Original Article

Compensatory mechanisms in adult degenerative thoracolumbar spinal deformity – Radiographic patterns, their reversibility after corrective surgery, and the influence of pelvic morphology

ABSTRACT

Objective: Loss of lumbar lordosis (LL) in degenerative deformity activates spinal compensatory mechanisms to maintain neutral C7 sagittal vertical axis (C7SVA), such as an increase in pelvic tilt (PT) and decreased thoracic kyphosis (TK). We study the extent to which PT increase and TK reduction contribute to the compensation of pelvic incidence (PI)-LL mismatch.

Methods: A cohort of 43 adult patients with adult degenerative thoracolumbar deformity were included in this retrospective study. Radiographic spinopelvic measurements were obtained before and after corrective surgery. Pearson correlations were calculated.

Results: Preoperative PI-LL mismatch significantly correlated with an increase in PT and a decrease in TK in the whole cohort $r = +0.66$ (95% confidence interval [CI] 0.44–0.8) and $r = -0.67$ (95% CI – 0.81––0.47), respectively, at a relative rate of 0.37 (standard deviation [SD]: 0.07) and – 0.57 (SD: 0.09), respectively. In patients with low PI, only TK showed a significant correlation with PI-LL mismatch, $r = -0.56$ (95% CI – 0.8 to – 0.16), at a rate of – 0.57 (SD: 0.19). The high PI subgroup showed a significant correlation with PT, TK, and C7SVA, $r = 0.62$ (95% CI 0.26–0.82), $r = -0.8$ (95% CI – 0.9––0.58), and $r = 0.71$ (95% CI 0.41–0.87) at rates of 0.48 (SD: 0.11), –0.72 (SD: 0.12), and 0.62 (SD: 1.27).

Conclusions: Decreased TK represented a more consistent compensatory mechanism in patients with high and low PI when compared to an increase in PT. PI-LL mismatch induced more pronounced changes in TK than did PT in both subgroups. Patients with high PI relied more on increases in PT and a relative decrease in TK to compensate for PI-LL mismatch than patients with low PI.

Keywords: Adult spinal deformity, pelvic incidence, pelvic tilt, sagittal balance, thoracolumbar deformity

INTRODUCTION

Loss of lumbar lordosis (LL) in adult degenerative and adult spinal deformity (ASD) can activate compensatory mechanisms to maintain a neutral C7 sagittal vertical axis (C7SVA).[1,2] In the context of ASD, positive sagittal imbalance – a parameter strongly correlated with a disability, pain, and negative health outcomes[3] – may be offset by decreased thoracic kyphosis (TK) or increased pelvic tilt (PT).[4,5] However, these compensatory changes are energy-dependent and may ultimately cause fatigue and decreased health status.[6]

In the case of ASD, loss of LL is insidious and driven primarily by multisegmental disc degeneration with the potential for

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significant disability if substantial pelvic incidence (PI)-LL mismatch develops.[7] The primary goal of surgical correction is to restore age-appropriate spinopelvic alignment balance[8] as restoration of sagittal balance and PI-LL mismatch are closely linked to improved pain and functional status postoperatively.[7] Failure to achieve age-appropriate alignment goals postoperatively with persisting PI-LL mismatch has been linked to an increased risk of adjacent segment disease, junctional failure and junctional kyphosis, and overall disability.[9] Risk of reoperation has been shown to be 10 times higher in those with unresolved PI-LL mismatch when compared to those with the restoration of PI-LL postoperatively.[9]

Postoperative "normalization" of activated compensatory mechanisms impacts spinal alignment and should be considered when planning surgical intervention. In the present study, we investigate if the activation of compensatory mechanisms is uniform or whether individual pelvic parameters have an influence. Further, we explore the extent to which compensatory alignment changes regress after corrective surgery to better predict long-term spinal alignment after corrective surgery.

METHODS

Approval for this study was obtained by the local institutional review board. An institutional database of patients with ASD, who underwent surgical treatment at a single institution has been searched for eligible patients. Inclusion criteria were pathologic PI-LL at baseline, minimum of three-level fusion, normal postoperative sagittal alignment parameters (C7SVA as well as PI-LL), and postoperative follow-up whole spine X-ray within 6 weeks of surgery. Exclusion criteria were incomplete pre- or postoperative whole spine standing X-rays. After screening of the database, a cohort of 43 adult patients with adult degenerative thoracolumbar deformity were included in this retrospective study, and the following radiographic measurements were obtained before and after corrective surgery: C7SVA, TK, T10L2 sagittal Cobb angle, LL, PT, and PI. Parameters were measured using Surgimap Spine software (Nemaris INC., New York, NY, USA) and then extracted into a spreadsheet. Patients were divided into low PI (40.4°, standard deviation [SD]: 6.2) and high PI (57.2°, SD: 6.9) subgroups. For the whole cohort as well as the low and high PI subgroups, Pearson correlations were calculated for preoperative PI-LL mismatch and preoperative PT, TK, T10L2, and C7SVA using GraphPad (Graphpad Holdings, LLC; San Diego, USA). Further correlations were calculated for perioperative change in PI-LL and perioperative change in PT, TK, T10L2 as well as C7SVA. The results were compared between low and high PI subgroups.

RESULTS

A total of 43 patients were identified in this retrospective study. Preoperative whole spine standing X-rays were used to determine C7SVA, TK, T10L2 sagittal Cobb angle, PT, PI, and PI-LL. Patients then have been dichotomized into low and high PI subgroups, which is shown in Table 1.

Preoperative PI-LL mismatch significantly correlated with an increase in PT and a decrease in TK in the whole cohort $r = +0.66$ (95% confidence interval [CI] 0.44–0.8), $P < 0.0001$ and $r = -0.67$ (95% CI $-$ 0.81–$-$0.47), $P < 0.0001$, respectively, at a relative rate of 0.37 (SD 0.07) and -0.52 (SD 0.09), respectively, [Table 2 and Figure 1]. PI-LL mismatch correlated with T10-12 angle with $r = 0.42$ (95% CI 0.14–0.64), $P = 0.0043$ [Table 2].

In patients with low PI, only TK showed a significant correlation with PI-LL, $r = -0.56$ (95% CI $-$ 0.8 to -0.16), at a rate of $-$ 0.57 (SD 0.19). The high PI subgroup showed a significant correlation with PT, TK, and C7SVA, $r = 0.62$ (95% CI 0.26–0.82), $r = -0.8$ (95% CI $-$ 0.9–$-$0.58), and $r = 0.71$ (95% CI 0.41–0.87) at rates of 0.48 (SD: 0.11), 0.72 (SD: 0.12), and 0.62 (SD: 1.27) [Table 3].

Perioperative change in LL showed significant correlations with TK in the entire cohort, $r = +0.63$ (95% CI 0.31–0.82) at a rate of + 0.80 (SD: 0.20), with PT and TK (trend toward significance) in the low PI group, $r = -0.48$ (95% CI -0.77–0.02) and $r = +0.49$ (95% CI $-$ 0.06–0.8) at a rate of -0.44 (SD 0.20) and + 0.72 (SD 0.38) [Table 4]. In the high PI group, significant correlations were found for TK and C7SVA (trend toward significance), $r = 0.76$ (95% CI 0.31–0.93) and $r = -0.54$ (95% CI -0.86–0.09) at rates of 0.81 (SD: 0.22) and -2.3 (SD: 1.2). The ratio of PT: TK change preoperatively was 0.46 (SD: 0.28) in the low PI group and 1.47 (SD: 2.16) in the high PI group.

Table 1: Baseline radiographic parameters

	Low PI group	High PI group
n	21	22
PI	40.4±6.2 (21-48)	57.2±6.9 (49-77)
PI-LL	11±11.7 (−20-31)	22.8±19.1 (−18-63)
T10-L2	3±11.4 (−24-27)	3.2±13.4 (−21-30)
PT	16.3±8.2 (−4-29)	25.7±8.4 (11-54)
TK	40.9±11.7 (18-60)	31.1±17.2 (5-77)
C7SVA	79.6±64.9 (−43-254)	82.2±62.2 (−9-208)

Values are given as mean±SD (range). Patients have been dichotomized into low or high PI groups. Radiographic patient parameters at baseline in individuals with low and high PI. C7SVA - C7 sagittal vertical axis (mm), PI - Pelvic incidence (°), LL - Lumbar lordosis, PI-LL - PI-LL mismatch (°), PT - Pelvic tilt (°), T10-L2 - Sagittal Cobb angle T10-L2 (°), TK - Thoracic kyphosis (°)

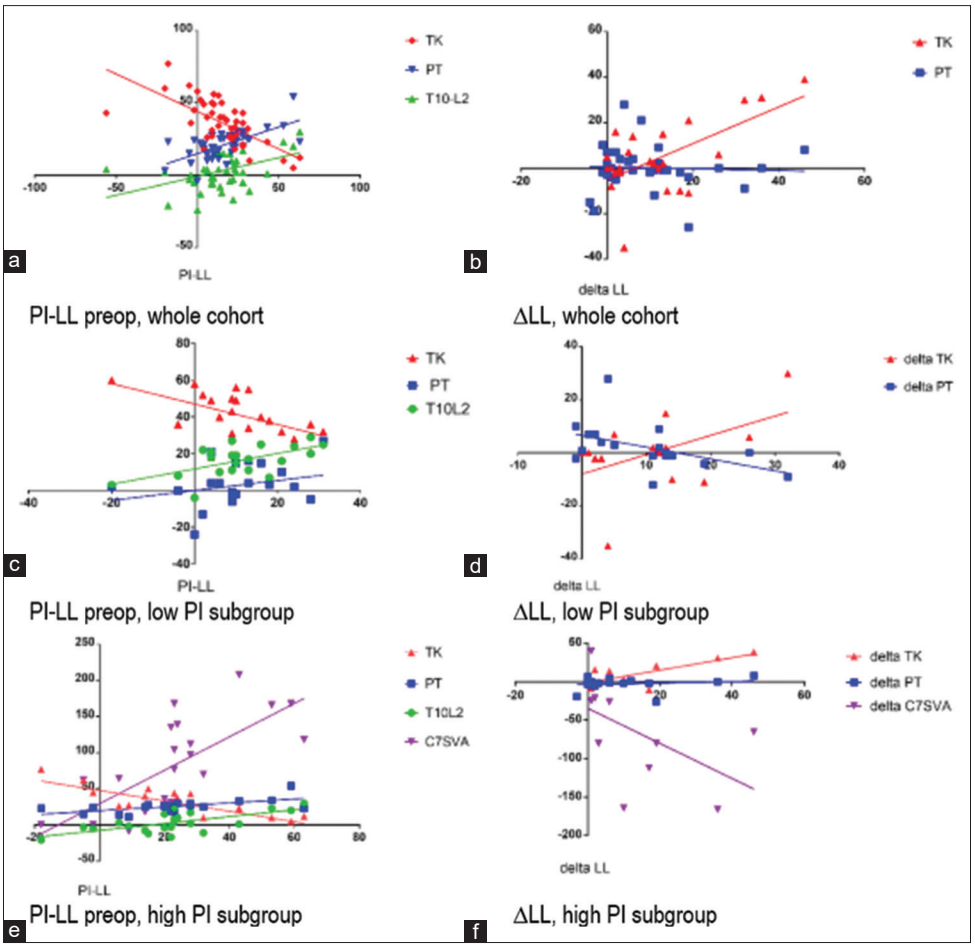

Figure 1: Correlations between preoperative PI-LL and perioperative change in PI-LL and sagittal spinopelvic parameters in the whole patient cohort as well as low and high PI subgroups. PI-LL - Pelvic incidence-lumbar lordosis, (a) PI-LL preoperative measures for whole cohort, (b) Change in lumbar lordosis for whole cohort, (c) PI-LL preoperative measures for low PI subgroup, (d) Change in lumbar lordosis preoperative measures for low PI subgroup, (e) PI-LL preoperative measures for high PI subgroup, (f) Change in lumbar lordosis preoperative measures for high PI subgroup

DISCUSSION

The results of the present study demonstrate that the degree of PI may influence the compensation patterns in patients with ASD and significant PI-LL mismatch. It was further shown that the overall reduction of TK was more consistently normalized after surgical deformity correction, while PT was not. Anticipating perioperative changes in PT and TK are important to consider in surgical planning.

Distinct spinal deformities can activate distinct compensation patterns. Lumbar hypolordosis is associated with an increase in PT and a decrease in TK.[2,5] Like the results of our study, Diebo *et al*. found a linear correlation between increases in PI-LL mismatch and both PT increase and TK decrease.[10] While reduction of TK is more frequently observed in younger patients (often under the age of 45) with a mobile, nonrigid spine, it requires contraction of the erector spinae muscle, as shown in Figure 2,[5] which has been linked to increased thoracic muscle pain over the course of the day due to muscle fatigue.[11] Previous studies have shown that compensatory adjustments in PT and TK maintain a neutral C7SVA up to a PI-LL mismatch of 30°.[10,12] Since PI-LL mismatch in our study cohort was between 10° and 22.8°, we expected to observe PT and TK modifications in response to ASD. As evident in Figure 2, abdominal, gluteal, and ischiocrural muscles primarily accomplish PT increase. Eventually, an increased PT maintains the sagittal vertical axis centered in the context of increasing PI-LL mismatch. However, it also correlated with clinical disability scores since it requires muscle activation.[13] As has been shown in previous studies, a compensatory increase in PT can normalize after surgical correction of spinal deformity.[12] Our results are congruent in showing a decrease in PT in the high PI group and suggested a more reliable increase of TK across high and low PI subgroups. Since the axis of rotation for PT regulations is the hip joint, osteoarthritis or dynamic hip pathology may confound findings and limit the body's capability to control PT.[14] Further, PT is influenced by hip flexors and back extensors, as well as abdominal wall muscles and gluteal muscles. Indeed,

Table 2: Preoperative radiographic measurements

	PI-LL versus T10-L2	PI-LL versus PT	PI-LL versus TK	PI-LL versus C7SVA
PI-LL preoperative, whole cohort				
Pearson r				
R	0.4218	0.6553	−0.6747	0.2502
95% CI	0.1428-0.6387	0.442-0.7985	−0.8095-−0.4725	−0.05038-0.5093
R^2	0.1779	0.4294	0.4553	0.06262
P				
P (two-tailed)	0.0043	<0.0001	<0.0001	0.1013
Slope	0.2597±0.08614	0.3677±0.06619	−0.519±0.08761	0.1884±0.1125
PI-LL preoperative, low PI subgroup				
Pearson r				
R	0.5957	0.2753	−0.5555	0.1116
95% CI	0.2208-0.8172	−0.1774-0.6319	−0.7962-−0.1628	−0.3363-0.5183
R^2	0.3549	0.07581	0.3085	0.01246
P				
P (two-tailed)	0.0044	0.2270	0.0089	0.6301
Slope	0.4194±0.1297	0.2687±0.2153	−0.5575±0.1915	0.6216±1.27
PI-LL preoperative, high PI subgroup				
Pearson r				
R	0.6808	0.6162	−0.804	0.7118
95% CI	0.3636-0.8566	0.2629-0.8238	−0.9153-−0.5785	0.4146-0.8718
R^2	0.4635	0.3797	0.6464	0.5067
P				
P (two-tailed)	0.0005	0.0023	<0.0001	0.0002
Slope	0.27±0.07715	0.4773±0.1148	−0.7215±0.1193	0.6216±1.27

Preoperative radiographic measurements in the whole patient cohort, as well as low and high PI subgroups. Correlations between sagittal parameters and PI-LL mismatch are given. CI - Confidence interval, C7SVA - C7 sagittal vertical axis, PI - Pelvic incidence, PI-LL - PI-lumbar lordosis mismatch, PT - Pelvic tilt, T10-L2 - Sagittal Cobb angle T10-L2, TK - Thoracic kyphosis

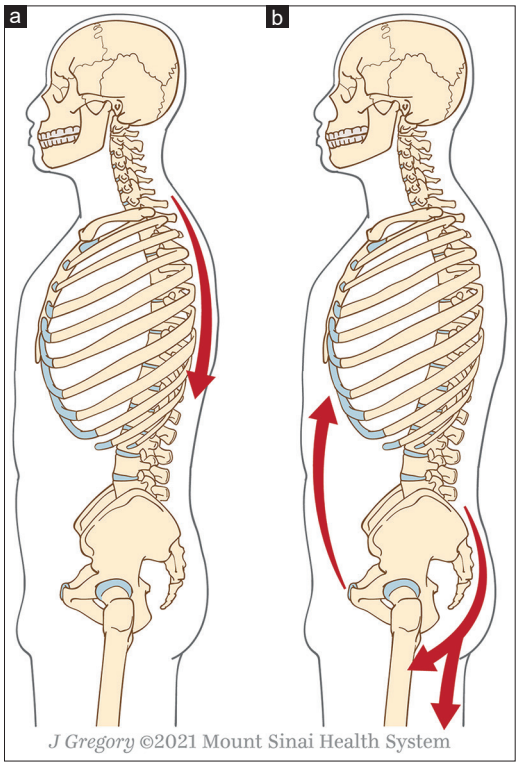

Figure 2: Mechanisms involved in reduction of TK (inlet a): Erector spinae activation, and increase in PT (inlet b): Rectus abdominis and gluteal muscle activation. PT - Pelvic tilt, TK - Thoracic kyphosis

atrophy of the thoracolumbar extensor muscles produces global kyphosis.[15]

While PT did not change postoperatively, there was marked variation in the range from −26° to 28°. Failure of perioperative PT to consistently correlate with change in PI-LL might be explained by the more complex mechanism of PT regulation, which is potentially influenced by hip joint pathologies. In our study, those patients with low PI relied more on TK reduction than changes in PT. Similarly, in a different study of 34 patients with ADS who underwent correction of lumbar deformity, a compensatory increase in PT on average only reduced by 8° while TK increased by 13°, while no change was observed in 11 of 34 of these patients.[16]

Patients with low PI have reduced capabilities of decreasing sacral slope and pelvic retroversion as seen in those with high PI.[17] Differences in PI compensation patterns between low and high PI subgroups in this study may underlie preoperative PI values. Baseline characteristics may be evaluated to predict when patients may present with a disability, and if earlier intervention may be warranted for those with high PI and exaggerated compensation of TK and PT. This subpopulation may benefit from a greater correction in both parameters postoperatively.

Table 3: Postoperative change in radiographic measures of lumbar lordosis in whole cohort, low pelvic incidence and high pelvic incidence subgroups

	Delta LL versus delta T10-L2	Delta PI-LL versus delta PT	Delta PI-LL versus delta TK	Delta PI-LL versus delta C7SVA
ΔLL, whole cohort				
Pearson r				
R	0.138	0.04679	−0.6334	
95% CI	−0.4209-0.1693	−0.3653-0.2815	0.3179-0.8227	
R^2	0.01905	0.002189	0.4012	
P				
P (two-tailed)	0.3774	0.7833	0.0007	
Slope	−0.1018±0.1141	−0.03929±0.1418	0.8061±0.2053	
ΔLL, low PI subgroup				
Pearson r				
R	0.06492	0.4821	−0.4877	0.3166
95% CI	−0.4933-0.3888	−0.7746-−0.01964	−0.05785-0.809	−0.7253-0.2572
R^2	0.004214	0.2324	0.2378	0.1002
P				
P (two-tailed)	0.7857	0.0428	0.0769	0.2701
Slope	−0.04801±0.174	−0.4455±0.2024	0.728±0.3762	−1.394±1.206
ΔLL, high PI subgroup				
Pearson r				
R	0.05297	0.1505	−0.7686	−0.5404
95% CI	−0.4841-0.3989	−0.3559-0.5885	0.313-0.9366	−0.8611-0.08795
R^2	0.002806	0.02264	0.5907	0.2921
P				
P (two-tailed)	0.8245	0.5643	0.0057	0.0861
Slope	−0.04358±0.1936	0.09308±0.1579	0.8101±0.2248	−2.283±1.185

Correlations between sagittal parameters andΔLL are given. CI - Confidence interval, C7SVA - C7 sagittal vertical axis, PI - Pelvic incidence, LL - Lumbar lordosis, PI-LL - PI-LL mismatch, PT - Pelvic tilt, T10-L2 - Sagittal Cobb angle T10-L2, TK - Thoracic kyphosis

Table 4: Correlations between sagittal parameters and preoperative PI-LL mismatch and change in LL postoperatively across groups

	T10-L2	PT	TK	C7SVA	PT/TK ratio
Preoperative PI-LL, whole cohort	+0.26 (±0.09)	+0.37 (±0.06)	−0.52 (±0.09)	-	-
PerioperativeΔLL, whole cohort	-	-	+0.81 (±0.21)	-	-
Preoperative PI-LL, low PI subgroup	+0.42 (±0.13)	0.27 (±0.22)	−0.56 (±0.19)	-	0.46 (±0.28)
PerioperativeΔLL, low PI subgroup	-	−0.45 (±0.2)	+0.73 (±0.38)	-	-
Preoperative PI-LL, high PI subgroup	+0.27 (±0.08)	0.48 (±0.11)	−0.72 (±0.12)	+0.62 (±1.27)	1.5 (±2.2)
PerioperativeΔLL, high PI subgroup	-	+0.09 (±0.16)	+0.81 (±0.22)	−2.28 (±1.90)	-

Values are given as Person correlation coefficients. Blank cells indicate that no statistically significant correlations were found. C7SVA - C7 sagittal vertical axis (mm), PI - Pelvic incidence (°), LL - Lumbar lordosis, PI-LL - PI-lumbar lordosis mismatch (°), PT - Pelvic tilt (°), T10-L2 - Sagittal Cobb angle T10-L2 (°), TK - Thoracic kyphosis (°)

A limitation of this study is the lack of a standardized postoperative physical therapy regimen, which might have had an impact on PT regulation after surgery.

Optimizing the outcome of surgical correction in ASD might require an in-depth understanding of compensation mechanisms and to predict the future changes of these mechanisms. Individual pelvic morphology as well as hip joint assessment should be considered when investigating the benefits of spinal deformity correction. Future studies may examine whether these radiographic and morphologic changes relate to meaningful clinical differences in function and pain scores.

CONCLUSIONS

A substantial decrease in TK represented a more consistent compensatory mechanism in patients with high and low PI when compared to an increase in PT. PI-LL mismatch induced more pronounced changes in TK than did PT in all groups. Postoperatively, the reversal of compensatory changes was more consistent for TK than for PT. Patients with high PI relied more on increases in PT and a relative decrease in TK to compensate for PI-LL mismatch than patients with low PI. Predicting postoperative changes of TK and PT might be important to determine mid- and long-term spinal alignment after spinal deformity correction.

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Conflicts of interest

There are no conflicts of interest.

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