Predicting the Unpredictable: Modeling Post-Operative Spinal Alignment in Adult Deformity Surgery

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INTRODUCTION: Post-operative sagittal alignment in adult spinal deformity (ASD) surgery involves complex reciprocal changes, challenging even experienced surgeons. Predicting these changes accurately is essential for optimizing surgical planning. While individual alignment parameters have been analyzed, a comprehensive, predictive approach incorporating multiple factors remains underdeveloped. Our study aims to evaluate the predictability of post-operative thoracic alignment using a combination of geometric-statistical modeling.

METHODS: This is a Retrospective analysis of a multicenter registry of ASD patients surgically treated with a posterior fusion from pelvis to either Upper Thoracic (UT: T2-4) or Lower Thoracic (LT: T9-11) , no revision surgery and 2-year minimum follow-up. Radiographic data collection included Thoracic kyphosis at different levels(T1–T12, T1–T4, T5–T8) and VPAs at 4 different vertebra (T1PA, T4PA, T9PA, L1PA). Changes in sagittal alignment from pre-op to 2 years post-op were assessed using multilinear regression models, including interaction and quadratic terms, to predict post-operative alignment based on pre-operative parameters and surgically modifiable factors. Predicted and actual post-op shapes were compared to evaluate the accuracy of the geometric-statistical model. Prediction errors were normalized as a percentage of the S1 superior endplate width.

RESULTS:

523 patients were included with a mean age of 64 ±10 years, mean BMI of 28.2 ±5.8, and 79% were female. Pre-operative SRS classification showed 38.8% of patients as type L, 38.0% as type N, and 21.0% as type D sagittal profiles, with moderate to severe deformities.

Changes in sagittal alignment (Figure 1) from preop to 2 years post-op revealed significant differences in both lumbar and thoracic sagittal Cobb angles. VPAs exhibited an increase at L4PA but decreased at all other levels. Stratification by UIV location revealed no significant differences in L1–S1 (p=0.254) and T1–T12 (p=0.963), while significant differences were observed in all VPA changes (all $p < 0.05$).

Prediction of thoracic Cobb angles demonstrated moderate accuracy (R^2: 0.46 to 0.7, RMSE ≤10.5°), while VPA predictions were highly accurate across both UT and LT groups (R^2: 0.8 to 1, RMSE <3°). Comparisons of predicted versus actual post-op sagittal shapes (Table 01) showed a median T1 positioning error of 36.7% of S1 width (IQR 18%–69%). UT patients demonstrated significantly lower errors (21.2% [IQR 11.8%–34.6%]) compared to LT patients (56.4% [IQR 26.5%–89.6%]; $p < 0.001$). More than 90% of UT patients had a T1 position within 50% of the S1 width in the anteroposterior axis. In contrast, LT patients had a broader range of deviations (Figure 2), with 25% exhibiting anterior overestimation and 25% posterior underestimation of reciprocal changes. Subsequent analysis demonstrated that LT patients with anterior errors had sharper post-op PJK angles (-27° vs. -16° and -12°, $p < 0.001$); those with posterior errors were older (67 vs. 65 and 64 yo, $p < 0.023$).

DISCUSSION AND CONCLUSION: Geometric-statistical modeling showed excellent accuracy for predicting VPAs and moderate accuracy for thoracic Cobb angles, supporting its potential utility in surgical planning. UT UIV placement was associated with significantly better alignment consistency and fewer prediction errors than LT placement. However, the variability observed in LT outcomes highlights the need for additional factors, such as thoracic flexibility and muscular evaluation, to refine predictive models further.

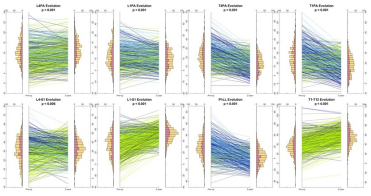

Figure 1: Evolution pre-to-2-year of the sagittal alignment. Individual line represents a patient, Green color is associated with an increase, Blue a decrease, Dark color with Upper Th. UIV, light with Lower Th. UIV. Histogram provided for pre-operative and post-operative variable, stratified by UIV position (Upper Th. - Red; Lower Th. - Yellow)

Table 1: Error in T1, T4, T9 and L1 position using a combination of geometric and statistic to estimate post-operative shape of the spine. Accuracy reported included Euclidean Distance (Total) and projected on the anteroposterior axis. Errors normalized as a percentage of S1 superior endplate.

	TOTAL	ANT-POST	ANT-POST (ABS ERROR)
T1 ALL	36.7% (18% to 69%)	1.2% (-26% to 33%)	30.3% (13% to 66%)
T4 ALL	27% (14% to 50%)	1.9% (-17% to 24%)	19.8% (7% to 44%)
T9 ALL	20.2% (11% to 33%)	0.7% (-8% to 9%)	8.3% (3% to 15%)
L1 ALL	17.7% (10% to 32%)	-0.2% (-5% to 5%)	5.5% (3% to 10%)
T1 UT	21.2% (12% to 35%)	0% (-17% to 17%)	16.9% (7% to 27%)
T4 UT	15.2% (9% to 23%)	1.2% (-5% to 8%)	6.6% (3% to 13%)
T9 UT	18.6% (10% to 31%)	0.8% (-4% to 7%)	5.7% (3% to 11%)
L1 UT	19.5% (10% to 34%)	0.9% (-4% to 6%)	5.2% (2% to 10%)
T1 LT	56.4% (27% to 89%)	1.9% (-50% to 50%)	50.2% (22% to 84%)
T4 LT	42.3% (24% to 65%)	7% (-40% to 38%)	38.8% (19% to 62%)
T9 LT	20.4% (13% to 34%)	0.7% (-9% to 10%)	10.1% (4% to 18%)
L1 LT	17% (10% to 31%)	-0.7% (-6% to 5%)	5.7% (3% to 10%)

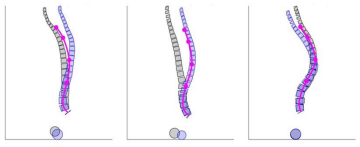

Figure 1: Schematic examples of patients with Lower Thoracic UIV and T1 position predicted either too anterior (left), properly predicted (middle) or predicted too anterior (right). The grey schematic represents pre-operative alignment, Blau real 2-year post-operative alignment, and Purple the predicted shape based on pre-operative alignment and sagittal correction