What determines immediate postoperative coronal balance and delayed global coronal balance after anterior spinal fusion for Lenke 5C curves?

Running title: Achieving balance in Lenke 5C curves

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Abstract

Purpose: To determine the factors associated with 6-weeks post-operative global coronal balance and delayed global coronal balance at 2-year follow-up after anterior spinal fusion for Lenke 5C curves.

Methods: 124 consecutive Lenke 5C curves with minimum 2-years follow-up was studied. Radiographic parameters were studied pre-operatively, six weeks post-operatively and at 2-years post-operatively. Coronal balance was measured by C7-CSVL and trunk shift <20mm. The study outcomes were patients with early coronal balance and those who had immediate imbalance but developed delayed balance. Multivariate regression analyses of associated factors were performed with cut-offs determined by receiver operating characteristic curve.

Results: 31.5% patients attained global coronal balance immediate postoperatively and 89.4% of the early imbalance cases showed spontaneous coronal balance at 2-year follow-up. Increased preoperative UIV tilt (OR 1.093; p=0.026; 95% CI: 1.011-1.182) and reduced immediate postoperative RSH difference (OR 0.963; p=0.015; 95% CI: 0.935-0.993) were associated with immediate postoperative balance. For those with immediate imbalance, larger preoperative major Cobb angle (OR 1.226; p=0.047; 95% CI: 1.003-1.499), less preoperative C7-CSVL (OR 0.829; p=0.016; 95% CI: 0.712-0.966) and less immediate postoperative LIV tilt (OR 0.728; p=0.013; 95% CI: 0.567-0.934) were associated with 2-year coronal balance. There was significant improvement in function (p=0.006), self-image (p=0.039) and total score domains (p=0.014) in immediate imbalance to 2-year balance and imbalance groups.

Conclusion: Successful balance is achieved with a parallel fusion mass when performing anterior spinal fusion for Lenke 5C curves. Patients should be reassured that most attain eventual coronal balance despite early imbalance.

Level of Evidence: Therapeutic III

Key Words: AIS; adolescent idiopathic scoliosis; ASF; Lenke; 5C; coronal balance; delayed balance

Declarations

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INTRODUCTION

Lenke 5C scoliotic curves are a type of adolescent idiopathic scoliosis (AIS) characterized by a major structural lumbar curve. This particular curve type has higher incidence of clinical and radiological global coronal imbalance.[1,2] The primary goal of the surgical treatment is to achieve a well-balanced spine in both coronal and sagittal planes while reducing the number of fused vertebral levels.[3,4] Lenke 5C curves have been treated by either anterior or posterior techniques with both techniques leading to good results.[5-7] In either case, selection of fusion levels and spontaneous correction of the compensatory curve is critical to achieve a well-balanced spine and to preserve motion segments in the lumbar spine.[7]

To date, evidence suggests that the lower instrumented vertebrae (LIV) is critical in predicting the post-operative global coronal balance, however there is still no consensus in the selection of LIV[1,2,5,8]. In a recent albeit small sized study[9], 23 cases treated by selective posterior lumbar instrumentation were retrospectively evaluated to discover that pre-operative LIV tilt, post-operative LIV tilt and pre-operative coronal imbalance are most significantly related to coronal imbalance. In a study by Wang *et al*[1], LIV – CSVL distance of less than 28 mm and pre-operative LIV tilt of less than 25° showed favourable post-operative coronal balance in long-term follow-up. With regards to the selection of LIV, a recent study has proposed that pre-operative LIV tilt exceeding 25° and its failure to correct to less than 8° in the post-operative period leads to poor coronal imbalance. The authors also proposed that if the LIV tilt is greater than 25°, one additional level distally should be instrumented.[5] Liu *et al*[2] published the role of UIV tilt as the possible mechanism of delayed compensation in coronal balance post-operatively. None of the studies could provide any conclusive cut-off values for UIV tilt in predicting favourable balance by 2-year follow-up.

Spinal flexibility is a key factor for planning the treatment of AIS.[10] It provides useful information regarding the surgical strategy and outcome prediction.[4,11,12] The mobility of spinal segments have strong influence on outcomes of AIS treatment.[13-16] Various types of radiographs have been reported such as supine, supine lateral bending, traction and fulcrum-bending radiographs.[4,11,15,17,18] Fulcrum bending radiographs are superior to supine lateral bending radiographs in terms of predicting curve correction by fulcrum flexibility and fulcrum bending correction index (FBCI).[19-22] In a recent study by Zhang *et al*[23], higher flexibility of the thoracic curve and better immediate spontaneous correction of thoracic curve are risk factors for thoracic decompensation in late follow-up. However, there has been no conclusive evidence for any cut-off limits for the curve flexibility in determining delayed decompensation.

Lenke 5C curves are notorious for residual coronal imbalance in the immediate post-operative period but often may resolve with follow-up. Factors associated with immediate post-operative coronal balance or delayed coronal balance are inconclusive especially for anterior spinal fusion (ASF) surgery. Hence, this study aims to determine radiographic factors associated with 6-weeks post-operative global coronal balance for Lenke 5C curves, and to determine radiographic factors associated with delayed global coronal balance at 2-year follow-up after ASF for Lenke 5C curves.

METHODS

This was a retrospective radiographic analysis of a cohort of 124 consecutive Lenke 5C patients with AIS who were operated by ASF at our institution from January 2005 to December 2017. We included all patients with at least 2-years follow-up. Exclusion criteria was any patients who did not adhere to our follow-up, had fusion of the thoracic curve, or utilized a posterior approach. All patients adhered to our follow-up protocol and no patients had fusion of the thoracic curve. Originally we had 140 patients with Lenke 5C curves during the study period but 16 patients were excluded because of posterior surgery. Patients had fulcrum-bending radiographs prior to surgery to assess the flexibility of the deformity and had fusion levels determined by achieving a balanced fusion block without shift on the fulcrum-bending radiographs.[12] The upper instrumented vertebra (UIV) and LIV were generally determined by the end vertebrae of the deformity. However, if the curve was very flexible with complete correction on the fulcrum-bending radiographs, a shorter fusion was considered especially for longer curves whereby the end vertebra was cranial to T11 and/or caudal to L3. For example a flexible T11-L4 curve could allow for T11-L3 fusion. This was to accommodate for a single thoracotomy to complete the surgery and to reduce the number of fused lumbar segments. Ethics was approved by the local institutional review board.

Surgical technique

A standard left-sided retroperitoneal approach was adopted. If instrumentation was at T12 or above, transdiaphragmatic thoracoabdominal exposure was used.[24] Complete discectomy to expose the posterior longitudinal ligament was performed at each disc level with removal of the cartilaginous endplates. The rib used for exposure was utilized as bone graft. Single bicortical screws instrumenting each vertebra was performed followed by rotation of a titanium rod into the true sagittal position. All patients utilized a thoracolumbar spine orthosis for 3 months during mobilization after surgery. After the orthosis was removed, all patients visited the physiotherapists for balance training.

Study parameters

Standing long cassette posteroanterior (PA) and lateral radiographs of whole spine were obtained with fulcrum-bending radiograph and a supine lumbosacral bending radiograph within one week of surgery. The lumbosacral bending radiograph was performed in the opposite direction of the fulcrum-bending radiograph in the maximum bending achievable in supine posture. Postoperatively, a standing PA whole spine radiograph was obtained 6-weeks after surgery (early postoperative) and at 2-years follow-up. The 6-week mark was used to avoid pain-related balance issues. Pre-operative parameters included the major curve Cobb angle, thoracic Cobb angle, fulcrum-bending major Cobb angle, radiographic shoulder height (RSH), C7-central sacral vertical line (C7-CSVL), truncal shift, apical vertebra translation, UIV tilt, LIV tilt, and LIV disc angle. Post-operative parameters included major curve Cobb angle, thoracic Cobb angle, RSH, C7-CSVL, truncal shift, fusion mass Cobb angle, fusion mass shift, UIV and LIV tilt. Coronal balance (**Fig. 1**) was measured and quantified by the perpendicular distance between the coronal C7 plumb line and the central sacral vertical line (C7-CSVL) and trunk shift (deviation between the center of the thorax at the level of the thoracic apex from the CSVL), with both fulfilling a value <20mm as balance.[8]

RSH was defined as the height difference in the soft tissue shadow of the two sides directly superior to the acromioclavicular joints. Fusion mass shift was measured by the distance between a perpendicular line drawn from the center of the lower endplate of the LIV and the midpoint of the upper endplate of the UIV. Fusion mass angle was defined as the Cobb angle measurement from the upper endplate of the UIV to the lower endplate of the LIV. The

UIV tilt was measured by the tilt angle of the upper endplate of the UIV to the horizontal plane. The LIV tilt was measured by the tilt angle of the lower endplate of the LIV to the horizontal plane. The LIV disc angle is measured by the angle between the lower endplate of the LIV and the upper endplate of the LIV+1. Left side LIV disc angle opening was considered positive while right sided opening was considered negative. This measurement was done on both fulcrum-bending and lumbosacral bending radiographs. Correction rates, fulcrum flexibility and fulcrum bending correction index (FBCI) were also calculated:

$$\text{Correction Rate \%} = \frac{\text{Preoperative Cobb Angle} - \text{Postoperative Cobb Angle}}{\text{Preoperative Cobb Angle}} \times 100\%$$

$$\text{Fulcrum Flexibility \%} = \frac{\text{Preoperative Cobb Angle} - \text{Fulcrum Bending Cobb Angle}}{\text{Preoperative Cobb Angle}} \times 100\%$$

$$\text{Fulcrum Bending Correction Index \%} = \frac{\text{Correction Rate}}{\text{Fulcrum Flexibility}} \times 100\ \%$$

All the radiographic measurements were performed independently by two readers who were blinded to the clinical information. The radiographs were randomized by another investigator and sent to the readers to measure. The measurements from the two readers which were within 1mm or 1° difference were averaged for a single measurement for analysis. Deviations were discussed and the readers agreed on the measurement recorded for analysis. All parameters were collected on radiographs using the DICOM-based Radworks 5.1 computer software program (Applicare Medical Imaging BV, Zeist, the Netherlands).

The refined 22-item Scoliosis Research Society questionnaire (SRS-22r) was used to determine patient-reported quality of life outcomes and is comprised of five domains (function, pain, appearance, mental health and satisfaction with treatment).[25] Its minimum clinically important difference (MCID), based on a 5-point scale, has been quoted as 0.2 for pain, 0.08 for function and 0.98 for appearance domains [26]. Mental health has no quoted MCID for the AIS population. Satisfaction with treatment is described and based on improvement or deterioration in domain scores.

Statistical analysis

Descriptive data was presented as mean ± standard deviation (SD). All analyses were performed with SPSS version 24.0 (IBM SPSS Inc, Chicago, IL, USA). The main study outcomes were 1) predictors of 6-week postoperative coronal balance (**Fig. 2A-C**), and 2) predictors of delayed coronal balance whereby patients who were initially imbalanced at 6-weeks post-operative period became balanced by 2-year follow-up (**Fig. 3A-C**). Normality tests were performed and nonparametric Mann Whitney U test was used for specific intergroup comparisons between patients in both outcome analyses. Univariate analysis using binary logistic regression was run testing any association between each independent variable and each of the two study outcomes. Continuous variables in this study included pre-operative major curve Cobb angle, fulcrum-bending Cobb angle, thoracic Cobb angle, radiographic shoulder height, truncal shift, C7-CSVL, apical translation, LIV disc angle in PA, fulcrum bending and side bending radiographs, UIV tilt, LIV tilt, fulcrum flexibility along with 6-weeks and 2-year follow-up post-operative parameters including correction rate, FBCI, major curve Cobb angle, thoracic Cobb angle, RSH, truncal shift, C7-CSVL, fusion mass Cobb angle, fusion mass shift, UIV and LIV tilt. Multivariate logistic regression model was then performed using factors with $p<0.15$ from the univariate analysis[27] for identifying predictive factors with odds ratio (OR) and its respective 95% confidence interval (CI). Furthermore, to look for the cut off-value of various preoperative parameters in predicting 6-weeks postoperative coronal balance, receiver operating characteristic (ROC) curve with calculated area under the curve (AUC), specificity and sensitivity analyses was utilized. Cut-off value was proposed for the factor which had reached statistical significance using Youden's index *(J)* as it combines sensitivity and specificity into a single measure. Similar ROC analysis was also performed to investigate any cut-off value for the significantly found predictor that predicted delayed global coronal balance by 2-year follow-up. A p-value of <0.05 was considered as statistically significant. Post-hoc power analysis was performed for significant factors.

RESULTS

Out of total 124 patients, 21.0% (26/124) were male and 79.0% (98/124) were female. The average age at surgery was 16.1±3.1 years. The mean number of instrumented levels was 5.0±1.0, and most frequently included T11-L3, while in 24 patients the LIV was found to be L4 and in 5 patients the LIV was L2. 79% (98/124) of the patients were of Risser stage 4 or above at the time of surgery. The baseline major Cobb angle was 53.1±7.6°, thoracic Cobb angle was 28.3±9.5° and fulcrum bending Cobb angle was 15.4±8.6°. The mean fulcrum flexibility was 71.6±14.0%, mean correction rate was 86.6±12.3% and FBCI was 125.5±31.0%.

Descriptive statistics of various parameters between the 6-week postoperative balance (n=39; 31.5%) and imbalance (n=85; 68.5%) groups are listed in table 1. The data had adequate power to differentiate those with trunk shift (0.99) and C7-CSVL deviation (1.00) postoperatively. Preoperative parameters were similar between groups and factors associated with either outcome is listed in table 2. When adjusted, the multivariate analysis (table 3) showed that increased preoperative UIV tilt (OR 1.093; p=0.026; 95% CI: 1.011-1.182) and reduced 6-week postoperative RSH difference (OR 0.963; p=0.015; 95% CI: 0.935-0.993) were associated of 6-week postoperative balance. The cut-off of 6-week postoperative RSH was 3.3mm (AUC 0.67; p=0.002; 95% CI: 0.574-0.773; sensitivity 67.1%; specificity 61.5%) and was associated with 6-week postoperative balance. No significant AUC was identified for preoperative UIV tilt.

Of the 85 patients with coronal imbalance postoperatively, 76 (89.4%) achieved delayed balance (Table 4). Those with late balance had larger Cobb angle, C7-CSVL and UIV tilt preoperatively and factors associated with delayed balance are listed in table 5. Multivariate analysis (table 6) showed that larger preoperative major Cobb angle (OR 1.226; p=0.047; 95% CI: 1.003-1.499), less preoperative C7-CSVL (OR 0.829; p=0.016; 95% CI: 0.712-0.966) and less 6-week postoperative LIV tilt (OR 0.728; p=0.013; 95% CI: 0.567-0.934) were the main predictors of 2-year coronal balance. A cut-off of preoperative major Cobb angle of 47.7° (AUC 0.73; p=0.022; 95% CI: 0.570-0.897; sensitivity 78.9%; specificity 77.8%) and preoperative C7-CSVL of 26.2mm (AUC 0.864; p<0.001; 95% CI: 0.784-0.944; sensitivity 88.9%; specificity 80.3%) predicted 2-year balance. No statistically significant AUC was identified for postoperative LIV tilt.

No statistical significant differences were observed in the overall SRS-22r scores between groups at pre-operative stage, 6-weeks post-operatively or at 2-year post-operatively (Table 7). There was significant improvement in function (p=0.006), self-image (p=0.039) and total score domains (p=0.014) at 2-years. Function domain scores fulfilled MCID for both delayed imbalance and balance groups.

DISCUSSION

A coronally well-balanced spine is the primary aim of any scoliosis deformity correction surgery. Good and comparable results have been reported with both anterior and posterior approaches in correcting Lenke 5C curves[6,7,28-31]. Yet, these curves are notorious for residual coronal imbalance in the immediate post-operative period but spontaneously resolves with follow-up.[1,2,5] In either surgical approach, correction of the major curve should proceed with spontaneous derotation and correction of minor curves.[32] In this study of 124 subjects with Lenke 5C curves, 31.5% patients attained global coronal balance at 6-weeks postoperatively based on our strict criteria and a significant number of the early imbalance cases (89.4%) showed spontaneous coronal balance at 2-year follow-up. We have identified increased preoperative UIV tilt and reduced 6-week postoperative RSH difference as potential radiographic factors associated with post-operative balance. Larger preoperative major Cobb angle, less preoperative C7-CSVL and less 6-week postoperative LIV tilt were potential radiographic factors associated with delayed balance. Despite these differences, patients in both groups had improved SRS-22r scores with the function domain reaching MCID.

Not many of our patients (31.5%) achieved global coronal balance in the 6-weeks post-operative period. We found potential factors associated with 6-week global balance to be preoperative UIV tilt and RSH although careful interpretation is necessary as the ORs may not be clinically significant. It is important to note that we adhere to a standardized end-to-end anterior spinal fusion and aim to achieve a squared fusion mass. Based on the concept of avoiding fusion mass shift[12], achieving a squared fusion mass should be a goal of the surgery as it aims to obtain parallel UIV and LIV. These are important radiological parameters that are correctable intraoperatively. However, it appears as though failure to achieve a squared fusion mass leads to better outcomes. Leaving a residual UIV tilt provides better accommodation for overall coronal balance. Our results suggest that patients with coronal balance have greater UIV tilt. Several studies also noted the UIV tilt as an important factor contributing coronal balance[2,9]. Liu *et al*[2] have proposed an average 5° increment in UIV tilt in their patients with delayed coronal balance. Providing a UIV tilt allows compensation with any residual thoracic curve. If complete correction of the deformity is achieved with squared fusion mass, the thoracic curve must also spontaneously correct or else the residual thoracic deformity will lead to imbalance. Huitema *et al*[33] observed a significant correlation in the correction rate of the Lenke 5C curves with spontaneous thoracic curve correction. Alpaslan *et al*[32] similarly suggested that incomplete correction of the major curve leads to suboptimal improvement of the minor curve. Therefore, better correction of the primary curve may result in more effective minor curve correction. However, in those patients with incomplete correction, less flexible thoracic curves or a more caudal UIV chosen precludes full correction.[34] Leaving a residual tilt may provide better coronal balance. The most likely compensatory maneuver for residual tilt and thoracic deformity is the position of the shoulders. As such, patients with coronal imbalance have larger differences in RSH. Through the ROC analysis, any RSH more than 3.3mm will lead to 6-week coronal imbalance. This relationship should be further studied with a larger cohort as the ROC is relatively small suggesting that there is only a partial significance of RSH on early coronal balance. Moreover, the RSH is normalized at 2-year follow-up suggesting that this appearance is trainable with physiotherapy and not indicative of later coronal balance.

Besides UIV and LIV tilt, derotation of the spine is an important factor to consider when accepting an intraoperative correction. In our cohort, all patients utilized single screw-rod construct. Despite some studies[35,36] suggesting similar coronal radiological parameters between single and dual rod constructs, Nambiar *et al*[36] suggested that dual-rod surgery led to slightly more loss in lumbar lordosis and resultant thoracic kyphosis postoperatively. This may be due to the improved coronal Cobb angle correction in their single-rod group. However, the axial plane was not studied due to the limitations of 2D radiographs. Luk *et al*[23] has showed that a coupled mechanism exists between coronal curve correction and the sagittal and rotational alignment change postoperatively. The amount of major curve correction may dictate the amount of reciprocal correction in the unfused segments. Although we only focused on the coronal plane measurements in this study, the effects of rotational correction and sagittal contouring should be studied in the future. Despite a complete discectomy to drive rotational correction, the use of a single-rod may influence the amount of derotation that actually occurs. The degree of sagittal and axial plane correction may provide evidence to the variable behavior of coronal balance in ASF despite a similar coronal correction.

Most of the patients (89.4%) who initially had coronal imbalance achieved delayed compensation of global coronal balance. It is reassuring to see that early coronal alignment does not indicate the 2-year alignment. With no significant loss of correction between 6-week and 2-year Cobb angle, the balance is trainable with physiotherapy. The preoperative and early postoperative parameters of major Cobb angle, C7-CSVL and LIV tilt are potential factors associated with delayed balance. With similar correction rates between the two groups, those with remained imbalance at 2-year had less comparable correction with a smaller preoperative major Cobb angle. This compounded with a more significant preoperative C7-CSVL suggests that inadequate correction cannot be compensated with the UIV or LIV tilt and residual thoracic curvature. Nevertheless, our results are likely underpowered with the limited number of patients who were persistently imbalanced. Better correction of the LIV tilt allows for more compensation potential postoperatively. Our findings of increased LIV tilt with follow-up support this. Li *et al*[5] also showed that pre-operative C7-CSVL, pre-operative LIV tilt and post-operative LIV tilt affected coronal balance outcomes. Similarly, Shetty *et al*[9] also proposed pre-operative LIV tilt, post-operative LIV tilt and pre-operative C7-CSVL as important factors contributing to coronal imbalance. A larger emphasis should be placed on correction of the Cobb angle and C7-CSVL. In these cases, surgeons may want to consider longer segment fusions, in which more cranial thoracic instrumentation requires multiple rib osteotomies. Thus, in cases with significant C7-CSVL deviation of 26.2mm or more, a posterior approach may be advisable to achieve a balanced fusion mass with parallel UIV and LIV. However, since our delayed imbalance group only had nine patients, our findings will require further validation in larger multicentre studies. This is probably also the reason for inability to obtain a statistically significant AUC for postoperative LIV tilt.

There are some important limitations to note. Due to the limited number of patients who had delayed imbalance at 2-year follow-up, the influence of reported radiographic parameters are unpowered and should be validated with a larger multicentre study. Despite utilizing the fulcrum-bending radiograph and FBCI to standardize our preoperative planning, the extent of anterior release and screw placement to achieve optimal correction may be variable leading to less significance on preoperative flexibility. We were also unable to obtain the flexibility of the thoracic curve which may influence the passive ability of the thoracic curve to compensate for any residual imbalance. It is important to note that the 6-week radiographs were obtained with the patient in orthosis and may have affected the overall balance of the patient. Nevertheless, we still observed patients who were imbalanced or balanced with the orthosis at 6-weeks. With all patients under similar postoperative care, the factors we have observed are applicable to this population. Moreover, our findings are only relevant to the coronal plane. The factors associated with sagittal and axial plane correction require further study. The 3D changes may have bearing on the outcomes of coronal balance. With a single-rod instrumentation, derotation of the scoliosis deformity may be inadequate.

We utilized a comprehensive panel of parameters to identify potential radiographic factors associated with coronal balance and delayed coronal balance after Lenke 5C surgery. Most patients showed a well-balanced spine at 2-years follow-up despite initial imbalance. Through a multivariate analysis, factors associated with balance outcomes are proposed when surgeons aim to achieve a parallel fusion mass intra-operatively. Increased preoperative UIV tilt and reduced 6-week postoperative RSH difference are associated with postoperative balance. Larger preoperative major Cobb angle, less preoperative C7-CSVL and less 6-week postoperative LIV tilt are associated with delayed coronal balance. These are valuable parameters to identify at the immediate post-operative period. As there were significant improvements in patient perceived outcome scores, patients should be reassured that most attain eventual coronal balance despite early imbalance.

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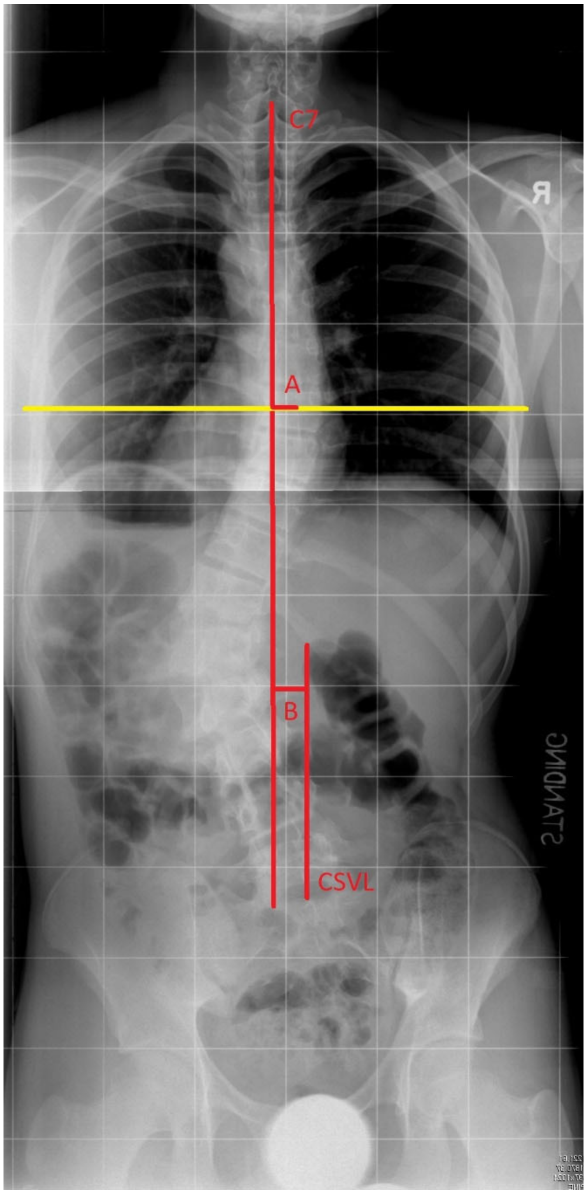
Figure Legends

Fig 1: Coronal balance is measured by (A) trunk shift and (B) C7-CSVL distance.

Fig. 2A-C: (A) PA radiographs of a patient showing sustained coronal balance pre-operatively (C7-CSVL: 16.9mm; trunk shift: 15.8mm); (B) at 6-weeks post-operatively (C7-CSVL: 14mm; trunk shift: 3.8mm); (C) and at 2-year follow-up (C7-CSVL: 4.7mm; trunk shift: 10.1mm).

Fig. 3A-C: (A) PA radiographs of a patient with a coronally well balanced spine pre-operatively (C7-CSVL: 6.2mm; trunk shift: 6.3mm); (B) 6-weeks post-operatively there was coronal imbalance with C7-CSVL distance of 45mm and trunk shift of 24.4mm; (C) at 2-year follow-up, delayed coronal balance with C7-CSVL distance of 2.6mm and trunk shift of 13.3mm was observed.



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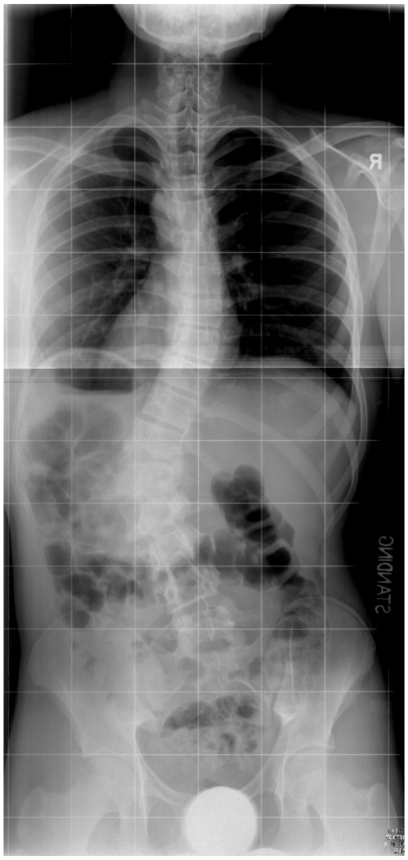

Fig. 2A

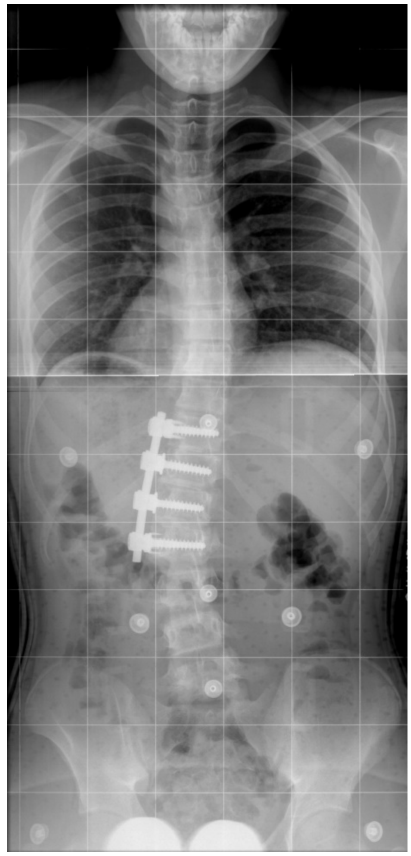

Fig. 2B

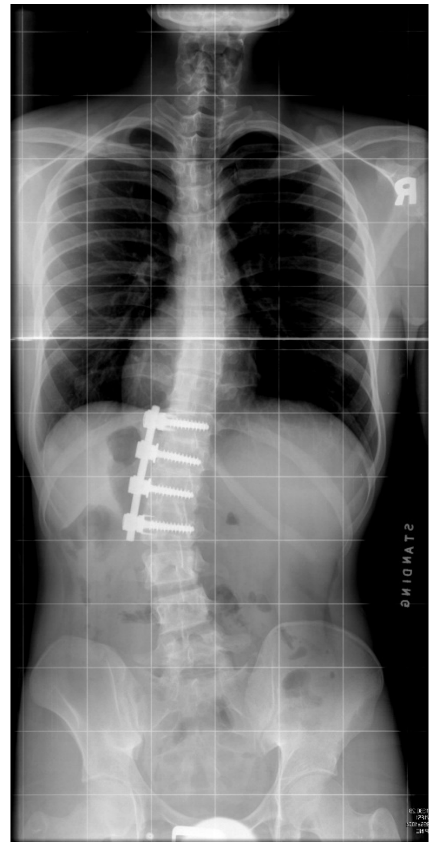

Fig. 2C

Fig. 3A-C: (A) PA radiographs of a patient with a coronally well balanced spine pre-operatively (C7-CSVL: 6.2mm; trunk shift: 6.3mm); (B) 6-weeks post-operatively there was coronal imbalance with C7-CSVL distance of 45mm and trunk shift of 24.4mm; (C) at 2-year follow-up, delayed coronal balance with C7-CSVL distance of 2.6mm and trunk shift of 13.3mm was observed.

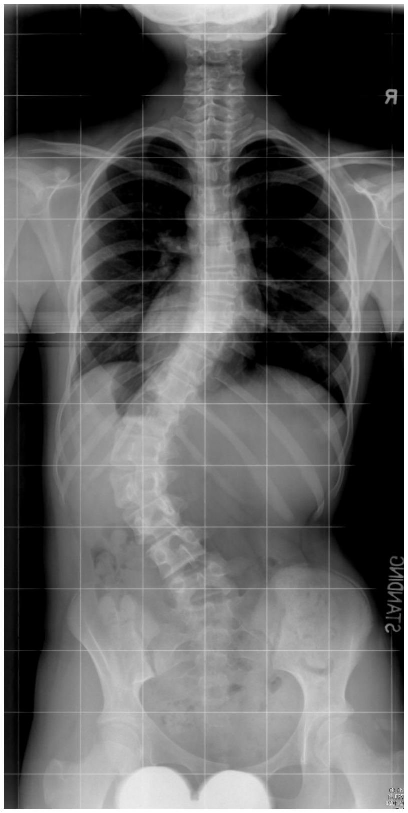

Fig. 3A

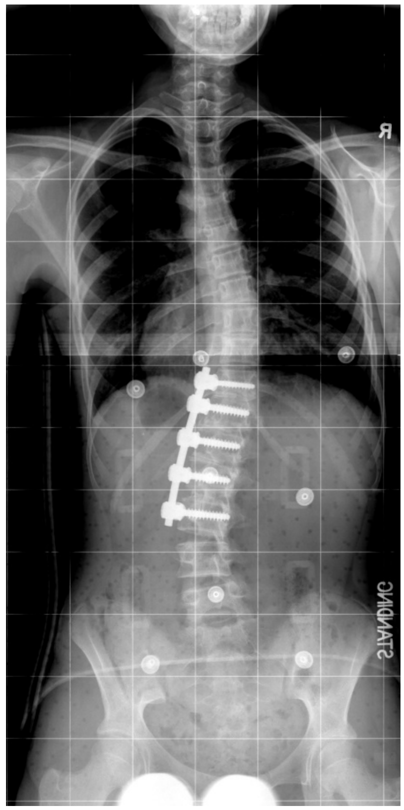

Fig. 3B

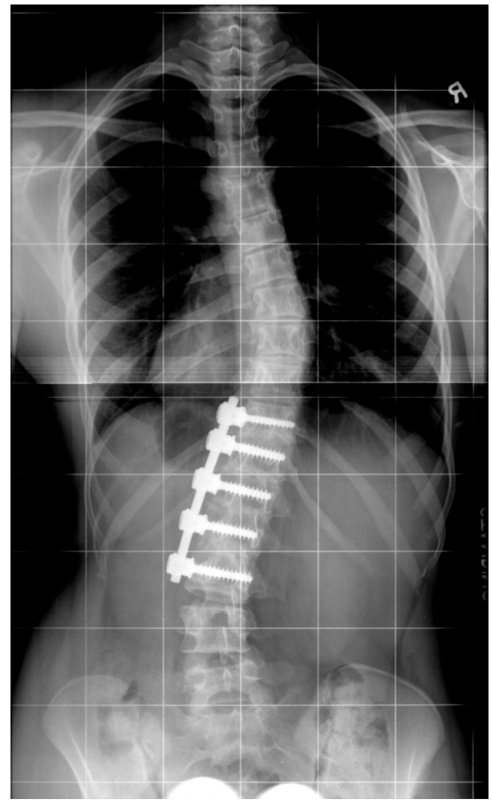

Fig. 3C

Table 1: Pre-operative and post-operative radiological parameters for 6-week postoperative balanced and imbalanced groups

Global balance / Parameters mean (SD)	6-week postoperative balance (n = 39)	6-week postoperative imbalance (n = 85)	p-value^	Post-hoc power analysis
Preoperative				
Major curve Cobb angle	54.1 (7.1)	52.7 (7.8)	0.157	
Fulcrum bending Cobb angle	14.8 (8.4)	15.6 (8.8)	0.617	
Thoracic Cobb angle	28.8 (9.8)	28.1 (9.4)	0.700	
RSH	-3.1 (14.6)	-4.0 (15.0)	0.688	
Trunk shift	15.4 (9.2)	16.3 (10.6)	0.716	
C7-CSVL	19.4 (21.1)	19.3 (10.8)	0.187	
Apex translation	49.6 (14.1)	52.9 (11.7)	0.476	
UIV tilt	23.3 (5.6)	21.6 (5.2)	0.100	
LIV tilt	30.0 (5.6)	29.8 (6.2)	0.825	
LIV disc angle	-2.4 (4.5)	-1.9 (5.6)	0.759	
Fulcrum Flexibility	73.2 (13.1)	70.8 (14.3)	0.353	
Surgical outcomes				
Immediate Postoperative				
Correction Rate (%)	85.7 (9.9)	86.9 (13.3)	0.128	
FBCI (%)	122.1 (32.1)	127.1 (30.5)	0.418	
Postoperative 2 years				
Correction Rate (%)	79.2 (15.6)	80.3 (15.8)	0.634	
FBCI (%)	113.4 (36.6)	117.4 (31.6)	0.496	
Postoperative parameters **6-weeks Postoperative**				
Major curve Cobb angle	7.5 (4.9)	6.9 (7.2)	0.093	
Thoracic Cobb angle	13.8 (8.2)	15.0 (7.4)	0.496	
RSH	-0.4 (13.6)	7.0 (15.6)	0.002*	Effect size: 0.51, α:0.05, power: 0.89

Truncal shift	7.7 (5.1)	14.5 (9.6)	< 0.001*	Effect size: 0.88, α:0.05, power: 0.99
C7-CSVL	11.9 (5.6)	36.0 (13.1)	< 0.001*	Effect size: 2.39, α:0.05, power: 1.00
Fusion mass Cobb angle	5.1 (3.4)	5.2 (5.8)	0.242	
Fusion mass shift	6.6 (7.7)	5.8 (11.2)	0.400	
UIV tilt	4.8 (3.2)	4.1 (3.8)	0.081	
LIV tilt	3.9 (2.9)	4.2 (3.8)	0.951	
2-year Postoperative				
Major curve Cobb angle	11.0 (8.2)	10.5 (8.5)	0.590	
Thoracic Cobb angle	16.4 (8.4)	17.4 (9.0)	0.749	
RSH	-2.8 (9.9)	-1.9 (8.6)	0.469	
Truncal shift	9.1 (8.2)	9.0 (6.7)	0.626	
C7-CSVL	9.7 (9.9)	8.1 (6.9)	0.638	
Fusion mass Cobb angle	7.2 (4.4)	6.0 (5.2)	0.042*	Effect size: 0.25, α:0.05, power: 0.35
Fusion mass shift	7.3 (9.3)	8.8 (10.8)	0.600	
UIV tilt	6.8 (3.7)	5.7 (3.8)	0.128	
LIV tilt	4.5 (3.4)	5.0 (4.2)	0.755	

CSVL: central sacral vertical line; UIV: upper instrumented vertebra; LIV: lower instrumented vertebra;

FBCI: fulcrum-bending corrective index; RSH: radiographic shoulder height

^ Mann-Whitney *U* test comparing mean ranks of the data between groups

Table 2: Univariate analysis of surgical outcome of 6-week postoperative balance

	Surgical outcome of 6-week postoperative balance				
	Regression coefficient	S.E.	Wald	p-value	Odds ratio (95% CI)
Preoperative parameters					
Chronological age	0.116	0.065	3.180	0.075	1.123 (0.989 – 1.277)
Risser staging (in gradings)			4.407	0.622	
Major curve Cobb angle	0.025	0.025	0.993	0.319	1.025 (0.976 – 1.077)
Fulcrum bending Cobb angle	-0.011	0.023	0.249	0.618	0.989 (0.945 – 1.034)
Thoracic Cobb angle	0.008	0.021	0.156	0.693	1.008 (0.968 – 1.050)
RSH	0.004	0.014	0.100	0.752	1.004 (0.978 – 1.032)
Trunk shift (absolute values)	-0.009	0.019	0.219	0.640	0.991 (0.954 – 1.029)
C7-CSVL (absolute values)	0.001	0.013	0.002	0.965	1.001 (0.975 – 1.027)
Apex translation	-0.022	0.016	1.875	0.171	0.979 (0.949 – 1.009)
UIV tilt	0.061	0.037	2.672	0.102	1.063 (0.988 – 1.143)
LIV tilt	0.005	0.032	0.028	0.867	1.005 (0.944 – 1.071)
LIV disc angle	-0.017	0.037	0.207	0.649	0.983 (0.915 – 1.057)
Fulcrum Flexibility	0.013	0.014	0.811	0.368	1.013 (0.985 – 1.041)
6-week postoperative parameters					
Major curve Cobb angle	0.012	0.029	0.183	0.669	1.012 (0.957 – 1.072)
Thoracic Cobb angle	-0.022	0.026	0.755	0.385	0.978 (0.930 – 1.029)
RSH	-0.036	0.015	6.090	0.014*	0.965 (0.938 – 0.993)
Truncal shift (absolute values)	-0.110	0.030	13.241	<0.001*	0.896 (0.845 – 0.951)
C7-CSVL (absolute values)	-0.690	0.180	14.666	<0.001*	0.501 (0.352 – 0.714)
Fusion mass Cobb angle	-0.004	0.038	0.013	0.910	0.996 (0.924 – 1.073)
Fusion mass shift	0.007	0.019	0.152	0.696	1.007 (0.971 – 1.045)
UIV tilt	0.052	0.052	1.029	0.310	1.054 (0.952 – 1.166)
LIV tilt	-0.027	0.058	0.212	0.645	0.974 (0.869 – 1.091)
Correction Rate (%)	-0.008	0.015	0.263	0.608	0.992 (0.962 – 1.023)
FBCI (%)	-0.005	0.007	0.681	0.409	0.995 (0.982 – 1.007)

CSVL: central sacral vertical line; UIV: upper instrumented vertebra; LIV: lower instrumented vertebra; FBCI: fulcrum-bending corrective index; RSH: radiographic shoulder height

Table 3: Multivariate regression predicting 6-week postoperative balance

Predictors	Regression Coefficient	SE	Wald Chi-square	p-values	Odds ratio	95% CI	Change in -2 log likelihood	Significance of change if factor is removed from model
Age at surgery (years)	0.115	0.071	2.599	0.107	1.122	0.976 – 1.290	2.851	0.091
Preoperative UIV tilt	0.089	0.040	4.948	0.026*	1.093	1.011 – 1.182	5.250	0.022*
6-week postoperative RSH	-0.037	0.015	5.893	0.015*	0.963	0.935 – 0.993	6.549	0.010*

UIV: upper instrumented vertebra; RSH: radiographic shoulder height; SE: standard error
Regression model: X^2 (3) = 13.953, p=0.003
Nagelkerke R Square =0.149. Percent predicted correctly by this prediction model is 71.0%.

Table 4: Pre-operative and post-operative parameters for delayed balance and imbalance groups

Global balance / Parameters mean (SD)	Delayed balance (n = 76)	Delayed imbalance (n = 9)	p-value^	Post-hoc power analysis
Preoperative				
Major curve Cobb angle	53.2 (8.0)	48.0 (5.0)	0.022*	Effect size: 0.78, α:0.05, power: 0.77
Fulcrum bending Cobb angle	16.0 (9.1)	12.8 (5.0)	0.420	
Thoracic Cobb angle	28.5 (9.6)	25.1 (7.7)	0.281	
RSH	-2.9 (9.6)	-13.2 (37.3)	0.943	
Trunk shift	15.7 (10.5)	21.1 (10.9)	0.083	
C7-CSVL	18.0 (10.5)	30.8 (4.4)	< 0.001*	Effect size: 1.59, α:0.05, power: 1.00
Apex translation	52.8 (11.6)	54.1 (13.1)	0.502	
UIV tilt	21.9 (5.1)	18.5 (4.6)	0.049*	Effect size: 0.70, α:0.05, power: 0.67
LIV tilt	29.9 (6.3)	29.3 (5.8)	0.743	
LIV disc angle	-1.8 (5.7)	-2.7 (4.9)	0.573	
Fulcrum Flexibility	70.5 (14.7)	73.1 (10.8)	0.689	
Surgical outcomes				
6-week postoperative				
Correction Rate (%)	87.3 (13.6)	84.0 (9.6)	0.194	
FBCI (%)	128.2 (31.0)	117.8 (26.3)	0.265	
2-year postoperative				
Correction Rate (%)	80.2 (16.0)	80.9 (14.8)	0.977	
FBCI (%)	117.8 (31.7)	113.9 (31.9)	0.797	
Postoperative parameters 6-week postoperative				
Major curve Cobb angle	6.9 (7.5)	7.7 (4.7)	0.324	
Thoracic Cobb angle	15.4 (7.5)	12.3 (6.0)	0.225	
RSH	6.8 (16.2)	8.7 (8.7)	0.753	
Truncal shift	14.3 (9.3)	15.5 (12.8)	0.994	
C7-CSVL	35.6 (13.0)	39.1 (14.1)	0.471	
Fusion mass Cobb angle	5.0 (5.8)	6.8 (6.0)	0.458	
Fusion mass shift	5.5 (10.9)	8.7 (13.5)	0.331	
UIV tilt	4.2 (4.0)	3.0 (2.5)	0.534	
LIV tilt	4.0 (3.5)	6.5 (5.4)	0.222	
2-year postoperative				
Major curve Cobb angle	10.6 (8.7)	10.5 (8.5)	0.814	
Thoracic Cobb angle	17.7 (8.5)	17.4 (9.0)	0.297	
RSH	-2.3 (8.7)	-1.9 (8.6)	0.214	
Truncal shift	7.6 (5.3)	9.0 (6.7)	< 0.001*	Effect size: 0.23, α:0.05, power: 0.13

C7-CSVL	6.7 (4.8)	8.1 (6.9)	0.001*	Effect size: 0.24, α:0.05, power: 0.13
Fusion mass Cobb angle	6.0 (5.2)	6.0 (5.2)	0.932	
Fusion mass shift	8.6 (10.7)	8.8 (10.8)	0.775	
UIV tilt	5.8 (3.7)	5.7 (3.8)	0.658	
LIV tilt	4.5 (3.6)	5.0 (4.2)	0.016*	Effect size: 0.13, α:0.05, power: 0.07

CSVL: central sacral vertical line; UIV: upper instrumented vertebra; LIV: lower instrumented vertebra; FBCI: fulcrum-bending corrective index; RSH: radiographic shoulder height

^ Mann-Whitney *U* test comparing mean ranks of the data between groups

Table 5: Factors associated with delayed coronal balance

	Outcome: 6-week postoperative imbalance with 2-year postoperative balance				
	Regression coefficient	S.E.	Wald	p-value	Odds ratio (95% CI)
Preoperative parameters					
Chronological age	0.022	0.148	0.022	0.881	1.022 (0.765 – 1.366)
Risser staging (in gradings)			3.933	0.686	
Major curve Cobb angle	0.130	0.068	3.597	0.058	1.138 (0.996 – 1.302)
Fulcrum bending Cobb angle	0.047	0.047	1.017	0.313	1.048 (0.956 – 1.149)
Thoracic Cobb angle	0.038	0.037	1.021	0.312	1.038 (0.965 – 1.117)
RSH	0.028	0.018	2.380	0.123	1.028 (0.992 – 1.066)
Trunk shift (absolute values)	0.038	0.037	1.021	0.312	1.038 (0.965 – 1.117)
C7-CSVL (absolute values)	-0.148	0.050	8.787	0.003*	0.863 (0.782 – 0.951)
Apex translation	-0.010	0.030	0.113	0.737	0.990 (0.934 – 1.050)
UIV tilt	0.153	0.085	3.247	0.072	1.166 (0.987 – 1.377)
LIV tilt	0.017	0.058	0.082	0.774	1.017 (0.908 – 1.139)
LIV disc angle	0.030	0.064	0.212	0.646	1.030 (0.908 – 1.168)
Fulcrum Flexibility	-0.013	0.025	0.267	0.605	0.987 (0.939 – 1.037)
6-week postoperative parameters					
Major curve Cobb angle	-0.015	0.046	0.105	0.745	0.985 (0.901 – 1.078)
Thoracic Cobb angle	0.061	0.051	1.419	0.234	1.063 (0.961 – 1.176)
RSH	-0.008	0.022	0.122	0.727	0.992 (0.950 – 1.036)
Truncal shift (absolute values)	-0.013	0.036	0.121	0.728	0.987 (0.920 – 1.060)
C7-CSVL (absolute values)	-0.019	0.025	0.568	0.451	0.982 (0.935 – 1.030)
Fusion mass Cobb angle	-0.042	0.050	0.728	0.394	0.958 (0.869 – 1.057)
Fusion mass shift	-0.022	0.027	0.670	0.413	0.978 (0.928 – 1.031)
UIV tilt	0.106	0.121	0.761	0.383	1.112 (0.876 – 1.411)
LIV tilt	-0.127	0.074	2.965	0.085	0.880 (0.761 – 1.018)
Correction Rate (%)	0.016	0.024	0.487	0.485	1.017 (0.971 – 1.065)
FBCI (%)	0.013	0.014	0.945	0.331	1.013 (0.987 – 1.041)

CSVL: central sacral vertical line; UIV: upper instrumented vertebra; LIV: lower instrumented vertebra; FBCI: fulcrum-bending corrective index; RSH: radiographic shoulder height

Table 6: Multivariate regression for predicting 2-year postoperative balance

Predictors	Regression Coefficient	SE	Wald Chi-squared	p-values	Odds ratio	95% CI	Change in -2 log likelihood	Significance of change if factor is removed from model
Preoperative Major curve Cobb angle (degrees)	0.204	0.103	3.948	0.047*	1.226	1.003 – 1.499	6.879	0.009*
Preoperative C7-CSVL	-0.250	0.086	8.458	0.004*	0.779	0.658 – 0.922	17.269	< 0.0001*
Preoperative RSH	0.026	0.025	1.080	0.299	1.026	0.978 – 1.076	1.653	0.198
Preoperative UIV tilt	0.019	0.104	0.034	0.854	1.019	0.831 – 1.250	0.034	0.854
6-week postoperative LIV tilt	-0.317	0.127	6.221	0.013*	0.728	0.567 – 0.934	6.970	0.008*

UIV: upper instrumented vertebra; RSH: radiographic shoulder height; SE: standard error
Regression model: X^2 (5) = 28.963, p<0.001

Nagelkerke R Square =0.588. Percent predicted correctly by this prediction model is 91.8%.

Table 7: Intergroup comparison of SRS-22r scores

SRS-22r domain and total scores Mean (SD)	6-week postoperative balance (n = 39)	6-week postoperative imbalance (n = 85)	p-values^	6-week postoperative imbalance		p-values^
				2-year balance (n = 76)	2-year imbalance (n = 9)	
Preoperative						
Function	4.79 (0.39)	4.77 (0.33)	0.692	4.77 (0.34)	4.80 (0.31)	0.924
Self-image	4.69 (0.37)	4.62 (0.46)	0.791	4.64 (0.44)	4.53 (0.59)	0.864
Mental health	3.24 (0.77)	3.55 (0.46)	0.218	3.55 (0.48)	3.53 (0.37)	0.864
Pain	4.11 (0.59)	4.21 (0.70)	0.490	4.21 (0.66)	4.23 (0.96)	0.747
Satisfaction with treatment	3.56 (0.68)	3.53 (0.68)	0.928	3.54 (0.80)	3.50 (0.87)	1.000
Total	4.18(0.37)	4.27 (0.33)	0.493	4.27 (0.32)	4.24 (0.45)	0.924
6-week postoperative						
Function	4.10 (0.74)	4.18 (0.93)	0.531	4.15 (0.98)	4.37 (0.45)	0.905
Self-image	4.23 (0.64)	4.19 (0.96)	0.661	4.16 (1.00)	4.37 (0.63)	0.798
Mental health	3.68 (0.64)	3.79 (0.83)	0.328	3.74 (0.86)	4.07 (0.50)	0.310
Pain	3.99 (0.58)	4.26 (0.67)	0.101	4.18 (0.68)	4.73 (0.33)	0.060
Satisfaction with treatment	3.81 (0.88)	4.00 (0.76)	0.479	3.98 (0.78)	4.08 (0.74)	0.947
Total	4.01 (0.46)	4.13 (0.52)	0.246	4.10 (0.54)	4.36 (0.27)	0.310
2-year postoperative						
Function	4.57 (0.45)	4.54 (0.75)	0.510	4.51 (0.77)	4.85 (0.19)	0.425
Self-image	4.42 (0.46)	4.54 (0.51)	0.187	4.51 (0.52)	4.80 (0.28)	0.282
Mental health	4.13 (0.72)	3.96 (0.56)	0.197	3.95 (0.58)	4.05 (0.19)	0.826
Pain	4.15 (0.47)	4.25 (0.71)	0.288	4.21 (0.72)	4.75 (0.19)	0.197
Satisfaction with treatment	4.34 (0.67)	4.05 (0.71)	0.103	4.03 (0.72)	4.33 (0.58)	0.524
Total	4.33 (0.38)	4.21 (0.76)	0.952	4.18 (0.78)	4.59 (0.08)	0.131

SRS-22r: 22-item refined Scoliosis Research Society questionnaire; SD: standard deviation

^ Mann-Whitney *U* test