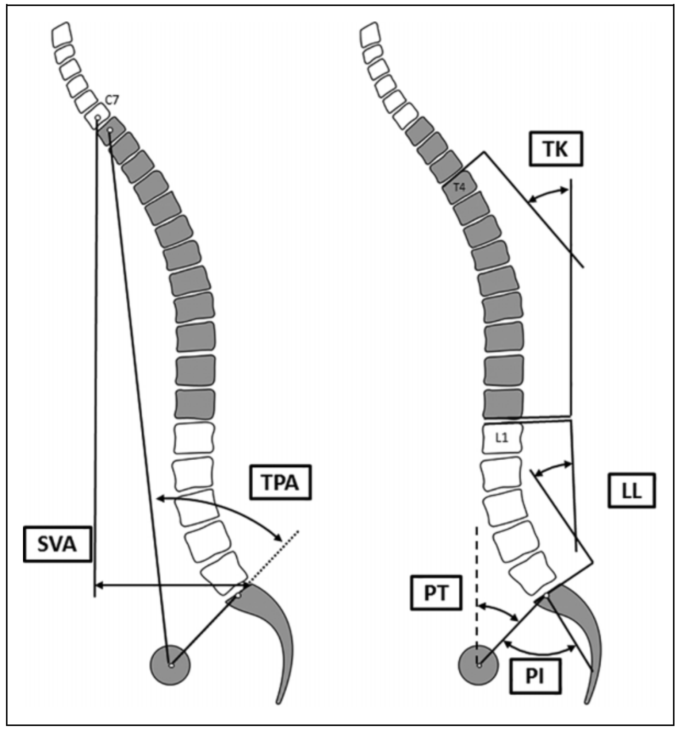

Figure 1. Radiographic parameters included on the analysis: pelvic incidence (PI), pelvic tilt (PT), lordosis (LL), thoracic kyphosis (TK), T1-pelvic angle (TPA), and sagittal vertical axis (SVA).

Method

Study Design

This study is a retrospective analysis of surgically treated ASD patients from a single-center, single-surgeon database with a minimum of 6 months of postoperative follow-up. Subjects were enrolled according to an institutional review board–approved protocol. Inclusion criteria include adult patients with spinal deformity, defined by sagittal vertical axis >50 mm, pelvic tilt >25°, pelvic incidence minus lumbar lordosis mismatch >10°, having undergone posterior spinal fusion with pedicle screws and rods. Exclusion criteria included a past history of trauma, cancer, and congenital deformity. A group of asymptomatic volunteers with no history of spinal problems from a prospective database served as the reference group to understand the natural anatomical relationship between lumbar lordosis and thoracic kyphosis. We can then use this relationship as a baseline comparison to identify how the curvature of the spines of patients who undergo ASD surgery are altered after the introduction of instrumentation and subsequent reciprocal change. The asymptomatic volunteers provided written informed consent to be part of the study.

Outcomes Measured

Demographic information was collected for both the ASD and asymptomatic patients including age, sex, and body mass index. X-rays were obtained in a free standing position of comfort, with finger on clavicles and shoulders in 45° forward elevation. Radiographs from both groups were analyzed to evaluate pelvic incidence (PI), pelvic tilt (PT), pelvic incidence minus lumbar lordosis mismatch (PI-LL), thoracic kyphosis (T4-T12), T1 pelvic angle (TPA), and sagittal vertical axis (SVA; Figure 1). Radiographic parameters were measured at standing (pre- and postoperatively) and supine (preoperatively) positions for the ASD patients, while the normative patients were measured as a single data point. Additional surgical information was obtained for the ASD group such as upper instrumented vertebrae and lower instrumented vertebrae. Proximal junctional kyphosis (PJK) angle, defined as the angle between the UIV (upper instrumented vertebra) inferior endplate and the UIV+2 superior endplate, was measured to identify ASD patients with radiographic PJK. Patients were considered to have a radiographic PJK if their postoperative PJK angle was

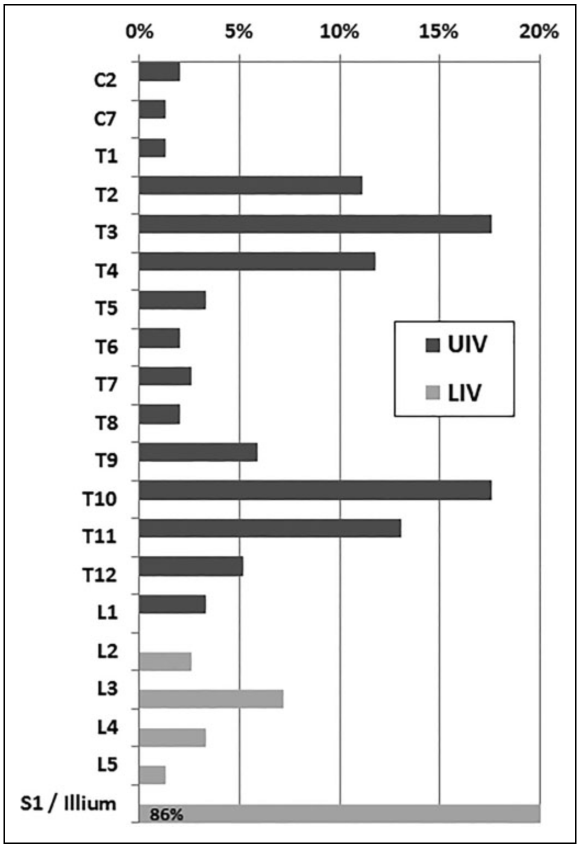

Figure 2. Upper instrumented vertebra (UIV) and lower instrumented vertebra (LIV) distribution in the entire ASD cohort.

>10° of kyphosis and if the change between baseline and postoperative at the same level was 10°.[16] Two reviewers were involved in the radiographic analysis, with one performing measurements and one performing verification. No interrater agreement analysis was done.

ASD patients were categorized based on the location of their spinal fusion: patients with posterior fusion from at least L1 to S1 were categorized as complete lumbar fusion, patients who had posterior instrumentation from L1 to L5 maximum were categorized as partial lumbar fusion, patients who had posterior instrumentation between T6 and L1 were categorized as partial thoracic fusion, and patients who had posterior instrumentation above T6 to L1 were categorized as complete thoracic fusion. These cutoffs were defined according to the UIV and LIV (lower instrumented vertebra) distribution in the database (Figure 2). Four patients underwent nonconventional levels of spinal fusion and thus were excluded. Based on this stratification, 3 groups of patients were created (Figure 3):

- "Thoracic Fusion" = complete fusion of the thoracic spine and partial fusion of the lumbar spine
- "Lumbar Fusion" = complete fusion of the lumbar spine and partial fusion of the thoracic spine
- "Complete Fusion" = complete fusion from sacrum to at least T5

Statistical Analyses

We first investigated the relationship between the thoracic and lumbar curves in the asymptomatic volunteers in order to establish a baseline understanding of the interplay between the 2 curves in a "normal" human spine without instrumentation. Linear regression and Pearson's correlations were performed between LL and TK within the asymptomatic group to identify the natural proportion between lordosis and kyphosis. For the ASD patients, bivariable correlations, partial correlation controlling for change in fused segments, and regression analysis through the origin were conducted between change in TK (ΔTK) and change in PI-LL (ΔPI-LL) before and after spinal fusion. Furthermore, a subanalysis utilizing bivariable correlation and regression through the origin was performed on patients with a flexible thoracic spine and a partial fusion of TK to evaluate percentage of change between ΔTK and ΔPI-LL before and after fusion. Flexible TK was defined as a change in TK between standing to supine >5° preoperatively. Patients with a complete fusion were further stratified based on ratio of ΔTK and ΔLL. Fisher's exact test was performed to compare differences in frequency distribution of radiographic PJK between patients with and without harmonious correction.

Results

Study Sample

Of the 167 ASD patients in the database, 153 met the inclusion criteria for the current study. Seventy-eight percent were women and 22% were men, with a mean age of 62.1 years (SD = 13.8 years), and a mean body mass index of 26.7 kg/m^2 (SD = 5.8 kg/m^2). A total of 119 asymptomatic volunteers with no history of spinal problems were also included to establish a baseline relationship between thoracic and lumbar curvature: 68.1% (N = 81) were female and 31.9% were male, with mean age of 50.7 years (SD = 17 years), and a mean body mass index of 28.0 kg/m^2 (SD = 6.0 kg/m^2).

Asymptomatic Volunteer

Pearson correlation analysis on LL and TK for the asymptomatic group revealed a statistically significant correlation between LL and TK ($r = 0.425$, $P < .001$). Linear regression revealed a statistically significant relationship between LL to TK for all 119 cases with the following coefficients: TK = 16.4 + 41% of LL ($r^2 = 0.205$, $P \leq .001$). Reciprocally, LL as a function of TK for the 119 volunteers revealed the following coefficients: LL = 40.8-43% of TK ($r^2 = 0.205$, $P \leq .001$).

ASD Patients

ASD patient demonstrated a moderate to severe sagittal deformity with 60.7% of the patient PT modifier at + or ++, 64.7% having a PI-LL modifier at + or ++, and 64.0% having a SVA

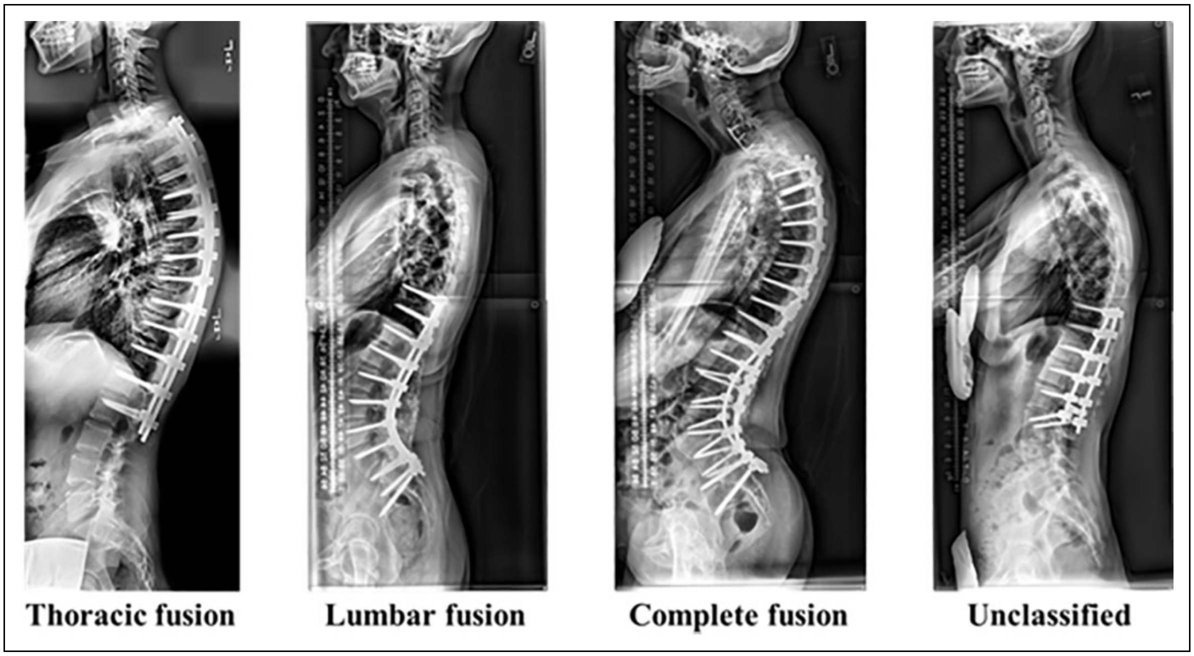

Figure 3. Case example of the 3 groups of fusion plus example of patient unclassified.

Table 1. Pre-to-Post Analysis of the ASD Cohort in Terms of Sagittal Alignment.

	Preoperative	Postoperative	*P*
PI	52.3 ± 14.0	51.3 ± 16.8	.221
PT	24.2 ± 10.8	18.9 ± 10.1	<.001
PI-LL	16.9 ± 19.4	−0.6 ± 17.7	<.001
T4-T12	−34.1 ± 18.8	−41.5 ± 13.3	<.001
TPA	23.1 ± 12.7	14.1 ± 10.6	<.001
SVA	68.5 ± 73.9	14.4 ± 53	<.001

Abbreviations: ASD, adult spinal deformity; PI, pelvic incidence; PT, pelvic tilt; LL, lumbar lordosis; PI-LL, pelvic incidence minus lumbar lordosis mismatch; T4-T12, thoracic kyphosis; TPA, T1 pelvic angle; SVA, sagittal vertical axis.

modifier at + or ++. As seen in Table 1, there was a marked improvement in the various sagittal parameters from pre- to postoperative. PT decreased from 24.2° to 18.9° ($P < .001$); PI-LL decreased from 16.9° to −0.6° ($P < .001$); T4-T12 thoracic kyphosis increased from −34.1° to −41.5° ($P < .001$); TPA normalized from 23.1° to 14.1° ($P < .001$); and preoperative SVA improved from 68.5 mm to 14.4 mm ($P < .001$) postoperative. The value of pelvic incidence is fixed for any given patient and as such remained constant from pre- to postoperative.[17]

The stratification by levels fused revealed that 18 subjects underwent complete thoracic fusion and partial lumbar fusion ("Thoracic Fusion" group). Seventy-two subjects underwent complete lumbar fusion and partial thoracic fusion ("Lumbar Fusion" group). Fifty-nine subjects underwent complete fusion of both the lumbar and thoracic spine ("Complete Fusion" group). Fusion levels ranged from T2/T3 to L2/L3 for "Thoracic Fusion," T9/T10/T11 to ilium for "Lumbar Fusion," and T2/T3/T4 to ilium for "Complete Fusion" (Table 2).

Table 2. Categorization of ASD Patients by Fusion Group.

	UIV	LIV	Number of Patients (%)
Thoracic fusion	T2/T3 (72.2%)	L2/L3 (77.6%)	18 (11.8%)
Lumbar fusion	T9/T10/T11 (73.6%)	Ilium (98.6%)	72 (47.1%)
Complete fusion	T2/T3/T4 (79.6%)	Ilium (96.6%)	59 (38.6%)

Abbreviations: ASD, adult spinal deformity; UIV, upper instrumented vertebra; LIV, lower instrumented vertebra.

Correlation and Regression Analysis

Overall, there was a significant correlation between ΔTK and ΔPI-LL ($r = 0.359$, $P < .001$) in ASD patients from pre- to postoperative. The "Thoracic Fusion" group demonstrated a statistically significant correlation between ΔPI-LL and ΔTK ($r = 0.716$, $P < .001$) with the following linear regression coefficients: ΔTK = 39% ΔPI-LL ($r^2 = 0.722$, $P < .001$). Partial correlation between ΔPI-LL and ΔTK controlling for ΔLL fused demonstrated a significant association between change in curvatures ($r = 0.648$, $P = .005$). Conversely, the "Lumbar Fusion" group demonstrated a weaker correlation between ΔPI-LL and ΔTK ($r = 0.235$, $P = .047$) and the regression yielded the following coefficients: ΔTK = 34% ΔPI-LL ($r^2 = 0.649$, $P < .001$; Figure 4).

Within the "Lumbar Fusion" group, a subanalysis was performed comparing the relationship between ΔPI-LL and ΔTK in patients with a flexible thoracic spine ("flexible" group) and in patients with a stiff thoracic spine ("stiff" group). A total of 53.1% of the patients in the "Lumbar Fusion" met the criteria for a flexible thoracic spine, with mean TK flexibility of 6.9 ± 8.9°. There was a lack of a statistically significant relationship

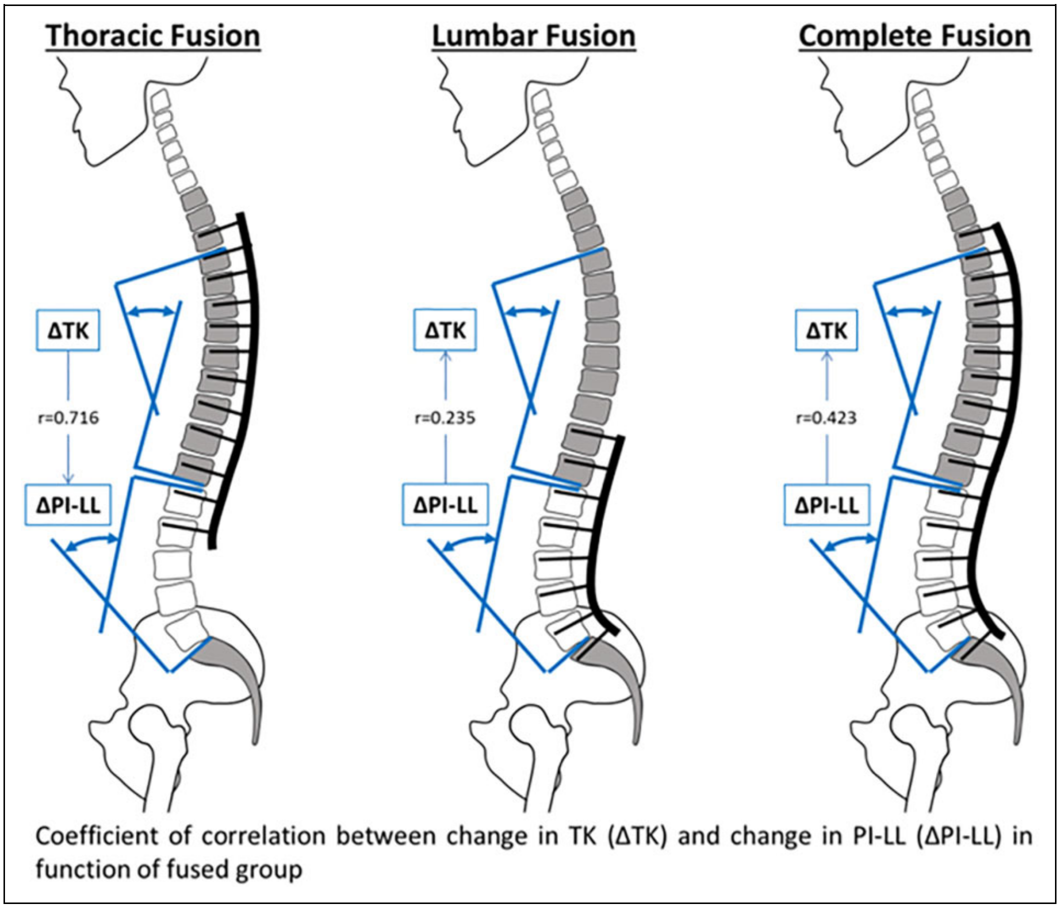

Figure 4. Summary of correlation between ΔLL and ΔTK.

between ΔPI-LL and ΔTK for the "stiff" group ($P = .927$). However, the "flexible" group demonstrated a statistically significant correlation between ΔPI-LL and ΔTK ($r = 0.618$, $P < .001$) with linear regression coefficients of ΔTK = 58% ΔPI-LL ($r^2 = 0.890$, $P < .001$; Table 3).

The "Complete Fusion" group exhibited a statistically significant correlation between ΔPI-LL and ΔTK ($r = 0.310$, $P = .016$) with linear regression coefficients of ΔTK = 21% ΔPI-LL ($r^2 = 0.310$, $P = .016$).

Table 3. Summary of Regression Between LL and TK.

	Regression	r^2	P
ASD patients			
Lumbar fusion	ΔTK = 34% ΔPI-LL	0.649	<.001
Not flexible	ns	ns	.927
Flexible	ΔTK = 58% ΔPI-LL	0.890	<.001
Thoracic fusion	ΔTK = 39% ΔPI-LL	0.722	<.001
Complete fusion	ΔTK = 21% ΔPI-LL	0.310	.016
Asymptomatic volunteer	TK = 16.4 + 41% LL	0.425	<.001

Abbreviations: ASD, adult spinal deformity; TK, thoracic kyphosis; PI, pelvic incidence; LL, lumbar lordosis; PI-LL, pelvic incidence minus lumbar lordosis mismatch.

Subanalysis on ΔLL and ΔTK Proportionality and PJK in "Complete Fusion" Group

We conducted a subanalysis of the complete fusion group with respect to how postoperative sagittal alignment related to the development of PJK. The threshold for kyphosis restoration was defined as ΔTK = 41% ΔLL, which was based off the relationship between TK and LL in the asymptomatic volunteers showing TK = 16.4 + 41% LL. The overall rate of radiographic PJK for ASD patients in the "Complete Fusion" group was 27.1%. Among all the patients who received complete fusion, 66.1% had ΔTK smaller than 41% of ΔLL, indicating a lack of kyphosis restoration compared with the increase in lordosis, whereas 33.9% had a change in TK greater than 41% of ΔLL, indicating kyphosis restoration in excess compared with LL correction. Using a Fisher's exact test, patients with kyphosis restoration in excess were less likely to develop PJK compared with patients with a lack of kyphosis restoration in relation to lordosis correction (11.1% vs 35.9%, $P = .048$).

Discussion

Posterior spinal fusion surgery has become an increasingly viable option in treating ASD patients who have exhausted nonsurgical treatment options. However, there is limited research conducted on how spinal stiffness from added instrumentation influences reciprocal changes in the unfused thoracic or lumbar spine.[7,18-20] Therefore, understanding the compensatory behavior of the unfused spine may aid in reducing adverse surgical outcomes and malalignment. In this study, we found that reciprocal change is affected by the level of spinal fusion as well as by the presence of the rib cage in the thoracic spine. Additionally, subanalysis on patients undergoing complete fusion of thoracic and lumbar spine revealed that those who had inadequate restoration of TK in relation to LL had a higher chance of developing PJK.

Asymptomatic patients were included in this study to elucidate the baseline anatomical relationship between TK and LL by radiographic analysis. Previously published results have shown there to be a significant association between LL and TK in asymptomatic patients.[1] In our study, we found a statistically significant relationship between TK and LL in asymptomatic volunteers with the following coefficients: TK = 16.4 + 41% of LL ($r^2 = 0.205$, $P \leq .001$). We then used this relationship between the thoracic and lumbar curves of asymptomatic volunteers as our standard to compare against the spines of patients who had undergone spinal fusion.

Analysis of the change in thoracic and lumbar sagittal curvatures (ΔTK vs ΔLL) from pre- to postoperative in ASD patients demonstrated that reciprocal changes were proportional to both the location of spinal fusion and the inherent stiffness of the spinal curvature. In the "Thoracic Fusion" group, the added instrumentation did not affect the normal relationship between the 2 spinal curves. In contrast, for the "Lumbar Fusion" group, the unfused thoracic spinal segments had a marked reduction in reciprocal change that deviated significantly from the normal, anatomical relationship between thoracic and lumbar curvature. Previous reports have described how the rib cage serves to add additional rigidity to the thoracic spine in comparison to the lumbar spine.[14,15] When a rigid element is introduced into the lumbar spine during fusion, the thoracic spine naturally attempts to undergo compensatory reciprocal change to reestablish the natural relationship between the 2 curves; however, because the thoracic spine is naturally stiffer compared with the lumbar spine, the introduction of a lumbar instrumentation leads to an alteration of the normal anatomical relationship.

This was further confirmed when the lumbar fusion group was stratified by flexible thoracic spine ($\Delta TK > 5°$) or stiff thoracic spine ($\Delta TK < 5°$). Although previous studies have investigated how changes in LL from spinal fusion affected TK, there has yet to be a study that substratified patients based on flexible or nonflexible thoracic spine.[7,19] The stiff thoracic spine group exhibited no significant correlation between ΔTK and ΔLL ($P = .927$), whereas the flexible thoracic spine group exhibited a statistically significant relationship of ΔTK = 58% ΔPI-LL ($r^2 = 0.890$, $P < .001$). These results emphasized that the lack of flexibility in the thoracic spine alters its ability to undergo reciprocal change. Patients without flexible thoracic spines were unable to fully respond to the lumbar-induced changes from lumbar fusion due to a physical limitation in their thoracic spine.

We then applied our findings from the thoracic and lumbar fusion groups to the patients who received a complete fusion of both their lumbar and thoracic spine. In the setting of a complete fusion, the natural proportion between TK and LL is completely altered by the presence of added instrumentation. In particular, stiff material (ie, cobalt-chrome) has been shown to significantly alter the physiological relationship between curves.[20] As a result, there is no reciprocal change since the entire spine is fused. Therefore, in patients who undergo complete fusion, the relationship between their thoracic and lumbar curves becomes dependent on the decisions of the surgeon, including level of spinal segments fused and instrument composition. This was affirmed by the change in the linear relationship between ΔTK and ΔLL in the "Complete Fusion" group (ΔTK = 21% ΔPI-LL, $r^2 = .310$, $P = .016$) compared with that seen in the "Lumbar Fusion" or "Thoracic Fusion" group.

Because of the surgeon's increased role in determining the new relationship between the thoracic and lumbar curvature of the "Complete Fusion" group, we wanted to further investigate how the degree of TK induced by the surgeon contributed to an increased risk of the development of PJK. Previous studies have showed that incomplete restoration of LL relative to TK along with failure to achieve adequate restoration of global sagittal alignment are associated with PJK onset.[21-24] Furthermore, inadequate restoration of TK at the instrumented segments may lead to a compensatory increase in TK at the noninstrumented upper junction, thus increasing the chance of PJK in such patients.[25,26] Based on our analysis of the asymptomatic volunteers, the ideal relationship between thoracic and lumbar curves was established as TK to be 41% of LL, with a deviation from this relationship indicating either inadequate or excessive kyphotic restoration. Our study showed that patients who had a lack of kyphosis restoration in relation to lordosis correction (defined as $\Delta TK < 41\% \Delta LL$) exhibited a higher rate of PJK in comparison to those who achieved kyphosis restoration in excess ($\Delta TK > 41\%$).

The findings for this article were limited to this specific study cohort, so analyses should be repeated in other samples to validate the findings. Additionally, we did not stratify the patients based on whether they were receiving a new primary surgery or a revision surgery, which may affect radiographic outcome, as we simply did not have the sample size to do so. ASD patient and asymptomatic volunteer were not age matched. Although there is undoubtedly some degree of spinal degeneration that encompasses the difference in ages between the 2 groups, an article published by Iyer et al in 2016 describing age-stratified normative values of sagittal alignment parameters demonstrated comparable spinal parameters in the age groups 51 to 60 years and 61 to 70 years in terms of global spinal alignment, TK, LL, and so on.[27] Last, although a mean follow-up time of 1 year should be sufficient to capture reciprocal change and the development of PJK as demonstrated by previous studies that have looked at time to development of reciprocal change/PJK, it is possible that a longer follow-up could have demonstrated further changes that are not appreciated in the present analysis.[28,29]

Conclusion

Posterior spinal fusion serves as an efficacious treatment for patients suffering from ASD, as shown in our study by the improvement in various spinal parameters that outline spinopelvic alignment. However, reciprocal changes in the spine beyond the focal corrections of fusion remain difficult to anticipate due to its multifocal etiology. This study serves to demonstrate how increased stiffness from spinal instrumentation and the presence of the rib cage in the thoracic spine can serve as drivers of reciprocal change. Thus, for future surgical planning, it is important to incorporate these variables into preoperative planning as doing so may help with preventing the development of postoperative adverse outcomes and surgical malalignments such as PJK. Future research should be conducted in regards to how the shape of a fused spine can reduce the rate of mechanical failure at the junction between the instrumented and un-instrumented portion of the spine.

Authors' Note

This study was institutional review boards (IRB) approved for the retrospective cohort. Prospective asymptomatic subjects were enrolled according to IRB protocol, and informed consent was obtained from each subject prior to enrollment in the study.

Declaration of Conflicting Interests

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ORCID iD

Renaud Lafage, MS https://orcid.org/0000-0002-4820-1835
Brandon B. Carlson, MD https://orcid.org/0000-0003-4627-4245

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