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Beyond Pelvic Incidence–Lumbar Lordosis Mismatch: The Importance of Assessing the Entire Spine to Achieve Global Sagittal Alignment

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Abstract

Study Design: Retrospective case series.

Objective: To investigate which sagittal parameters contribute to a normal sagittal vertical axis (SVA) when there is a pelvic incidence-lumbar lordosis (PI-LL) mismatch >10° following adult spinal deformity (ASD) correction.

Methods: We performed a retrospective review of ASD patients with >5 levels fused. Sagittal measurements between cohorts of postoperative PI-LL >10° and PI-LL<10° were compared. We correlated SVA to pelvic tilt (PT), thoracic kyphosis (TK), PI-LL, cervical lordosis (CL), and correlated the pre- to postoperative change in SVA to change in PT, change in TK, change in PI-LL, and change in CL. We also correlated SVA and the change in SVA to combined parameters of ((PI-LL) − PT + TK).

Results: We analyzed 52 patients with a mean age of 59 ± 16 years. In patients with a postoperative SVA <5cm, a smaller TK was seen when PI-LL >10° than when PI-LL<10° (15.45° vs 33.04°, $P = .0004$). Additionally, PT was larger when PI-LL >10° than when PI-LL <10° (25.73° vs 19.07°, $P = .006$). SVA correlated better with ((PI-LL) − PT + TK) ($R^2 = 0.51$) than with PI-LL alone ($R^2 = 0.33$). Lastly, there was no significant correlation between change in pre- to postoperative SVA with change in TK for all cases ($P = .73$), but in cases where change in PI-LL was <10°, there was a significant correlation between change in TK and change in SVA ($P = .009$).

Conclusion: Our results demonstrate that PT and TK, and not just PI-LL, play an important role in maintaining sagittal balance when there is a PI-LL mismatch >10°.

Keywords

sagittal balance, pelvic incidence, PI-LL, thoracic kyphosis, pelvic tilt, compensatory mechanisms

Introduction

Sagittal misalignment in adult spinal deformity has gained increasing attention for its association with negative health-related quality of life (HRQoL) and increased disability.[1-5] Increased sagittal vertical axis (SVA) and pelvic incidence–lumbar lordosis (PI-LL) mismatch, in particular, highly relate to adverse patient-reported outcomes.[6,7] The PI-LL mismatch correlates strongly with SVA and has become a focal target when planning adult deformity correction. The goals of surgical correction involve optimizing PI-LL and SVA to achieve global sagittal balance.[3,6,8]

With increasing SVA, an increase in the PI-LL mismatch recruits compensatory mechanisms of increased pelvic retroversion, reduced thoracic kyphosis (TK), increased knee flexion, and increased pelvic shift to balance the SVA, indicating that other sagittal parameters influence sagittal alignment.[9,10] Additionally, cervical sagittal parameters relate to HRQoL and disability, stressing the importance of considering

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Table 1. Preoperative, Postoperative, and Change From Pre- to Postoperative Coronal and Sagittal Measurements for All 52 Cases.

	Preoperative Mean	Postoperative Mean	Change	P^a
Coronal Cobb (°)	32.62 ± 21.04	15.96 ± 12.62	−16.66 ± 14.73	<.0001
PT (°)	23.52 ± 11.09	21.46 ± 7.46	−2.06 ± 10.41	.1601
PI (°)	56.58 ± 11.28	56.77 ± 10.78	0.19 ± 1.67	.4099
SS (°)	33.08 ± 11.19	35.35 ± 10.36	2.27 ± 9.85	.1028
LL (°)	38.08 ± 21.48	49.21 ± 15.24	11.13 ± 20.89	.0003
TK (°)	27.85 ± 17.68	27.55 ± 15.18	−0.5 ± 16.24	.8252
SVA (mm)	81.77 ± 84.06	30.54 ± 59.70	−51.23 ± 69.42	<.0001
PI-LL (°)	18.35 ± 19.98	7.63 ± 14.58	−10.71 ± 21.31	.0007
CL (°)	10.62 ± 15.73	8.38 ± 10.83	−2.43 ± 15.25	.3080

Abbreviations: PT, pelvic tilt; PI, pelvic incidence; SS, sacral slope; LL, lumbar lordosis; TK, thoracic kyphosis; SVA, sagittal vertical axis; CL, cervical lordosis.
[a]*P* value is comparing change from preoperative to postoperative measurements.

the entire spine when assessing patients with sagittal deformity.[11-13]

How compensatory mechanisms contribute to alignment when the SVA is normal but PI-LL > 10° has not been well investigated. Understanding what components of the spine help achieve a normal SVA when there is a high PI-LL mismatch (>10°), and how a pre- to postoperative change in SVA relates to changes in other sagittal parameters, is necessary to effectively plan corrective strategies. Other regions of the spine could be potential targets for deformity correction if adequate PI-LL mismatch cannot be achieved. Furthermore, understanding these compensatory mechanisms and dynamic relationships can potentially assist in minimizing postoperative complications.

Our objective was to investigate which sagittal parameters contribute to restoring normal SVA (<5 cm) when PI-LL mismatch is high (>10°) and how changes in specific sagittal measurements relate to changes in global sagittal alignment.

Methods

Patient Sample

This was a retrospective, single-center study examining adult spinal deformity patients who underwent >5 levels of fusion by a single surgeon between 2011 and 2015. We included patients undergoing primary or revision fusion. Adolescent patients were excluded. All patients had pre- and postoperative lateral, standing radiographs with the C7 vertebral body and both femoral heads visible. Measurements were made with Surgimap, a validated software.[14] Patient charts were accessed via the hospital's electronic medical record to obtain all demographic and operative information. This study was qualified as exempt by the Mount Sinai Hospital Institutional Review Board.

Coronal and Sagittal Measurements

We measured major coronal Cobb angles on all patients' pre- and postoperative anterior-posterior, standing radiographs. Sagittal measurements were made for PT, PI, sacral slope (SS), LL, TK, SVA, PI-LL, and cervical lordosis (CL). Postoperative radiographs were taken within 6 weeks of surgery. A single user measured each radiograph 3 times, and the average of the 3 separate measurements was used for data analysis.

Statistical Analysis

All statistical analyses were performed with Prism GraphPad V6 (La Jolla, CA). Changes in pre- to postoperative alignment measurements were compared with a paired *t* test.

To assess the difference in measurements when there is a high versus low postoperative PI-LL mismatch, we divided our patients into a group with a postoperative SVA < 5 cm and either a postoperative PI-LL < 10° or PI-LL > 10°. Measurements between these cohorts were compared with an unpaired *t* test.

We correlated and performed linear regressions to examine the relationship between SVA and other sagittal measurements, namely, PT, TK, PI-LL, and CL. We also correlated the change in SVA to the change in the aforementioned sagittal parameters. Correlations were also performed between the SVA and change in SVA to combined parameters of ((PI-LL) − PT + TK). All correlations were univariate and performed with all 52 patients. Statistical significance was considered at *P* value <.05.

Results

Patient Sample

We investigated 52 patients consisting of 17 men and 35 women with a mean age of 59 ± 16 years. The average number of operative levels was 11 ± 4. Thirty-two patients had a diagnosis of degenerative kyphoscoliosis and 20 had flat back deformity.

Coronal and Sagittal Measurements

Table 1 summarizes pre- and postoperative coronal and sagittal measurements. The average change in Cobb from pre- to postoperative was −16.66 ± 14.73°, which was statistically significant ($P = <.0001$). There was a statistically significant average change in pre- to postoperative PI-LL (−10.71 ± 21.31,

Table 2. Demographic and Preoperative Alignment Comparisons Between Patients With a Postoperative SVA < 5 cm and Either a PI-LL > 10° or PI-LL < 10°.

	PI-LL > 10°, N = 11	PI-LL < 10°, N = 28	*P*
Age	60.54 ± 18.03	60.40 ± 14.11	.9796
Number of levels	10.45 ± 3.67	11.43 ± 3.92	.4820
Preoperative coronal Cobb (°)	39.76 ± 13.63	31.54 ± 22.21	.2613
Preoperative SVA (mm)	39.78 ± 60.42	68.04 ± 83.23	.3136

Abbreviations: PI, pelvic incidence; LL, lumbar lordosis; SVA, sagittal vertical axis.

$P = .0007$) and SVA (−51.23 ± 69.42, $P = <.0001$). There was no statistically significant change in PT, TK, or CL from pre- to postoperative (Table 1).

Comparisons Between Patients With Normal SVA and Either a PI-LL > 10° or PI-LL < 10°

Thirty-nine patients had a postoperative SVA <5 cm. Of these 39, 11 had a PI-LL > 10° and 28 had a PI-LL < 10°. There was no significant difference between the 2 cohorts with respect to age, number of levels fused, preoperative coronal Cobb angle, and preoperative SVA (Table 2). Figure 1 shows representative radiographs of patients with a normal postoperative SVA and either a PI-LL greater than 10 or less than 10, and Figure 2 demonstrates that when comparing the cohorts of high versus low postoperative PI-LL, the group with the high mismatch had a statistically greater PT (25.73 ± 7.02° vs 19.07 ± 6.16°, $P = .006$) and a statistically smaller TK (15.45 ± 13.68° vs 33.04 ± 11.94°, $P = .0004$). There was no statistically significant difference in the mean postoperative SVA between these 2 groups. The 13 patients with postoperative SVA > 5 cm had an average postoperative PT, TK, and PI-LL of 22.43 ± 8.80°, 27.00 ± 17.65°, 19.21 ± 15.56°, respectively. Only 2 of these patients had a postoperative PI-LL < 10°.

Correlations Between Postoperative SVA and Individual and Combined Parameters

Regarding postoperative PT, TK, and PI-LL, there was only a statistically significant correlation between postoperative SVA and PI-LL ($P = <.0001$, $R^2 = 0.33$) as well as postoperative SVA and CL ($P = .03$, $R^2 = 0.09$) for all 52 cases. There was no statistically significant correlation between SVA and PT ($P = .25$) or TK ($P = .87$).

We combined the 3 parameters PI-LL, PT, and TK and correlated them to postoperative SVA in the following ways: SVA versus PI-LL, SVA versus (PI-LL) − PT, SVA versus (PI-LL) + TK, and SVA versus (PI-LL) − PT + TK. The *P* value for all of these correlations was $P = <.0001$. The R^2 value was lowest for SVA versus PI-LL ($R^2 = 0.33$; Figure 3A), and incrementally increased with subtraction of PT ($R^2 = 0.39$), addition of TK ($R^2 = 0.41$), and was highest for SVA versus ((PI-LL) − PT + TK) ($R^2 = 0.51$; Figure 3B). These correlations were performed using all 52 cases.

Correlations Between Change in SVA and Change in Individual and Combined Parameters

We found a statistically significant correlation between change in SVA and change in PI-LL, PT, and CL ($P = <.0001$, .02, and <.0001; Table 3). There was no significant correlation between change in SVA and change in TK when examining all cases ($P = .73$). When only examining cases where change in PI-LL was small (<10°), though, the correlation between change in SVA and change in TK became significant ($P = .009$), and the correlations between change in SVA and change in PI-LL, PT, and CL became insignificant ($P = .78$, .58, and .16, respectively; Table 4). In cases where change in PI-LL > 10°, correlation between change in SVA and change in PI-LL, PT, TK, and CL are similar to the correlations for all cases (Table 5).

We found similar patterns for the correlations of change in SVA to change in combined parameters as we did for correlations between postoperative SVA and the combined parameters. That is, the correlation of change in SVA to change in PI-LL was statistically significant with a *P* value of <.0001 and R^2 value of 0.43 (Figure 4A). When change in PT was subtracted from change in PI-LL (Δ(PI-LL) − ΔPT), the *P* value was <.0001 and the R^2 value increased to 0.47. When change in TK was added to change in PI-LL ((Δ(PI-LL) + ΔTK), the *P* value was <.0001 and the R^2 value increased to 0.53. Last, when the change in TK was added and the change in PT is subtracted from the change in PI-LL (Δ(PI-LL) − ΔPT + ΔTK), the *P* value remained at <.0001 and the R^2 value increases to 0.69 (Figure 4B). These correlations were performed with all 52 cases.

Discussion

Our objective with this retrospective cohort study was to determine which sagittal parameters contribute to a normal SVA when PI-LL > 10°, and to better understand how sagittal parameters change after surgical deformity correction. Investigating this has important implications for deformity surgeons, and our results suggest that surgical correction affects multiple segments of the spine and pelvis, beyond the commonly discussed sagittal parameters.

Diebo et al examined patients with sagittal spinal misalignment and divided patients into PI-LL groups of 0° to 10°, 10° to 20°, 20° to 30°, and 30° to 40°.[9] They found that increasing PI-LL was associated with increased pelvic retroversion, reduction of TK, increased knee flexion, and increased pelvic shift. They also demonstrated that compensation for positive sagittal imbalance via PT and TK became exhausted after about 20° and 30° of PI-LL mismatch, respectively. We obtained similar results, though we only examined patients with a normal postoperative SVA of <5 cm, and divided them into groups of either a PI-LL < 10° or PI-LL > 10°. There was on average 7.16° of additional pelvic retroversion and 16.80° of reduced

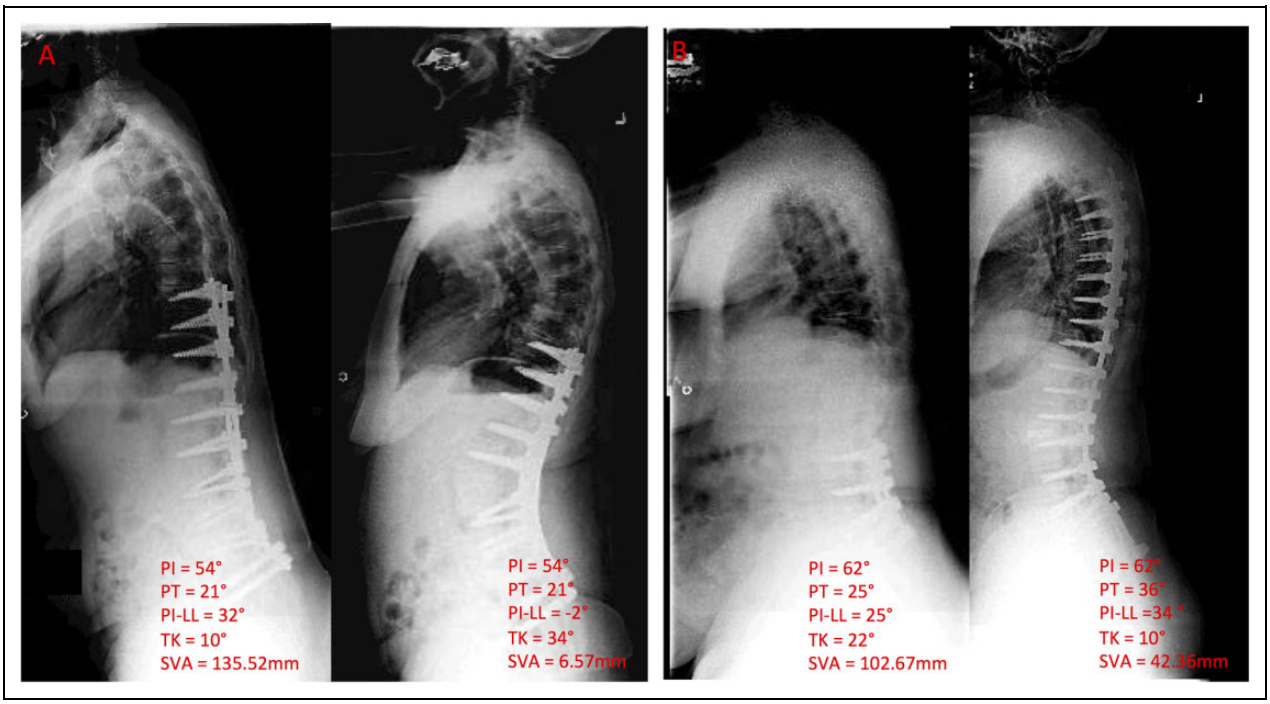

Figure 1. Representative standing, lateral radiographs of patients in each cohort. (A) Pre- and postoperative radiographs of a patient with a normal postoperative SVA and postoperative PI-LL < 10°. (B) Pre- and postoperative radiographs of a patient with a normal postoperative SVA despite a postoperative PI-LL > 10°, exhibiting increased PT and reduced TK.

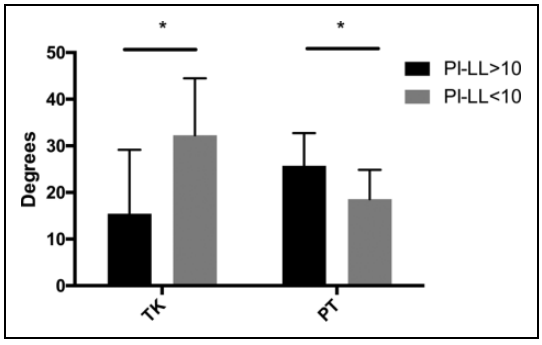

Figure 2. Histograms comparing TK and PT in patients with SVA < 5 cm and either a PI-LL > 10° or PI-LL < 10°. *Indicates significant differences. Error bars represent standard deviation.

TK in the high mismatch group compared to the low mismatch group. With a PI-LL higher than the target <10°, our patients were able to improve global sagittal alignment by a compensatory increase in PT and a decrease in TK. This indicates an inverse relationship between PT and TK to maintain normal SVA within this subset of patients. This is consistent with several prior studies addressing changes in sagittal balance in patients with underlying pathology.[15-17] While this compensation improves SVA, it is important to consider that a persistent PI-LL mismatch and overcompensated PT and TK may predispose to complications such as adjacent segment pathology, proximal junctional kyphosis, and pseudarthrosis.[18-20] Neurologic complications may result from proximal junctional failure, and therefore preoperative assessment and corrective planning should take into account both the pelvic orientation and thoracic spine in addition to the PI-LL.

Roussouly and Pinheiro-Franco described how the biomechanical relationship between SS, LL, and TK affects SVA.[15] High SS correlates with increased LL, TK, and CL to balance the SVA, and if the LL is low, TK must decrease to align the SVA. This essentially translates into $SS - LL + TK \propto SVA$. By substituting SS for PI-PT ($SS = PI-PT$), we arrive at our equation of $PI - PT - LL + TK$, rearranged to $(PI-LL) - PT + TK$, which is what we correlated to SVA. Intuitively, a high PI pushes the SVA forward, LL pulls the SVA back (so this must be subtracted), PT pulls the SVA back (so this must be subtracted), and TK pushes the SVA forward (so this must be added) to aggregate a final approximation of SVA. This supports our prior findings of an inverse relationship between PT and TK that affects SVA. We saw that this equation had a stronger correlation to SVA ($R^2 = 0.54$) than PI-LL alone ($R^2 = 0.30$). Similarly, we saw an increased association between ΔSVA versus $\Delta(PI-LL) - \Delta PT + \Delta TK$ ($R^2 = 0.69$) than ΔSVA versus ΔPI-LL alone ($R^2 = 0.43$), suggesting multiple parameters, in addition to PI-LL, are important to consider for patients with sagittal misalignment.

Our regression analysis with SVA as the independent variable and $((PI-LL) - PT + TK)$ as the dependent variable shows that when SVA = 50 mm, the value of $((PI-LL) - PT + TK) = 16.22°$. Thus, based on our findings, the target postoperative value for $((PI-LL) - PT + TK)$ should be less than <16° to improve sagittal balance, and should take into account PT and

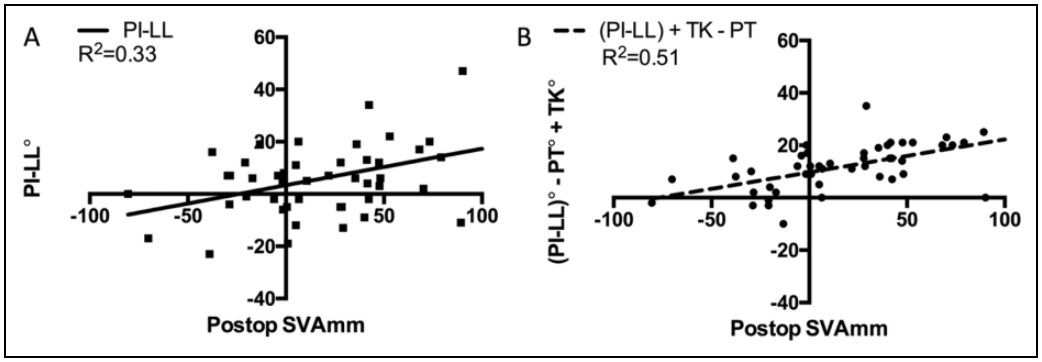

Figure 3. Correlations between (A) postoperative SVA and PI-LL alone, or (B) (PI-LL) − PT + TK. A stronger correlation and better model fit is seen between SVA and the combined parameters than with SVA and PI-LL alone.

Table 3. *P* Values and R^2 Values for Correlations of Change in SVA to Change in Other Parameters for All 52 Cases.

	Change in SVA Versus Change in PI-LL	Change in SVA Versus Change in PT	Change in SVA Versus Change in TK	Change in SVA Versus Change in CL
R^2 value	0.43	0.11	0.002	0.31
P value	<.0001	.0176	.7318	<.0001

Abbreviations: SVA, sagittal vertical axis; PI, pelvic incidence; LL, lumbar lordosis; PT, pelvic tilt; TK, thoracic kyphosis; CL, cervical lordosis.

Table 4. *P* Values and R^2 Values for Correlations of Change in SVA to Change in Other Parameters Only for Cases Where Change in PI-LL Mismatch Is Small (<10°), N = 20.

	Change in SVA Versus Change in PI-LL	Change in SVA Versus Change in PT	Change in SVA Versus Change in TK	Change in SVA Versus Change in CL
R^2 value	0.005	0.02	0.32	0.11
P value	.7745	.5792	.0089	.1598

Abbreviations: SVA, sagittal vertical axis; PI, pelvic incidence; LL, lumbar lordosis; PT, pelvic tilt; TK, thoracic kyphosis; CL, cervical lordosis.

Table 5. *P* Values and R^2 Values for Correlations of Change in SVA to Change in Other Parameters Only for Cases Where Change in PI-LL Mismatch Is High (>10°), N = 32.

	Change in SVA Versus Change in PI-LL	Change in SVA Versus Change in PT	Change in SVA Versus Change in TK	Change in SVA Versus Change in CL
R^2 value	0.55	0.19	0.05	0.46
P value	<.0001	.0128	.2065	.0003

Abbreviations: SVA, sagittal vertical axis; PI, pelvic incidence; LL, lumbar lordosis; PT, pelvic tilt; TK, thoracic kyphosis; CL, cervical lordosis.

TK as they are critical to achieving an SVA < 50 mm. The interplay between multiple parameters of the spine must be considered when planning deformity correction, and the focus should involve the entire spine. It is important, though, that PT not increase to >20° to 22° because of associations with negative HRQoL reported in other studies.[21,22] There must be a delicate balance between sagittal spinopelvic parameters in order to achieve the greatest patient outcome.

Similar efforts have attempted to define novel angles to simplify the sagittal measurements of patients.[23,24] Obeid et al defined global tilt as the summation of C7 vertical tilt and pelvic tilt. The author's objective was to obtain a measurement that was minimally affected by patient position and would therefore make sagittal balance easier to interpret.[23] Another study by Diebo et al investigated radiographic parameters beyond just the spine and pelvis to include the lower extremity as well.[24] They defined the global sagittal axis as the angle between a line from the C7 vertebral body to the femoral condyles and another line from the femoral condyles to the posterosuperior corner of the sacral endplate. They found this angle to correlate more strongly with HRQoL scores than any other sagittal measurement. Our results contribute to the overall discussion of sagittal balance and how sagittal parameters interact and affect one another.

When examining our cases for change in radiographic parameters, we found a statistically significant correlation between change in SVA and change in PI-LL, PT, and CL, but not a significant correlation with change in TK. Given the correlation between SVA and PI-LL seen in the literature, the correlation between a change in SVA and a change in PI-LL was expected. We also expectedly found that as SVA was corrected, the PT was reduced because correction of the SVA relieves the need to compensate through pelvic retroversion. As the SVA was corrected, the lordosis in the cervical spine was decreased because hyperlordosis of the neck may no longer be required to maintain horizontal gaze. Protopsaltis et al showed that when controlling for global sagittal misalignment, correction of cervical sagittal misalignment correlated with improved HRQoL.[11] This highlights how regions of the spine are interrelated and that preoperative surgical planning should encompass the entire spine. This is further supported by our observation that there was not a significant correlation between change in SVA and change in TK for all cases, but in cases where the change in PI-LL was low (<10°) there was a significant correlation between change in SVA and change in TK.

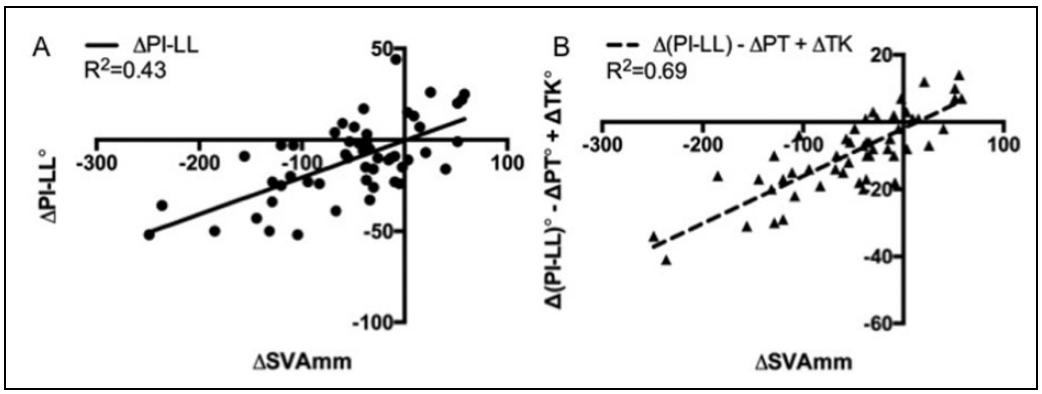

Figure 4. Correlations between (A) pre- to postoperative change in SVA and change in PI-LL alone, or to (B) change in (PI-LL) − change in PT + change in TK. A stronger correlation and better model fit is seen between change in SVA and change in the combined parameters than with change in SVA and change in PI-LL alone.

The average change in PI-LL was just over 10° for all cases. When we examined the cases where the change in PI-LL was smaller than this, the correlation between change in SVA and change in TK became significant, and the correlation between change in SVA and change in PI-LL, change in PT, and change in CL became nonsignificant. Despite a small change in PI-LL (<10°), the SVA still had an average change of 44 mm that correlated only to a change in TK, suggesting thoracic hypokyphosis became the major compensatory mechanism to restore sagittal balance.

Our results not only support PI-LL as a major determinant of SVA but also reinforce that the entire spine influences sagittal balance. These findings highlight the dynamic approach of planning adult deformity correction. An assessment of the entire spine should precede surgical planning and correction.

Limitations

Our study involved a heterogeneous population, and in future prospective studies, we aim to stratify our population into distinct groups of diagnoses and levels fused to reduce any confounding effects. Additionally, we had a small number of patients with normal postoperative SVA but a PI-LL mismatch >10°. Despite our statistically significant results with this small population, a larger sample size for this cohort is needed to improve the power of our study. Of the 13 patients with a postoperative SVA > 5 cm, only 2 had a PI-LL < 10°, which limited our ability to compare the sagittal parameters of these 2 patients to those with a postoperative SVA > 5 cm and PI-LL > 10°. Last, our analysis was confined to radiographs of the pelvis and proximal structures, so we could not account for lower limb compensatory mechanisms.

Conclusion

When there was a normal SVA and PI-LL was >10°, the thoracic and cervical spines straightened and the pelvis retroverted. Additionally, when the PI-LL mismatch was small, PT and TK played an important role in maintaining a normal sagittal balance. It is paramount, though, that TK does not overcompensate to pathologic levels or severe complications may occur. Our findings support the concept that sagittal balance involves numerous parameters, namely, PT, TK, and CL. These findings improve our understanding of global sagittal balance and the dynamic relationship of various sagittal parameters in patients with adult spinal deformity. Studies such as this can help direct our goals for corrective osteotomies, guide future prospective studies, and improve our preoperative patient assessment and risk stratification.

Authors' Note

This study was qualified as exempt by the Mount Sinai Hospital Institutional Review Board. The article does not contain information about medical device(s)/drug(s).

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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