Fulcrum flexibility of the main curve predicts postoperative shoulder imbalance in selective thoracic fusion of adolescent idiopathic scoliosis

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Abstract

Purpose

To identify preoperative predictors for postoperative shoulder imbalance (PSI) after corrective surgery of adolescent idiopathic scoliosis (AIS) using the fulcrum bending radiograph to assess flexibility.

Methods

A consecutive surgical cohort of AIS patients undergoing selective thoracic fusion with alternate-level pedicle screw fixation was prospectively studied. Preoperative antero-posterior, lateral and fulcrum bending radiographs were analyzed. Postoperatively, a minimum of two years clinical and imaging follow-up was performed of all patients. PSI was defined as a radiographic shoulder height difference of more than 20 mm.

Results

A total of 80 patients were included and 14 patients (18%) were confirmed with PSI at final follow-up. Flexibility of MT curve was an independent risk factor for PSI (odds ratio (OR) = 3.3 per 10% decrease, 95% confidence interval (CI): 1.6-8.2). 27 patients had a preoperative MT flexibility of <55% (OR=11.5, 95% CI: 2.8-46.2). Postoperative T1 tilt was significantly higher in the PSI group ($p<0.001$) and a T1 tilt of more than 9° resulted in 7.2 times higher odds of developing PSI (95% CI: 2.0-26.0). Fulcrum bending correction index (FBCI) was significantly higher in the PSI group at final follow-up and 25 patients had a final postoperative MT FBCI above 120% (OR=8.5 (95% CI: 2.3-31.0).

Conclusions

A low preoperative curve flexibility is a significant predictor for PSI. The surgical strategy should consider proximal fusion if low-flexibility MT curves and/or less aggressive MT curve correction. Achieving a level T1 should be a main priority during intraoperative correction and may require fusion of the PT curve.

Level of evidence

III

Key words

Adolescent idiopathic scoliosis; postoperative shoulder imbalance; fulcrum bending flexibility; fulcrum bending correction index; T1 tilt

Introduction

Contemporary surgical treatment for adolescent idiopathic scoliosis (AIS) involves correction of the structural part of the deformity while allowing the non-structural components to spontaneously correct[1-3]. As such, one of the key objectives of AIS surgery is to achieve a stable and balanced spine with the least number of fusion levels[4,5]. Less fusion levels also equates to less instrumentation, decreased risk of complications and reduced health-care costs[4,6-8]. Postoperative shoulder imbalance (PSI) is a common complication after AIS surgery and may occur as a postoperative decompensation of shoulder balance or a persisting preoperative shoulder imbalance inadequately corrected during surgery[9-12]. Postoperative shoulder imbalance is universally considered a poor outcome as it causes unsatisfactory appearance in young patients[9,13-15].

The preoperative identification of patients at risk of developing PSI remains challenging but a key concept is to correctly identify the need for fusion of the proximal thoracic (PT) curve[16]. Lenke *et al*[3,17] assigned structural criteria with a side bending PT Cobb angle ≥25° and/or T2-T5 kyphosis <20° as indication for fusion of the PT curve. Although the PT curve may be more rigid compared to the main thoracic (MT) curve, inclusion of all non-flexible PT curves has been shown to not always be necessary[18,19]. Others have added that the anticipated effect of MT curve correction on shoulder balance should be taken into account and that in cases of a substantial preoperative left shoulder elevation, the entire proximal curve should be fused[20,21]. At our institution, we do not employ the criteria proposed by Lenke *et al*[17] for PT fusion as we use the fulcrum bending radiograph (FBR) to access curve flexibility. Generally speaking, in small and/or flexible PT curves, surgeons' decision to fuse the PT curve relies on the presence of preoperative left shoulder elevation, higher left first rib, negative T1 tilt, and a significant clinical scapular hump.

Postoperative shoulder imbalance may be associated with an increased correction of the MT curve or a PT/MT curve mismatch suggesting that the amount of curve correction should be differentiated between patients[10,22,23]. Whether this differentiation should depend on the preoperative flexibility of the spine is not known. While PT flexibility has been shown to correlate with postoperative T1 tilt and PT curve correction, it does not appear to predict PSI[14,22]. However, it remains unknown whether the flexibility of the MT or lumbar curve may affect PSI in AIS patients.

In lieu of the aforementioned gaps in knowledge, the primary aim of the following study was to identify preoperative predictors of PSI at a minimum of two years in a cohort of AIS patient undergoing selective thoracic fusion. Secondarily, we also sought to determine clinically meaningful thresholds for when fusion of the PT curve should be considered.

Methods

Following ethics committee approval, we performed a prospective study of a consecutive series of AIS patients treated surgically from December 2004 to October 2009 with alternate-level pedicle screw instrumentation at a single institution[5,24]. Only patients with selective fusion of the MT curve with two-year follow-up were included.

All patients underwent FBR of the MT curve prior to surgery. The methods for obtaining FBRs and the determination of fusion levels have been previously reported[25-28]. In short, the patient was hinged over a radiolucent fulcrum while in the lateral decubitus position. For lumbar curves, the fulcrum was placed directly under the apex of the curve, whereas for MT curves it was placed under the rib corresponding to the apex of the curve. Patients in which fusion of the PT curve was considered underwent FBR of the PT curve where the fulcrum was placed in the axilla, while the ipsilateral arm is placed below the patient's head.

Standing antero-posterior (AP) and lateral digital plain radiographs were assessed preoperatively, immediate postoperatively and at final postoperative follow-up. From the AP radiograph, the following variables were measured: T1 tilt, clavicle angle, Cobb angle and apical translation of the PT, MT, and lumbar curves. Listing was also measured as the distance from the C7 plumb line to the central sacral vertical line (CSVL). Additionally, the following variables were measured:

a) Radiographic shoulder height (RSH) was defined as the height difference in the soft tissue shadow directly superior to the acromioclavicular joints (**Figure 1**).
b) Wedging of the apical PT vertebra was defined as a change of more than 5° between the angle of the upper and lower endplate of the apical vertebrae.
c) Rotation of the apical PT vertebra was assessed according to the method of Nash-Moe[29]. Rotation was considered present in grade 2 or 3.
d) Fusion mass shift: A perpendicular line is drawn from the lower endplate of the lower instrumented vertebrae (LIV). Fusion mass shift is the distance from this line to the midpoint of the upper endplate of the upper instrumented vertebrae (UIV) (**Figure 1**)[4].
e) Fusion mass angle was defined as the Cobb angle measured from the upper endplate of the UIV and the lower endplate of the LIV.
f) LIV angle was defined as the angle of the intervertebral disc below the LIV. It was measured by the angle made from the lower endplate of the LIV and the upper endplate of LIV+1 vertebra (**Figure 1**)[30].
g) LIV tilt was defined as the tilt angle of the lower endplate of the LIV towards the horizontal parallel line.

h) First rib angle (FRA) was defined as the tilt of a tangential line that connected both the superior borders of first ribs (**Figure 1**)[31].

i) Trapezius length (TL) was defined as the difference of the horizontal distance of the T2 pedicle to second rib–clavicle intersection between left and right side (**Figure 1**)[31].

From the lateral radiograph, the thoracic kyphosis (T5-T12) and lumbar lordosis (L1-S1) were measured[32]. The PT curve was considered fused when the UIV was T2 or T1. From the FBR, the Cobb angle of the curve was measured and the fulcrum flexibility of the PT, MT and lumbar curves were calculated as follows[24]:

$$\text{Correction rate}(\%) = \frac{\text{Preoperative Cobb angle} - \text{postoperative Cobb angle}}{\text{Preoperative Cobb angle}} * 100\%$$

$$\text{Fulcrum flexibility} = \frac{\text{Preoperative standing Cobb angle} - \text{Fulcrum bending Cobb angle}}{\text{Preoperative standing Cobb angle}} * 100\%$$

Subsequently, the fulcrum bending correction index (FBCI) of the main curve was calculated:

$$\text{FBCI} = \frac{\text{Correction rate}}{\text{Fulcrum flexibility}} * 100\%$$

All image data were stored in our archiving and communication system with DICOM-based software (Radworks™ 5.1; Applicare Medical Imaging BV, Zeist, The Netherlands). All measurements were performed by two readers independently and blinded to patient information. The mean of the two measurements were taken as the final measurement if differences in angles were <5° or distance measurements were <5mm. Any angle or distance differences more than described were discussed among the two readers and a final measurement was made by consensus. Additional variables included age, sex-type and Risser grade before surgery. The presence of a significant preoperative proximal scapular hump was noted as a binary variable and was based on a subjective description by the observer during assessment of the forward bending test.

Statistical analysis

The primary outcome measure was PSI, which was defined as an absolute RSH ≥ 20 mm at final follow-up, which is above the 95^{th} percentile in normal subjects[33]. All statistical analyses were performed using R version 3.3.2 (R core team, 2014, Vienna, Austria). Data is reported as counts, proportions (%), mean ± standard deviation or median with interquartile range (IQR). Continuous data was compared between groups using the non-parametric Wilcoxon rank sum test due to the small size of the PSI group. Categorical variables were compared using Pearson's chi-squared test or Fisher's exact test where applicable. The preoperative radiographs were analyzed with univariate comparative analysis to identify variables that were associated with PSI at final follow-up. All variables with a p-value of <0.1 were included in a standard multivariate logistic regression with PSI as the dependent variable. Collinearity was assessed with the variance inflation factor and a test for interaction was performed between all included variables. Odds ratios (OR) and their corresponding 95% confidence intervals (CIs) were obtained. Radiographs at final postoperative follow-up were analyzed with univariate comparative analysis to access the compensatory mechanisms in patients with PSI. A p-value ≤0.05 was considered significant. Clinically relevant thresholds were assessed with sensitivity analysis and receiver operating characteristics (ROC) analysis. As part of that analysis, the area under the curve (AUC) provided a measure of the ability of the suggested predictor to predict PSI. An AUC between 0.90-1.00 indicated exceptional discrimination, 0.80-0.89 excellent, 0.70-0.79 acceptable, 0.60-0.69 fair, and 0.50-0.59 failed discrimination[34]. The suggested thresholds were determined after careful evaluation of the ROC curve, the density plots and the parameter variation (e.g. the 75th percentile).

Results

A total of 80 patients were included with a median follow-up of 36 months (IQR: 27-45 months). Eighty-five percent were female and the mean preoperative Cobb angle of the MT and PT curve was 59±11° and 35±10°, respectively. Mean MT curve correction at final follow-up was 66±12% and mean correction of the PT curves was 42±20%. Mean preoperative RSH was -1±13 mm. At the immediate postoperative follow-up, the mean RSH was 17±12 mm and 36 patients (45%) met the criteria for PSI. At final follow-up, the mean RSH was 8±11 mm and 14 patients (18%) were confirmed with PSI. All patients with final PSI had a postoperative left shoulder elevation with T1 tilt towards the right (left side higher/positive T1 tilt) (**Figure 2**) and 9 out of 14 patients met the criteria for PSI at the immediate follow-up.

Preoperative predictors of PSI

At the preoperative stage, the PSI and no-PSI groups did not differ in shoulder balance parameters, MT Cobb angle or apical translation of the PT, MT or lumbar curve ($p \geq 0.116$). The FBR flexibility of the PT curve was assessed in 28 patients and there was no difference in flexibility between the groups ($p=0.380$) and the presence of clinically evident proximal scapular hump was equally distributed between the groups ($p=0.990$) **(Table 1)**. The groups differed in PT Cobb angle ($p=0.096$), wedging of the PT apical vertebra ($p=0.056$) and lumbar Cobb angle ($p=0.075$) but a statistically significant difference was found only for rotation of the PT apical vertebra ($p=0.034$) and flexibility of the MT curve ($p<0.001$).

The multivariate logistic regression showed that independent predictors for PSI at final follow-up were flexibility of the MT curve (OR=3.3 per 10% decrease in flexibility, 95% CI: 1.6-8.2) and rotation of the PT apical vertebra (OR=9.7, 95% CI: 1.2-138.6) (**Table 2**). No significant collinearity or interaction was found in the model ($p > 0.05$).

Final follow-up

At the final follow-up, the PSI and no-PSI groups did not differ in Cobb angle or apical translation of the PT, MT or lumbar curve ($p > 0.05$) (**Table 3**). The median T1 tilt was 6° [IQR: 3-9°] and 11° [IQR: 9-14] in the no-PSI and PSI groups, respectively ($p=0.001$) and median list was -4 mm [IQR: -13 to 3 mm] vs. 3 mm [IQR: -5 to 15 mm] ($p = 0.056$). Eight versus two patients had a list of more than 20 mm at final follow-up in the no-PSI and PSI groups, respectively ($p = 0.989$). MT curve correction was not different between the groups, but when adjusted for the difference in preoperative flexibility there was a significant association between MT curve correction and PSI (OR: 2.6, 95% CI: 1.1-6.6 per 10% increase in curve correction). No such effect was found for PT or lumbar curve correction ($p \geq 0.272$). Median MT FBCI was 103% [IQR: 91-118%] versus 139% [IQR: 120-172%] in the no-PSI and PSI groups, respectively ($p<0.001$). A significant correlation was found between final postoperative RSH and preoperative flexibility (Pearson's $r = -0.32$, $p = 0.001$), final T1 tilt (Pearson's $r = 0.60$, $p < 0.001$) and final MT FBCI (Pearson's $r = 0.41$, $p < 0.001$).

ROC curve analysis was performed to determine the performance of MT flexibility for predicting PSI (**Figure 4**). AUC was 0.83 (95% CI: 0.70–0.95) and 27 patients had a preoperative MT flexibility of < 55% (OR = 11.5, 95% CI: 2.8-46.2). At this threshold, the sensitivity and specificity of MT flexibility to discriminate between PSI and no-PSI patients was 79% (95% CI: 49-95%) and 76% (95% CI: 64-85%), respectively. Final T1 tilt and FBCI were categorized based on the 75th quartile (**Table 2**) (**Figure 3**) and the risk of PSI was assessed. Twenty-seven patients had a final postoperative T1 tilt above 9° (OR= 7.2 (95% CI: 2.0-26.0) and 25 patients had a final postoperative MT FBCI above 120% (OR = 8.5 (95% CI: 2.3-31.0).

Discussion

The rate of PSI after selective thoracic fusion for AIS was 18% after a minimum of two-year follow-up. A 10% decrease in preoperative MT flexibility "tripled" the odds of developing PSI. Furthermore, an increased correction of the MT curve was associated with a risk of PSI when adjusted for the difference in MT flexibility. FBCI, which incorporates both flexibility and curve correction, was markedly higher in the PSI group at both immediate and final follow-up and the correlation with RSH was stronger for FBCI than for flexibility alone. Almost all patients with a FBCI above 150% (n=7) developed PSI and we have proposed that a sensible cut-off may be a maximum of 20% "over correction" (FBCI = 120%) to reduce the risk of PSI. Alternatively, one may consider fusion of the PT curve in non-flexible curves in order not to compromise the amount of MT curve correction.

At the final postoperative follow-up, T1 tilt was significantly associated with PSI and showed the best correlation with RSH of any parameter (**Table 3**) (**Figure 3**). We found that a residual T1 tilt above 9° was associated with a seven-fold increase in the odds of developing PSI. Other studies have found similar correlation between postoperative T1 and RSH[35,36]. We propose the leveling of T1 should be a key objective of surgery and if this cannot be achieved fusion of the PT curve should be considered. The Lenke classification provides a useful terminology in terms of defining “structural” versus “non-structural” curves based on standard side-bending films, however the classification does not specifically address the correction of shoulder imbalance. The present study found that ≥ 9° T1 angulation may serve as a clinically useful guide intraoperatively. We propose that a modest postoperative T1 angulation can be accepted but that a substantial residual inclination should be avoided by including the PT curve in the fusion.

The proposed cut-offs in the present study may serve as “surgical guidelines” to reduce the risk of PSI but, as they are based on the current data, they should be validated in future studies to ensure external validity. While a majority of surgeons recommend the FBR to be part of preoperative assessment of AIS patients[37] we acknowledge that this method is not universally used. We expect that the suggested guidelines can be useful in conjunction with other methods of flexibility assessment but would encourage future studies to confirm this assertion.

We assessed additional structural criteria of the PT curve, such as apical rotation and/or wedging, which could aid fusion level selection. While the difference in apical rotation did reach statistical significance, considering the large confidence interval a larger cohort would be required to assess the practical use of this parameter in predicting PSI.

Some advocate that due to the inherent stiffness of the PT, a relative overcorrection of the MT curve would result in shoulder imbalance and that the choice to fuse the PT curve should also depend of the PT/MT curve ratio[12,38]. Our analysis showed that correction ratio, flexibility ratio or PT flexibility were not good predictors of PSI (**Table 1 and 3**). As the current cohort were all Lenke type 1 with small or absent PT curves PT flexibility was only assessed in 28/80 patients and hence the role of the PT flexibility in these patients would require a focused study to elaborate.

At the final postoperative follow-up, a shift in list from a left side C7 plumb line (negative values) in the no-PSI group to a right side plumb line in the PSI group was observed. This is not surprising since all PSI patients have left shoulder elevation which would likely drive the global balance to the right (**Figure 2**) (**Table 3**). The rate of coronal imbalance > 20 mm[39] was low in both groups.

Cao *et al*[40] found a higher rate of distal adding-on in patients without PSI in line while Matsumoto *et al*[22] found a lower clavicle angle in adding-on patients suggesting that distal compensatory mechanisms play a key role in maintaining shoulder balance. Fusion mass shift has been reported to be part of this mechanism[28] but such a coupling cannot be verified in the present study. Also, we did not find that LIV angle, tilt or residual lumbar or PT curve magnitude to be associated with PSI at final follow-up (**Table 3**). Hence, we cannot, based on the current data, make any conclusions as to the importance of these compensatory mechanisms.

It should be noted that the correlation between FBCI, T1 and RSH were only moderate and a proportion of PSI patients did not have a high FBCI or T1 tilt (**Figure 3**). AIS patients exhibit a range of compensatory mechanisms and the reasons behind the development of PSI are likely multifactorial. As this was an observational study it is likely that the predictive ability of preoperative T1 tilt and shoulder parameters are underestimated as these parameters are routinely considered for the fusion strategy which introduces bias in the analysis for these parameters.

Preoperative flexibility showed excellent discriminatory ability in terms of predicting PSI (AUC=0.83) and the current data suggests that in patients with non-flexible MT curves the surgical strategy should encompass either less aggressive correction of the MT curve and/or inclusion of the PT curve in the fusion. Leveling of T1 during surgery should be a key objective to minimize the risk of PSI even further.

The main limitation of study was that we only included patients with MT curves undergoing selective thoracic fusion. As such, our results cannot be readily transferred to other curve types as the influence on RSH differs when fusion includes the lumbar or proximal thoracic region. The association between thoracic fusion on development of PSI is complicated and a multitude of different parameters have been suggested to influence shoulder height postoperatively. To assess the role of preoperative flexibility our analyses inevitably included a series of univariate analyses to ensure that our results were not influenced by unrecognized confounding factors. Due to the limited amount of patients in this series our results should be interpreted with caution. As such, we consider our analysis exploratory and would encourage future studies to validate these findings.

Conclusion

This is the first study to show that the flexibility of the main curve is an independent preoperative predictor for the development of PSI after a minimum of two-year follow-up. The surgical strategy for AIS should not be to maximize curve correction in all patients but rather “incorporate” evaluation of preoperative flexibility. In non-flexible MT curves, proximal fusion of the PT curve and/or less aggressive correction of the MT curve should be considered. T1 tilt is an important element in PSI and achieving a level T1 should be a main priority during intraoperative correction. However, if a level T1 cannot be achieved, fusion of the PT curve should be considered.

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Figure legends

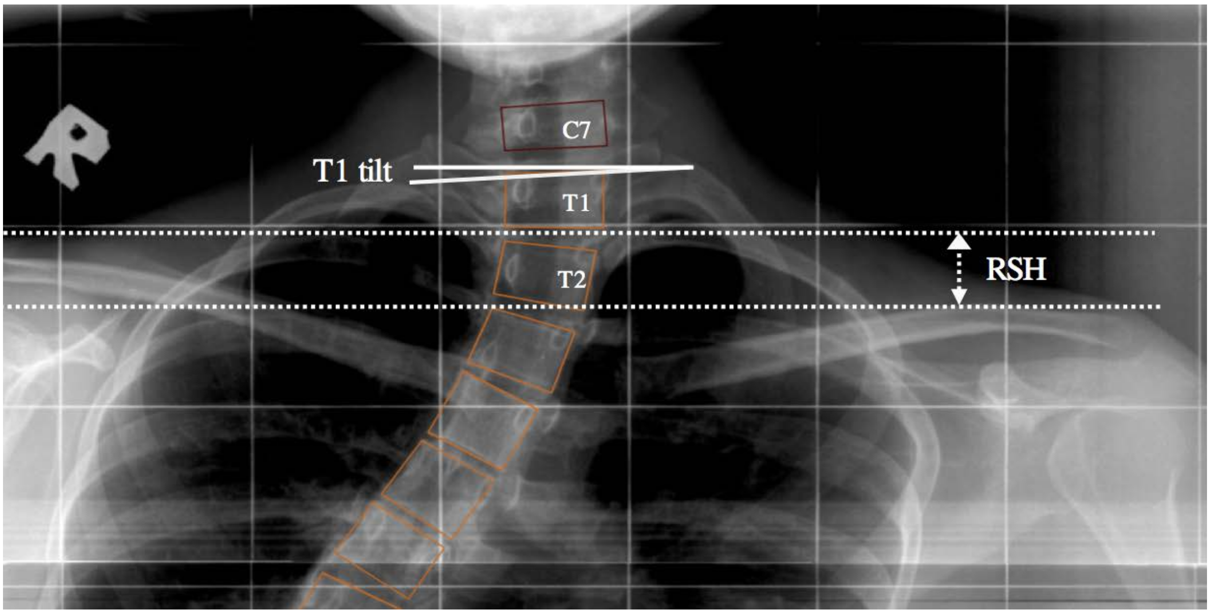


Figure 1: Guide to measurements made. T1 tilt: Positive T1 tilt indicates a higher left side T1 tilt. RSH: Radiographic shoulder height. Positive RSH indicates left shoulder elevated.

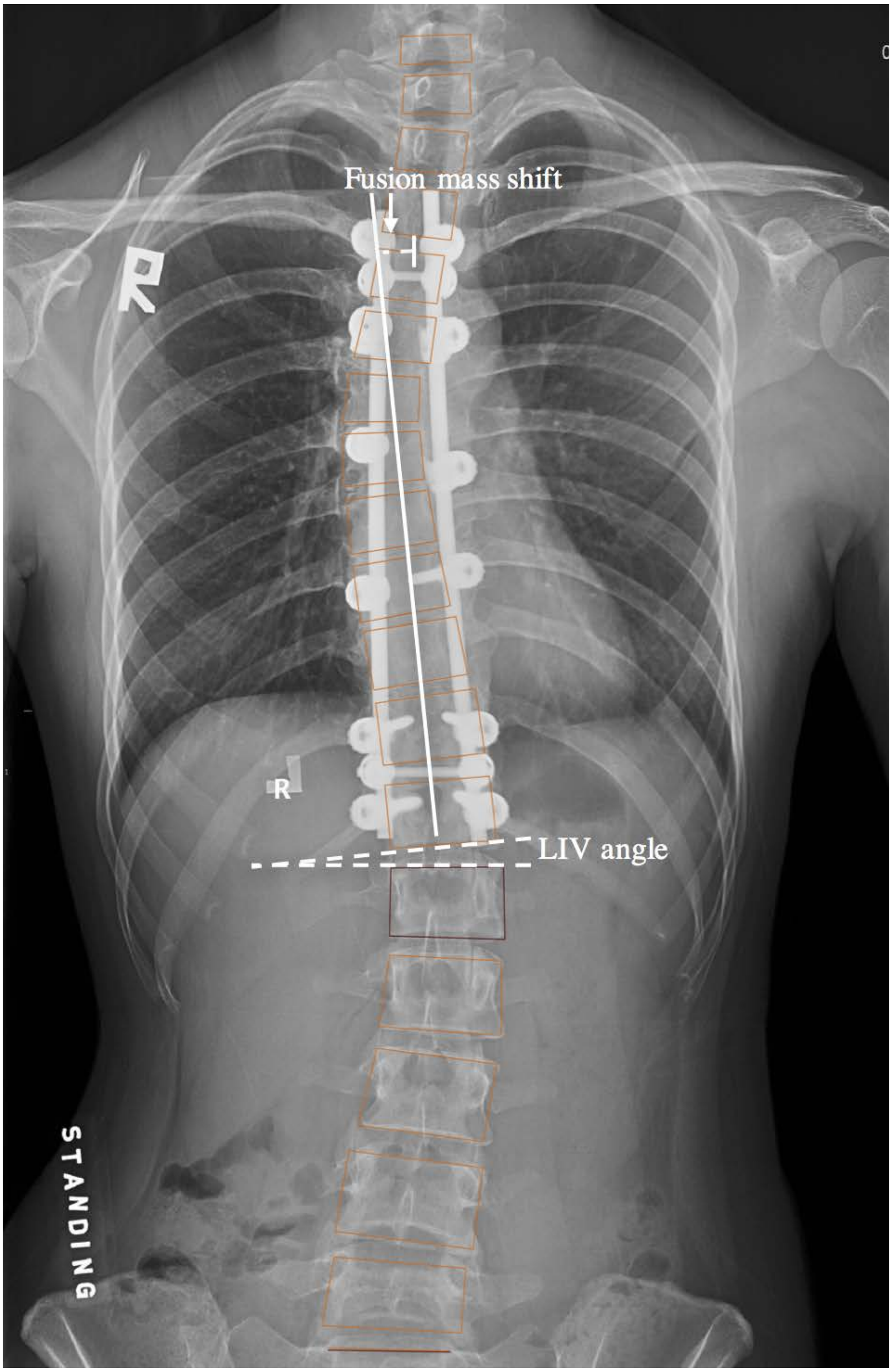


Figure 2: Guide to measurements made. The fusion mass shift is measured by drawing a perpendicular line from the lower endplate of the lower instrumented vertebrae (LIV) and the distance from this line to the midpoint of the upper endplate of the upper instrumented vertebrae (UIV).

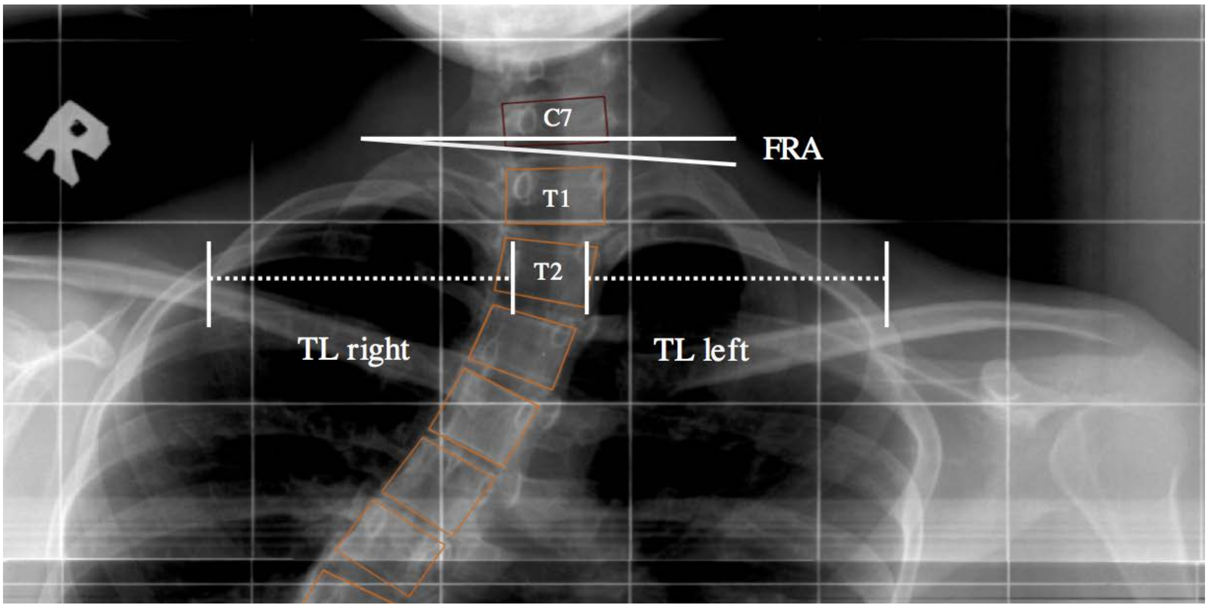


Figure 3: Guide to measurements made. FRA: First rib angle. Positive FRA indicated an inclination to the right of this reference line. TL: Trapezius length: A positive value was adopted when the horizontal distance was larger on the left side.

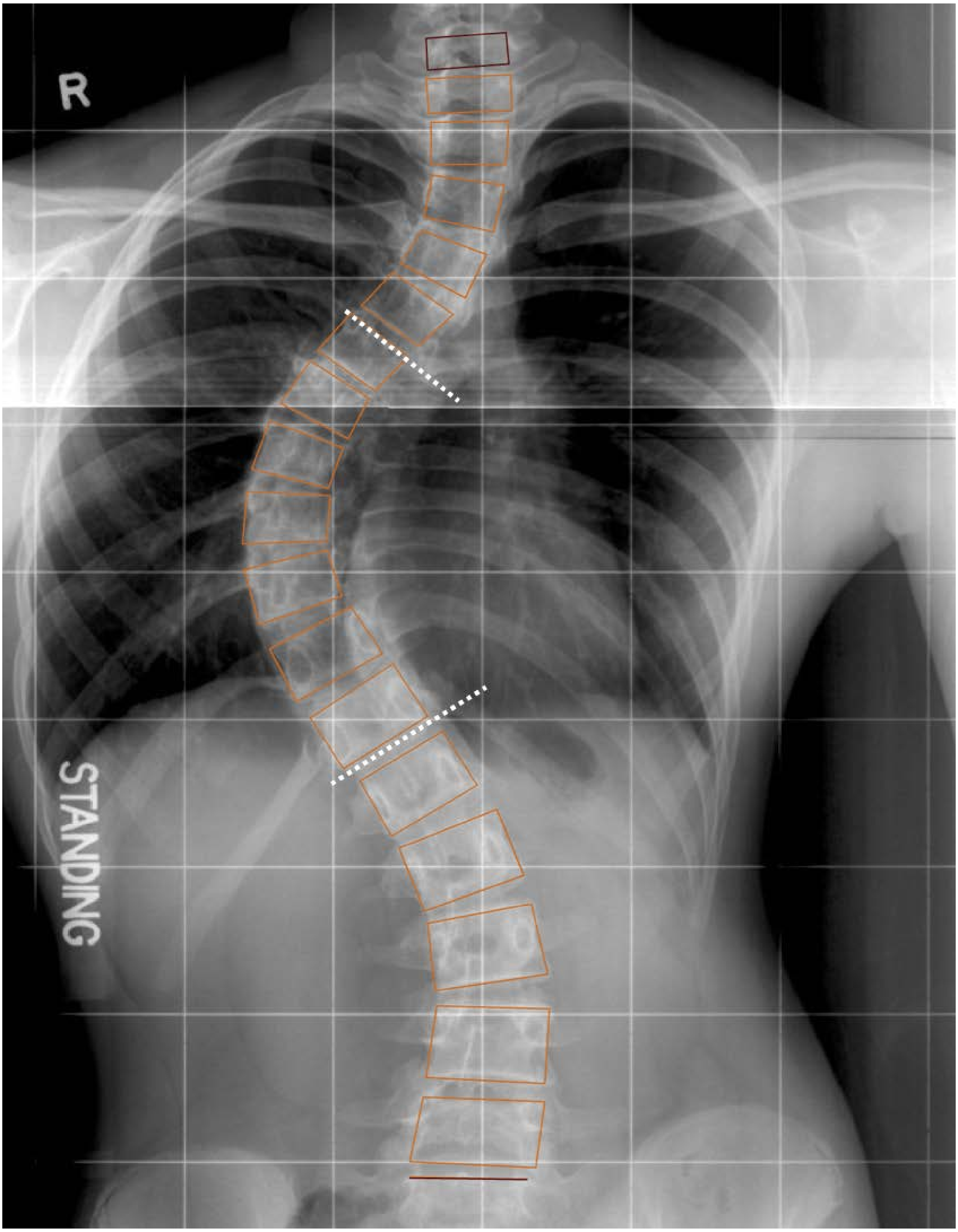
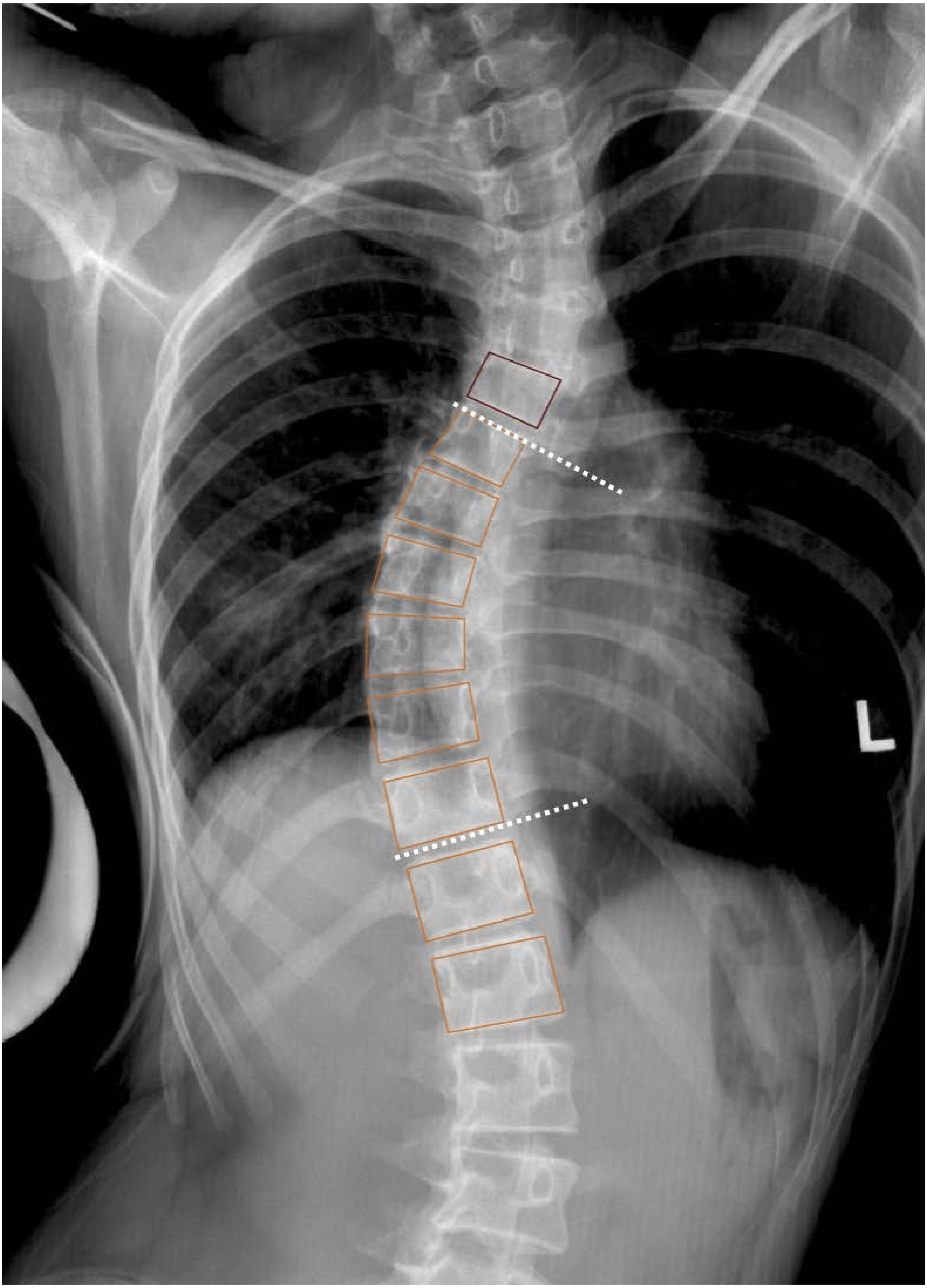
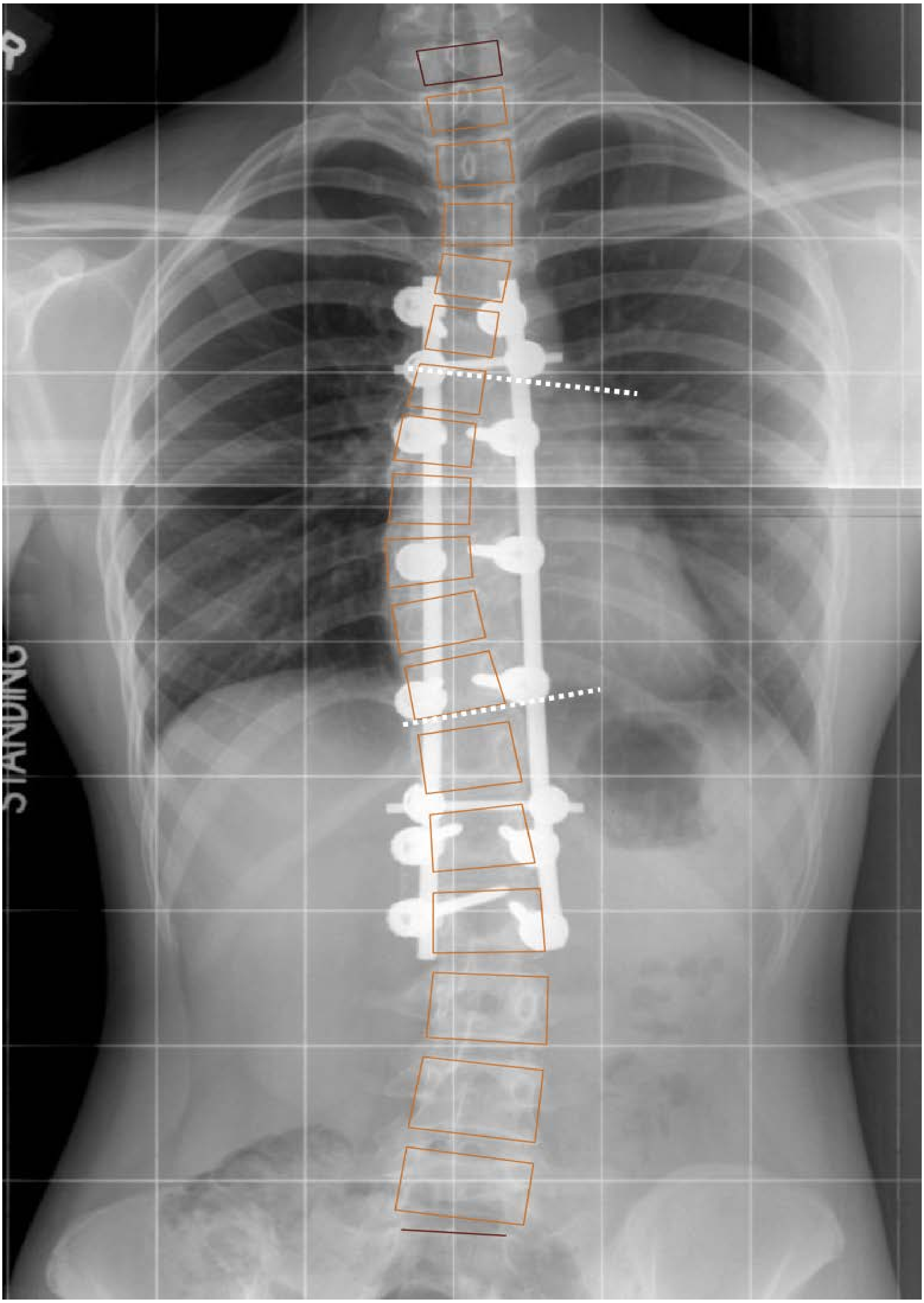


Figure 4: (A) Antero-posterior (AP) standing radiograph showing a main thoracic (MT) curve with a 70° Cobb angle, a proximal thoracic (PT) curve of 38°, a 5mm radiographic shoulder height (RSH) and a 3° T1-tilt.



(B) Fulcrum right-bending radiograph with a MT curve with 40° Cobb angle corresponding to 43% flexibility.



(C) AP standing radiograph showing a MT curve with a 19° Cobb angle corresponding to a fulcrum flexibility index of 170%. The PT curve is 16°, RSH is 20 mm and T1-tilt is 10°.

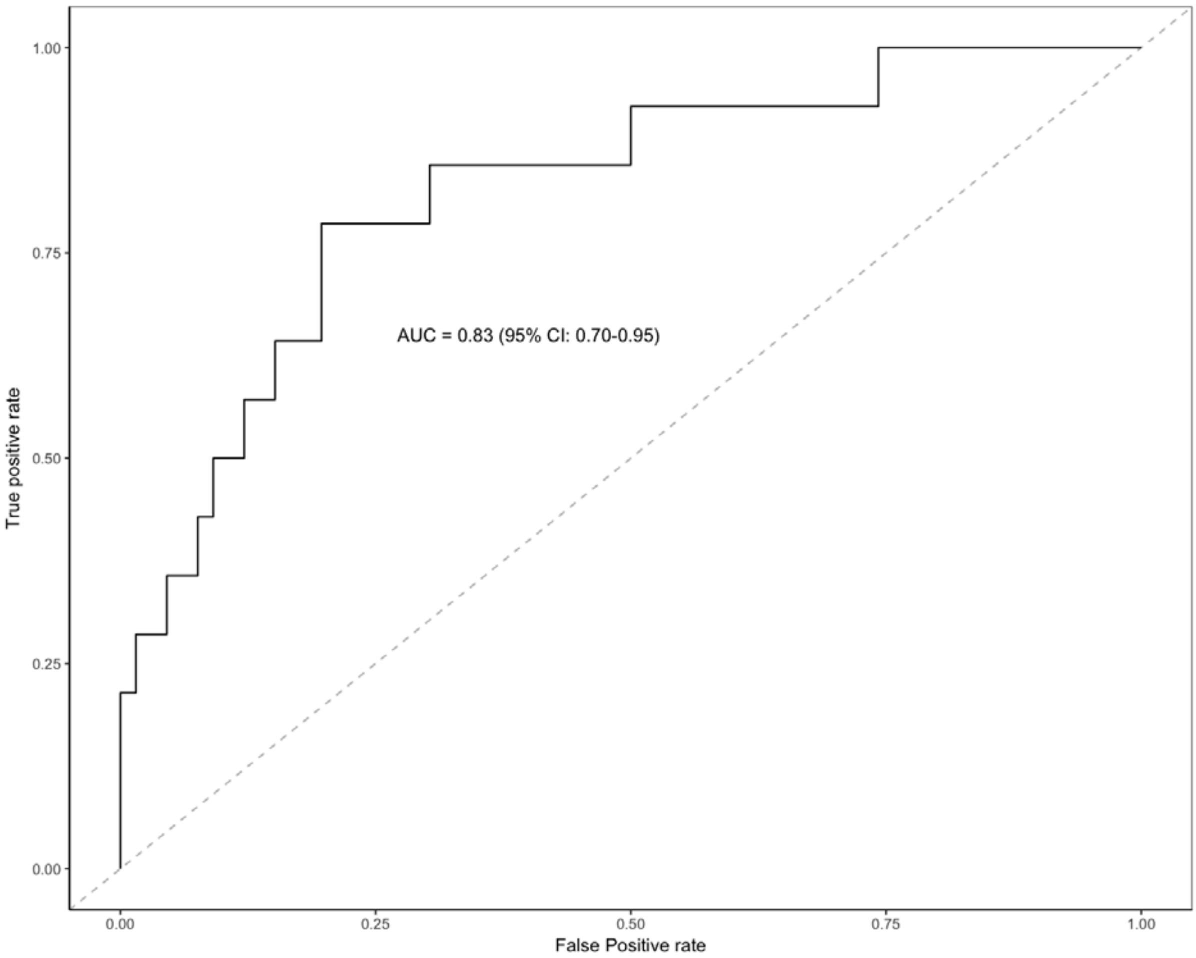


Figure 5: Receiver operating characteristic curve analysis for main thoracic curve flexibility as a predictor of postoperative shoulder imbalance. AUC: area under the curve.

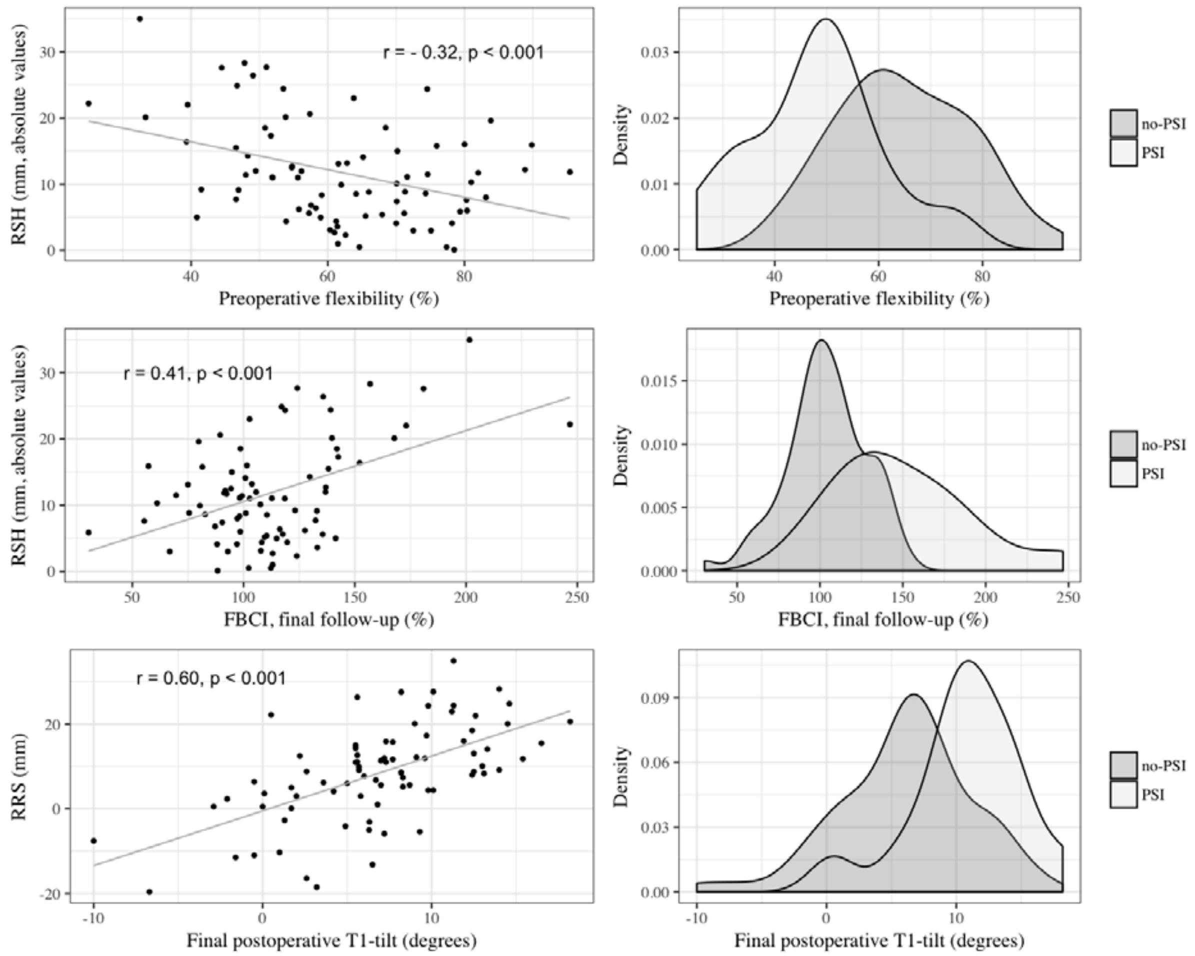


Figure 6: *On the left*: Scatter plot of preoperative main thoracic flexibility, fulcrum-bending correction index (FBCI) and T1-tilt at final follow-up showing the correlation for each variable with radiographic shoulder height (RSH) at final follow-up. *On the right*: Density plot showing the distribution of values between postoperative shoulder imbalance (PSI) and no-PSI patients. The density plot illustrates where relevant clinical thresholds may be set based on the current data.

Table 1. Preoperative variables			
	No PSI, n = 66 **median (IQR)**	**PSI, n = 14** **median (IQR)**	**p-value**
Age, years	14.0 [13.0, 16.0]	14.0 [12.2, 15.0]	0.813
Risser	3.5 [1.0, 4.8]	4.0 [3.0, 4.0]	0.964
Proximal hump on clinical examination			
No	65 (98%)	14 (100%)	
Yes	1 (2%)	0	0.990
Radiographic shoulder height, mm*	-1.0 [-10.8, 7.2]	6.1 [-7.1, 10.6]	0.190
Clavicle angle, °*	0.0 [-2.0, 1.9]	1.5 [-0.9, 2.7]	0.186
First rib angle, °*	0.6 [-3.8, 4.4]	2.5 [-1.0, 3.8]	0.548
Trapezius length, mm*	-7.4 [-13.7, -2.5]	-4.4 [-10.4, -0.7]	0.535
Shoulder level			
Right shoulder elevated > 10 mm	18 (27.3)	4 (28.6)	
Shoulder level <10 mm difference	35 (53.0)	4 (28.6)	
Left shoulder elevated > 10 mm	13 (19.7)	6 (42.9)	0.126
T1 tilt, ° *	3.3 [-2.8, 7.8]	3.5 [-0.1, 10.4]	0.535
List, mm**	7.9 [-4.2, 15.4]	4.9 [-3.4, 15.5]	0.690
Proximal thoracic curve			
Cobb angle, °	34.7 [27.3, 40.0]	43.4 [31.9, 46.4]	**0.096**
Apical translation, mm	8.7 [4.1, 15.9]	8.0 [6.3, 21.1]	0.418
Fulcrum flexibility (n = 28), %	47.1 [35.5, 60.2]	35.7 [22.6, 47.6]	0.380
Rotation of the apical vertebra			
Grade 0 or 1	32 (48.5)	2 (14.3)	
Grade 2 or 3	34 (51.5)	12 (85.7)	**0.034**
Wedge of the apical vertebra			
No	48	6	

	Yes	18	8	**0.056**
Main thoracic curve				
	Cobb angle, °	57.0 [52.0, 61.8]	62.0 [55.0, 76.5]	0.116
	Apical translation, mm	57.0 [42.7, 68.2]	56.2 [34.1, 61.4]	0.474
	Fulcrum bending flexibility, %	63.5 [55.7, 74.5]	48.4 [40.7, 53.7]	**< 0.001**
Lumbar curve				
	Cobb angle, °	29.9 [24.5, 36.3]	36.8 [29.2, 39.0]	**0.075**
	Apical translation, mm	10.8 [4.5, 15.0]	6.9 [3.5, 8.9]	0.197
	Fulcrum bending flexibility, %	68.1 [53.4, 89.3]	63.0 [48.1, 80.7]	0.565
PT vs. MT flexibility ratio (n = 28)		73.5 [63.7, 82.0]	70.0 [51.2, 84.9]	0.954

*Positive values indicate left-side elevation; ** Positive values indicate C7 plumb line falling to the right of the central sacral vertical line.

IQR: Interquartile range; PT: Proximal thoracic; MT: Main thoracic

Table 2. Multivariate logistic regression with preoperative parameters as independent variables and postoperative shoulder imbalance at final follow-up as the dependent variable.		
	Odds ratio **(95% confidence interval)**	**p-value**
Cobb angle, proximal curve, preoperative, °	1.01 (0.91-1.12)	0.890
Rotation of apical PT vertebra (ref: y)	9.66 (1.20-138.55)	**0.050**
Wedging of apical PT vertebra (ref: y)	0.40 (0.04-3.42)	0.420
Cobb angle of lumbar curve, preoperative, °	1.12 (1.01-1.27)	0.366
Fulcrum flexibility, MT curve, (per 10% decrease)	3.28 (1.64-8.16)	**0.003**

PT: proximal thoracic; MT: main thoracic

Table 3. Radiographic variables at final postoperative follow-up				
		No PSI (n=66) **median (IQR)**	**PSI (n=14)** **median (IQR)**	**p-value**
T1 tilt (mm)		6.4 (2.8, 9.0)	11.2 (9.2, 13.7)	**0.001**
Proximal thoracic curve				
	Cobb angle, °	20.3 (13.5, 25.6)	19.4 (16.5, 28.3)	0.718
	Apical translation, mm	11.1 (4.4, 17.4)	9.4 (5.1, 13.0)	0.844
	Curve correction, %	40.7 (31.6, 56.0)	42.0 (34.7, 62.6)	0.444
Main thoracic curve				
	Cobb angle, °	20.1 (16.1, 24.1)	20.2 (15.9, 25.2)	0.955
	Apical translation, mm	15.6 (9.7, 22.3)	12.8 (7.5, 18.8)	0.208
	Curve correction, %	66.3 (58.3, 72.0)	66.1 (62.1, 74.9)	0.586
	Fulcrum bending flexibility index, %	102.5 (91.4, 118.3)	139.4 (120.0, 171.7)	< **0.001**
Lumbar curve				
	Cobb angle, °	9.9 (2.6, 16.9)	12.9 (5.1, 20.1)	0.217
	Translation, apical vertebra, mm	8.1 (3.9, 15.7)	10.4 (2.5, 18.3)	0.909
	Curve correction, %	68.1 (53.4, 89.3)	63.0 (48.1, 80.7)	0.565
PT vs. MT curve correction ratio		67.1 (46.4, 83.1)	65.1 (51.2, 81.4)	0.825
List, mm		-3.6 (-12.5, 3.1)	3.0 (-5.0, 14.7)	0.056
Fusion block shift, mm		-8.0 (-19.2, 6.0)	-12.8 (-18.3, -4.8)	0.457
Cobb angle, fusion block, °		14.6 (10.6, 19.0)	13.9 (7.3, 17.9)	0.470
Lowest instrumented vertebra angle, °		2.6 (0.0, 6.1)	1.9 (0.2, 5.5)	0.486
Lowest instrumented vertebra tilt, °		-0.4 (-3.9, 2.5)	-1.0 (-2.8, 4.0)	0.980

IQR: Interquartile range; PT: Proximal thoracic; MT: Main thoracic; PSI: postoperative shoulder imbalance