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ORIGINAL ARTICLE

Predictors of shoulder level after spinal fusion in adolescent idiopathic scoliosis

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Abstract

Background For patients with adolescent idiopathic scoliosis, shoulder balance influences their treatment satisfaction and psychological well-being. Several parameters are known to affect postoperative shoulder balance, but few prognostic models are as yet available.

Purpose This study aimed to identify independent predictive factors that can be used to assess preoperatively which patients are at risk of postoperative shoulder elevation, and to build a linear prediction model.

Methods $N = 102$ patients with all Lenke types were reviewed radiographically before surgery and 1 year afterward. The outcome measures were coracoid height difference (CHD), clavicular angle (CA), and clavicle–first rib intersection difference (CiRID). Predictive factors commonly used in the literature were investigated using correlation analysis and statistical testing. Significant contributing factors were included in three multiple linear regression models (for CHD, CA, and CiRID).

Results The mean shoulder level (CHD) significantly changed from a lower left shoulder value of −8.5 mm before surgery to 3.3 mm at the follow-up examination. A high preoperative left shoulder level by CiRID, a large amount of Cobb angle correction of the distal thoracic curve, a low preoperative Cobb angle in the lumbar curve, and a structural proximal thoracic curve proved to be determinants and thus risk factors for left-sided shoulder elevation after surgery. The three models predicting CHD, CA, and CiRID at the follow-up examination included these four risk factors and were significant.

Conclusions Preoperative variables have the strongest influence on shoulder level after spinal instrumentation. Additionally, extensive correction of the distal thoracic curve can cause elevation of the left shoulder.

Keywords Adolescent idiopathic scoliosis · Shoulder balance · Prediction model · Corrective surgery

Introduction

Good outcomes after surgical treatment for adolescent idiopathic scoliosis (AIS) have for a considerable period been primarily defined by adequate correction of the spinal curves on all three planes. In addition, other factors such as shoulder level, clinical rib and lumbar hump, as well as scar size, play a major role in the evaluation of treatment success. These factors influence not only the surgeon's degree of satisfaction with the procedure, but—more importantly—patients' satisfaction with the therapy and also their psychological well-being afterward [1–8].

The type of scoliotic curvature has an influence on both the preoperative and postoperative shoulder level in AIS. In the literature, Lenke 2 curves or King V curves (double

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thoracic curves) in particular [9, 10] have been reported to be associated with elevation of the left shoulder before and also after surgery [11, 12]. Patients with this type of curve are at risk of severe shoulder imbalance, particularly if the high thoracic structural curve is not included in the spinal instrumentation [13, 14].

Other factors potentially influencing postoperative shoulder level have been analyzed by several authors. Previous studies have found that various radiographic measures of preoperative shoulder level [3, 8, 14–17], as well as numerous preoperative variables for spinal curvatures and fusion technique [3, 8, 11, 12, 15, 18–21], are predictive for postoperative shoulder balance. Many different variables are consequently in clinical use. However, it is unclear which of the various factors are the most relevant, and there is a lack of data in the literature comparing the various factors in systematic analyses. There is also a scarcity of linear prediction models.

The aim of this study was to identify the most relevant independent predictive variables for postoperative shoulder level in patients with AIS, from among the various factors previously described. All Lenke types were to be included. The study also aimed to identify predictive factors that may even be independent of the Lenke type. In contrast to similar investigations, which have usually categorized influencing variables dichotomously to determine risk factors, the intention in the present study was to build linear models using nominal, ordinal and interval data to enhance the accuracy of linear prediction.

Materials and methods

Patient data were collected from the spinal deformity database at a single institution. The institution's ethics committee approved the study (reg. no. 2009-350-f-S). A total of 210 scoliosis patients were available in the database. The inclusion criteria for this study were adolescent idiopathic scoliosis, right thoracic curve pattern, treatment with posterior spinal fusion (PSF) or anterior spinal fusion (ASF) and a minimum follow-up period of 12 months, as the literature shows that a stable situation in relation to shoulder level is reached 1 year after surgery [22, 23]. Patients who underwent revision operations after the index corrective procedure were excluded from the study, as well as all patients with nonidiopathic scoliosis and patients with reasons for shoulder imbalance other than idiopathic scoliosis. Variables noted for the study included gender, age at surgery, age at follow-up, upper instrumented vertebra (UIV), type of surgical approach (PSF vs. ASF), and radiographic measurements (see below).

The patients were selected for either PSF or selective ASF. PSF included posterior corrective pedicle screw instrumentation with a dual-rod titanium system and addition of autologous local bone graft and silicate-substituted calcium phosphate as the bone graft substitute. All ASF patients underwent open procedures with disc resection and titanium screw fixation with the dual-rod system in the convexity of the curve. In ASF cases, the proximal end vertebrae were chosen as the UIV, whereas in PSF cases the UIV was determined in accordance with the recommendations in the literature regarding preoperative Cobb angle and the flexibility of the proximal curve and preoperative shoulder level [24].

Standing anteroposterior and lateral radiographs of the whole spine were taken preoperatively, postoperatively, and at the follow-up examination, with a tube–film distance of 3 m. The radiographs depicted the relevant anatomic structures in the shoulders. Side-bending radiographs were taken preoperatively. The digitized images were saved and processed using the PACS program (GE Medical Systems, 2006).

The parameters used for radiographic evaluation included the Cobb angles of the proximal thoracic curve (PTC), distal thoracic curve (DTC) and lumbar or thoracolumbar curve (LC) on preoperative, side-bending, postoperative, and follow-up radiographs and vertebral apical rotation (in accordance with Perdriolle and Vidal [25]) on preoperative images. In addition, the Lenke classification was used [9, 26]. Curve flexibilities (flex) and curve correction rates (corr) were calculated using the formulas: flex (%) = (preoperative coronal Cobb angle − side-bending Cobb angle)/preoperative coronal Cobb angle × 100% and corr (%) = (preoperative Cobb angle − postoperative Cobb angle)/preoperative Cobb angle × 100% [11, 20, 27].

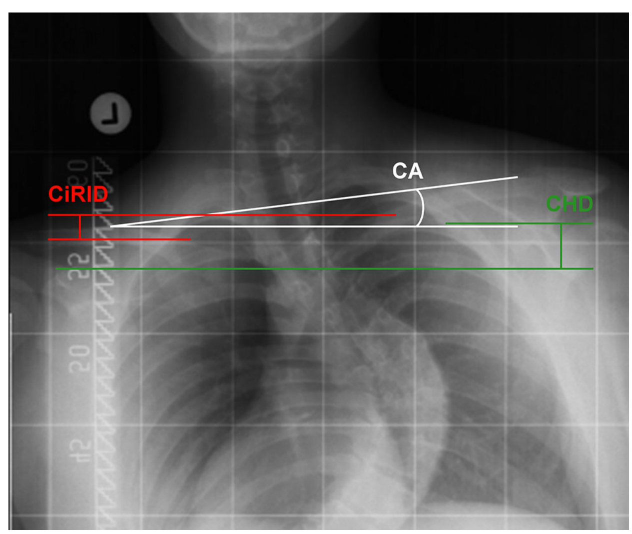

Fig. 1 Sample radiograph illustrating how the three outcome shoulder parameters (*CHD* coracoid height difference, *CA* clavicular angle, *CiRID* clavicle–first rib intersection difference) were obtained

Three measurements for shoulder level (Fig. 1) were chosen due to their good reliability [28] and ability to predict clinical shoulder imbalance [29]. Their reliability was also tested on a subset of patients (see below). The variables were assessed preoperatively and at follow-up. Coracoid height difference (CHD, in millimeters) was the distance between two horizontal lines touching the upper margins of the two coracoid processes [7, 19]. The clavicular angle (CA, in degrees) described the angle between a horizontal tangent at the highest point of the left clavicle and the line between the highest points of both the left and right clavicles [7, 8, 19, 30, 31]. The clavicle–first rib intersection difference (CiRID, in millimeters) was defined by the distance between two horizontal lines through the superior medial intersection point of the first rib with the clavicle on each side.

The T1 Tilt Angle (T1T, in degrees) was defined as the degree of inclination of the T1 cephalad end plate toward the horizontal line [16, 19, 30, 31].

In all of these shoulder parameters and in T1 tilt angle, a positive value represents elevation on the left side, whereas a negative value indicates that the left side is lowered.

To obtain the reliability of our measurements, a sample of 30 preoperative or follow-up radiographs was randomly chosen. Cobb angles, shoulder parameters and T1 Tilt Angles were remeasured independently by two of the authors. One of them had performed the initial measurements in all 102 patients more than 6 months before these second measurements.

The prospectively collected data were analyzed in an exploratory way using IBM SPSS Statistics for Windows, version 22 (IBM Corporation, Armonk, New York, USA). Intraclass correlation coefficients (ICC) were calculated to assess test–retest and inter-rater reliability. Potential factors influencing shoulder balance at follow-up were investigated and compared using correlation analyses, testing, and linear regression analysis. Spearman's rank-order correlation coefficients of potential predictive factors for postoperative shoulder balance were calculated in a two-tailed fashion. Statistical testing was carried out using the Mann–Whitney *U* test (for two independent samples, e.g., postoperative shoulder level in patients with structural vs. non-structural PTC), the Kruskal–Wallis test (for >2 independent samples, e.g., postoperative shoulder level in patients with different PTC rotations), the Wilcoxon signed rank test (for paired samples, e.g., preoperative vs. postoperative shoulder level) and the Chi^2 test (for cross tables, e.g., location of the upper instrumented vertebra vs. structurality of the proximal thoracic curve). To identify the most relevant among the significant factors, multiple regression analyses were performed with the target variable of shoulder level at follow-up (CHD, CA, CiRID). The threshold for including variables in the multiple linear regression analysis was $P = 0.05$, with stepwise model selection. *P* values <0.05 were considered statistically significant. Graphs were created using R (R Development Core Team, version 3.2.5, Vienna, Austria) and Matlab®, version 2015a (The MathWorks, Natick, Massachusetts, USA).

Results

$N = 102$ consecutive patients (86 females, 16 males) with a mean follow-up period of 14 months met the inclusion criteria and were available for the study. PSF was performed in 77 patients (with anterior release in six patients) while selective ASF was performed in 25 patients between June 2009 and February 2014. The mean age in the study group at the time of surgery was 15.8 years (range 11–26 years). Among the 102 individuals, 45 patients had Lenke type 1 curves, 14 had type 2, 12 had type 3, two had type 4, 17 had type 5, and 12 had type 6.

Table 1 shows that postoperative improvements were significant for proximal thoracic, distal thoracic and lumbar curves. Patients with a rigid PTC (Lenke types 2 and 4) had a significantly higher correction rate of the PTC than patients with a flexible PTC (Lenke types 1, 3, 5, 6). All left shoulder parameters at the follow-up examination were significantly higher than the corresponding preoperative levels (Table 2). Differentiating patients with a rigid PTC (Lenke types 2 and 4) from those with a flexible PTC (Lenke types 1, 3, 5, and 6) showed that both groups developed left shoulder elevation (Figs. 2, 3; Table 2)—bearing in mind that only those with Lenke type 2 and 4 curves underwent complete instrumentation of the PTC.

The test–retest reliability and inter-rater reliability of the Cobb angles, shoulder measurements and T1 tilt angle in a subsample proved excellent with intraclass correlation coefficients >0.90 (Table 3).

CHD, CA, and CiRID correlated significantly with each other, with coefficients ranging from 0.77 to 0.93. Their correlations with T1T were significant, but weaker ($r = 0.58$–0.61). Structural proximal thoracic curves were significantly associated with more proximal upper levels of instrumentation compared to non-structural proximal thoracic curves ($P < 0.0001$, Table 4).

In correlation analysis, preoperative shoulder parameters (CHD, CA, CiRID), preoperative Cobb angle of the PTC, absolute and relative correction of the PTC, preoperative Cobb angle of the LC, absolute correction of the LC and preoperative Cobb angle ratios (PTC:DTC, DTC:LC, PTC:LC) were significant univariable predictors of shoulder level at the follow-up examination (Table 5). Preoperative T1 Tilt angle and absolute correction of the DTC were significant univariable predictors for some shoulder parameters at the follow-up examination.

Table 1 Descriptive preoperative and postoperative statistics for the whole patient cohort and two subcategories (structural proximal thoracic curves or non-structural proximal thoracic curves) in relation to spinal curves

	Preoperative Cobb angle	Flexibility	Correction rate	Postoperative Cobb angle	Preoperative vs. postoperative	Follow-up Cobb angle
Proximal thoracic curve						
All	29° ± 15°	34 ± 25%	24 ± 48%	20° ± 10°	$P < 0.0001$	19° ± 11°
Structural PTC	45° ± 18°	21 ± 17%	42 ± 16%	27° ± 14°	$P < 0.0001$	29° ± 13°
Non-structural PTC	26° ± 12°	37 ± 26%	21 ± 51%	18° ± 8°	$P < 0.0001$	17° ± 9°
	$P < 0.0001$	$P = 0.039$	$P = 0.038$	$P = 0.018$		$P < 0.0001$
Distal thoracic curve						
All	56° ± 19°	35 ± 17%	58 ± 20%	23° ± 12°	$P < 0.0001$	25° ± 11°
Structural PTC	66° ± 17°	33 ± 16%	64 ± 16%	25° ± 14°	$P < 0.0001$	26° ± 13°
Non-structural PTC	54° ± 19°	36 ± 18%	57 ± 21%	22° ± 11°	$P < 0.0001$	25° ± 10°
	$P = 0.037$	$P = 0.655$	$P = 0.350$	$P = 0.437$		$P = 0.807$
Lumbar curve						
All	43° ± 13°	61 ± 21%	62 ± 18%	16° ± 8°	$P < 0.0001$	18° ± 9°
Structural PTC	34° ± 12°	60 ± 24%	63 ± 12%	14° ± 8°	$P = 0.001$	14° ± 9°
Non-structural PTC	44° ± 13°	62 ± 20%	62 ± 19%	16° ± 8°	$P < 0.0001$	19° ± 9°
	$P = 0.007$	$P = 0.789$	$P = 0.832$	$P = 0.290$		$P = 0.065$

PTC proximal thoracic curve

Moreover, having a structural proximal thoracic curve (including a higher proximal instrumentations level) was a significant univariable predictor of a higher left shoulder at the follow-up examination compared to patients with a non-structural PTC (Table 2). Apical rotation of the PTC of at least 10° (Perdriolle) was a significant univariable predictor of higher left shoulder levels (CHD, CiRID) at the follow-up examination ($P \leq 0.027$). The surgical approach used (PSF vs. ASF) did not predict postoperative elevation of the left shoulder ($P \geq 0.180$).

To identify the most relevant among the significant factors, multiple regression analyses were performed with the target variable of shoulder level at follow-up (CHD, CA, CiRID). The three regression equations are:

$$\mathrm{CHD}_{\text{follow-up}} = 0.498 \times \mathrm{CiRID}_{\text{preop.}} - 0.222 \times \text{LC Cobb angle}_{\text{preop.}} + 0.245 \times \Delta\,\mathrm{DTC} + 5.865$$

$$\mathrm{CA}_{\text{follow-up}} = 0.126 \times \mathrm{CiRID}_{\text{preop.}} - 0.054 \times \text{LC Cobb angle}_{\text{preop.}} + 0.053 \times \Delta\,\mathrm{DTC} + 1.609$$

$$\mathrm{CiRID}_{\text{follow-up}} = 0.318 \times \mathrm{CiRID}_{\text{preop.}} - 0.124 \times \text{LC Cobb angle}_{\text{preop.}} + 5.769 \times \mathrm{PTCstructural} + 8.450$$

where predictors: $\mathrm{CiRID}_{\text{preop.}}$: preoperative clavicle–first rib intersection difference, ΔDTC: absolute correction angle of distal thoracic curve, LC Cobb $\text{angle}_{\text{preop.}}$: preoperative lumbar curve Cobb angle, PTCstructural: proximal thoracic curve is structural.

The respective adjusted R^2 values were 0.343 for the model $\mathrm{CHD}_{\text{follow-up}}$, 0.264 for the model $\mathrm{CA}_{\text{follow-up}}$ and 0.429 for the model $\mathrm{CiRID}_{\text{follow-up}}$.

A higher preoperative left shoulder level (CiRID) and greater absolute correction of the DTC were predictive for left shoulder elevation at follow-up. By contrast, higher preoperative LC Cobb angles were associated with lower left shoulders at the follow-up examination. Patients with structural PTC were at particular risk of having left shoulder elevation at follow-up. A difference of 5 mm in preoperative CiRID had effects on the shoulder level at the follow-up examination that were similar to a difference of 10° in DTC correction; and to a preoperative LC Cobb angle differing by 10°. Altogether their effect on the predicted shoulder level at follow-up was less than the effect of the PTC being structural. The highest adjusted R^2 value was found for the CiRID model at follow-up, indicating that this model appeared to be the best. Figure 4 visualizes the relationships of the variables derived from the regression equations, focusing on CiRID and CHD at follow-up, as these two factors had the best adjusted R^2 values.

Discussion

Possible reasons for shoulder imbalance after surgical correction of AIS have previously been investigated by several research groups. Most importantly, the rigidity of

Table 2 Left shoulder level and T1 Tilt Angle statistics (mean ± SD) for all patients and two subcategories (structural proximal thoracic curves or non-structural proximal thoracic curves) before surgery and at the follow-up examination

	Preoperative	Follow-up	
CHD			
All	−9 ± 11 mm	3 ± 10 mm	$P < 0.0001$
Structural PTC	0 ± 11 mm	10 ± 8 mm	$P = 0.004$
Non-structural PTC	−10 ± 10 mm	2 ± 10 mm	$P < 0.0001$
	$P = 0.002$	$P = 0.005$	
CA			
All	−3° ± 3°	1° ± 3°	$P < 0.0001$
Structural PTC	−1° ± 2°	3° ± 2°	$P = 0.001$
Non-structural PTC	−3° ± 3°	0° ± 2°	$P < 0.0001$
	$P = 0.003$	$P = 0.001$	
CiRID			
All	−3 mm ± 7 mm	3 ± 6 mm	$P < 0.0001$
Structural PTC	−1 mm ± 6 mm	10 ± 7 mm	$P < 0.0001$
Non-structural PTC	−4 mm ± 6 mm	2 ± 5 mm	$P < 0.0001$
	$P = 0.007$	$P < 0.0001$	
T1T			
All	−2° ± 8°	2° ± 7°	$P < 0.0001$
Structural PTC	5° ± 10°	10° ± 6°	$P = 0.02$
Non-structural PTC	−3° ± 7°	1° ± 6°	$P < 0.0001$
	$P < 0.0001$	$P < 0.0001$	

CA clavicular angle, *CHD* coracoid height difference, *CiRID* clavicle–first rib intersection difference, *PTC* proximal thoracic curve, *T1T* T1 tilt angle

the proximal thoracic curve in AIS has been described as a key component involved in the postoperative shoulder level. The behavior of a rigid PTC and the need to instrument it were consequently analyzed in earlier reports. In double thoracic AIS, King et al. [10] proposed left shoulder or first rib elevation, relative rigidity of the PTC, and a positive T1T as indications for instrumentation of the PTC with a Harrington rod. The Lenke classification [9, 26] later recommended a PTC bending Cobb angle >25° and/or T2–T5 kyphosis >20° as indications for proximal fusion, with good results in other reports [32, 33].

For the present report, a heterogeneous cohort of 102 patients with all curve types after PSF or ASF was studied retrospectively using linear regression analysis. The types and levels of instrumentation were chosen in accordance with the current literature. As with Kuklo et al. [8, 18], it was not found that UIV or the type of surgery were associated with postoperative shoulder elevation.

The patients in the present study had elevations of the left shoulder level after surgery similar to the cases described by other authors [19, 33]. They included patients with structural PTC (Lenke 2, 4), as found by Li et al. [33]. However, there were no significant differences in shoulder elevation as a result of surgery between individuals with fused or unfused PTC ($P \geq 0.338$). The criteria for proximal instrumentation used here were therefore relatively valid.

The Cobb angles and shoulder levels among the patients in this study were within the range described for other cohorts in the literature [3, 8, 16, 18, 19, 31, 32]. A high upper level of instrumentation was chosen less frequently in the patients in the present study in comparison with Yagi et al. [15]. Test–retest reliability and inter-rater reliability of the Cobb angles and shoulder measurements were excellent in a subsample of 30 radiographs. It was therefore valid to use these parameters for further analysis.

Four independent predictive factors for shoulder level at the follow-up examination were identified using multiple linear regression, on the basis of significant correlations. First, the preoperative shoulder level appeared to be the most relevant factor contributing to the postoperative shoulder level. Earlier reports reported correlations with the postoperative shoulder height for preoperative shoulder height difference [15–17], clavicular angle [3, 8, 19, 30, 34], clavicle height difference [19], first rib angle [3], clavicle–rib intersection difference [19], and clavicle–chest cage angle difference (CCAD) [15]. Luhmann et al. [31] did not find any significant correlations between the preoperative clavicular angle and postoperative radiographic shoulder height. By contrast, the present findings support the view that the postoperative shoulder height is influenced by the preoperative shoulder level. The reliable variables CHD, CA and CiRID were investigated. Linear regression analysis showed that CiRID was the best out of these three predictors of shoulder level at the follow-up examination. Hong et al. [19] found that CHD and CA predicted postoperative shoulder imbalance aggravation equally well, but they did not quantify aggravation in their analysis. As the correlations between preoperative T1T and shoulder level at follow-up were weak, we would agree with previous reports that rejected preoperative T1T as a predictive factor for the postoperative shoulder level [14, 30, 31]. The association between preoperative T1T and postoperative shoulder elevation described earlier [3, 19] is probably of less practical relevance in comparison with other shoulder parameters.

The second major variable for predicting postoperative shoulder level in this study was the amount of Cobb angle correction of the DTC. Shoulder elevation has previously been reported to be associated with strong correction of the DTC [3, 11, 12, 15, 16, 19, 21, 33, 34]. Although this

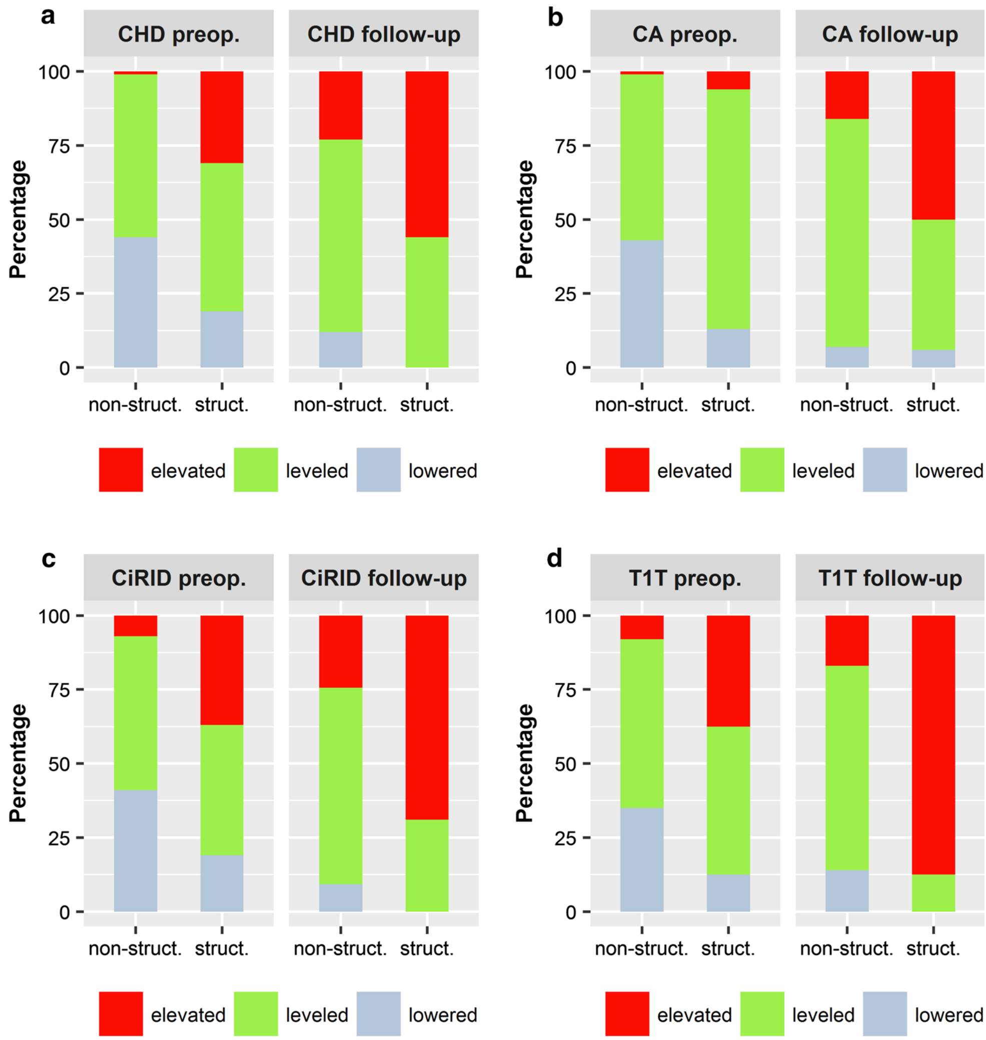

Fig. 2 Numbers of patients with elevated/leveled/lowered left shoulders or T1 Tilt before surgery and at the follow-up examination, showing the differences between Lenke 1, 3, 5, 6 curves (non-structural proximal thoracic curve) and Lenke 2, 4 curves (structural proximal thoracic curve). For this diagram, leveled shoulders were defined as **a** -10 mm $\leq$ coracoid height difference (CHD) $\leq$ 10 mm; or **b** $-3°\leq$ clavicular angle (CA) $\leq 3°$; or **c** -5 mm $\leq$ clavicle–first rib intersection difference (CiRID) $\leq$ 5 mm; or **d** $-5° \leq$ T1 tilt angle (T1T) $\leq 5°$ [3, 14, 16, 28, 29, 33]

parameter cannot be measured before surgery to perform a risk assessment, it still is highly relevant and needs to be considered in patients undergoing scoliosis surgery as soon as the operative treatment is planned. This variable had a major relevance both in univariable analysis and in multiple regression. Relative overcorrection of a right thoracic DTC can lead to postoperative left shoulder elevation and this problem became more common after the establishment of segmental instrumentations that allow stronger correction [3, 12, 16]. This factor does not appear in the regression equation for CiRID, but it is still an essential component of postoperative shoulder imbalance, as it may aggravate shoulder elevation during surgery in several different curve types [35]. As a practical consequence, we would suggest limiting the amount of Cobb angle correction of the DTC by performing only slight concave distraction and instead focusing on derotation of the DTC.

Third, a relationship was found between a larger preoperative LC Cobb angle and less shoulder elevation at the follow-up examination. This correlation was present in the overall analysis of all Lenke types, but also in a subgroup analysis for Lenke 1 and 2 curves (non-structural lumbar curves; $r \leq -0.300$, $P \leq 0.021$). This supports the findings of previous reports [19–21] hypothesizing a compensatory function of unfused lumbar curves reducing shoulder elevation that occurs due to thoracic instrumentation. In contrast to these findings, Cao et al. [11] in a report on Lenke 2 curves did not describe any significant differences in preoperative LC Cobb angles in a comparison of patients with shoulder balance vs. imbalance at follow-up.

In addition to the potentially protective effect of mild lumbar curves in relation to postoperative shoulder elevation, structural lumbar curves of course require instrumentation for purposes of trunk balancing, which can also influence shoulder balance [36].

The fourth major predictive factor for postoperative shoulder level identified in the regression analysis was whether the PTC is structural in accordance with Lenke's criteria [9, 26]. As noted before, a structural PTC is a risk factor for developing shoulder elevation after surgery

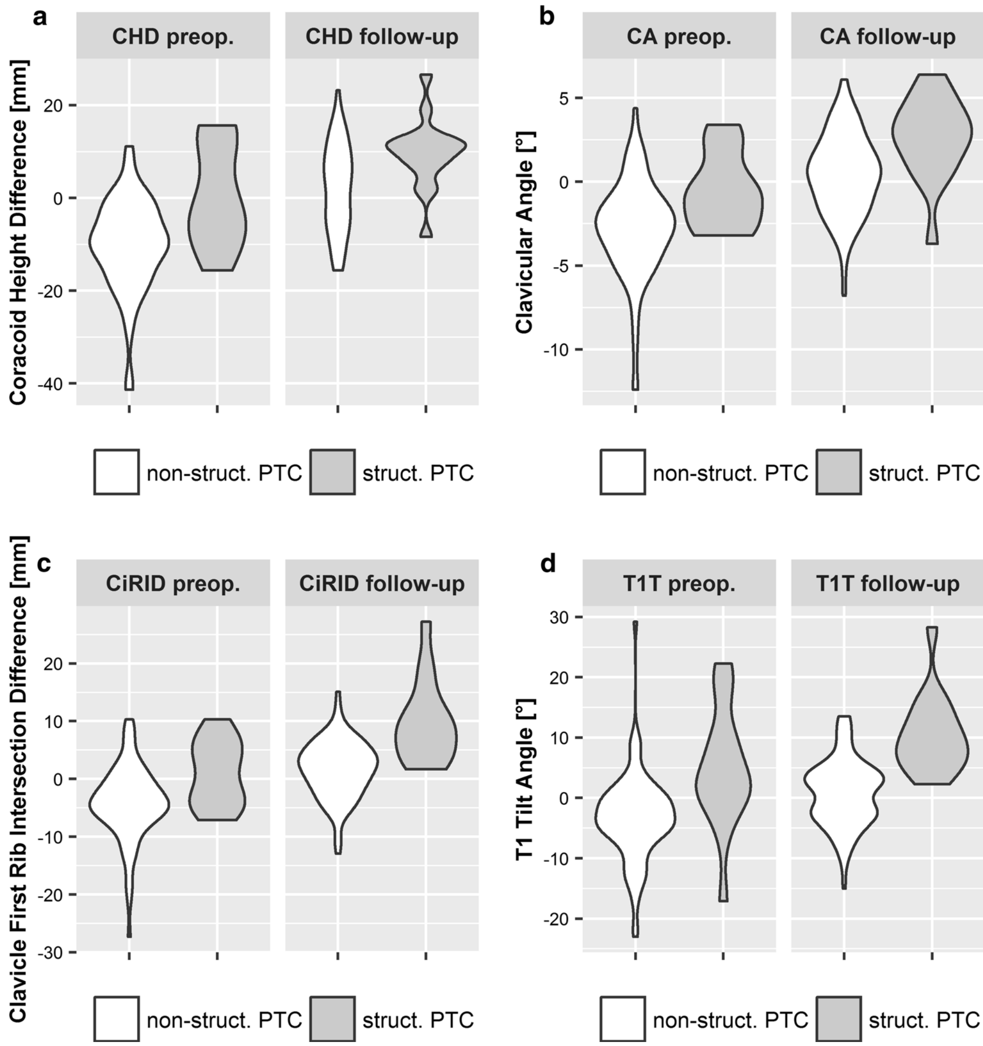

Fig. 3 Shoulder asymmetry according to **a** coracoid height difference (CHD), **b** clavicular angle (CA), **c** clavicle–first rib intersection difference (CiRID), and **d** T1 tilt angle (T1T) before surgery and at follow-up. The *width* of each plot represents the percentage of patients with the corresponding shoulder height

Table 3 Intraclass correlation coefficients (ICC) and their 95% confidence intervals (95% CI) comparing initial and repeated measurements of shoulder parameters, T1 tilt angles and Cobb angles on 30 randomly selected radiographs

	Test–retest reliability		Inter-rater reliability	
	ICC	95% CI	ICC	95% CI
CHD	0.996	0.991, 0.998	0.991	0.982, 0.996
CA	0.995	0.989, 0.998	0.941	0.877, 0.972
CiRID	0.958	0.912, 0.980	0.951	0.898, 0.977
T1T	0.982	0.963, 0.992	0.983	0.964, 0.992
PTC	0.990	0.978, 0.995	0.974	0.945, 0.988
DTC	0.995	0.990, 0.998	0.986	0.972, 0.994
LC	0.986	0.971, 0.993	0.980	0.958, 0.990

CA clavicular angle, *CHD* coracoid height difference, *CiRID* clavicle–first rib intersection difference, *DTC* distal thoracic curve, *LC* lumbar curve, *PTC* proximal thoracic curve, *T1T* T1 tilt angle

[8, 13, 16, 22, 33]. This factor played a role in predicting CiRID at follow-up, but an influence on CHD and CA at follow-up was only evident in the univariable analysis. The upper level of instrumentation needs to be selected with consideration of the fact that patients with Lenke 2 and 4 curves are at particular risk of having an imbalanced shoulder level—i.e., left shoulder elevation. The flexibility of the PTC and shoulder level at the follow-up examinations did not correlate significantly in the present report, or in the case series described by Smyrnis et al. [3]. Also, the preoperative PTC Cobb angle did not predict postoperative shoulder level in the multiple regression models presented here. It showed relatively high univariable correlations with all shoulder parameters at the follow-up examination nonetheless. So its relevance as a predictor of postoperative shoulder level remains unclear and should be evaluated in further multivariable analyses that consider the individual Lenke types.

Regression models were used in earlier studies to find preoperative predictors for postoperative shoulder level [3, 15–18, 21]. However, a consistent threshold value for defining imbalanced shoulders is lacking in the literature [3, 7, 11, 16, 29, 30, 37]. Since all binary models

Table 4 Upper instrumented vertebrae in patients with non-structural proximal thoracic curves (i.e., Lenke 1, 3, 5, 6 curves) vs. structural proximal thoracic curves (i.e., Lenke 2, 4 curves)

UIV location	No. of patients with non-structural PTC	No. of patients with structural PTC
Apical vertebra of PTC or higher	4	9
Between apical vertebra and lower end vertebra of PTC	26	5
Below lower end vertebra of PTC	56	2

PTC proximal thoracic curve, *UIV* upper instrumented vertebra

Table 5 Correlation coefficients for shoulder parameters at the follow-up examination and potential predictive factors for them in univariable analysis

	CHD at follow-up	CA at follow-up	CiRID at follow-up
CHD preop. (mm)	0.349*	0.339*	0.321*
CA preop. (°)	0.278*	0.321*	0.364*
CiRID preop. (mm)	0.296*	0.307*	0.469*
T1T preop. (°)	0.238*	0.194	0.343*
PTC preop. (°)	0.379*	0.332*	0.341*
PTC flexibility (%)	−0.076	−0.089	−0.202
PTC correction (%)	0.279*	0.217*	0.244*
PTC difference (°)	0.384*	0.320*	0.342*
DTC preop. (°)	0.170	0.186	0.039
DTC flexibility (%)	−0.016	−0.030	0.038
DTC correction (%)	0.165	0.148	0.162
DTC difference (°)	0.236*	0.230*	0.141
LC preop. (°)	−0.351*	−0.329*	−0.387*
LC flexibility (%)	0.030	0.040	0.077
LC correction (%)	−0.053	−0.018	−0.073
LC difference (°)	−0.281*	−0.249*	−0.323*
PTC:DTC ratio of Cobb angle	0.272*	0.207*	0.307*
DTC:LC ratio of Cobb angle	0.378*	0.335*	0.348*
PTC:LC ratio of Cobb angle	0.394*	0.320*	0.375*

Correction, relative correction; difference, absolute correction angle; flexibility, relative flexibility

CA clavicular angle, *CHD* coracoid height difference, *CiRID* clavicle–first rib intersection difference, *DTC* distal thoracic curve, *LC* lumbar curve, *preop.* preoperative, *PTC* proximal thoracic curve, *T1T* T1 tilt angle

* Indicates significant correlations at the 5% level

[15, 17, 21] need to define such a threshold, the present study used nominal data to build a linear prediction model, without a need to define a threshold for imbalanced shoulders. As a consequence, the results make it possible to quantify the extent to which each of the four parameters in the multivariable analysis contributed to postoperative shoulder level changes. The effects of a difference of 5 mm in preoperative CiRID, a difference of 10° in DTC correction and a difference of 10° in preoperative LC Cobb angle on the shoulder level at the follow-up examination were similar according to the models. A structural PTC even had a higher relevance than these factors. Smyrnis et al. [3] also built a linear model to estimate the postoperative shoulder level, but they only analyzed the influence of six preoperative variables, in a smaller cohort of 56 patients. Since the preoperative shoulder level has been found to predict postoperative shoulder balance in most multivariable models in the literature [3, 15, 17, 21], including our own models, it appears to be a highly relevant factor.

This study has several limitations. Only a few patients with structural PTC (especially Lenke 4 curves) were included. It is therefore difficult to make reliable prognostic statements for this specific subgroup. Moreover, global coronal parameters such as trunk balance and sagittal parameters that might influence shoulder level were not taken into account. Patient-reported outcomes and clinical shoulder parameters were not assessed, although the best radiographic results do not always correlate with patient perception or clinical findings [7, 37, 38]. In

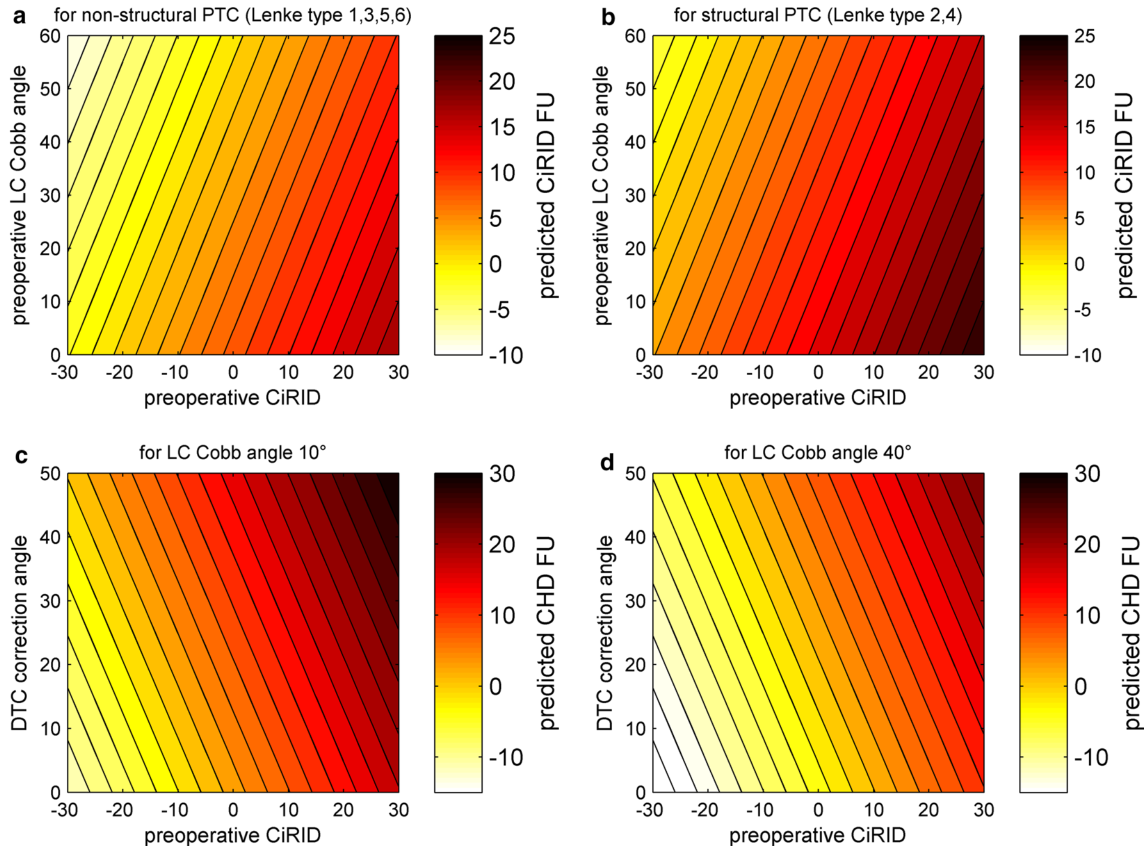

Fig. 4 Linear regression models predicting clavicle–first rib intersection difference (CiRID, **a**, **b**) at follow-up or coracoid height difference (CHD, **c**, **d**) at follow-up. These outcome criteria are shown relative to the *color scale* at the right of each figure. To determine the predicted shoulder level at follow-up, the figure that fits the patient's curve type needs to be picked (i.e., PTC structural vs. PTC non-structural or LC Cobb angle approx. 10° or approx. 40°). In the heat map, an individual patient's values for the continuous influencing factors are chosen (i.e., preoperative CiRID on the abscissa and preoperative lumbar curve Cobb angle or absolute distal thoracic curve correction angle on the ordinate). The *color* of the field where two perpendiculars from the patient's values intersect refers to the predicted shoulder height (s. *color scale*)

addition, the regression models have not been tested with a separate set of patients. Future research on this topic should also focus on specific curve types and use multivariable approaches to allow more detailed predictions on the individual patient level.

Conclusions

- Preoperative shoulder level, the amount of Cobb angle correction of the distal thoracic curve, the preoperative Cobb angle of the lumbar curve, and the structurality of the proximal thoracic curve are relevant determinants of shoulder elevation after surgery.
- In the study cohort, the effect of preoperative shoulder level on shoulder height at the follow-up examination was approximately twice as high as distal thoracic Cobb angle correction or the preoperative Cobb angle of the lumbar curve.
- Patients with rigid proximal thoracic curves (Lenke 2 and 4) are at particular risk of postoperative shoulder elevation even with proximal thoracic instrumentation.
- The preoperative clavicle–first rib intersection difference was a better predictor of the postoperative shoulder level than the preoperative coracoid height difference or the preoperative clavicular angle in a multiple regression model.

Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

References

1. Haher TR, Merola A, Zipnick RI, Gorup J, Mannor D, Orchowski J (1995) Meta-analysis of surgical outcome in adolescent idiopathic scoliosis. A 35-year English literature review of 11,000 patients. Spine (Phila Pa 1976) 20(14):1575–1584

2. Danielsson AJ, Wiklund I, Pehrsson K, Nachemson AL (2001) Health-related quality of life in patients with adolescent idiopathic scoliosis: a matched follow-up at least 20 years after treatment with brace or surgery. Eur Spine J 10(4):278–288
3. Smyrnis PN, Sekouris N, Papadopoulos G (2009) Surgical assessment of the proximal thoracic curve in adolescent idiopathic scoliosis. Eur Spine J 18(4):522–530. doi:10.1007/s00586-009-0902-3
4. Iwahara T, Imai M, Atsuta Y (1998) Quantification of cosmesis for patients affected by adolescent idiopathic scoliosis. Eur Spine J 7(1):12–15
5. Smith PL, Donaldson S, Hedden D, Alman B, Howard A, Stephens D, Wright JG (2006) Parents' and patients' perceptions of postoperative appearance in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 31(20):2367–2374. doi:10.1097/01.brs.0000240204.98960.dd
6. Sanders JO, Polly DW Jr, Cats-Baril W, Jones J, Lenke LG, O'Brien MF, Stephens Richards B, Sucato DJ, AIS Section of the Spinal Deformity Study Group (2003) Analysis of patient and parent assessment of deformity in idiopathic scoliosis using the Walter Reed Visual Assessment Scale. Spine (Phila Pa 1976) 28(18):2158–2163. doi:10.1097/01.BRS.0000084629.97042.0B
7. Qiu X, Ma W, Li W, Wang B, Yu Y, Zhu Z, Qian B, Zhu F, Sun X, Ng BK (2009) Discrepancy between radiographic shoulder balance and cosmetic shoulder balance in adolescent idiopathic scoliosis patients with double thoracic curve. Eur Spine J 18(1):45–51
8. Kuklo TR, Lenke LG, Graham EJ, Won DS, Sweet FA, Blanke KM, Bridwell KH (2002) Correlation of radiographic, clinical, and patient assessment of shoulder balance following fusion versus nonfusion of the proximal thoracic curve in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 27(18):2013–2020
9. Lenke LG, Betz RR, Haher TR, Lapp MA, Merola AA, Harms J, Shufflebarger HL (2001) Multisurgeon assessment of surgical decision-making in adolescent idiopathic scoliosis: curve classification, operative approach, and fusion levels. Spine (Phila Pa 1976) 26(21):2347–2353
10. King HA, Moe JH, Bradford DS, Winter RB (1983) The selection of fusion levels in thoracic idiopathic scoliosis. J Bone Jt Surg Am 65(9):1302–1313
11. Cao K, Watanabe K, Hosogane N, Toyama Y, Yonezawa I, Machida M, Yagi M, Kaneko S, Kawakami N, Tsuji T, Matsumoto M (2014) Association of postoperative shoulder balance with adding-on in Lenke Type II adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 39(12):E705–E712. doi:10.1097/BRS.0000000000000325
12. Chang DG, Kim JH, Kim SS, Lim DJ, Ha KY, Suk SI (2014) How to improve shoulder balance in the surgical correction of double thoracic adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 39(23):E1359–E1367. doi:10.1097/BRS.0000000000000578
13. Lenke LG, Bridwell KH, O'Brien MF, Baldus C, Blanke K (1994) Recognition and treatment of the proximal thoracic curve in adolescent idiopathic scoliosis treated with Cotrel-Dubousset instrumentation. Spine (Phila Pa 1976) 19(14):1589–1597
14. Lee CK, Denis F, Winter RB, Lonstein JE (1993) Analysis of the upper thoracic curve in surgically treated idiopathic scoliosis. A new concept of the double thoracic curve pattern. Spine (Phila Pa 1976) 18(12):1599–1608
15. Yagi M, Takemitsu M, Machida M (2013) Chest cage angle difference and rotation of main thoracic curve are independent risk factors of postoperative shoulder imbalance in surgically treated patients with adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 38(19):E1209–E1215. doi:10.1097/BRS.0b013e31829e0309
16. Suk SI, Kim WJ, Lee CS, Lee SM, Kim JH, Chung ER, Lee JH (2000) Indications of proximal thoracic curve fusion in thoracic adolescent idiopathic scoliosis: recognition and treatment of double thoracic curve pattern in adolescent idiopathic scoliosis treated with segmental instrumentation. Spine (Phila Pa 1976) 25(18):2342–2349
17. Zang L, Fan N, Hai Y, Lu SB, Su QJ, Yang JC, Guan L, Kang N, Meng XL, Liu YZ (2016) Evaluation of the predictors of postoperative aggravation of shoulder imbalance in severe and rigid thoracic or thoracolumbar scoliosis. Eur Spine J 25(10):3353–3365
18. Kuklo TR, Lenke LG, Won DS, Graham EJ, Sweet FA, Betz RR, Bridwell KH, Blanke KM (2001) Spontaneous proximal thoracic curve correction after isolated fusion of the main thoracic curve in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 26(18):1966–1975
19. Hong J, Suh S, Modi HN, Yang J, Park S (2013) Analysis of factors that affect shoulder balance after correction surgery in scoliosis: a global analysis of all the curvature types. Eur Spine J 22(6):1273–1285
20. Lee CS, Chung SS, Shin SK, Park YS, Park SJ, Kang KC (2011) Changes of upper thoracic curve and shoulder balance in thoracic adolescent idiopathic scoliosis treated by anterior selective thoracic fusion using VATS. J Spinal Disord Tech 24(7):462–468. doi:10.1097/BSD.0b013e318204d553
21. Koller H, Meier O, McClung A, Hitzl W, Mayer M, Sucato D (2015) Parameters leading to a successful radiographic outcome following surgical treatment for Lenke 2 curves. Eur Spine J 24(7):1490–1501. doi:10.1007/s00586-015-3772-x
22. Elfiky TA, Samartzis D, Cheung WY, Wong YW, Luk KD, Cheung KM (2011) The proximal thoracic curve in adolescent idiopathic scoliosis: surgical strategy and management outcomes. Global Spine J 1(1):27–36. doi:10.1055/s-0031-1296054
23. Yong MR, Izatt MT, Adam CJ, Labrom RD, Askin GN (2012) Secondary curve behavior in Lenke type 1C adolescent idiopathic scoliosis after thoracoscopic selective anterior thoracic fusion. Spine (Phila Pa 1976) 37(23):1965–1974. doi:10.1097/BRS.0b013e3182583421
24. Newton PO, O'Brien MF, Shufflebarger HL, Betz RR, Dickson RA, Harms J (2010) Idiopathic scoliosis. The harms study group treatment guide. Thieme, New York
25. Perdriolle R, Vidal J (1985) Thoracic idiopathic scoliosis curve evolution and prognosis. Spine (Phila Pa 1976) 10(9):785–791
26. Lenke LG, Betz RR, Harms J, Bridwell KH, Clements DH, Lowe TG, Blanke K (2001) Adolescent idiopathic scoliosis: a new classification to determine extent of spinal arthrodesis. J Bone Jt Surg Am 83-A(8):1169–1181
27. Elsebaie HB, Dannawi Z, Altaf F, Zaidan A, Al Mukhtar M, Shaw MJ, Gibson A, Noordeen H (2016) Clinically orientated classification incorporating shoulder balance for the surgical treatment of adolescent idiopathic scoliosis. Eur Spine J 25(2):430–437
28. Hong JY, Suh SW, Yang JH, Park SY, Han JH (2013) Reliability analysis of shoulder balance measures: comparison of the four available methods. Spine (Phila Pa 1976) 38(26):E1684–E1690
29. Akel I, Pekmezci M, Hayran M, Genc Y, Kocak O, Derman O, Erdogan I, Yazici M (2008) Evaluation of shoulder balance in the normal adolescent population and its correlation with radiological parameters. Eur Spine J 17(3):348–354. doi:10.1007/s00586-007-0546-0
30. Ilharreborde B, Even J, Lefevre Y, Fitoussi F, Presedo A, Souchet P, Pennecot GF, Mazda K (2008) How to determine the upper level of instrumentation in Lenke types 1 and 2 adolescent idiopathic scoliosis: a prospective study of 132 patients. J Pediatr Orthop 28(7):733–739. doi:10.1097/BPO.0b013e318185a36b
31. Luhmann SJ, Sucato DJ, Johnston CE, Richards BS, Karol LA (2016) Radiographic assessment of shoulder position in 619 idiopathic scoliosis patients: can T1 tilt be used as an

intraoperative proxy to determine postoperative shoulder balance? J Pediatr Orthop 36(7):691–694
32. Cil A, Pekmezci M, Yazici M, Alanay A, Acaroglu RE, Deviren V, Surat A (2005) The validity of Lenke criteria for defining structural proximal thoracic curves in patients with adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 30(22):2550–2555
33. Li M, Gu S, Ni J, Fang X, Zhu X, Zhang Z (2009) Shoulder balance after surgery in patients with Lenke Type 2 scoliosis corrected with the segmental pedicle screw technique. J Neurosurg Spine 10(3):214–219
34. Matsumoto M, Watanabe K, Kawakami N, Tsuji T, Uno K, Suzuki T, Ito M, Yanagida H, Minami S, Akazawa T (2014) Postoperative shoulder imbalance in Lenke Type 1A adolescent idiopathic scoliosis and related factors. BMC Musculoskelet Disord. doi:10.1186/1471-2474-15-366
35. Kwan MK, Chan CY (2016) Is there an optimal upper instrumented vertebra (UIV) tilt angle to prevent post-operative shoulder imbalance and neck tilt in Lenke 1 and 2 adolescent idiopathic scoliosis (AIS) patients? Eur Spine J. doi:10.1007/s00586-016-4529-x
36. Trobisch PD, Samdani AF, Pahys JM, Cahill PJ (2011) Postoperative trunk shift in Lenke 1 and 2 curves: how common is it? and analysis of risk factors. Eur Spine J 20(7):1137–1140. doi:10.1007/s00586-011-1820-8
37. Matamalas A, Bagó J, D'Agata E, Pellisé F (2015) Does patient perception of shoulder balance correlate with clinical balance? Eur Spine J 25(11):3560–3567
38. Yang S, Feuchtbaum E, Werner BC, Cho W, Reddi V, Arlet V (2012) Does anterior shoulder balance in adolescent idiopathic scoliosis correlate with posterior shoulder balance clinically and radiographically? Eur Spine J 21(10):1978–1983. doi:10.1007/s00586-012-2434-5