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Surgical Planning for Adult Spinal Deformity: Anticipated Sagittal Alignment Corrections According to the Surgical Level

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Abstract

Study Design: Retrospective cohort study.

Objectives: Establish simultaneous focal and regional corrective guidelines accounting for reciprocal global and pelvic compensation.

Methods: 433 ASD patients (mean age 62.9 yrs, 81.3% F) who underwent corrective realignment (minimum L1-pelvis) were included. Sagittal parameters, and segmental and regional Cobb angles were assessed pre and post-op. Virtual postoperative alignment was generated by combining post-op alignment of the fused spine with the pre-op alignment on the unfused thoracic kyphosis and the pre-op pelvic retroversion. Regression models were then generated to predict the relative impact of segmental (L4-L5) and regional (L1-L4) corrections on PT, SVA (virtual), and TPA.

Results: Baseline analysis revealed distal (L4-S1) lordosis of 33 $\pm$ 15°, flat proximal (L1-L4) lordosis (1.7 $\pm$ 17°), and segmental kyphosis from L2-L3 to T10-T11. Post-op, there was no mean change in distal lordosis (L5-S1 decreased by 2°, and L4-L5 increased by 2°), while the more proximal lordosis increased by 18 $\pm$ 16°. Regression formulas revealed that Δ10° in distal lordosis resulted in Δ10° in TPA, associated with Δ100 mm in SVA or Δ3° in PT; Δ10° in proximal lordosis yielded Δ5° in TPA associated with Δ50 mm in SVA; and finally Δ10° in thoraco-lumbar junction yielded Δ2.5° in TPA associated with Δ25 mm in SVA and no impact on PT correction.

Conclusions: Overall impact of lumbar lordosis restoration is critically determined by location of correction. Distal correction leads to a greater impact on global alignment and pelvic retroversion. More specifically, it can be assumed that 1° L4-S1 lordosis correction produces 1° change in TPA / 10 mm change in SVA and 0.5° in PT.

Keywords
adult spinal deformity, sagittal alignment, surgical planning, simulation, segmental correction, regional correction, predictive model

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Introduction

Adult spinal deformity is a highly common pathology in the older population, often associated with significant pain and disability. Growing evidence supports the clinical role of the sagittal component of the deformity, with progressive loss of lumbar lordosis (LL) and increased truncal inclination associated with poor patient-reported health-related quality of life (HRQoL).[1-3] Restoring sagittal alignment during surgical treatment of spinal deformity is critical to improving outcomes. Despite the proven relevance of achieving proper alignment, advanced but yet simple guidelines are still missing, and a large proportion of patients remain malaligned postoperatively.[4]

Global alignment is often characterized by the sagittal vertical axis (SVA), defined as the offset between the C7 plumbline to the posterosuperior corner of the sacrum.[5] Adult spinal deformity often starts with regional loss of lordosis followed by compensatory mechanisms to maintain an upright posture. SVA is useful in assessing globally truncal inclination and is one of the most correlated parameters with patient-reported outcomes.[6] However, defining alignment is more than a simple plumbline offset, and studying the position of the pelvis is essential to understand the body's reaction to a deformity. Pelvic tilt (PT), first described by Duval-Beaupere, is defined as the angle between the vertical and a line from the center of the femoral heads to the midpoint of the sacral endplate.[7] PT quantifies the pelvic rotation around the femoral heads, an established compensatory mechanism for anterior sagittal malalignment. Both SVA and PT are key components of the current ASD classification.[8] Suboptimal values represent reliable predictors of adverse clinical symptoms. Both parameters are not independent and have a dynamic relationship defining the overall spinal alignment. For a given alignment without changing any curvature, an increase in PT will decrease SVA, and vice versa.

Corrective surgery to restore ASD alignment relies on focal techniques that mostly have a direct impact on regional curvatures, which ultimately leads to a change in global alignment. Many studies have examined the quantitative effects of the degree and location of local correction on global parameters. Lafage et al described the relationship between the level and degree of pedicle subtraction osteotomy (PSO) on PT and SVA.[9] They found that a lower level of PSO has a larger impact on PT correction. This can be explained by a larger SVA correction achieved by a lower PSO level and a subsequent PT change in response to altered mass distribution above the pelvic, highlighting the dynamic interplay between PT and SVA.

Surgical planning for ASD in light of the complex interdependent spinopelvic parameters is challenging; having reliable predictive formulas could help in achieving better postoperative outcomes. While a published report has investigated the impact of regional correction on global alignment (SVA) and pelvic compensation (PT),[10] little is known about the impact of segmental correction in obtaining the desired global alignment. The goal of this study was to develop new predictive formulas to fine-tune truncal inclination and pelvic retroversion goals based on segmental and regional correction of the lumbar spine.

Method

Patient Population

This study was a retrospective review of a prospectively collected multicenter database of adult spinal deformity patients. Patients were enrolled into the ongoing database through an institutional review board approved protocol across all centers. The ethical approval was obtained from the Institutional Review Board of Hospital for Special Surgery prior to conducting the study (IRB No. 2014-357). Informed consent was obtained from all participating patients. Patients were enrolled if they met the following criteria: age > 18 years and spinal deformity confirmed by at least one of the following measures: scoliosis Cobb angle $> 20°$, SVA > 5 cm, pelvic tilt (PT) $>$ $25°$, and TK $> 60°$. For the current analysis, only patients with a minimum of 2-year follow-up data who underwent a complete fusion of the lumbar spine (L1 to S1 minimum) were retained.

Data Collection and Radiographic Parameters

Demographic information (age, sex, and BMI) were collected. Full-length, freestanding lateral, and anteroposterior spine radiographs were collected preoperatively and postoperatively. Identification and mapping of various anatomical landmarks were performed using validated software[11] (SpineView, ENSAM Laboratory of Biomechanics) to calculate the following parameters (Figure 1): PI, PT, mismatch between PI and LL (PI-LL), T1-pelvic angle (TPA), sagittal vertical axis (SVA), distal and proximal lumbar lordosis (i.e. L4-S1 and L1-L4), and thoraco-lumbar alignment (T10-L1). In addition, segmental angles for each vertebral level were calculated as the Cobb angle between the superior endplate of the vertebral level of interest and the superior endplate of the subjacent vertebral level.

In an effort to analyze the truncal correction independently of pelvic correction or thoracic reciprocal changes occurring after the realignment procedure, a simulated intermediary position was modeled (Figure 2) by applying the surgically induced lordosis while maintaining the preoperative PT and thoracic alignment. This intermediate simulated position allowed quantification of the SVA (ΔSVAsim) and TPA (ΔTPAsim) correction free of any reciprocal change.

Statistical Analysis

Demographic and radiographic data were described and analyzed at each time point. Multilinear regressions were generated to predict the simulated global alignment and the postoperative PT based on the segmental and regional corrections. The overall objective of these simulations was to investigate the impact of the location of correction on spino-pelvic alignment. Data were analyzed using SPSS software (SPSS, Inc.). Statistical analyses were 2-sided, and the level of significance was set to 0.05.

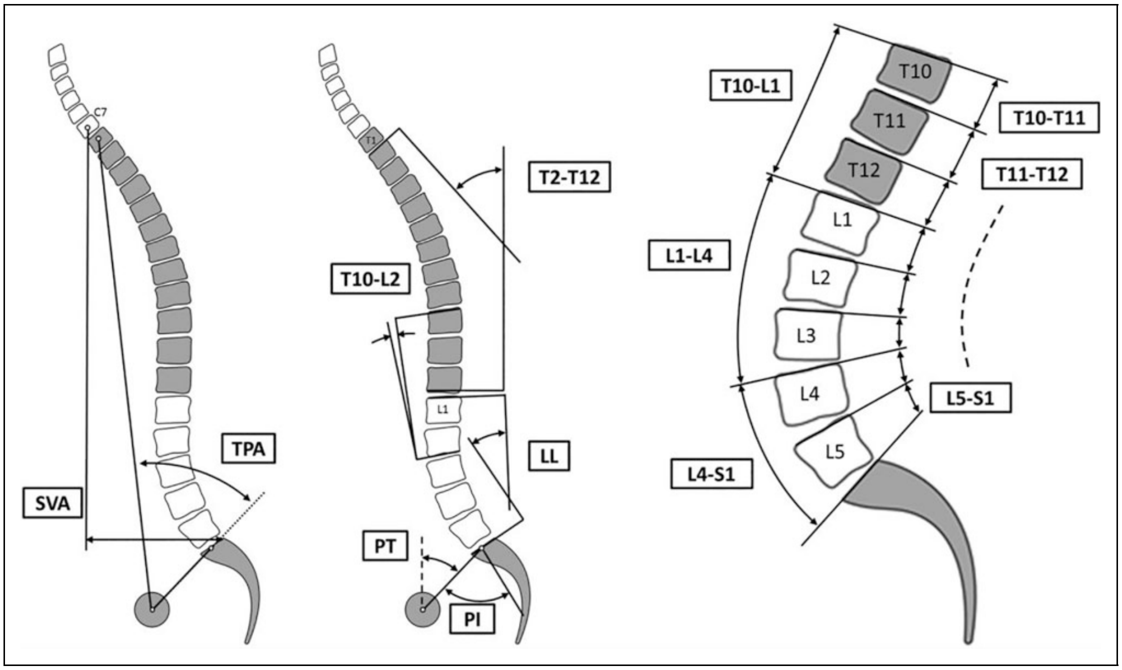

Figure 1. Radiographic parameters collected for this study including global parameters, regional parameters, and segmental parameters.

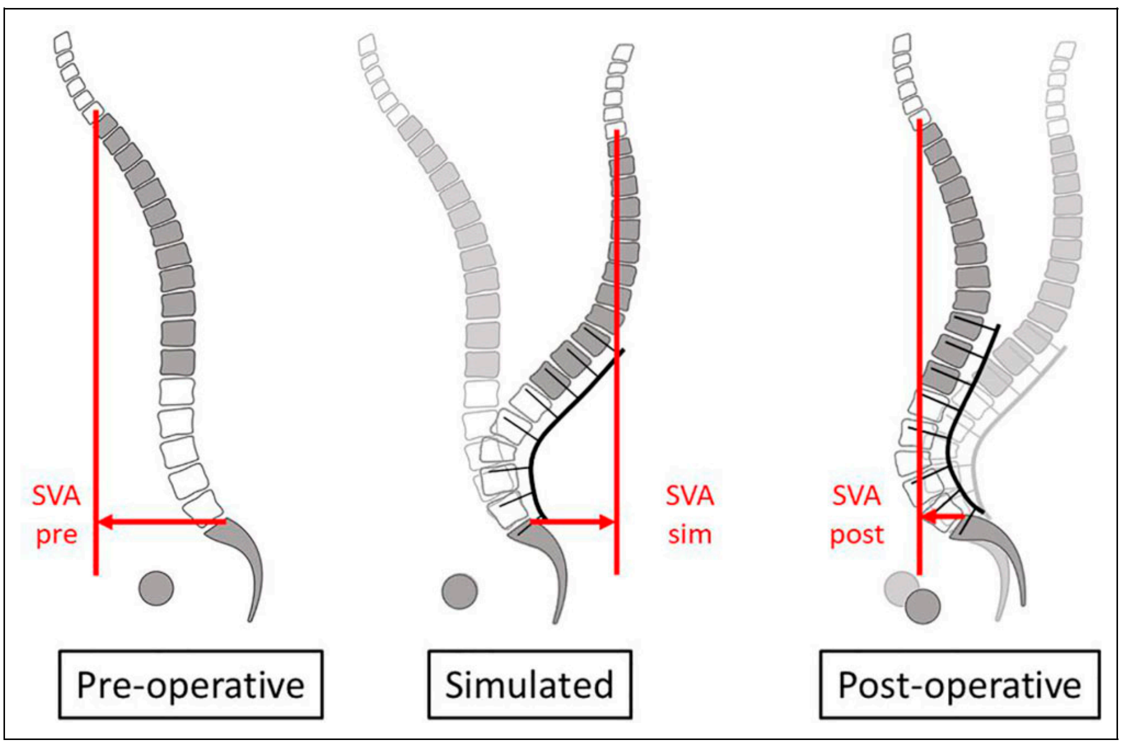

Figure 2. Pre-operative alignment (left), simulated (middle) and post-operative alignment (right). The simulated position is the result of the surgical correction before the relaxation of the thoracic compensation and pelvic retroversion.

Results

Cohort Description

A total of 433 out of 667 patients met inclusion criteria, the mean age of the cohort was 62.9 ± 9.7 years, the mean BMI was 28.1 ± 5.5 kg/m^2, and 81.3% were female. The mean follow-up period was 26.6 ± 6.4 months. At baseline, the cohort exhibited a moderate to severe malalignment (Table 1), as demonstrated by the SRS-Schwab classification modifiers with, respectively, 32.6%, 47.1%, 36.3% of the patients having

Table 1. Preoperative, Postoperative and Change in Sagittal Alignment as Well as Pre-to-Post Test (Pair t-Test).

	Pre-op		2-year		Change		
	Mean	StD	Mean	StD	Mean	StD	P
PI	55.3	12.3	55.4	12.4	0.0	2.8	0.741
PT	26.4	10.2	22.7	10.0	−3.7	8.3	<0.001
PI-LL	20.6	19.0	3.8	14.9	−16.9	16.7	<0.001
L1-S1	34.7	19.9	51.6	13.7	16.9	16.7	<0.001
T10-L2	−15.1	18.6	−9.0	13.4	6.1	17.8	<0.001
T2-T12	−34.8	18.5	−53.3	18.3	−18.4	14.7	<0.001
TPA	25.9	12.4	18.6	10.7	−7.3	10.7	<0.001
SVA	79	71	33	53	−46	66	<0.001

Table 2. Preoperative and Postoperative Regional and Segmental Alignment of the Thoracolumbar Spine.[a]

		Pre-op		2-year change		
		Mean	StD	Mean	StD	P
Segmental angles	L5-S1	19.5	9.6	−2.3	8.5	<0.001
	L4-L5	13.5	8.8	1.5	9.1	0.001
	L3-L4	6.5	8.5	6.0	10.9	<0.001
	L2-L3	−0.8	8	6.7	8.5	<0.001
	L1-L2	−4	7.4	4.9	6.7	<0.001
	T12-L1	−4.1	6.7	2.5	6.7	<0.001
	T11-T12	−3.3	5.4	−1.0	6.1	0.001
	T10-T11	−2	5.1	−3.1	7.2	<0.001
Regional angles	L4-S1	33	14.7	−0.7	12.8	0.231
	L1-L4	1.7	17.5	17.7	15.9	<0.001
	T10-L1	−9.3	13.3	−1.7	13.8	0.011

[a] Positive values denote a lordotic alignment/change, while negative values denote a kyphotic alignment/change.

a sagittal modifier grade of ++ in PT, PI-LL, and SVA. As illustrated in (Table 1), at 2-year follow-up, there was a significant improvement in all the sagittal spino-pelvic parameters ($P < 0.001$).

Preoperative segmental alignment demonstrated a flattening of the superior portion of the lumbar spine (L1-L4) associated with a kyphotic segmental alignment from L1-L2 to T10-T11 (Table 2). At 2-year follow-up, there was a significant difference in all the segmental angles, except L4-S1. This can be explained by the observed increase in L4-L5 lordosis associated with a decrease in L5-S1 lordosis. The largest segmental correction occurred at L3-L4 (+6.0 ± 10.9) and L2-L3 (+6.7 ± 8.5), while small kyphotic changes were observed from T10 to T12.

Prediction of Postoperative Alignment

Prediction of the expected changes in alignment was carried out in 2 steps: prediction of the global alignment changes (i.e. ΔSVAsim and ΔTPAsim) on the simulated position, followed by a prediction of the pre-to-post change in pelvic rotation (i.e. ΔPT)

Global alignment correction from pre-op to the simulated position. Linear regressions to predict ΔSVAsim and ΔTPAsim based on focal and regional correction all demonstrated excellent results, with r-square values above 0.94. Analysis of the standardized coefficients (Table 3) revealed that on average:

- 1° of distal lordosis correction results in a correction of **1° in TPAsim**, and **10 mm in SVAsim**
- 1° of proximal lordosis correction results in a correction of **0.5° in TPAsim**, and **5 mm in SVAsim**

Table 3. Multilinear Regression Predicting Δtpasim, ΔSVAsim, ΔPT Using Segmental or Regional Correction Thoraco-Lumbar Corrections.

		TPA correction before thoracic reciprocal changes		SVA correction before thoracic reciprocal changes		PT correction after thoracic reciprocal changes	
		Real pred.	Rounded	Real pred.	Rounded	Real pred.	Rounded
Segmental angles	constant	–	–	–	–	2.178	2.00
	L5-S1	−0.797	−1	−8.527	−10	−0.526	−0.5
	L4-L5	−0.702	−1	−7.536	−10	−0.408	−0.5
	L3-L4	−0.586	−0.5	−6.441	−5	−0.36	−0.5
	L2-L3	−0.575	−0.5	−6.281	−5	−0.361	−0.25
	L1-L2	−0.473	−0.5	−5.491	−5	−0.319	−0.25
	T12-L1	−0.441	−0.5	−4.607	−5	−0.209	−0.25
	T11-T12	−0.304	−0.25	−3.689	−2.5	−0.218	−0.25
	T10-T11	−0.368	−0.25	−3.755	−2.5	−0.278	−0.25
	Mean error	0.07	0.72	1.85	18.90	0.00	−0.25
	Mean abs Error	2.32	3.75	27.80	42.44	3.82	4.14
	RMSE	3.19	4.90	37.68	55.18	5.08	5.54
Regional angles	constant	–	–	–	–	2.42	2.50
	L4-S1	−0.747	−1	−7.997	−10	−0.456	−0.5
	L1-L4	−0.555	−0.5	−6.142	−5	−0.346	−0.25
	T10-L1	−0.364	−0.25	−3.999	−2.5	−0.227	−0.25
	Mean error	−0.33	1.12	−2.56	22.81	−0.22	1.50
	Mean abs Error	3.18	4.50	36.53	50.19	4.15	4.33
	RMSE	4.30	5.91	49.30	65.76	5.50	5.85

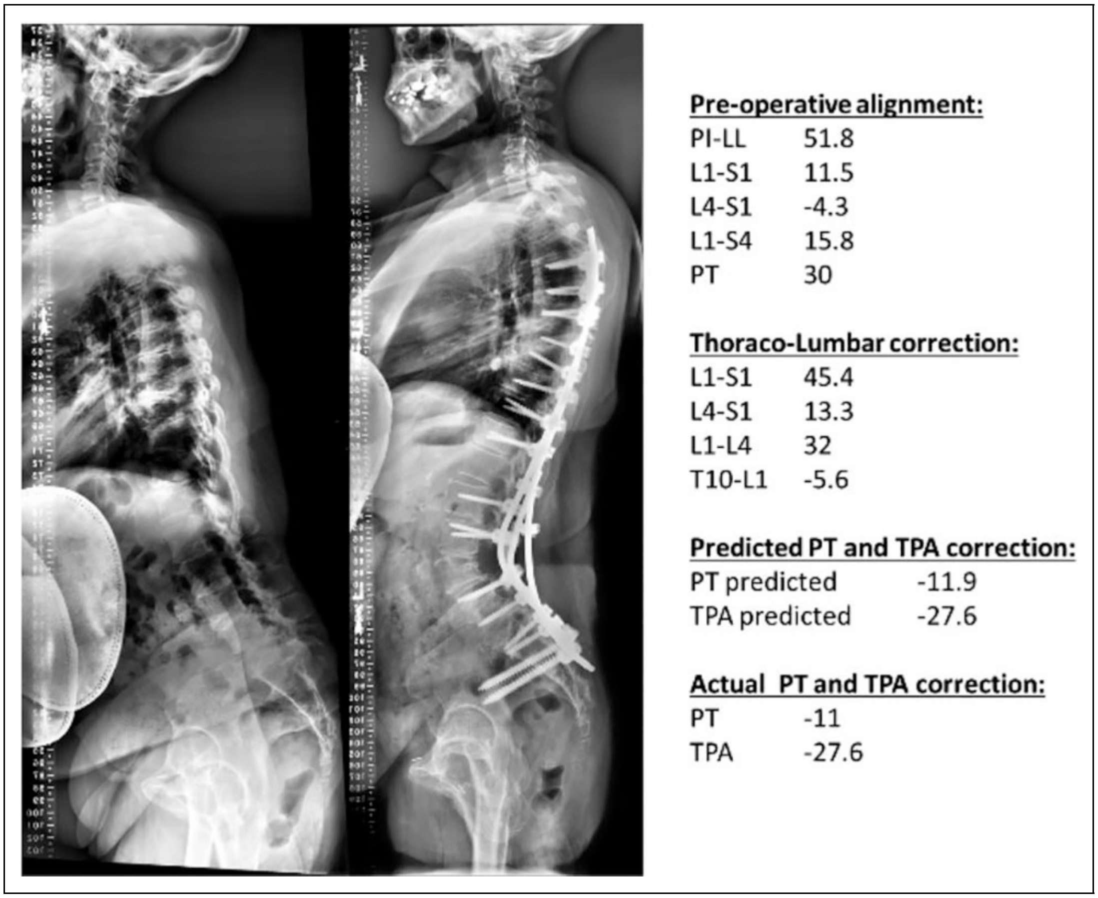

Figure 3. Case example 1 (Large correction).

- 1° of TL correction results in a correction of **0.25° in TPAsim**, and **2.5 mm in SVAsim**

PT correction after reciprocal change: Predictions of PT correction yielded moderate to good results depending on the type of independent predictors considered with r-square of 0.642 with segmental angles, 0.615 with regional angles, and 0.652 with ΔTPAsim. Coefficients of regression suggested that 1° of distal lumbar lordosis correction led to 0.5° in PT correction, 1° of proximal lumbar lordosis correction led to 0.25° in PT correction, and 1° of TL junction correction induced 0.25° in PT correction (Table 3).

Case Examples

Large correction. This patient (Figure 3) presented with a sizable spino-pelvic mismatch (PI-LL = 52°). The surgical correction consisted of a 45° restoration of L1-S1 lordosis with 2/3 located between L1-L4 (L3 PSO) and a small correction of the thoracolumbar kyphosis. Based on the developed formulas, the anticipated outcomes of this strategy would be a 27.6° and 12° correction of TPA and PT. At the 2-year postoperative evaluation, the actual decreases in TPA and PT were 27.6° and 11°, respectively.

Overcorrection of lumbar lordosis. This patient (Figure 4) presented with degenerative scoliosis and a maintained lumbar alignment (PI-LL = 10°). The patient underwent a T10-Pelvis posterior fusion, with an increase in lumbar lordosis of 20°. Despite this overcorrection, the model predicted a 5° correction in PT, along with a 12° correction of TPA. Postoperative 2-year follow-up showed a change in PT of 6.3° and a correction of TPA of 13.7°

Proximal correction of the lumbar spine. For this revision case (Figure 5) with a previous L4-L5 fusion, the surgical strategy called for a 10° increase in proximal lordosis, without any change in the distal lordosis (due to the existing fusion). The predictive model showed no change in pelvic retroversion and a minimum change in global alignment despite a lumbar realignment of 10°. At 2-year post-op, change in PT was 0° associated with a change in TPA of 3°.

Discussion

In this cohort of ASD patients, preoperative sagittal alignment was characterized by an overall loss of lumbar sagittal curvature proximally and a kyphotic alignment between the L1 and L2 vertebrae. Description of the segmental correction showed that most of the lordotic change occurred between L4 and L1,

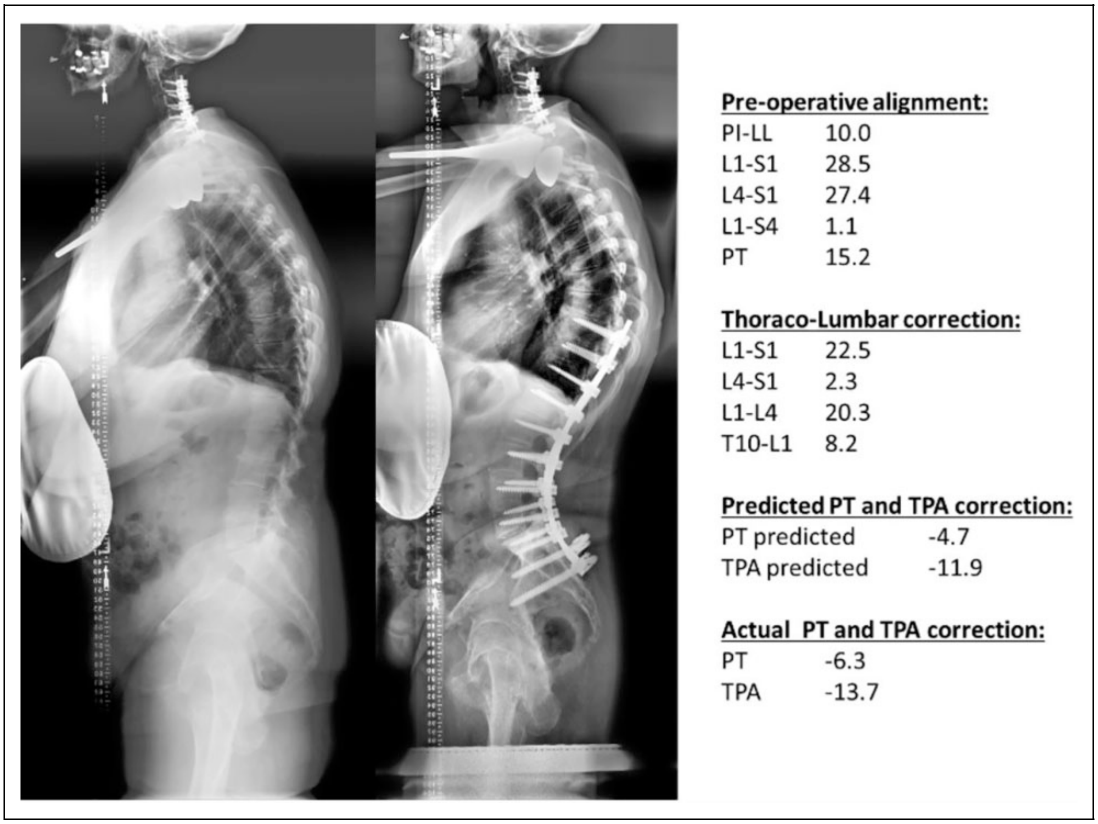

Figure 4. Case example 2 (Overcorrection of lumbar lordosis).

while L4-S1 distal lordosis did not significantly increase between pre- and post-op. The predictive formula for global alignment free of reciprocal change demonstrated excellent results. The error of prediction using segmental alignment was relatively low and close to the measurement error, making it usable in a clinical setting. Finally, the prediction of postoperative pelvic retroversion using only segmental alignment demonstrated acceptable results.

The importance of restoring global sagittal alignment is widely recognized in the spine community. However, describing and understanding the numerous factors affecting post-operative sagittal alignment is challenging, and more than 50% of patients remain with a suboptimal alignment after deformity correction.[4] Recently, optimizing preoperative surgical planning by analyzing the immediate impact of surgical correction on overall alignment outcomes has been the focus of many studies. When ASD surgery is performed, correction of the deformity driver will lead to a global relaxation of the spinopelvic axis and induce spontaneous correction of compensatory mechanisms. An ideal planning method would incorporate how operative techniques influence truncal global inclination (TPA and SVA) and the PT, 2 of the alignment parameters most correlated with HRQoL measures. This study provides a new model that includes more detailed vertebral segmental alignment in the planning process.

In our cohort, the preoperative segmental alignment demonstrated an overall loss of proximal lordosis with a kyphotic alignment starting at L1-L2. Surgical correction of the loss of lumbar lordosis occurred mainly at the L1-L4 segments. On average, there was no alignment change/correction at the L4-S1 segment. Interestingly, a deeper look at this segment revealed a kyphotic change at L5-S1 combined with a lordotic change at L4-L5, in line with another published report.[12] This pattern of correction here does not achieve a normal distribution of lumbar lordosis. Pesenti et al.[13] demonstrated that in asymptomatic adults the distal lumbar lordosis was about 35° and accounted for 62% of the total lordosis, with (L5-S1) specifically responsible for 35%. In the present study, preoperative deformity demonstrated a larger deformity proximally, therefore the correction needed to occur more proximally. However, distal alignment should not deteriorate while achieving a normal lumbar shape. To support our findings, we also see that patients with greater global correction had most of the correction located at the L3-L4 and L2-L3 levels. These levels represent the most common location of major osteotomy, as demonstrated by Diebo et al.[14] With the current trend of decreased use of major osteotomies and increased correction at the distal levels through the disc spaces, these results may be different in a more recent cohort. Examining PT change in our study shows patients with significant global correction had an improved PT, while patients with a maintenance/deterioration of their global alignment tend to worsen their pelvic compensation. Previous reports state that up to 66% of patients had increases in PT postoperatively (25% had >5 degrees of

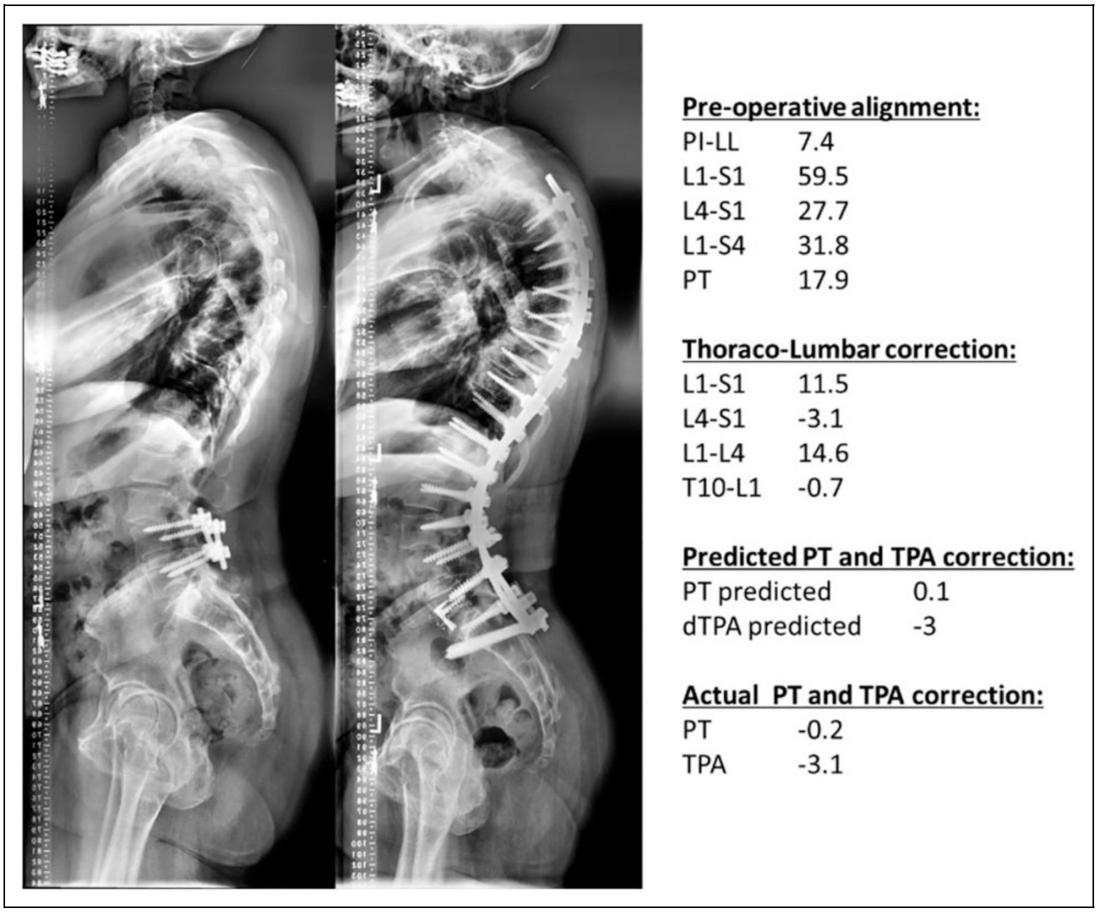

Figure 5. Case example 3 (Proximal correction of the lumbar spine).

deterioration).[15] Insufficient correction and/or unanticipated reciprocal changes can explain this sub-optimal postoperative outcome.

Predicting postoperative alignment is not easy and requires more than just experience. A survey study reported difficulties for experienced spine surgeons to predict postoperative alignment,[16] highlighting the need for predictive formulas and advanced computer planning.[17] Published predictive methods include a variety of formulas ranging from simple (Lumbar Lordosis > Thoracic Kyphosis +20°), to more complex ones that include compensatory mechanisms. Not surprisingly, the more complex ones tend to be more accurate but at the same time are less practical in daily practice. As demonstrated by Langella and colleagues, computer-assisted methods could address this challenging question and permit the use of machine learning algorithms that continue to improve with time and data.[18]

The formulas developed in the current investigation include different layers of parameters that reflect regional (distal lordosis, proximal lordosis) and segmental (individual levels) change for more detailed prediction. They are adapted for clinical use and can be integrated into digital planning tools. Prediction of pelvic retroversion compared to a previously published formula had a slightly lower r-square (0.6 vs 0.8).[19] The current prediction is based only on fused segments, while previous formulas require the ability to anticipate reciprocal changes in the thoracic spine. Decomposition of SVA correction and PT correction allows anticipation of the maximum correction of SVA without any deterioration of pelvic retroversion. Classic prediction does not differentiate SVA correction from PT correction and requires knowing or assuming the ratio of closure between the truncal and pelvic correction.[9,20] Furthermore, the developed method in the present study enables understanding of a result that seems counter-intuitive: the lower the correction is performed in the lumbar spine, the larger the pelvic correction compared to the SVA correction.[9] From a geometric point of view, a lower correction should induce a larger global correction due to the lever arm effect. As the truncal inclination and pelvic retroversion are not independent from each other, a portion of the global correction is consumed in correcting the pelvic retroversion.

This study is limited by its retrospective nature. Also, it does not include the actual preoperative planning. Therefore, the postoperative alignment was defined as preoperative planning with perfect surgical execution. In addition, the widespread use of predictive formulas is contingent on their ability to be generalized to a large population. This cohort has a large variability of surgical techniques used across several years. Finally, this is a radiographic study only, and outcomes do not account for the effect of neural element decompression, muscle quality, or other dynamic effects between balance and alignment.

Conclusion

In conclusion, the overall effect of lumbar lordosis restoration depends on the vertebral levels at which correction is achieved. A more distal correction will lead to more global change and more PT correction. As a rule of thumb: 1° of correction between L4 and S1 will at best correct the SVA by 10 mm and will induce a 1° change in TPA and a 0.5° change in PT. Based on regional (PI-LL) and segmental alignment objectives in the context of global alignment (TPA/SVA) and PT, preoperative planning can be customized to be patient-specific, rather than relying on the overly generalized assumption that all patients warrant the same correction at the same vertebral levels.

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Declaration of Conflicting Interests

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