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DEFORMITY

Identifying Thoracic Compensation and Predicting Reciprocal Thoracic Kyphosis and Proximal Junctional Kyphosis in Adult Spinal Deformity Surgery

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Study Design. Retrospective analysis.

Objective. To define thoracic compensation and investigate its association with postoperative reciprocal thoracic kyphosis and proximal junctional kyphosis (PJK)

Summary of Background Data. Adult spinal deformity (ASD) patients recruit compensatory mechanisms like pelvic retroversion and knee flexion. However, thoracic hypokyphosis is a less recognized compensatory mechanism.

Methods. Patients enrolled in a multicenter ASD registry undergoing fusions to the pelvis with upper instrumented vertebra (UIV) between T9 and L1 were included. Patients were divided into those with postoperative reciprocal thoracic kyphosis (reciprocal kyphosis [RK]: change in unfused thoracic kyphosis [TK] $\geq$15°) with and without PJK and those who maintained thoracic alignment (MT). Thoracic compensation was defined as expected thoracic kyphosis (eTK) minus preoperative TK.

Results. For RK (n = 117), the mean change in unfused TK was 21.7° *versus* 6.1° for MT (n = 102) and the mean PJK angle change was 17.6° *versus* 5.7° for MT (all $P < 0.001$). RK and MT were similar in age, body mass index (BMI), sex, and comorbidities. RK had larger preoperative PI–LL mismatch (30.7 *vs.* 23.6, $P = 0.008$) and less preoperative TK (22.3 *vs.* 30.6, $P < 0.001$), otherwise sagittal vertical axis (SVA), pelvic tilt (PT), and T1 pelvic angle (TPA) were similar. RK patients had more preoperative thoracic compensation (29.9 *vs.* 20.0, $P < 0.001$), more PI–LL correction (29.8 *vs.* 17.3, $P < 0.001$), and higher rates of PJK (66% *vs.* 19%, $P < 0.001$). There were no differences in preoperative health-related quality of life (HRQOL) except reciprocal kyphosis (RK) had worse Scoliosis Research Society questionnaire (SRS) appearance (2.2 *vs.* 2.5, $P = 0.005$). Using a logistic regression model, the only predictor for postoperative reciprocal thoracic kyphosis was more preoperative thoracic compensation. Postoperatively the RK and MT groups were well aligned. Both younger and older (>65 yr) RK patients had greater thoracic compensation than MT counterparts. The eTK was not significantly different from the postoperative TK for the RK group without PJK ($P = 0.566$).

Conclusion. The presence of thoracic compensation in adult spinal deformity is the primary determinant of postoperative reciprocal thoracic kyphosis and these patients have higher rates of proximal junctional kyphosis.

Key words: adult spinal deformity, compensatory mechanism, proximal junctional kyphosis, reciprocal thoracic kyphosis.

Level of Evidence: 3

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Sagittal spinal malalignment has been shown to correlate with disability.[1–5] In the setting of sagittal spinal deformity, there is a predictable compensatory response in order to maintain standing alignment.[4,9–12] A deformity localized to one or more of the spinal regions will lead to compensatory changes in adjacent spinal regions, the pelvis and, potentially, the lower extremities when the deformity magnitude is large enough.[12]

The pelvis is a key compensatory mechanism in the modulation of standing alignment.[4,13] Pelvic retroversion has been shown to be one of the first mechanisms of compensation adopted by patients with spinal deformity.[4,12,13] Diebo *et al*[12] demonstrated that when pelvic compensation is exhausted, larger magnitude spinal deformities often lead to the activation of lower extremity compensatory mechanisms.

In the case of lumbar flatback deformity, some patient will decrease their thoracic kyphosis to compensate for the loss of lumbar lordosis.[11,12] This method of compensation requires good flexibility of the thoracic spine and the motor strength to maintain the hypokyphosis. However, thoracic hypokyphosis is the least explored of all compensatory mechanisms described in the literature.[12,16] Recognizing preoperative thoracic compensation potentially may have implications for postoperative standing alignment because, as Klineberg *et al*[30] demonstrated, increased reciprocal thoracic kyphosis occurs after lumbar pedicle subtraction osteotomy (PSO) and this may diminish the global correction.

Therefore the purposes of this study are (1) to quantify the magnitude of preoperative thoracic compensation in patients with adult spinal deformity; (2) to investigate which patients respond to deformity correction with reciprocal thoracic kyphosis and the preoperative and perioperative factors that underlie this response; and (3) to determine if thoracic compensation and the development of reciprocal thoracic kyphosis are related to proximal junctional kyphosis.

METHODS

Patient Population

This is a retrospective review of a multicenter database of adult spinal deformity (ASD) patients. Institutional review board (IRB) approval was obtained at each site prior to study initiation. All patients were older than 18 years and prospectively enrolled if they met radiological criteria of ASD (coronal Cobb angle $>20^\circ$, sagittal vertical axis [SVA] >5 cm, pelvic tilt [PT] $>25^\circ$, or thoracic kyphosis [TK] $>60^\circ$) or retrospectively included if they underwent a 3-column osteotomy (3CO). Patients were excluded from the database if their spinal deformity was due to neuromuscular, infectious, or malignant etiologies. The series included both primary and revision cases. Further inclusion criteria for this study were 6-week and 1-year follow-up, fusion of at least five levels, iliac fixation, and an upper instrumented vertebral level (UIV) between T9 and L1.

Data Collection

Demographic data included age, sex, body mass index (BMI), and the history of previous spine surgery. In addition, surgical characteristics, such as the number of levels fused, the use of 3CO, UIV, operative time, and estimated blood loss (EBL), were recorded. Complication and revision data were recorded. Full-length free-standing radiographs were obtained at baseline, 6 weeks postoperatively, and 1 year postoperatively. Radiographs were measured using a dedicated and validated software (Spineview, ENSAM Paris-Tech, Paris, France).[17] All radiographic measurements were performed at a central location by a dedicated team independent from the spine surgeons. Health-related quality of life (HRQOL) outcomes, consisting of the Oswestry Disability Index (ODI), Short Form 36 physical and mental component scores (SF-36 PCS, MCS), Scoliosis Research Society-22 questionnaire (SRS-22), were collected at baseline and each postoperative visit.

Radiographic Parameters

Sagittal radiographic spino-pelvic parameters (Figure 1) included pelvic incidence (PI), pelvic tilt (PT), lumbar lordosis (LL), lumbo-pelvic mismatch as defined by pelvic incidence minus lumbar lordosis (PI–LL), T1 pelvic angle (TPA), T4–T12 thoracic kyphosis (TK), and sagittal vertical axis (SVA). Kyphosis was also measured across the fused (fused TK) and unfused regions (unfused TK).

Thoracic Compensation

For all patients at baseline, the amount of thoracic compensation for spinal deformity was defined as the difference between the baseline standing TK and the expected TK. Expected TK (eTK) was calculated from a validated formula from Schwab *et al*[15] that provides ideal TK and LL values based on the patient's PI:

$$\mathrm{LL} = \frac{1}{2}(\mathrm{PI} + \mathrm{TK}) + 10$$

Solving the formula for TK and extrapolating for ideal lumbopelvic alignment by substituting the LL with PI, the formula is simplified as follows: $\mathrm{eTK} = \mathrm{PI} - 20^\circ$.

Reciprocal Changes Groups

Patients were grouped according to amount of reciprocal change that developed postoperatively. Reciprocal change was assessed using the change in the unfused thoracic kyphosis angle (unfused TK) from baseline to postoperative. Patients with unfused TK more than or equal to 15° were classified in the reciprocal kyphosis (RK) group; while patients with unfused TK less than 15° were classified in the maintained thoracic alignment (MT) group (Figure 2A–F).

PJK

Proximal junctional kyphosis (PJK) was defined based on commonly used criteria: a kyphotic angle between the inferior endplate of the upper instrumented vertebra (UIV) and the superior endplate of the second vertebra

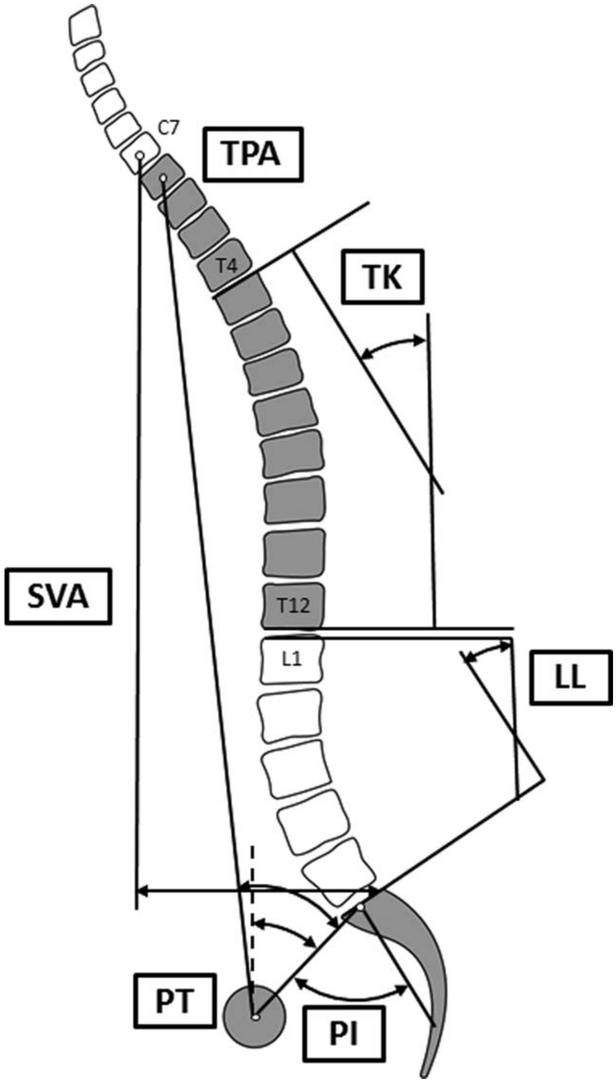

Figure 1. Sagittal radiographic spino-pelvic parameters. LL indicates lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; TPA, T1 pelvic angle; TK, T4–T12 thoracic kyphosis; SVA, sagittal vertical axis.

above the UIV (UIV+2) greater than 10° and a change between baseline and 1-year follow-up for the same segment greater than 10°.[18]

Statistical Analysis

The RK and MT groups were compared using independent *t* tests for continuous variables, including demographics, preoperative and postoperative HRQOL, and radiographic parameters, including thoracic compensation. The incidence of PJK was compared between the groups using Chi-square tests. Logistic regression modeling was performed to predict reciprocal kyphosis using several well-described variables of interest, including age, baseline radiographic parameters, and HRQOL scores. Sub-analysis included comparisons of patient age (<65 and >65 yr). Statistical analysis was performed using IBM SPSS Statistics v. 20.0.0 (IBM Corp., Armonk, NY). Level of significance was set at $P < 0.05$.

RESULTS

Patient Sample

A total of 219 patients were included, with mean age 62.6 ± 10.3 years, BMI 28.6 ± 6.0 kg/m^2, Charlson Comorbidity Index 1.9 ± 1.8, 69% female, and 69% revision cases. The cohort had severe sagittal malalignment as demonstrated by PT 27.6 ± 10.2°, PI–LL 27.4 ± 20.0°, TPA 28.6 ± 12.8°, and SVA 97.0 ± 80.2 mm. Mean PI for the cohort was 57.1 ± 13.5°, mean TK was 26.1 ± 16.8°, mean expected TK was 37.1 ± 13.5°, and mean thoracic compensation was 10.9 ± 21.8°. There were 101 patients (46%) who underwent 3CO, most commonly at L3 (n = 38) and L4 (n = 35).

RK *versus* MT

There were 117 patients (53%) with reciprocal thoracic kyphosis (RK) and 102 patients (47%) who maintained thoracic alignment (MT) after surgery. RK and MT groups were similar in baseline demographic parameters and comorbidities (Table 1). There were no differences in baseline HRQOL between the groups, with the exception that the RK group had a lower score for SRS-Appearance domain (2.2 *vs.* 2.5; $P = 0.005$). There were no differences between groups in PI, PT, TPA, SVA, or expected TK (Table 1), but the RK group had greater PI–LL deformity (30.8° *vs.* 23.6°; $P = 0.008$). Notably, the RK group also had significantly smaller preoperative TK (22.3° *vs.* 30.6°; $P < 0.001$) and a greater TK compensation (13.6° *vs.* 7.7°; $P < 0.001$). Upon logistic regression analysis, the only predictor for developing reciprocal kyphosis was baseline thoracic compensation ($P = 0.028$).

Postoperatively, RK and MT groups were again similar in PT, TPA, and SVA (Table 2). At both 6 weeks and 1 year postoperatively, the RK group had a smaller value for PI–LL than the MT group (1.0° *vs.* 6.5°; $P = 0.004$ at 6 wks; 2.3° *vs.* 7.6°; $P = 0.05$ at 1 yr). By design, the change in unfused kyphosis (unfused TK) was significantly larger in the RK group (21.7° *vs.* 6.1°, $P < 0.001$). The RK group also had a greater T4–T12 TK (45.2° *vs.* 39.5°; $P = 0.006$), greater unfused TK (44.5° *vs.* 39.3°, $P = 0.015$), greater maximum TK (56.0° *vs.* 50.1°, $P = 0.008$), and PJK angle (21.1° *vs.* 15.0°, $P < 0.001$). There were no differences in HRQOL between groups for any outcome instrument ($P > 0.102$ for all) at both 6 weeks and 1 year.

Changes from pre- to postoperative alignment are shown in Table 3. The RK group underwent greater changes in T4–T12 TK (+22.9° *vs.* +9.2°, $P < 0.001$) and maximum TK (+13.1° *vs.* +2.0°, $P < 0.001$) than the MT group. However, the RK group also underwent significantly greater correction in pelvic, lumbar, and global alignment: the decrease was greater for PT (−7.3° *vs.* −4.6°, $P = 0.012$), SVA (−72.6 mm *vs.* −46.8 mm, $P = 0.007$), TPA (−12.6° *vs.* −8.1°, $P = 0.001$), and PI–LL (−29.8° *vs.* −17.3°, $P < 0.001$). The groups were similar in pre- to postoperative changes (baseline to 6 wk and 1 yr) in HRQOL for all scores. There was no significant difference between the eTK and the postoperative TK for the RK group without PJK (35.6° *vs.* 42.0°, $P = 0.051$) as shown in Table 4.

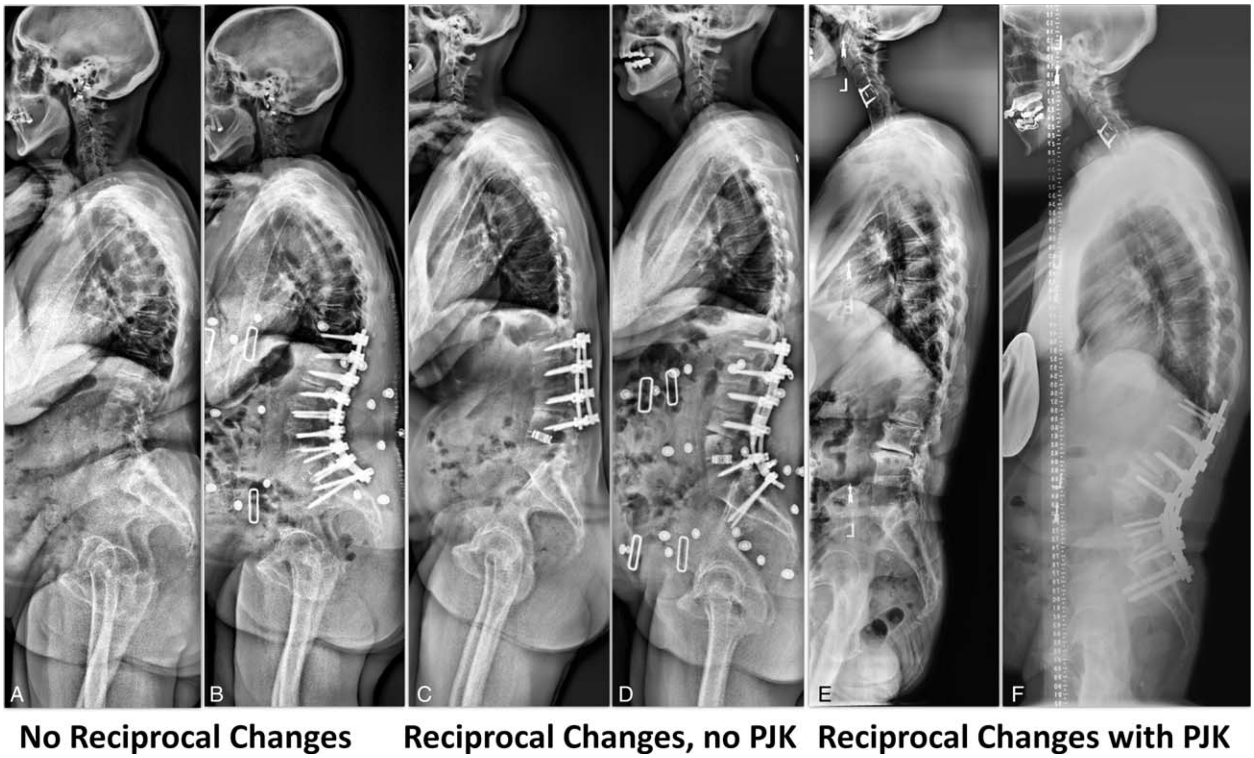

Figure 2. Preoperative and postoperative lateral full-spine radiographs of three patients representative of the no reciprocal changes or maintained thoracic alignment (MT: **A** is pre-op and **B** is post-op) group and the reciprocal thoracic kyphosis groups (RK: **C** and **D**) without and with proximal junctional kyphosis (**E** and **F**).

Age Analysis

When categorized by age (<65 yr and >65 yr), baseline TK was significantly smaller in patients who developed reciprocal kyphosis regardless of age. Among the 102 patients who developed RK, older patients (mean age 71.5 yr) had significantly larger baseline TK than younger (mean age 53.6 yr) patients (older: 26.0° *vs.* younger: 19.5°, $P = 0.005$). There were no other differences in baseline alignment. For the MT group, preoperative and postoperative alignments were similar between older and younger patients. Postoperative alignments were also similar between young MT and young RK patients. Among elderly

TABLE 1. Baseline Demographics and Radiographic Parameters for Reciprocal Kyphosis (RK) and Maintained Thoracic Alignment (MT) Groups

Parameter	RK (n = 117)		MT (n = 102)		*P*
	Mean	SD	Mean	SD	
Age	62.5	(11)	62.6	(9.7)	0.948
BMI	28.4	(5.9)	28.7	(6.2)	0.720
Gender (% female)	73%		65%		0.139
% Revision	66%		74%		0.134
% 3CO	50%		41%		0.117
PI	55.9	(14.0)	58.4	(12.9)	0.172
PT	27.9	(10.8)	27.3	(9.4)	0.630
PI−LL	30.8	(18.8)	23.6	(20.7)	0.008
TPA	29.9	(13.1)	27.2	(12.4)	0.130
SVA	105.5	(80.2)	87.0	(79.4)	0.091
TK	22.3	(15.9)	30.6	(16.9)	<0.001
Expected TK	35.9	(14)	38.4	(12.9)	0.172
TK compensation	13.6	(22.2)	7.7	(21.0)	0.048

3CO indicates 3-column osteotomy; BMI, body mass index; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; TPA, T1 pelvic angle; TK, T4−T12 thoracic kyphosis; SVA, sagittal vertical axis.

TABLE 2. Postoperative Radiographic Parameters for Reciprocal Kyphosis (RK) and Maintained Thoracic Alignment (MT) Groups

Parameter	RK (n = 117)		MT (n = 102)		*P*
	Mean	SD	Mean	SD	
PT	20.5	(10.1)	22.6	(8.7)	0.106
PI–LL	1.0	(14.7)	6.5	(13.5)	0.004
TPA	17.3	(10.3)	19.7	(8.8)	0.060
SVA	34.3	(50.1)	42.1	(50)	0.258
TK (T4–T12)	45.2	(14.1)	39.5	(16.2)	0.006
Unfused TK	44.5	(16)	39.3	(15.2)	0.015
TK (Max)	56.0	(16.9)	50.1	(14.9)	0.008
PJ angle	−21.1	(12.4)	−15.0	(10.5)	<0.001

LL indicates lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; TPA, T1 pelvic angle; TK, T4–T12 thoracic kyphosis; SVA, sagittal vertical axis.

TABLE 3. Changes in Radiographic Parameters from Baseline to Postoperative for Reciprocal Kyphosis (RK) and Maintained Thoracic Alignment (MT) Groups

Parameter	RK (n = 117)		MT (n = 102)		*P*
	Mean	SD	Mean	SD	
Unfused TK	+21.7	(9.5)	+6.1	(5.7)	<0.001
TK (T4–T12)	+22.9	(9.5)	+9.2	(8.5)	<0.001
PJ angle	+17.6	(7.8)	+5.7	(4.9)	<0.001
PI–LL	−29.8	(13.7)	−17.3	(16.5)	<0.001
PT	−7.3	(7.5)	−4.6	(8.1)	0.012
SVA	−72.6	(65.4)	−46.8	(72.8)	0.007
TPA	−12.6	(9.1)	−8.1	(10.8)	0.001

LL indicates lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SD, standard deviation; SVA, sagittal vertical axis; TPA, T1 pelvic angle; TK, T4–T12 thoracic kyphosis.

patients only, the RK group had significantly smaller postoperative PI–LL (0.0° *vs.* 7.6°, $P = 0.008$) and a trend for a smaller SVA (37.0 mm *vs.* 56.2 mm, $P = 0.052$) at both 6 weeks and 1 year.

PJK Analysis

PJK developed in 35% of all patients. This included 66% (n = 76) of the RK group and 19% (n = 20) of the MT group ($P < 0.001$). Characteristics of the RK patients with and without PJK and the MT patients are shown in Table 5. PJK patients had comparable age and sex distribution (65%, 71.7%, and 74% of patients were females, $P = 0.420$). Patients had also comparable height, weight, and BMI.

Baseline thoracic compensation was highest for reciprocal kyphosis patients, regardless of PJK. Similarly, RK patients underwent significantly greater changes in PI–LL and SVA. Postoperatively, the RK with PJK group had significantly larger PT comparing to the RK without PJK

TABLE 4. Expected TK, Preoperative TK, and Postoperative TK for the Reciprocal Kyphosis (RK) Groups With and Without PJK and for the Maintained Kyphosis (MT) Group

Parameter	RK no PJK	RK w/PJK	MT	*P* Value
Preop TK	22.3° ± 15.9*	22.4° ± 17.0*	30.6° ± 16.8*	0.002‡
Post TK	42.0° ± 12.4	47.2 ± 14.7†	39.5° ± 16.2	0.004‡
Expected TK	35.6° ± 12.8*	36.0° ± 14.7†,*	38.4° ± 12.9*	0.392

**Denotes significant differences between expected TK and preoperative TK (P < 0.05).*

†Denotes significant differences between expected TK and postoperative TK (P < 0.05).

‡Denotes significant differences between RK no PJK, RK w/PJK, and MT groups (P < 0.05).

The expected TK versus postoperative TK in the RK, no PJK, and MT groups were similar (P = 0.051, P = 0.566). MT indicates maintained kyphosis group; RK no PJK, reciprocal kyphosis group without proximal junctional kyphosis; RK w/PJK, reciprocal kyphosis group with proximal junctional kyphosis.

TABLE 5. Alignment Parameters for the Maintained Thoracic Alignment (MT), Reciprocal Kyphosis (RK) Without PJK, and RK With PJK Groups

Parameter	RK no PJK N = 39	RK with PJK N = 76	MT N = 102	*P*
Age	62.3	62.5	62.6	0.991
Baseline thoracic compensation	13.0	13.6	7.7	0.002
Postoperative PT	17.1	22.1	22.6	0.006
PT change	−8.5	−6.7	−4.6	0.020
Postoperative PI−LL	−1.8	1.5	6.5	0.002
PI−LL change	−31.0	−29.5	−17.3	<0.001
Post SVA	30.2	36.5	42.1	0.438
SVA change	−84.7	−66.4	−46.8	0.011
Post TPA	14.2	18.7	19.7	0.009
TPA change	−14.6	−11.8	−8.1	0.001
Post PJ angle	−15.6	−24.0	−15.0	<0.001
PJK angle change	−9.4	−21.9	−5.7	<0.001
Post TK	42.0	47.2	39.5	<0.001
TK change	+19.5	+24.8	+9.2	<0.001

''Change'' refers to differences in alignment from baseline to postoperatively for a given parameter. LL indicates lumbar lordosis; PI, pelvic incidence; PJK, Proximal Junctional Kyphosis; PT, pelvic tilt; SVA, sagittal vertical axis; TPA, T1 pelvic angle; TK, T4–T12 thoracic kyphosis.

group. Final SVA was similar between the groups, however, TPA was significantly higher in RK with PJK group comparing to RK without PJK. The groups were similar in HRQOL at baseline, 6 weeks, and 1 year postoperatively.

DISCUSSION

Correction of sagittal spinal deformity has been shown to significantly improve health related quality of life. Such improvements in disability are correlated to larger corrections and optimal postoperative standing alignment.[1–4,32] Conversely, proximal junctional kyphosis has been shown to diminish global corrections and PJK is more prevalent in larger corrections.[18–29] So a balance exists between performing the corrections necessary to attain good global alignment while avoiding the overcorrections that may predispose to the development of PJK. Recent studies suggest that these windows for optimal spinal alignment are different for elderly and younger patients.[14] Therefore, careful preoperative planning of sagittal spinal deformity corrections may aid in the attainment of postoperative alignments within the optimal range for a given patient.[16]

One of the problems with developing an effective preoperative plan is the difficulty in predicting the postoperative response of preoperative compensatory mechanisms.[4,9–12] Corrections of pelvic retroversion and lower extremity compensation result directly from the improvement in sagittal spinal alignment.[10–13] In contrast, compensation through thoracic hypokyphosis has not been well investigated.[12,16] Klineberg *et al*[30] demonstrated that patients undergoing lumbar PSO will exhibit increased postoperative thoracic kyphosis. These reciprocal changes in adjacent spinal regions have been observed for deformities centered in other spinal regions as well.[31] Diebo *et al*[12] found that patients with larger pelvic incidence/lumbar lordosis mismatches have less thoracic kyphosis, however, the magnitude of thoracic hypokyphotic compensation was not quantified in that study.

This study demonstrates that thoracic compensation can be computed using a mathematical formula that expresses the interrelationship between pelvic incidence, lumbar lordosis, and thoracic kyphosis. In patients with pathologic loss of lumbar lordosis, pathologic or compensatory changes in thoracic alignment can make it difficult to determine what a given patient's optimal regional alignment may be. Among asymptomatic subjects, thoracic kyphosis correlates well with lumbar lordosis and lumbar lordosis correlates well with pelvic incidence, but the correlation between thoracic kyphosis and pelvic incidence is not as strong.[7] However, in sagittal deformities resulting from pathologic loss of lumbar lordosis, we can calculate an ideal lumbar lordosis from the pelvic incidence and in turn we can determine the thoracic kyphosis that would match an optimal lumbar lordosis. Pelvic incidence has been useful in guiding our understanding of what the lumbar lordosis should be for a given patient.[4,6,8] Schwab *et al*[15] created an equation that determines optimal lumbar lordosis from its most close correlates, the pelvic incidence and thoracic kyphosis [$LL = 1/2(PI + TK) + 10$]. Therefore, this equation was solved for TK by substituting an ideal LL for a given PI magnitude. This leads to the following calculations for an uncompensated, expected thoracic kyphosis: $eTK = PI - 20$. The magnitude of thoracic compensation was determined by subtracting the actual preoperative standing thoracic kyphosis from the expected thoracic kyphosis (Thoracic compensation = eTK − preopTK). The expected thoracic kyphosis was not statistically different from the postop thoracic kyphosis for the maintained group and the reciprocal change group without PJK. This demonstrates that in these patients the degree of reciprocal thoracic kyphosis can be anticipated and accounted for in preoperative planning.

In patients where reciprocal kyphosis is anticipated, the operating surgeon may consider surgical instrumentation that extends higher into the upper thoracic spine to prevent potential loss of correction.

This study classifies patients into two groups depending on the change in thoracic alignment in response to spinal deformity correction: the reciprocal kyphosis (RK) group were those who had greater than 15° change in kyphosis of their unfused thoracic spine whereas the maintained kyphosis (MT) group had less than 15° change (Figure 2). The reciprocal kyphosis group had a greater magnitude of preoperative thoracic compensation (29.9° *vs.* 20°, $P < 0.001$) and this thoracic compensation resulted from a smaller preoperative thoracic kyphosis (22.3° *vs.* 30.6°, $P < 0.001$). Moreover the RK group had larger PI–LL mismatch (30.8° *vs.* 23.6°, $P = 0.008$) despite having similar global deformity as defined by the TPA and SVA. This demonstrates that the RK group had more lumbar flatback deformity but with the capacity to compensate with thoracic hypokyphosis, the global deformity matched that of the MT group. The only baseline difference in HRQL was that of SRS appearance and this may reflect the fact that patients with larger flatback deformities and a greater need to compensate with thoracic hypokyphosis may be more cognizant of the appearance of that deformity. Therefore, it is not surprising that the RK underwent a larger PI–LL correction. However, both groups had significant improvements in HRQL from the preoperative to the final postoperative time point.

Interestingly, when analyzing the elderly patients (>65 yr), these same relationships were maintained. While, older patients had significantly larger thoracic kyphosis than younger patients, the baseline thoracic kyphosis was still smaller for elderly patients who developed reciprocal kyphosis. The elderly may be less able to compensate with thoracic hypokyphosis because of increased stiffness from spondylosis, loss of disc height, and the aging process progress. Diebo *et al*[12] found that elderly patients with sagittal spinal deformity had a lower capacity for thoracic compensation compared with younger patients. The results of this study corroborate that finding, however, when explored further, a subset of elderly patients maintain the ability to compensate with thoracic hypokyphosis and these patients underwent reciprocal change in their thoracic alignment after correction of their deformities.

Smith *et al*[31] and colleagues demonstrated that patients with lumbar flatback deformity (PI–LL >10) but without large global deformities (SVA < 5 cm) benefit just as much from deformity correction as those with global deformities more than 5 cm. Though they did not assess the magnitude of preoperative thoracic compensation or postoperative reciprocal thoracic kyphosis in those patients, that group represents patients with the ability to compensate for their deformities with thoracic hypokyphosis, similar to the RK group in this study. The Smith *et al* study did not differentiate between compensation with increased pelvic tilt and thoracic hypokyphosis. Elderly patients in that study were less likely to be well compensated, corroborating the results in this study.

The primary limitation of the present study is the retrospective design. In addition, although 1-year follow-up should be sufficient to capture the reciprocal changes in thoracic alignment and PJK, it is possible that longer-term follow-up could demonstrate differences in HRQOL between the groups that are not appreciated in the present analysis. The strengths of the study include the multicenter design and the use of multiple validated measures of HRQOL. Furthermore, all radiographic measures were performed at a single center with extensive experience in image analysis to minimize measurement variation.

CONCLUSION

This is the first report to quantify preoperative thoracic compensation through hypokyphosis. The presence of preoperative thoracic compensation in adult spinal deformity patients is the primary determinant of postoperative reciprocal thoracic kyphosis and these patients are more likely to have proximal junctional kyphosis. The postoperative thoracic kyphosis was not significantly different from the expected thoracic kyphosis calculated mathematically; the exceptions to this were the patients that had reciprocal thoracic kyphosis with PJK. Identifying patients with preoperative thoracic compensation can aid in planning deformity surgeries as the reciprocal kyphosis that occurs postoperatively can be anticipated and accounted for when setting the final alignment target.

Key Points

- The primary factor associated with the propensity to develop postoperative reciprocal thoracic kyphosis more than 15° is the presence of preoperative thoracic compensation.
- Thoracic compensation can be quantified by solving an equation that quantifies the magnitude of lumbar lordosis necessary to balance a spine with a given thoracic kyphosis and pelvic incidence.
- Patients exhibiting preoperative thoracic compensation were more likely to develop proximal junctional kyphosis.

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