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ORIGINAL ARTICLE

Accurate prediction of spontaneous lumbar curve correction following posterior selective thoracic fusion in adolescent idiopathic scoliosis using logistic regression models and clinical rationale

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Abstract

Introduction Accurate prediction of spontaneous lumbar curve correction (SLCC) after selective thoracic fusion (STF) remains difficult. This study sought to improve prediction accuracy of SLCC. The hypothesis was preoperative and intraoperative variables could predict SLCC < 20°.

Methods A multicenter observational prospective analysis was conducted to determine predictors of SLCC in AIS patients that had posterior STF. Curve types included major thoracic curves (Lenke 1, 3–4).The primary outcome variable was to establish prediction models, and a postoperative lumbar curve (LC) ≤ 20° was defined as the target variable. Multivariate logistic regression models were established to study the relationship between selected variables and a LC ≤ 20° versus a LC > 20° at ≥ 2-year follow-up. Single and dual thresholds models in perspective of clinical rationales were applied to find models with the highest positive/negative predictive values (PPV/NPV). The secondary outcome measure was SRS scores at ≥ 2-year follow-up.

Results 410 patients were included. At ≥ 2-year follow-up 282 patients had LC ≤ 20°. These patients had better SRS-22 scores than those with LC > 20° ($P = 0.02$). The postoperative LC and LC ≤ 20° were predicted by preoperative LC and LC-bending Cobb angle ($P < 0.01$, $r = 0.4$–0.6). Logistic regression models could be established to identify patients at risk for failing the target LC ≤ 20°.For preoperative LC and LC-bending, the prediction model achieved a NPV/PPV of 80%/72%. If the postoperative main thoracic curve is combined with the preoperative LC and a gray area for difficult decisions was allowed, model accuracy could even be improved (NPV/PPV = 96%/81%).

Conclusion An accurate prediction model for postoperative SLCC was established based on a large analysis of prospective STF cases. These models can support prediction and understanding of postoperative SLCC aiding in surgical decision making when contemplating a selective thoracic fusion.

W. Hitzl shared first authorship.

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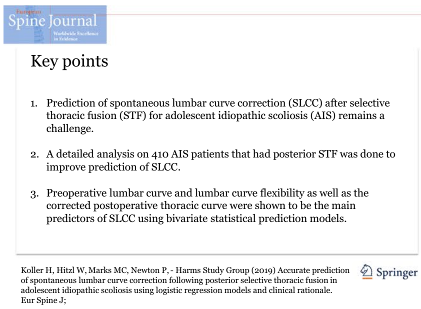
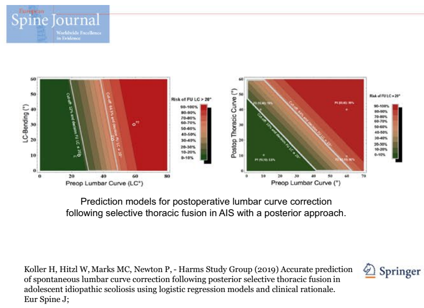
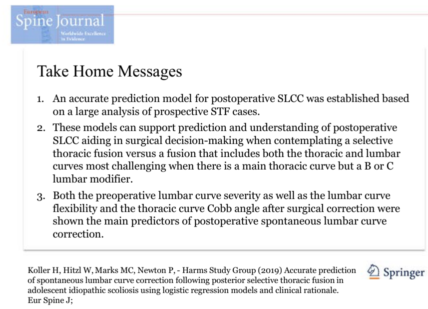
Extended author information available on the last page of the article

Graphical abstract

These slides can be retrieved under Electronic Supplementary Material.







Keywords Selective thoracic fusion · Scoliosis · Surgery · Lumbar curve · Prediction

Introduction

A right-sided major thoracic curve in a patient with adolescent idiopathic scoliosis (AIS) is the most common curve pattern requiring surgical treatment. Ideally, a fusion is as short as possible while achieving the underlying goal of preventing scoliosis progression while maintaining global balance. When a "minor" lumbar curve also exists, there is often debate about whether this curve also requires fusion. It has been known since the recommendations of Moe that an isolated fusion of the thoracic curve (e.g., selective thoracic fusion) may lead to acceptable overall correction. The goals of a selective thoracic fusion (STF) for the "false double major" curve are to halt curve progression, restore balance, correct major trunk deformity and create spontaneous lumbar curve correction (SLCC) while fusing the lowest number of segments [1–4]. The merits of STF have been confirmed both clinically and biomechanically. With a more distal lowest instrumented vertebra (LIV) in the lumbar spine, there are increased disk pressure and segmental motion in the adjacent level, while overall lumbar motion is reduced and the risk for disk degeneration is elevated [5–16]. Long-term studies have shown that with a mild to moderate residual lumbar curve (LC), immediate postoperative SLCC is well achieved after STF [1, 2, 17–21]. The coronal balance parameters largely stabilize by three-month postoperative [22], and significant changes are less predictable thereafter [17, 18, 22].

The definition of a postoperative ideal target LC magnitude in STF is still lacking. Some studies have advocated radiographic risk factors for degeneration adjacent to the fusion, which are related to the magnitude of the residual LC. These factors include the level of LIV [23], a L4 takeoff (TO) > 7° [23] and LIV-TO > 10° [23]. Based on the analysis of patient-specific radiographic results by several surgeons in a study of Schulz et al. [24], the authors could define ideal surgical outcomes as a LC < 26° as well as a LC-correction > 37%, deformity-flexibility quotient < 4, a central sacral vertical line deviation (CSVL) ≤ 2 cm, and a trunk shift of < 1.5 cm. Patients with these "ideal" radiographic parameters had less pain and were more satisfied. Based on unsatisfying radiographic outcomes with clinical relevance in some patients, other authors have defined suitable targets as LC ≤ 20° [25], LC < 25° [26], LC < 35° [19], LIV-TO < 5° [27], and LIV-TO < 10° [23, 28]. In a study of 273 patients that had STF using an anterior technique, Koller et al. [25] showed that patients with a postoperative LC ≤ 20° were more likely to sustain an "excellent" outcome in patients with a LC > 20°.

Given that surgeons may not absolutely agree on a postoperative target LC following STF, the question remains regarding accurate prediction of SLCC. This remains difficult and fusing too much or too little of the spine especially if a large residual deformity remains may have long-lasting effects [29].

Currently, the posterior approach is the most common approach used for STF. Therefore, the objectives of our study were to improve the prediction of SLCC following STF using a posterior technique. Based on a target SLCC, the aim of this study was to test several logistic regression models to identify parameters best predicting the target SLCC with a secondary aim to provide surgeons with an additional tool to improve planning of AIS surgery.

Materials and methods

Through a multicenter, prospective database study including AIS patients undergoing surgery in the years 2003 to 2011, AIS patients with a major thoracic curve (MTC) that had posterior STF were included in this analysis. Minimum postoperative follow-up (FU) was 2 years. Patients selected had no revision surgery. The characterization of scoliosis curve pattern was done using the

Lenke classification. Only types 1, 3, and 4 were included. Patients with a type A lumbar modifier were subclassified into patients with type A-L and type A-R [30]. Only curve types suitable for STF, e.g., type A-L, B, or C lumbar compensatory curve, were included in the analysis. Type 1 A-R was excluded. All patients were treated with a posterior approach with modern screw-rod constructs. Patients had either all-pedicle screw constructs or a screw-rod construct that had ≥ 80% pedicle screw usage. Preoperative, postoperative, and 2-year follow-up radiographs were centrally measured for standard radiographic scoliosis parameters. The thoracic kyphosis was measured from the upper end plate of T2 to the lower end plate of T12. Curve flexibility (%/°) and MTC and LC-correction were calculated (%/°). The scoliosis correction index (SCI) for the MTC was calculated comparing the postoperative MTC-correction (%) divided by the preoperative MTC-flexibility (%) [25]. A SCI of 1 indicates that surgical MTC-correction equals the bending film correction of the MTC. On the postoperative coronal radiographs, the upper and lower instrumented vertebrae (UIV and LIV) were determined.

To assess clinical outcomes, the SRS-22 scores were evaluated. Self-image and satisfaction domains as well as the SRS-22 total score were utilized in the analysis.

The previous studies indicated that LC ≤ 26° best meets the expectations of a target Cobb angle [24]. In addition, a previous study showed that using LC ≤ 20° as target variable generated statistically sound prediction models for SLCC by STF using an anterior approach [25]. In the preceding study, a stepwise regression analysis includes coronal and sagittal plane radiographic variables to best predicting a target LC ≤ 20° at follow-up. With high accuracy, the predictive information was provided by preoperative LC and LC-bending as well as postoperative MTC. Hence, in the current study on 410 patients with a posterior approach for STF, a postoperative LC ≤ 20° was defined as target variable to establish the prediction models.

We analyzed whether patients with LC > 20° at follow-up and patients with ≥ 80% pedicle screw constructs had different clinical and radiographic outcomes for continuous and discrete variables if compared to patients with a postoperative LC ≤ 20°.

Statistical analysis

Data were carefully checked for outliers by using normal probability plots. Cross-tabulation tables together with Fisher's exact test or Pearson's Chi-square test were computed. 95% confidence intervals (CI) for means and differences of means were computed, and LSD tests were used as post hoc tests. Correlation analyses were done to examine the relationships of clinically relevant radiographic parameters that were used in the decision making process for STF (e.g., postoperative MTC, preoperative LC and MTC, and LC-bending). Univariate and multivariate linear regression models were used to analyze the relation between predictor variables (e.g., preoperative LC or LC-bending) and output variables (e.g., follow-up LC).

Stepwise multivariate linear and logistic regression analyses were conducted to study the relation among selected variables and a LC > 20° at 2-year follow-up. In a first step, only one cutoff was used in the logistic regression model. Although this model already yielded clinically useful information, the authors attempted to further optimize the model by using a gray area (area of no decision) in a second step and hence to increase the model's accuracy. For this goal, the surgeon together with the statistician defined clinically mindful conditions in terms of clinical equipoise and used two cutoffs in order to define a gray area. The clinical rationales were: given the model predicts a positive result (i.e., FU LC > 20°), we allowed it to wrongly predict in less than 20%. This corresponds to a positive predictive value (PPV) ≥ 80%. Given the model predicts a negative result (i.e., FU LC ≤ 20°), we allowed a wrong prediction (i.e., LC > 20°) in less than 10%, i.e., a negative predictive value (NPV) ≥ 90%. Given a patient effectively shows a negative result at the FU, the model is allowed to make a wrong prediction in ≤ 10%. This corresponds to a specificity ≥ 90%. Given that a patient actually shows a positive result at follow-up, the model is allowed to make a wrong prediction in ≤ 10%, i.e., a sensitivity ≥ 90%. Finally, the model should make a decision in at least more than one-third of patients.

All reported tests were two-sided, and P values < 0.05 were considered as statistically significant. Data are reported as mean and ± 1 standard deviation (SD). Statistical analyses were performed with NCSS (NCSS 10, Kaysville, UT), Mathematica 11.1 (Wolfram Research, Champaign, IL), STATISTICA 13 (StatSoft, Tulsa, OK), and PASW 22 (IBM, SPSS Statistics for Windows, Armonk, NY).

Results

Sample characteristics

410 AIS patients with posterior STF met the inclusion criteria for this evaluation. The sample included 115 male (28%) and 295 female patients (72%). Mean age was 15 ± 2.5 years (10–21 years). Patients had Risser sign 3 ± 1.6 (Risser 0–5). 336 patients (82%) had Risser ≥ 2.

The LIV was at or above L1 in all patients with T9 being the most proximal LIV. The LIV was T9 in one patient (0.2%), T10 in five patients (1.2%), T11 in 47 patients (11.5%), T12 in 155 patients (37.8%), and L1 in

Table 1 Comparison of clinical and radiographic outcome differences between patients with all-pedicle screw constructs and patients with ≥ 80% screw density

Parameter	Pedicle screw density		*P* value
	≥ 80% screw density* (mean ± 1SD)	100% screw density (mean ± 1SD)	
2 yrs F/U: SRS22-Self-Image	4.4 ± 0.6	4.5 ± 0.5	ns
2 yrs F/U: SRS 22-Satisfaction	4.6 ± 0.7	4.6 ± 0.6	ns
2 yrs F/U: SRS 22-Total	4.4 ± 0.5	4.5 ± 0.4	ns
Patient age at surgery	14.7 ± 2.2	14.5 ± 2.1	ns
Risser (1–5)	3.2 ± 1.5	3.0 ± 1.5	ns
Pre-op MTC (°)	52.5 ± 9.6	52.2 ± 10.6	ns
Pre-op LC (°)	35 ± 8.8	35.0 ± 9.3	ns
MTC-bending (°)	34.2 ± 14.3	32.0 ± 14.0	ns
LC-bending (°)	12.5 ± 9.5	13.2 ± 10.1	ns
Pre-op C7-CSVL (cm)	− 0.3 ± 1.6	− 0.7 ± 1.9	ns
Pre-op TK (°)	29.5 ± 14.2	29.6 ± 13.9	ns
Pre-op LL (°)	− 58.8 ± 12.4	− 60.8 ± 12.0	ns
Post-op MTC (°)	16.2 ± 6.7	17.6 ± 6.8	ns
Post-op LC (°)	16.4 ± 8.3	17.3 ± 9.1	ns
Post-op C7-CSVL (cm)	− 1.6 ± 1.6	− 1.3 ± 1.7	ns
Post-op TK (°)	30.2 ± 8.3	27.6 ± 9	$P = 0.005$
Post-op LL (°)	− 51 ± 11.4	− 52.7 ± 12.2	ns
Follow-up MTC (°)	19 ± 7.5	21.2 ± 7.4	$P = 0.005$
Follow-up LC (°)	16.8 ± 7.9	17.5 ± 8.6	ns
Follow-up C7-CSVL (cm)	− 1.0 ± 3.4	− 0.9 ± 1.4	ns
Follow-up TK (°)	31.7 ± 9.4	29.4 ± 10.0	$P = 0.03$
Follow-up LL (°)	− 57.2 ± 11.3	− 57.6 ± 11.7	ns

ns Nonsignificant statistical difference, *F/U* Follow-up, *MTC* Main thoracic curve, *LC* Lumbar curve, *TK* Thoracic kyphosis, *LL* Lumbar lordosis, and *C7-CSVL* Deviation of C7 plumb-line off central sacral vertical line

*Screw density is ≥ 80% but not 100%

202 patients (49.3%). The UIV was at T1 in four patients (1%), at T2 in 63 patients (15.4%), at T3 in 124 patients (30.3%), at T4 in 177 patients (43.2%), at T5 in 40 patients (9.8%), and at T6 in two patients (0.5%).

According to the Lenke classification, the study sample used for prediction model analysis included 354 patients (86.4%) with type 1 curve, 37 patients (9%) with type 3 curves, and 19 patients (4.6%) with type 4 curves. Coronal plane lumbar modifier was type AL in 175 patients (42.7%), type B in 128 patients (31%), and type C in 107 patients (26.1%). Sagittal plane modifier was type "-"in 77 patients (18.8%), "normal" in 292 patients (71.2%), and "+" in 37 patients (9%).

All 410 patients had ≥ 80% pedicle screws (80–100%), while 267 patients (65.1%) had all-pedicle screw constructs (100%). Patients with all-pedicle screw constructs revealed no significant clinical differences compared to patients with ≥ 80% pedicle screw constructs. Results are listed in detail in Table 1.

Radiographic results

Results of radiographic measurements are summarized in Table 2. Analysis of the postoperative evolution of the LC from early postoperative radiographs to 2-year postoperative showed an average loss of SLCC of 0.3° ± 6.1°. The statistical analysis showed a strong correlation between preoperative LC and immediate postoperative LC ($r = 0.7$, $P < 0.01$) and preoperative and the 2-year postoperative follow-up LC ($r = 0.61$, $P < 0.001$, Fig. 1). Likewise, the linear regression analysis showed a significant correlation between pre-op LC-bending and early postoperative LC ($r = 0.53$, $P < 0.01$) and the 2-year postoperative LC ($r = 0.4$, $P < 0.001$, Fig. 2). The immediate postoperative LC was on average 4° ± 9.2° larger than the preoperative LC-bending value. At final follow-up, the difference was 4.2° ± 10°.

The preoperative MTC ($r = 0.3$, $P < 0.001$) and MTC-bending ($r = 0.3$, $P < 0.001$) were mild predictive variables for postoperative MTC. The same interdependency was found for preoperative and follow-up data points (MTC-bending: $r = 0.2$, $P < 0.001$; preoperative MTC: $r = 0.3$,

Table 2 Radiographic results in 410 AIS patients that had STF

Radiographic parameter	Pre-op Mean ± 1SD (95% CI)	Post-op Mean ± 1SD (95% CI)	2 years FU Mean ± 1SD (95% CI)	*P* value pre-op vs. post-op	*P* value post-op vs. F/U
Main thoracic curve (°)	52.3 ± 10.3 (51.3–53.3)	17.1 ± 6.8 (16.5–17.8)	20.4 ± 7.5 (19.7–21.1)	*P* < 0.0001	*P* < 0.0001
MTC-bending (°)	32.8 ± 14.2	–	–	–	–
MTC-flexibility (%)	38.2 ± 20.7	–	–	–	–
MTC-correction (%)	–	66.9 ± 12.4	60.5 ± 14.1	–	–
Lumbar curve (°)	35 ± 9.1 34.1–35.9	17 ± 8.8 (16.1–17.9)	17.2 ± 8.4 (16.4–18.0)	*P* < 0.0001	ns
LC-bending (°)	13.0 ± 9.9	–	–	–	–
LC-flexibility (%)	64.5 ± 23.3	–	–	–	–
LC-correction (%)**	–	52.3 ± 19.1	51.2 ± 20.1	–	–
Thoracic kyphosis (°)	29.5 ± 13.9 (28.2–30.9)	28.5 ± 8.9 (27.6–29.4)	30.3 ± 9.8 29.3–31.2	*P* = 0.05	*P* < 0.0001
Lumbar lordosis (°)	− 60 ± 12.1 (− 61.2 to − 58.8)	52.3 ± 11.6 (− 53.4 to − 51.1)	57.4 ± 11.6 (− 58.5 to − 56.2)	*P* < 0.0001	*P* < 0.0001
C7-CVSL (cm)	− 1.4 ± 1 (− 0.7 to − 0.4)	1.8 ± 1.3 (− 1.5 to − 1.2)	1.4 ± 2.1 (− 1.2 to − 0.7)	*P* < 0.0001	*P* = 0.0001
Difference post-op LC to LC at 2 years	–	–	− 0.3 ± 6.1*	–	–

CI Confidence interval for means, *ns* No statistically significant difference, *FU* Follow-up, *MTC* Main thoracic curve, *LC* Lumbar curve, and *C7-CSVL* Deviation of C7 plumb-line off central sacral vertical line

*–indicates postoperative loss of LC-correction (= increase in LL postoperative), **equal to changes in spontaneous lumbar curve correction

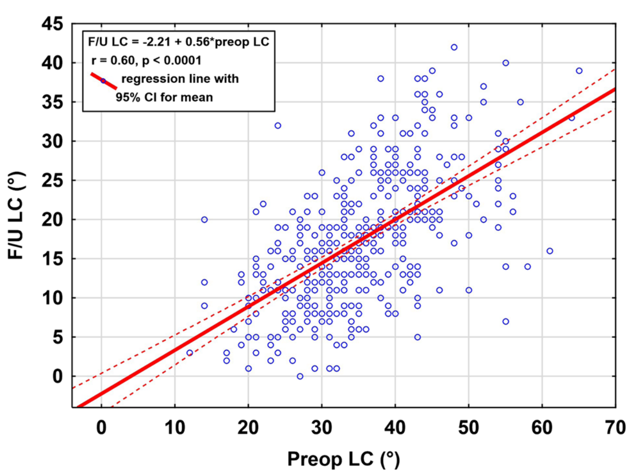


Fig. 1 Correlation between preoperative LC and follow-up LC data in 410 AIS patients who had STF using posterior approach

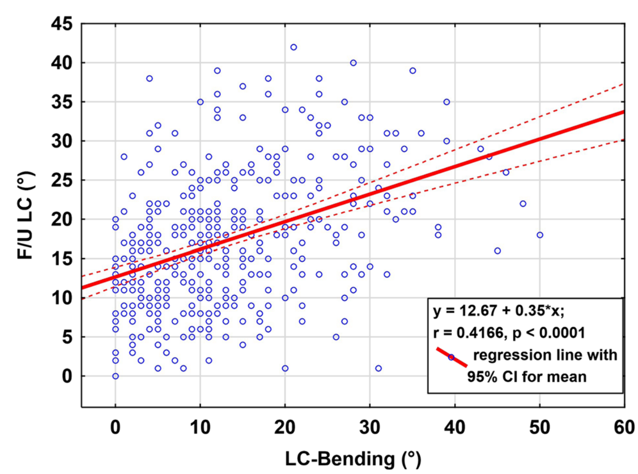


Fig. 2 Correlation between LC-bending and follow-up LC data in 410 AIS patients who had STF using posterior approach

$P < 0.001$). The postoperative MTC was 15.6° ± 13.8° smaller than the MTC-bending value and 12.4° ± 14.3° smaller at latest follow-up. In general, a satisfying postoperative MTC-correction was achieved, as indicated by a SCI of 2.9 ± 4.6.

Statistical analysis revealed a strong correlation between preoperative LC and preoperative MTC values ($r = 0.66$, $P < 0.001$). Similar correlations were found immediate postoperatively ($r = 0.58$, $P < 0.001$) and at 2-year follow-up ($r = 0.6$, $P < 0.0001$). Accordingly, there was a significant correlation between MTC-flexibility (°/%) and LC-flexibility ($r = 0.4$, $P < 0.001$). The correction of MTC and LC (°/%) was significantly correlated postoperatively ($r = 0.6$, $P < 0.001$) and at latest follow-up ($r = 0.6$, $P < 0.001$). Importantly, the postoperative LC-correction was strongly associated with the MTC-correction ($r = 0.6$, $P < 0.001$). That is to say there was greater SLCC when there was greater

Table 3 Comparison of patients with LC > 20° and LC ≤ 20° for various outcome measures

Parameter	Lumbar curve at 2 yrs follow-up		*P* value
	LC > 20°	LC ≤ 20°	
2 years F/U: SRS22-Self-Image	4.3 ± 0.6	4.5 ± 0.5	*P* < 0.0001
2 years F/U: SRS 22-Satisfaction	4.5 ± 0.8	4.6 ± 0.6	*P* = 0.01
2 years F/U: SRS 22-Total	4.4 ± 0.5	4.5 ± 0.4	*P* = 0.02
Patient age at surgery	14.3 ± 2.0	14.7 ± 2.2	ns
Risser (1–5)	3.0 ± 1.5	3.1 ± 1.5	ns
Difference btw. post-op LC and F/U LC (°)*	− 2.4 ± 6.7	0.6 ± 5.4	*P* < 0.0001
Pre-op MTC (°)	55.6 ± 11.7	50.8 ± 9.2	*P* < 0.0001
MTC-bending (°)	37.5 ± 15.5	30.7 ± 13	*P* < 0.0001
Pre-op LC (°)	41.7 ± 8.0	32 ± 7.8	*P* < 0.0001
LC-bending (°)	18.4 ± 10.7	10.5 ± 8.5	*P* < 0.0001
Pre-op C7-CSVL (cm)	− 1.1 ± 1.4	− 0.3 ± 1.9	*P* < 0.0001
Pre-op TK (°)	31.2 ± 13.7	28.4 ± 14.0	ns
Pre-op LL (°)	− 60.9 ± 12.0	− 59.7 ± 12.3	ns
Post-op MTC (°)	21.3 ± 6.9	15.3 ± 5.9	*P* < 0.0001
Post-op LC (°)	25 ± 7.5	13.4 ± 6.7	*P* < 0.0001
Post-op C7-CSVL (cm)	− 1.8 ± 1.7	− 1.2 ± 1.6	*P* = 0.0005
Post-op TK (°)	29.3 ± 9	28.1 ± 8.8	*P* = 0.0005
Post-op LL (°)	− 52 ± 12.4	52 ± 11.8	ns
Follow-up MTC (°)	25.5 ± 6.9	18.1 ± 6.5	*P* < 0.0001
Follow-up LC (°)	27.2 ± 5.1	12.7 ± 5.0	*P* < 0.0001
Follow-up C7-CSVL (cm)	− 17 ± 3.6	− 0.6 ± 1.3	*P* = 0.001
Follow-up TK (°)	32.2 ± 10.2	29.2 = 9.5	*P* = 0.006
Follow-up LL (°)	− 58.8 ± 11.9	− 56.8 ± 11.4	ns

ns No statistically significant difference, *F/U* Follow-up, *MTC* Main thoracic curve, *LC* Lumbar curve, *TK* Thoracic kyphosis, *LL* Lumbar lordosis, and *C7-CSVL* Deviation of C7 plumb-line off central sacral vertical line

*–Indicates postoperative loss of LC-correction (increase in LL postoperative)

MTC-correction. Analysis of correlation strength between the postoperative LC and the postoperative MTC as well as the preoperative LC and LC-bending rendered stable conditions for analysis of SLCC.

Analysis of SLCC prediction

At follow-up, 128 patients (31.2%) had a LC > 20° and 282 patients (68.8%) had a LC ≤ 20°. Stratification of patients with a LC of ≤ 20° vs. LC > 20° revealed significant differences for the various radiographic parameters evaluated (Table 3). Patients with a LC ≤ 20° also had significantly higher (better) SRS-22 total scores ($P = 0.02$) though mean differences were small. Group differences are summarized in Table 3.

A multivariate regression model to predict postoperative LC by using preoperative LC and LC-bending was found. The regression equation was 2-year post-op LC (°) = -1.42 + 0.5*pre-op LC (°) + 0.0915*pre-op LC-bending (°) ($r = 0.61$, $r^2 = 0.37$). This model showed only small differences between raw predicted values and observed post-op LC data (median = 0.05°, 95% CI = 2–27°; $R = 0.6$, Fig. 3).

For preoperative LC and LC-bending, the logistic regression model in which 100% of patients were classified showed the following prediction performance: specificity of 91% and sensitivity of 51%, NPV of 80% and PPV of 72%.

A prediction model with two cutoffs instead of one for preoperative LC and LC-bending fulfilling the above-defined conditions was also established. It showed the highest accuracy when using two cutoffs (specificity 90%, sensitivity 90%, NPV 96%, PPV 77%, total correct predictions: 90%, classification of 37% of patients). A contour plot of this bivariate logistic regression model is illustrated in Fig. 4 revealing the significant interaction of preoperative LC and LC-bending in predicting the risk for a residual LC > 20° at 2-year follow-up. The surface of this contour plot is dissected into ten parts indicating different risks for LC > 20°. Along the diagonal contour lines, the risk for an LC > 20° at follow-up is constant. The green areas indicate low risk, and the red areas indicate medium to high risk. The legend

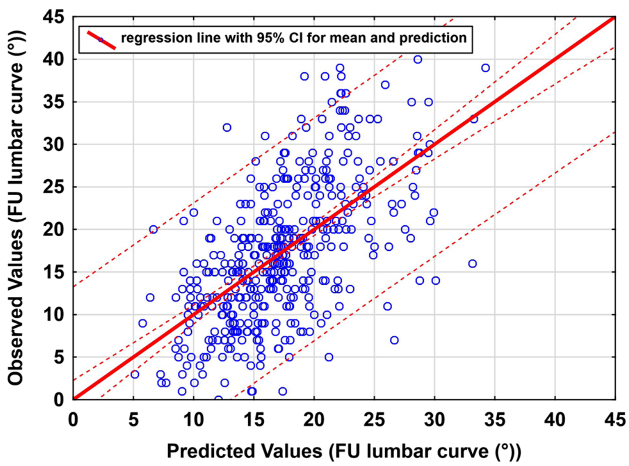


Fig. 3 Predicted versus observed values for follow-up lumbar curve magnitude based on the preoperative LC and LC-bending data

indicates the corresponding risk for a residual LC > 20°. To demonstrate how the model works, we discuss three patients P1, P2, and P3 in Fig. 4. P1 has a preoperative LC of 25° and a preoperative LC-bending of 10°. These parameters are within the dark green area, which indicates that the risk for a LC > 20° is between 0 and 10%. If the patient's preoperative LC is 60° and the preoperative LC-bending is 30°, as in P2, the associated risk of the LC > 20° is between 94%. P2 lies within the red area. If the patient's preoperative LC is 45° and the preoperative LC-bending decreases to 20°, and the patient reaches P3, which was associated with a risk of 63%. The expected postoperative correction of MTC is another valuable piece of information a surgeon can use for planning for SLCC in the individual patient. Given the aforementioned conditions for clinical risk stratification, a model that takes correction of MTC (postoperative MTC) and preoperative LC into consideration was found and is illustrated in Fig. 5. If postoperative MTC, which is a parameter influenceable by the surgeon, is selected together with preoperative LC, model accuracy could even be improved if compared with the combination of preoperative LC and LC-bending data (specificity of 92%/sensitivity of 90%, NPV of 95%/PPV of 81%, classified patients 50%, correct classification in 91%). Two cutoffs are at 10% and 64% for MTC-correction. To be useful, the surgeon must make some reasonable estimate of the anticipated percentage correction of the MTC. Again, four example points are shown for illustration and better understanding.

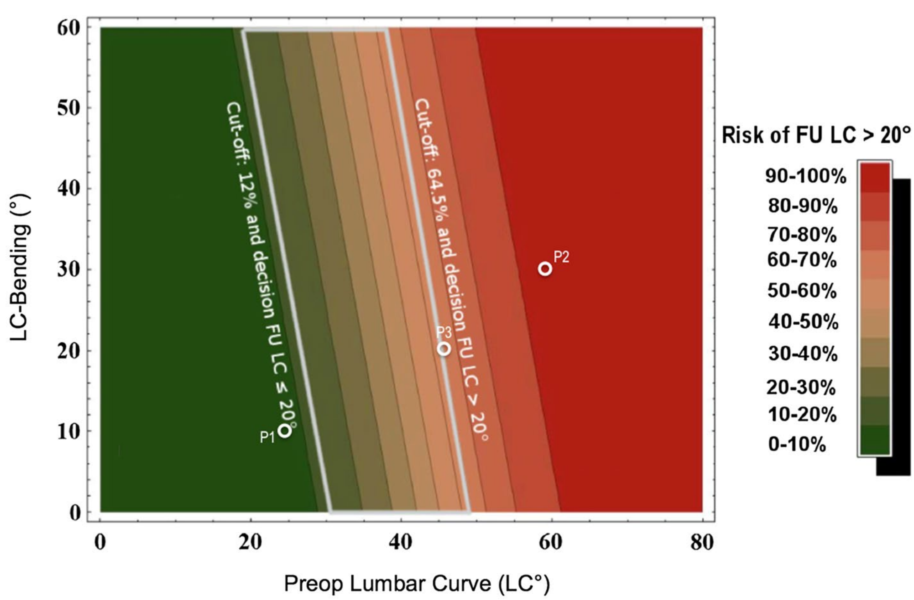
Both graphs may be useful for the surgeon during the decision making process whether to do a STF or not in the individual patient and curve pattern.

Discussion

For fusion-level selection and the determination of whether or not to include the lumbar C modifier curve in the treatment of MTC scoliosis, the surgeon relies on the ratio between MTC and LC magnitude, trunk shift, patient age, maturity, body weight and activity level as well as surgeon dependent factors including experience, surgical technique, and the average correction rate achieved by the surgeon [25, 31, 32]. The current study aimed at adding a tool to the surgeon's armamentarium that enhances decision making in STF versus longer fusions into the lumbar spine.

With the analysis of a sample of 410 AIS patients including only patients with posterior STF, accurate prediction models for postoperative SLCC and LC ≤ 20°/LC > 20° were established. In combination, the models can be helpful in the prediction and understanding of postoperative SLCC.

Fig. 4 Contour plot of bivariate logistic regression model with preoperative LC and LC-bending as predictors. Colors indicate risk for LC > 20° at follow-up (FU). Specificity: 90%, sensitivity: 90%, NPV: 96%, PPV: 77%, 63% of all patients were unclassified, total correct predicted patients: 90%. Along the contour lines dissected in ten parts, the risk for an LC > 20° is constant. Data of three example patients (P1, P2, and P3) together with their preoperative LC, LC-bending, and risk for LC > 20 °C at follow-up are drawn. These three example patients are discussed in the results section



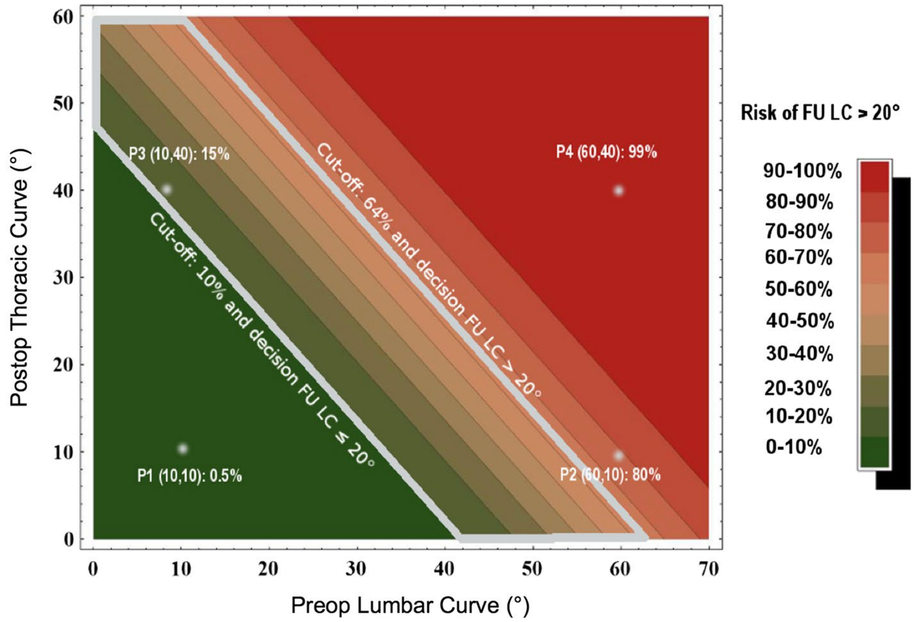


Fig. 5 Contour plot of bivariate logistic regression model with preoperative LC and postoperative main thoracic curve (MTC) as predictors. Colors indicate risk for LC > 20° at follow-up (FU). Specificity: 92%, sensitivity: 90%, NPV: 95%, PPV: 81%, 50% of all patients were unclassified, total correct predicted patients: 90%. Along the contour lines dissected in ten parts, the risk for an LC > 20° is constant. Data of four example patients (P1–P4) are drawn

The inclusion of a target outcome in the analysis, e.g., a LC ≤ 20°/LC > 20°, contributed to the development of clinically feasible models. Sample characteristics reported in the literature, including age and follow-up length [2, 19, 25, 29, 33–36], are similar to the variables reported in our study. In the current study, one model is based on preoperative LC and LC-bending data (Fig. 4), and the other model uses postoperative MTC-correction and preoperative LC (Fig. 5). Postoperative MTC can only be estimated before surgery, but is a variable that can be directly influenced by each surgeon's individual techniques.

To effectively apply both models in daily practice, the performance of the models has to fulfill some clinical rationales. In order to meet these conditions, advanced statistical methods were used with two cutoffs instead of only one cutoff, so a gray area was generated. This further increased model accuracy. Preoperative variables along with surgical data can be used to predict in which patients the uninstrumented lumbar spine will have a postoperative residual LC ≤ 20°.

The previous studies also attempted to predict SLCC using linear regression analysis [37, 38]. However, either re-testing accuracy of a small test sample in an independent cohort was lacking or predictive power was small [25, 38]. In a multicenter study by Abel et al. [38] on 123 patients that had STF, the authors used preoperative LC and L4 take-off angle as predictor variables of follow-up LC. The linear regression model explained only 40% of the variance of postoperative LC. In another study [39] on 24 AIS patients with Lenke type 1C or 2C curves, prediction for postoperative coronal balance after STF was calculated based on the preoperative coronal balance data. R^2 was 0.38 only. In a similar statistical fashion, several authors tried to define predictive equations for postoperative LC [37, 40, 41], but advanced statistical methods for prediction accuracy, error ranges for predicted postoperative LC values, or a scatter plot showing observed and predicted postoperative LC values were not provided. The apical vertebral rotation of the LC correlates with increasing LC Cobb angle, and it was suggested that it predicts SLCC [19, 32]. However, several authors did not observe significant change in the apical vertebral rotation of the LC after STF [1, 19] and its prediction strength was shown inferior in comparison to that of the preoperative LC and LC-bending [25]. Other studies on STF have focussed on the spinal level of the LIV and showed improved SLCC when the LIV descended to lumbar levels [42], which is an intuitive finding. The LIV position, however, had no influence on SLCC in the current sample with large number of patients.

It is important to understand in which areas prediction models provide accurate prediction. To address these goals, the authors defined surgically sound cutoffs with the statistician that would render a model useful in clinical practice. If patient's parameters do not fall into the model prediction area, no prediction is calculated by the model rather than a less accurate prediction. This objective was accomplished by using different cutoffs within the bivariate model. In clinical practice, most patients in whom a STF is considered will fall within the area where the model provides a prediction.

The prediction of the model is always to be interpreted with the perspective of the other clinical and radiographic variables known [25, 32] to also influence the decision process toward a STF. However, this prediction model offers valuable insight into the postoperative behavior of the LC.

Notably, in the current study, patients with a LC ≤ 20° had significant better SRS-22 total scores ($P = 0.02$) adding evidence to the use of a target LC ≤ 20° as done in the previous studies [25]. Patients with LC ≤ 20° had smaller preoperative LC (av. 32° vs. 42°) and smaller curve magnitude in the bending films (av. 10° vs. 18°). Based on intergroup differences for the means ± 1SD of the patients with a follow-up LC ≤ 20°/LC > 20° (summarized in Table 3) and in perspective of the bivariate regression model (shown in Fig. 4), surgeons might face difficulties in particular in patients with preoperative LC ≥ 40° and/or a LC-bending of ≥ 20° to achieve a postoperative LC ≤ 20° using posterior STF. Although a LC ≤ 20° may be considered ideal, many will also accept a LC ≤ 30°, which would increase the preoperative LC and LC-bending appropriate for STF accordingly. This study was not designed to determine the "acceptable" residual LC, but rather predict in which patients a STF will result in that residual curve being less than 20°.

The statistical approach selected for the current study does not imply that a prediction will be made for a single patient based on the equations only. However, the model supports the decision making process. The model might particularly support surgeons who have defined their optimum SLCC at a LC ≤ 20° and who select a posterior approach for STF. The model using the postoperative MTC predicted the LC best which is intuitive as both the preoperative and postoperative correlations between MTC and LC were strong in our study. This emphasizes the point that greater MTC-correction predicts greater SLCC. There may be concerns of greater coronal decompensation following greater MTC-correction, especially in the early postoperative period; however, at 2 years, the LC-correction had high correlation with MTC-correction [25, 29].

This study analyzed AIS patients that had a posterior approach for STF. Average postoperative SLCC was 52%. In a previous study by Koller et al. [25] on 273 patients that had an anterior approach for STF, postoperative SLCC was 47%. In a matched-pairs study comparing anterior and posterior STF, the authors identified small, but nonsignificant differences regarding SLCC [29, 43]. The differences are largely related to the difference in MTC-correction achieved, in particular with the use of modern screw-rod constructs in comparison with anterior techniques. The prediction models introduced for posterior STF in the current study and for anterior STF [25] show similar accuracy, with improvements achieved in this study. To work with accurate prediction modeling, the use of the dedicated model is recommended for both anterior and posterior STF. It clearly defines the areas of high prediction and where it performs best. This definition of model applicability is very important for any statistic model or equation to be used in clinical practice. Accordingly, it is of interest to note that Lenke 2 curves were not included in our model. Compensation of postoperative shoulder height imbalance in Lenke 2 curves is usually achieved by SLCC or distal lumbar adding-on [44, 45]. In addition, AIS curve pattern with lumbar modifier type A-R, which was an exclusion criterion in our study, is more common in Lenke 2 curves. In clinical practice of the author, the model provides accurate prediction of postoperative LC in perspective of a target MTC achieved during surgery (see Fig. 5).

Patients that achieved a target LC ≤ 20° were shown to achieve better clinical outcomes in terms of the SRS-22. These patients also had on average no significant postoperative LC increase in comparison with patients with LC > 20° (Table 3). In another study by Benett et al. [31], patients with greater percent correction of MTC and LC were most likely to attain the minimal clinically important difference in their patient-reported outcomes postoperatively. The rationales for the definition of this target in the current study were also based on the previous studies and expert opinions [23–26, 28]. Our findings support that a postoperative LC of equal to or smaller than 20° is a reasonable target variable also in future studies that might further improve prediction modeling. Nevertheless, patients with a residual postoperative LC > 20° still can have long-term maintenance of the residual LC and excellent clinical outcomes in many cases. We believe STF is a valuable means of preserving lumbar motion, and a modest residual LC is favorable compared to a fusion into the distal lumbar spine for many patients.

Conclusion

An accurate prediction model for postoperative SLCC was established based on a large analysis STF cases. These models can support prediction and understanding of postoperative SLCC aiding in surgical decision making when contemplating a selective thoracic fusion versus a fusion that includes both the thoracic and lumbar curves. Both patient- and curve-specific characteristics, such as the preoperative lumbar curve severity and the lumbar curve flexibility, as well as factors that can be controlled by the surgeon, the postoperative Cobb angle, were shown significant predictors of postoperative spontaneous lumbar curve correction.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Edwards CC, Lenke LG, Peelle M, Sides B, Rinella A, Bridwell KH (2004) Selective thoracic fusion for adolescent idiopathic scoliosis with C modifier lumbar curves: 2- to 16-years radiographic and clinical results. Spine 29:536–546
2. Min K, Haefeli M, Mueller D, Klammer G, Hahn F (2012) Anterior short correction in thoracic adolescent idiopathic scoliosis with mini-open thoracotomy approach: prospective clinical radiological and pulmonary function results. Eur Spine J Suppl 6:S765–S772
3. Newton PO, Yaszay B, Upasani VV et al (2010) Preservation of thoracic kyphosis is critical to maintain lumbar lordosis in the surgical treatment of adolescent idiopathic scoliosis. Spine 35:1365–1370
4. Boniello AJ, Hasan S, Yang S, Jalai CM, Worley N, Passias PG (2015) Selective versus nonselective thoracic fusion in Lenke 1 C curves: a meta-analysis of baseline characteristics and postoperative outcomes. J Neurosurg Spine 23:721–730
5. Green DW, Lawhorne TW, Widmann RF, Kepler CK, Ahern C, Mintz DN, Rawlins BA, Burke SW, Boachi-Adjei O (2011) Long-term magnetic resonance imaging follow-up demonstrates minimal transitional level lumbar disc degeneration after posterior spine fusion for adolescent idiopathic scoliosis. Spine 36:1948–1954
6. Fabricant PD, Admoni S, Ipp LS, Green DW, Widmann RF (2011) Are patients participating in sports after posterior spine fusion for adolescent idiopathic scoliosis? Distal level of fusion correlates with postoperative activity level. In: 46th SRS annual meeting Louisville/USA
7. Lee MC, Õunpuu S, Solomito M, Smith BG, Thomson JD (2013) Loss in spinal motion from inclusion of a single midlumbar level in posterior spinal fusion for adolescent idiopathic scoliosis. Spine 38:E1405–E1410
8. Luk KD, Lee FB, Leong JC, Hsu LC (1987) The effect on the lumbosacral spine of long spinal fusion for idiopathic scoliosis. A minimum 10-year follow-up. Spine 12:996–1000
9. Ouellet JA, Johnston CE 2nd (2002) Effect of grafting technique on the maintenance of coronal and sagittal correction in anterior treatment of scoliosis. Spine 27:2129–2135
10. Schwab F, Dubey A, Gamez L, El Fegoun AB, Hwang K, Pagala M, Farcy JP (2002) Adult scoliosis: a quantitative radiographic and clinical analysis. Spine 27:387–392
11. Ilharreborde B, Morel E, Mazda K, DeKutoski MB (2009) Adjacent segment disease after instrumented fusion for idiopathic scoliosis. J Spinal Disord 22:530–539
12. Auerbach JD, Lonner BS, Errico TJ, Freeman A, Goerke D, Beaubien BP (2012) Quantification of intradiscal pressures below thoracolumbar spinal fusion constructs. Spine 37:359–366
13. Buttermann GR, Beaubien BP (2008) In vitro disc pressure profiles below scoliosis fusion constructs. Spine 33:2134–2142
14. Sitte I, Kathrein A, Prof Pfaller K, Pedross F, Klosterhuber M, Lindtner R, Zenner J, Ferraris L, Meier O, Koller H (2013) Morphological differences in adult idiopathic scoliosis: a histological and ultrastructural investigation. Spine 38:1672–1680
15. Marks M, Newton PO, Petcharaporn M, Bastrom TP, Shah S, Lonner B, Betz R, Miyanji F (2012) Postoperative segmental motion of the unfused spine distal to the fusion in 100 patients with adolescent idiopathic scoliosis. Spine 37:826–832
16. Enercan M, Kahraman S, Cobanoglu M, Yilar S, Gokcen BH, Karadereler S, Mutlu A, Ulusoy LO, Ozturk C, Erturer E, Gebes E, Sanli T, Alanay A, Hamzaoglu A (2015) Selective thoracic fusion provides similar health-related quality of life but can cause more lumbar disc and facet joint degeneration: a comparison of adolescent idiopathic scoliosis patients with normal population 10 years after surgery. Spine Deform. 3:469–475
17. Larson AN, Fletcher N, Richards BS (2011) Lumbar curve is stable after selective thoracic fusion for adolescent idiopathic scoliosis: a 20-year follow-up. Spine 37:833–839
18. Yong MO, Izat MT, Adam CJ, Labrom RD, Askin GN (2012) Secondary curve behaviour in Lenke Type 1C adolescent idiopathic scoliosis after thoracoscopic selective anterior thoracic fusion. Spine 37:1965–1974
19. Chang K-W, Leng X, Zhao W, Chen Y-Y, Chen T-C, Chang K-I (2011) Broader curve criteria for selective thoracic fusion. Spine 36:1658–1664
20. Dobbs BD, Lenke L, Yongjung JK, Kamath G, Peelle MW, Bridwell KH (2006) Selective posterior thoracic fusions for adolescent idiopathic scoliosis. Spine 31:2400–2404
21. Tis JE, O'Bien MF, Newton PO, Lenke LG, Clements DH, Harms J, Betz RR (2009) Adolescent idiopathic scoliosis treated with open instrumented anterior spinal fusion—Five-year follow-up. Spine 35:64–70
22. Leroux J, Mac-Thiong J-M, Labelle H, Parent S (2011) Postoperative changes in coronal balance after surgical correction of adolescent idiopathic scoliosis using pedicle screw constructs. In: IMAST 2011, Kopenhagen/Denmark
23. Nohara A, Kawakami N, Seki K, Kazuyoshi M, Tsuji T, Saito T, Kawakami K (2011) The effects on the lumbar disc degeneration of spinal fusion for scoliosis patients—a minimum ten-year follow-up. In: 46th annual SRS meeting, Louisville/USA
24. Yaszay B, Asgahr J, Bastrom TP, Smdani A, Sturm P, Betz RR, Shufflebarger HL, Newton PO (2012) Determining optimal postoperative coronal parameters for selective thoracic fusion. In: 19th IMAST, Istanbul/Turkey
25. Koller H, Meier O, Albrecht H, Schmidt R, Zenner J, Hitzl W (2014) Selective thoracic fusion in AIS curves: the definition of target outcomes improves the prediction of spontaneous lumbar curve correction (SLCC). Eur Spine J 23:1263–1281
26. Bergoin M (2013) Anterior instrumentation (dual screws single rod system) for the surgical treatment of idiopathic scoliosis in the lumbar are: a prospective study on 33 adolescents and young adults, based on a new system of classification. Eur Spine J Suppl 2:S149–S163
27. Yazici M, Cil A, Pekmezci M, Acaroglu E (2005) The effect on the lumbosacral spine of long spinal fusion for idiopathic scoliosis. A minimum 10-year follow-up. In: 40th annual meeting of SRS, Miami/USA
28. Kusakabe T, Gaines RW (2008) Results of short bone-on-bone instrumentation for single curve adolescent idiopathic scoliosis after mean follow-up of 6 years. IMAST, Hongkong
29. Jansen RC, Rhijn LW, Duinkerke E, Ooij A (2007) Predictability of the spontaneous lumbar curve correction after selective thoracic fusion in idiopathic scoliosis. Eur Spine J 16:1335–1342
30. Miyanji F, Pawelek JB, Van Valin SE, Upasani VV, Newton PO (2008) Is the lumbar modifier useful in surgical decision making?: defining two distinct Lenke 1A curve patterns. Spine 33:2545–2551
31. Bennet JT, Samdani AF, Bastrom TP, Ames RJ, Miyanji F, Pahys JM, Marks MC, Lonner BS, Newton PO, Shufflebarger HL, Yaszay B, Jm Flynn, Betz RR, Cahill PJ (2017) Factors affecting the outcome in appearance of AIS surgery in terms of the minimal clinically important difference. Eur Spine J 26:1782–1788

32. Fischer CR, Kim Y (2011) Selective fusion for adolescent idiopathic scoliosis: a review of current operative strategy. Eur Spine J 20:1048–1057
33. Lenke LG, Betz RR, Bridwell KH et al (1999) Spontaneous lumbar curve coronal correction after selective anterior or posterior thoracic fusion in adolescent idiopathic scoliosis. Spine 24:1663–1671
34. Schulte TL, Liljenqvist Hierholzer E, Bullmann V, Halm HF, Lauber S, Hackenberg L (2006) Spontaneous correction and derotation of secondary curves after selective anterior fusion of idiopathic scoliosis. Spine 31:315–321
35. Muschik MT, Kimmich H, Demmel T (2006) Comparison of anterior and posterior double-rod instrumentation for thoracic idiopathic scoliosis: results of 141 patients. Eur Spine J 15:1128–1138
36. Betz RR, Harms J, Clements D, Lenke L, Low T, Shufflebarger Jeszensky D, Beele B (1999) Comparison of anterior and posterior instrumentation for correction of adolescent thoracic idiopathic scoliosis. Spine 24:225–239
37. Mason DE, Schindler A, King N (1998) Estimation of the lumbar curve magnitude with correction of the right thoracic curve in idiopathic scoliosis. J Pediatr Orthop 18:602–605
38. Abel MF, Herndon SK, Sauer LD et al (2011) Selective versus nonselective fusion for idiopathic scoliosis: does lumbosacral takeoff angle change? Spine 36:1103–1112
39. Ishikawa M, Cao K, Pang L, Watanabe K, Yagi M, Hosogane N, Machida M, Shiono Y, Nishiyama M, Fukui Y, Matsumoto M (2015) Postoperative behavior of thoracolumbar/lumbar curve and coronal balance after posterior thoracic fusion for Lenke 1C and 2C adolescent idiopathic scoliosis. J Orthop Sci 20:31–37
40. Patel PN, Upasani VV, Bastrom TP, Marks MC, Pawelek JB, Betz RR, Lenke LG, Newton PO (2008) Spontaneous lumbar curve correction in selective thoracic fusions of idiopathic scoliosis: a comparison of anterior and posterior approaches. Spine 33:1068–1073
41. Uehara M, Takahashi J, Ikegami S, Kuraishi S, Futatsugi T, Oba H, Takizawa T, Munakata R, Koseki M, Kato H (2018) Prediction of spontaneous lumbar curve correction after posterior spinal fusion for adolescent idiopathic scoliosis Lenke type 1 curves. Clin Spin Surg 30:1–10
42. Takahashi J, Newton PO, Ugrinow V, Bastrom TP (2011) Selective thoracic fusion in adolescent idiopathic scoliosis. Spine 36:1131–1141
43. Abel MF, Herndon SK, Sauer LD, Novicoff WM, Smith JS, Shaffrey CI (2011) Selective versus nonselective fusion for idiopathic scoliosis—does lumbosacral takeoff angle change? Spine 36:1103–1112
44. 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 20:1137–1140
45. 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 24:1490–1501

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