Clinical Study

ASJ

Asian Spine J. 2025;19(1): 102-111
https://doi.org/10.31616/asj.2024.0491
PISSN 1976-1902 • eISSN 1976-7846

APSS-ASJ Best Clinical Research Award

This is the 2024 APSS-Asian Spine Journal Best Paper Award.

Lateral view fulcrum bending radiographs predict postoperative hypokyphosis after selective thoracic fusion in adolescent idiopathic scoliosis

Victoria Yuk Ting Hui, Jason Pui Yin Cheung, Prudence Wing Hang Cheung

Department of Orthopaedics and Traumatology, The University of Hong Kong, Pok Fu Lam, Hong Kong SAR, China

Received Nov 15, 2024; **Revised** Dec 5, 2024; **Accepted** Dec 16, 2024
Corresponding author: Prudence Wing Hang Cheung
Department of Orthopaedics and Traumatology, The University of Hong Kong, 5/F, Professorial Block, Queen Mary Hospital, 102 Pokfulam Road, Pokfulam, Hong Kong SAR, China
Tel: +852-2255-3553, **Fax:** +852-2817-4392, **E-mail:** gnuehcp6@hku.hk

Study Design: A retrospective observational study.
Purpose: To identify the surgical and preoperative risk factors on fulcrum bending radiographs for postoperative hypokyphosis in patients with Lenke 1 adolescent idiopathic scoliosis (AIS).
Overview of Literature: AIS is associated with thoracic hypokyphosis. Persistent hypokyphosis causes reduced pulmonary function and spinopelvic malalignment. Indications for Ponte osteotomies and releases to improve postoperative kyphosis restoration in patients with hypokyphosis are still unclear. Previous studies have demonstrated that kyphosis correction was limited by sagittal flexibility based on lateral view fulcrum bending radiographs.
Methods: Patients with Lenke 1 AIS undergoing posterior spinal fusion were included. Standing and fulcrum bending radiographs on the coronal and sagittal planes were analyzed at preoperative, immediate, and 2-year postoperative periods. The primary outcome was postoperative hypokyphosis (T5–12 thoracic kyphosis [TK] <20°). Risk factors for postoperative hypokyphosis were identified by multivariate logistic regression, and the optimal cutoff for significant risk factors was determined by receiver operating characteristic analysis.
Results: In total, 156 patients were included in the analysis, of which 68 (43.6%) were hypokyphotic at 2-year follow-up. Low T5–12 TK on lateral view fulcrum bending films (immediate postoperative odds ratio [OR], 0.870; 95% confidence interval [CI], 0.826–0.917; 2-year postoperative OR, 0.916; 95% CI, 0.876–0.959; $p<0.001$) and high convex side implant density (2-year postoperative OR, 1.749; 95% CI, 1.056–2.897; $p=0.03$) were significant risk factors for postoperative hypokyphosis. Other baseline demographic and surgical factors did not affect postoperative kyphosis correction. The T5–12 TK cutoff on fulcrum bending for 2-year postoperative hypokyphosis was 12.45° (area under the curve, 0.773; 95% CI, 0.661–0.820).
Conclusions: Fulcrum bending radiography is useful in assessing coronal and sagittal flexibility for preoperative planning. In patients with T5–12 kyphosis <12.5° on lateral view fulcrum bending radiographs, Ponte osteotomies or releases, or a decrease in convex side implant density should be considered to improve kyphosis restoration and reduce the risk of 2-year postoperative hypokyphosis.

Keywords: Thoracic vertebrae; Adolescent idiopathic scoliosis; Posterior spinal fusion; Fulcrum bending; Hypokyphosis

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity characterized by the lateral deviation of the spine, axial rotation, and thoracic hypokyphosis [1]. Surgery aims to restore coronal and sagittal balance; however, some patients remain hypokyphotic postoperatively [2]. In particular, posterior spinal fusion (PSF) may lead to further iatrogenic loss of thoracic kyphosis (TK) [3]. Persistent thoracic hypokyphosis is associated with spinopelvic malalignment: loss of lumbar lordosis [3], cervical kyphosis [4], and spinopelvic incongruence, leading to extensor muscle fatigue [5] and lower back pain [6]. Poor sagittal alignment in adulthood may lead to early cervical [7,8] and lumbar spine degeneration [3]. Moreover, thoracic hypokyphosis was positively correlated with diminished pulmonary function [9,10].

Intraoperative TK correction is affected by the inherent sagittal flexibility of the spine. Luk et al. [11] utilized fulcrum bending radiographs to identify the coronal sagittal coupling behavior of the spine *in vivo*: coronal deformity correction would lead to corresponding changes in the sagittal plane. TK tends to normalize under fulcrum bending correction of the coronal curve, and kyphosis correction on fulcrum bending was correlated with the direction of postoperative correction. No difference was found in the correction between the screw–rod constructs and the hook–rod systems; thus, in sagittal correction, the natural coupling behavior plays a more important role than the implant system.

Surgical factors can influence TK correction. Lower implant density [12], stiffer rod material [13], larger rod diameter [14], and certain curve correction maneuvers such as posteromedial translation and rod rotation techniques [15] could improve sagittal correction. Some studies have suggested the use of Ponte osteotomies [16-18] or releases [19,20] to improve sagittal correction; however, its indications remain unclear because of conflicting evidence on its efficacy and safety [21,22]. Although Ponte osteotomies improved coronal and sagittal correction for patients who were hypokyphotic, it increased operating times and blood loss [23] but did not improve patient-reported outcomes [24]. Consequently, the routine use of Ponte osteotomies in patients with hypokyphosis remains controversial because of its limited benefits and potential surgical risks. Thus, we hoped to define the indications for the use of Ponte osteotomies and releases by utilizing fulcrum bending radiographs to denote when TK would fail to normalize postoperatively.

This study aimed to investigate the relationship between fulcrum bending and postoperative kyphosis correction, identify the surgical risk factors and risk factors on fulcrum bending radiographs for postoperative hypokyphosis, and establish a cutoff of the identified risk factors for postoperative hypokyphosis. The hypothesis was that a low kyphosis on lateral fulcrum bending radiographs is a risk factor for postoperative hypokyphosis.

Materials and Methods

Study design

This single-center retrospective review included patients with Lenke 1 AIS undergoing single-stage PSF with pedicle screw constructs between 2003 and 2021 with a follow-up of 2 years. One or two additional hooks may be used if the pedicle screws cannot be inserted. The exclusion criteria were as follows: (1) missing standing lateral or fulcrum bending radiographs, (2) patients undergoing revision surgeries, (3) patients undergoing Ponte osteotomies or releases, and (4) unclear visualization of the T5–T12 TK in lateral view fulcrum bending radiographs.

This study was conducted in compliance with the Declaration of Helsinki. The study protocol was approved by the institutional review board (IRB) of The University of Hong Kong/Hospital Authority Hong Kong West Cluster (HKU/HA HKW IRB reference no., UW24-363) with a waiver of informed consent given the retrospective nature of the study. This study adhered to data-protection measures including patient deidentification.

Standing coronal and lateral radiographs were obtained at the preoperative, immediate postoperative, and 2-year follow-up periods. Radiographical assessment included the following: on the coronal plane, proximal thoracic, main thoracic, thoracolumbar Cobb angles, Risser staging, and apical vertebral rotation using the Nash and Moe classification [25]; on the sagittal plane, the T1–T12 TK, T5–T12 TK, T10–L2 thoracolumbar kyphosis, L1–S1 lumbar lordosis, and sagittal vertical axis. The technique of obtaining fulcrum bending radiographs was described by Cheung et al. [26,27]: briefly, the patient is placed in lateral decubitus position and passively bent over a radiolucent fulcrum at the apex of the curve (Fig. 1). Coronal and lateral view radiographs were taken with the patient in the fulcrum bending position to determine the fulcrum flexibility of the main curve [28] and the T5–T12 TK. Demographic

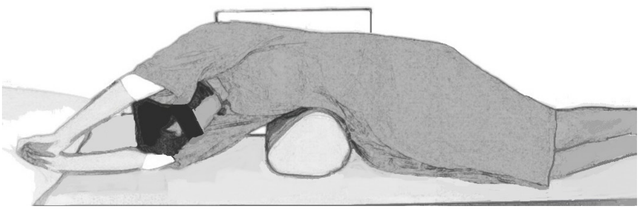

Fig. 1. With the patient in lateral decubitus position, a fulcrum is placed at the rib corresponding to the apex of the curve. Coronal and lateral radiographs are taken with patient in this position.

and surgical factors, including implant density and rod material, were gathered. Implant density was calculated using the following equation:

$$\text{Implant density}=\frac{\text{number of implants}}{2\times\text{number of fused levels}}$$

Radiographical measurements were performed by one researcher (V.Y.T.H.).

The fusion levels were selected using the strategy described by Luk et al. [29] based on fulcrum bending radiographs. Briefly, the fusion mass was squared by maintaining the fusion mass Cobb angle <20° and fusion mass shift <20 mm [30]. The surgical technique was standardized with Schwab grade 1 osteotomies without additional osteotomies or releases [31]. The rod contouring technique was standardized by differential rod contouring: the concave hyperkyphotic rod was first loaded, followed by rod rotation and locking of the distal screws. Then, the hypokyphotic convex rod was loaded to correct the rib hump and thereby rotate the spine to the concavity. Segmental concave side distraction and convex side compression followed for further coronal correction.

Study outcome

The primary outcome measure was postoperative hypokyphosis, defined by the T5–T12 TK with TK <20°, TK of 20°–40° and TK >40° as hypokyphotic, normokyphotic, and hyperkyphotic, respectively [32].

Statistical analysis

The demographic, radiographic, and surgical characteristics of the patients with different kyphotic profiles at the 2-year follow-up were compared using the Kruskal-Wallis and chi-square tests for continuous and categorical data, respectively. Potential preoperative radiographic and surgical risk factors for postoperative hypokyphosis were identified using point biserial

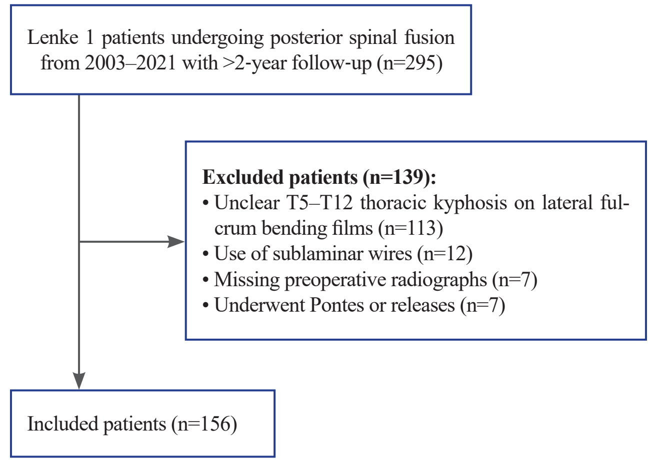

Fig. 2. Inclusion and exclusion flowchart.

regression. Factors with $p<0.15$ were then entered into a multivariate logistic regression model to determine risk factors significant for postoperative hypokyphosis [33]. The cutoffs of significant risk factors for 2-year postoperative hypokyphosis were identified using a receiver operating characteristic curve. Finally, the surgical outcomes of patients with lordotic thoracic spines preoperatively (T5–T12 kyphosis <0°) were evaluated.

Intraobserver reliability was assessed using the intraclass correlation coefficient (ICC), where ICC ≥0.7 was considered good reliability. The ICCs of T5–T12 TK on fulcrum bending and standing were 0.821 and 0.919 respectively [34]. Statistical analyses were performed using IBM SPSS Statistics ver. 28.0 (IBM Corp., Armonk, NY, USA). Significance was set at $p<0.05$.

Results

In total, 156 patients were included in this study; the inclusion and exclusions are detailed in Fig. 2. In this study, 75.6% of the patients had Lenke 1A, 16.7% had Lenke 1B, and 7.7% had Lenke 1C curves. At the 2-year follow-up, the proportion of patients with hypokyphosis decreased from 66.0% (n=103) preoperatively to 43.6% (n=68). Preoperatively, there was no significant difference in demographic and surgical factors between patients with different kyphotic profiles at 2-year follow-up ($p>0.10$). Patients with hypokyphosis achieved significantly more kyphosis correction on fulcrum bending ($p<0.001$). Detailed comparisons of the surgical, demographic, and radiographic characteristics are presented in Table 1.

Regarding surgical characteristics, the mean implant density was 1.16±0.14. No difference was found in kyphosis correction with different rod materials ($p=0.429$):

 https://doi.org/10.31616/asj.2024.0491

Table 1. Demographic and surgical characteristics of patients with different kyphotic profiles at 2-year follow-up

Characteristic	Hypokyphotic (n=68)	Normokyphotic (n=83)	Hyperkyphotic (n=5)	*p*-value
Demographic				
Age (yr)[a]	14.3 (13.2 to 16.7)	15.3 (13.4 to 17.1)	12.7 (12.4 to 13.6)	0.132
Risser[a]	3 (2 to 4)	4 (2 to 4)	4 (4 to 4)	0.193
Apical vertebral rotation[a]	2 (1 to 2)	2 (2 to 2)	2 (2 to 2)	0.221
Sex (females)[b]	56 (82.4)	10 (12.0)	0 (0)	0.403
Surgical				
Rod type (Ti)[b]	66 (97.1)	80 (96.4)	5 (100.0)	**<0.001**
Implant density	1.14 (1.11 to 1.25)	1.14 (1.11 to 1.25)	1.25 (1.14 to 1.25)	0.311
Preoperative				
PT Cobb (°)	28 (22 to 35.2)	29.6 (21.9 to 34)	30.1 (22.9 to 31.7)	0.958
MT Cobb (°)	55.8 (50.9 to 62)	56.2 (52.1 to 60.7)	49.8 (49.6 to 50.3)	0.123
TL/L Cobb (°)	33.4 (26.8 to 37.8)	31.9 (25.9 to 38.2)	37.3 (30.7 to 43.3)	0.398
MT curve flexibility	0.67 (0.57 to 0.79)	0.64 (0.51 to 0.72)	0.75 (0.64 to 0.76)	0.139
T1–12 TK (°)	23.6 (13.6 to 31.4)	33.5 (25.6 to 43.2)	36.8 (33.3 to 41.4)	**<0.001**
T5–12 TK (°)	10.0 (1.3 to 15.4)	20.6 (12.9 to 26.9)	23.3 (22.1 to 24.5)	**<0.001**
T10–L2 thoracolumbar kyphosis (°)	–8.1 (–13.7 to –3.3)	–5.9 (–13.8 to 0.8)	–1.8 (–3.5 to –1)	0.212
L1–S1 lumbar lordosis (°)	50.4 (42.8 to 60.4)	57.3 (48.6 to 63.7)	58.1 (54.3 to 63.1)	**0.023**
Sagittal vertical axis (mm)	–15.8 (–29.2 to 7.8)	–10.6 (–28.2 to 7.1)	–31.1 (–35.8 to –27.3)	0.184
T5–12 TK on fulcrum bending (°)	8.4 (2.5 to 17.8)	18.5 (12.5 to 23.5)	20.3 (9.4 to 20.4)	**<0.001**
TK correction on fulcrum bending (°)	1.1 (–3.2 to 4.9)	–1.6 (–8.5 to 5)	–13.9 (–17.2 to –1.7)	**0.030**
Immediate postoperative				
PT Cobb (°)	17.1 (12.8 to 21.6)	17.5 (12.7 to 23.2)	17.5 (17.5 to 20.4)	0.865
MT Cobb (°)	14 (11.1 to 20.5)	17 (12.8 to 22.8)	18.1 (11.5 to 19.5)	0.069
TL/L Cobb (°)	10.7 (5.8 to 16.5)	14.1 (9.7 to 19.3)	19.0 (1.3 to 19)	0.145
MT correction rate	0.75 (0.65 to 0.81)	0.7 (0.61 to 0.77)	0.67 (0.64 to 0.75)	**0.030**
T1–12 TK (°)	27.3 (20.2 to 32.3)	36.9 (28.5 to 42.5)	39.0 (30.5 to 48)	**<0.001**
T5–12 TK (°)	13.1 (8.4 to 16.3)	22.2 (18.5 to 26.3)	21.1 (19.2 to 29.4)	**<0.001**
T10–L2 thoracolumbar kyphosis (°)	–6.4 (–10.9 to –2.4)	–4.0 (–10 to 1.6)	–2.7 (–10.9 to 0.0)	0.314
L1–S1 lumbar lordosis (°)	47.3 (36.8 to 54.4)	50 (45.7 to 57.1)	48.7 (44.2 to 53.8)	0.057
Sagittal vertical axis (mm)	–5.4 (–20.9 to 16.8)	–15.8 (–31.8 to 14.9)	0.0 (0.0 to 28)	0.168
T5–12 TK correction (°)	3.6 (–0.6 to 6.3)	1.7 (–5.7 to 8.0)	–5.3 (–9.5 to 7.3)	0.301
2-Year follow-up				
PT Cobb (°)	15.1 (9.5 to 22)	16.3 (12 to 23.9)	15.1 (12.9 to 16.3)	0.676
MT Cobb (°)	18.3 (15.2 to 21.6)	21.5 (16.7 to 26.9)	22.6 (18.3 to 23.6)	**0.013**
TL/L Cobb (°)	10.9 (4.8 to 17.9)	14.8 (9.6 to 19.3)	18.8 (7.3 to 24.8)	**0.049**
MT correction rate	0.67 (0.63 to 0.74)	0.61 (0.52 to 0.71)	0.55 (0.53 to 0.6)	**0.015**
T1–12 TK (°)	24.9 (19.2 to 33.4)	39.3 (33.2 to 46.1)	50.3 (36.3 to 55)	**<0.001**
T5–12 TK (°)	14.3 (10.7 to 17)	27.7 (23.2 to 30.7)	40.3 (26.5 to 43)	**<0.001**
T10–L2 thoracolumbar kyphosis (°)	4.1 (–0.4 to 10.6)	7.6 (1.1 to 12.3)	12.3 (3.7 to 15.8)	0.550
L1–S1 lumbar lordosis (°)	–5.3 (–9.2 to –1.2)	–3.2 (–8.2 to 1.8)	–6.7 (–11.3 to 0)	**0.013**
Sagittal vertical axis (mm)	52.1 (45.4 to 60.4)	57.5 (50.5 to 64.4)	57.4 (57.2 to 64.2)	0.893
T5–12 TK correction (°)	–8.7 (–27.3 to 14)	–10.3 (–28.8 to 8.1)	–9.7 (–14.5 to 13.3)	0.085

Values are presented as median (Q1 to Q3) or number of patients (%) unless otherwise stated. Bolded factors indicate statistical significance.
PT, proximal thoracic; MT, main thoracic; TL/L, thoracolumbar/lumbar; TK, thoracic kyphosis.
[a]By independent-samples Kruskal-Wallis test. [b]By chi-square test.

Table 2. Results of point biserial regression for potential risk factors of hypokyphosis at immediate postoperative and 2-year follow-up

Preoperative parameters	Immediate postoperative		2-year follow-up	
	Coefficient/test statistic[a)]	*p*-value	Coefficient/test statistic[a)]	*p*-value
Demographic factors				
Age	–0.035	0.661	–0.091	0.256
Gender	0.015[b)]	0.904	1.250[b)]	0.264
Risser	–0.072	0.370	**–0.138**	**0.086**
Apical vertebral rotation	–0.039	0.632	**–0.140**	**0.082**
Curve type	2.468[b)]	0.291	1.697[b)]	0.428
Radiographical factors				
PT Cobb	0.078	0.341	0.033	0.684
MT Cobb	0.064	0.430	0.029	0.717
TL/L Cobb	0.112	0.164	0.029	0.716
MT curve flexibility	**0.187**	**0.020***	**0.162**	**0.044***
T1–T12 TK[c)]	–0.403	<0.001*	–0.436	<0.001*
T5–12 TK[c)]	–0.462	<0.001*	–0.488	<0.001*
T10–L2 thoracolumbar kyphosis	**–0.156**	**0.052***	**–0.135**	**0.093***
L1–S1 lumbar lordosis	**–0.142**	**0.077***	**–0.200**	**0.012***
T5–12 TK on fulcrum bending	**–0.524**	**<0.001***	**–0.425**	**<0.001***
Surgical factors				
Concave side implant density	–0.124	0.124	–0.042	0.605
Convex side implant density	**0.058**	**0.469**	**0.204**	**0.011***

Bolded factors were entered into the logistic regression model.
PT, proximal thoracic; MT, main thoracic; TL/L, thoracolumbar/lumbar; TK, thoracic kyphosis.
*$p<0.05$ (Statistical significance). [a)]Pearson's *r* was used unless specified. [b)]Pearson chi-square statistic was used. [c)]Factors were excluded due to multicollinearity.

96.8% (n=151) used titanium, 2.6% (n=4) used cobalt-chromium, 0.6% (n=1) used cobalt-chromium rod on the concave side and titanium rod on the convex side.

T5–T12 kyphosis correction on fulcrum bending was proportional to postoperative correction (immediate postoperative, $r=0.540$, $p<0.001$; 2-year follow-up, $r=0.369$; $p<0.001$). A negative correlation was found between preoperative T5–12 kyphosis on standing and fulcrum bending ($r=-0.497$, $p<0.001$); patients with more severe hypokyphosis could achieve more kyphosis correction. T5–12 kyphosis tended to normalize postoperatively (immediate postoperative, $r=-0.737$, $p<0.001$; 2-year follow-up, $r=-0.619$, $p<0.001$), as predicted on fulcrum bending. However, significant differences were noted between the T5–12 kyphosis on fulcrum bending and postoperatively ($p<0.001$).

Of all preoperative factors (Table 2), T5–12 kyphosis on fulcrum bending was the only significant risk factor for postoperative hypokyphosis (immediate postoperative odds ratio [OR], 0.870; 95% confidence interval [CI], 0.826–0.917; $p<0.001$; 2-year follow-up OR, 0.916; 95% CI, 0.876–0.959; $p<0.001$) (Table 3), whereas a 10% increase in convex side implant density was associated with a 74.9% increase in the risk of postoperative hypokyphosis at 2-year follow-up (OR, 1.749 per 10% increase; 95% CI, 1.056–2.897; $p=0.03$) (Table 3). The cutoff of T5–12 kyphosis on fulcrum bending for 2-year postoperative hypokyphosis was 12.45° (area under the curve, 0.773; 95% CI, 0.661–0.820; sensitivity, 0.773, specificity, 0.662).

Among the 14 patients with a lordotic thoracic spine preoperatively, one patient became normokyphotic at 2-year follow-up. However, there was no significant difference in the baseline demographic and radiological characteristics between the normokyphotic and hypokyphotic groups ($p>0.10$) (Table 4).

Discussion

Although coronal correction remains the primary objective in patients with AIS undergoing surgery, there is increasing emphasis on restoring sagittal balance to prevent early degenerative changes caused by spinopelvic malalignment [35]. Ideal TK targets have been widely discussed in the literature as arbitrary cutoffs [35,36] or patient-specific targets according to spino-

Table 3. Multivariate logistic regression for postoperative hypokyphosis at immediate postoperative and at 2-year follow-up

Predictor	OR (95% CI)	*p*-value[a)]
Immediate postoperative		
MT curve flexibility	4.562 (0.366–56.859)	0.238
Preoperative thoracolumbar kyphosis	0.995 (0.956–1.035)	0.798
Preoperative lumbar lordosis	1.005 (0.967–1.045)	0.790
T5–12 TK on fulcrum bending	0.870 (0.826–0.917)	<0.001*
Concave side implant density	0.280 (0.002–50.243)	0.631
2-Year follow-up		
Risser		
0	1	
1	0.739 (0.125–4.37)	0.739
2	1.326 (0.295–5.961)	0.713
3	1.687 (0.303–9.408)	0.551
4	0.529 (0.140–2.005)	0.349
5	0.737 (0.177–3.061)	0.674
Apical vertebral rotation		
1	1	
2	0.722 (0.295–1.768)	0.476
3	0.356 (0.093–1.359)	0.131
MT curve flexibility	4.140 (0.251–68.186)	0.319
Preoperative thoracolumbar kyphosis	0.991 (0.95–1.033)	0.663
Preoperative lumbar lordosis	0.987 (0.951–1.025)	0.504
T5–12 TK on fulcrum bending	0.916 (0.876–0.959)	<0.001*
Convex side implant density	1.749 (1.056–2.897)	0.030*

OR, odds ratio; CI, confidence interval; MT, main thoracic; TK, thoracic kyphosis.
*$p<0.05$ (Statistical significance). [a)]*p*-value of multivariate logistic regression.

pelvic parameters [37]. However, the introduction of excessive kyphosis to meet these ideal targets could result in adjacent segment disease [38]. Nonetheless, regardless of the "ideal" kyphosis, assessing whether patients will become normokyphotic (≥20°) following coronal curve correction and instrumentation is challenging. This study evaluated the surgical and preoperative risk factors on fulcrum bending radiographs for postoperative hypokyphosis in patients with Lenke 1. A low T5–12 kyphosis on fulcrum bending and high convex side implant density were risk factors for postoperative hypokyphosis (Figs. 3, 4).

Various techniques have been suggested to assess coronal curve flexibility to predict postoperative outcomes including fulcrum bending [26,39-41] and side bending [42]. Specifically, fulcrum bending radiographs can also be used to predict sagittal correction. Luk et al. [11] demonstrated the natural coronal sagittal coupling of the spine on fulcrum bending radiographs, where correcting the coronal curve resulted in some degree of sagittal correction. A positive relationship was found between the coupled sagittal changes and postoperative sagittal correction, indicating that the inherent sagittal flexibility of the spine hinders sagittal curve correction. Furthermore, patients with hypokyphosis tended to achieve more sagittal correction, demonstrating the tendency of the spine to "self-normalize [11]." This is in line with the findings of this study: sagittal correction on fulcrum bending was proportional to postoperative outcomes at immediate (r=0.540) and 2-year postoperative (r=0.369) periods; TK tended to normalize postoperatively (r=–0.737).

To the best of our knowledge, this study is the first

Table 4. Baseline characteristics and postoperative outcomes in patients with lordotic thoracic spines preoperatively

Parameter	Normokyphotic (n=1)	Hypokyphotic (n=13)	*p*-value[a)]
Risser	4	3 (2 to 4)	0.571
Apical vertebral rotation	2.0	2.0 (1.0 to 2.0)	0.714
MT curve flexibility	0.70	0.62 (0.58 to 0.79)	0.857
Preoperative MT Cobb (°)	51.2	52.2 (49.1 to 57.8)	1.000
Preoperative T5–T12 TK (°)	–4.8	–6.9 (–11.1 to –2.5)	1.000
Preoperative T10–L2 thoracolumbar kyphosis (°)	–10.9	–13.4 (–18.7 to –12.8)	0.571
Preoperative L1–S1 lumbar lordosis (°)	49.6	41.2 (37.4 to 42.6)	0.429
T5–12 TK on fulcrum bending (°)	0.2	1.2 (–4.5 to 3.1)	1.000
Postoperative T5–T12 TK (°)	11.1	6.3 (2.9 to 9.9)	0.571
2-Year follow-up T5–T12 TK (°)	20.7	10.8 (8.5 to 15.7)	0.143
Convex side implant density	5.7	6.0 (5.6 to 6.3)	0.857

Values are presented as median or median (Q1 to Q3) unless otherwise stated.
MT, main thoracic; TK, thoracic kyphosis.
[a)]*p*-value of Mann-Whitney *U* test.

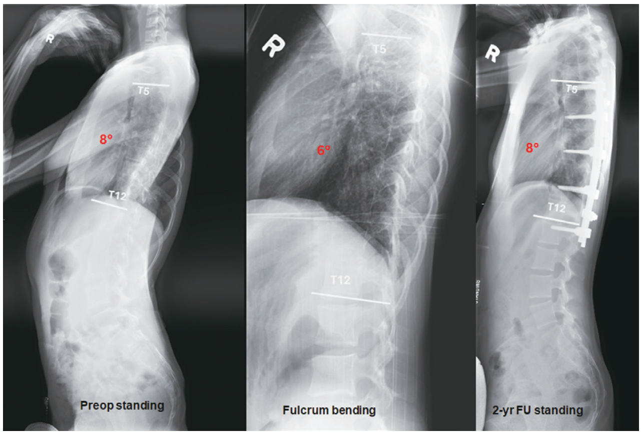

Fig. 3. Adolescent idiopathic scoliosis (AIS) patient with thoracic hypokyphosis showing decrease in T5–12 thoracic kyphosis on fulcrum bending, 2-year postoperative alignment showed no improvement in kyphosis. Preop, preoperative; FU, follow-up.

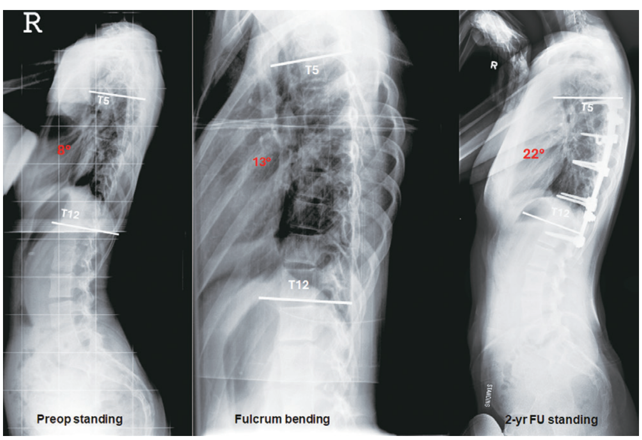

Fig. 4. Adolescent idiopathic scoliosis (AIS) patient with thoracic hypokyphosis showing increase in T5–12 thoracic kyphosis (TK) to 13° on fulcrum bending (>12.5°). Postoperative alignment revealed normalisation of TK (>20°). Preop, preoperative; FU, follow-up.

to demonstrate the predictive value of fulcrum bending radiographs for postoperative hypokyphosis: high T5–12 TK on fulcrum bending significantly decreases the risk of hypokyphosis by 13.0% and 8.4% at immediate and 2-year postoperative periods, respectively. Patients with rigid sagittal profiles on coronal bending are unlikely to achieve complete kyphosis restoration by coronal curve correction with alternate pedicle screw constructs alone. In the long term, normalization of TK would cause reciprocal changes in unfused segments: improving lumbar lordosis and cervical kyphosis and preventing degenerative changes [43]. A previous study also reported low TK and small coronal curve magnitude as risk factors for hypokyphosis at 2-year follow-up [14]. The present findings propose a correlation between coronal curve flexibility (r=0.187) and low kyphosis (r=0.462) with postoperative kyphosis; however, it was not a significant risk factor after adjusting for other preoperative factors. Moreover, previous studies were limited by the inclusion of multiple curve types (Lenke 1, 2, 3, 4, and 6) with more than one structural curve. This may cause heterogeneity in the results as patients undergoing longer fusions have a higher risk of postoperative hypokyphosis [44].

Significant differences remain between sagittal correction on coupling and postoperatively (p<0.001). Additional correction can be attributed to surgical factors. Angelliaume et al. [45] reported better T4–12 kyphosis restoration by cobalt-chromium than titanium rods, with less loss of correction over time [46]. In the present study, although titanium rods were used in most patients, the differences in rod materials yielded no difference in kyphosis correction (p>0.40). This could be due to the large differences in the number of patients in each group, which limited the statistical power.

Furthermore, intraoperative correction maneuvers, additional osteotomies, and releases could improve kyphosis correction. Pesenti et al. [15] compared four correction maneuvers, including in situ bending, rod derotation, cantilever, and posteromedial translation techniques. They reported that the posteromedial translation improved and the cantilever technique significantly worsened postoperative kyphosis correction. Conversely, evidence on the effect of Ponte osteotomies and releases on postoperative sagittal correction is conflicting [16-18]; thus, these procedures are not routinely used in all patients because of the increased operative risk [21,22]. Nevertheless, because the surgical procedure was standardised in this study, the effects of correction maneuver, Ponte osteotomies and releases were not evaluated. The proposed T5–12 TK cutoff of <12.5° on fulcrum bending could be a viable indication to use Ponte osteotomies or releases to improve kyphosis restoration in patients at risk for hypokyphosis.

The effect of implant density on kyphosis restoration remains controversial. Previous studies have discovered that high implant density on the concave side could prevent the flattening of the recontoured kyphotic rod, which improved postoperative kyphotic outcomes [12,44,47]. Larson et al. [48] reported decreased TK in high implant density fusions at 1-year follow-up. This is in line with the present findings that a high convex side implant density increased the risk of hypokyphosis at the 2-year follow-up. This could be due to the compression of the convex anchors following rod insertion: a higher anchor density would lead to stronger compressive forces, causing more posterior column shortening and kyphosis loss postoperatively.

TK restoration is crucial in lordotic thoracic curves to prevent future degenerative changes. Newton et al. [49] studied 60 patients with AIS presenting with >7° lordosis treated with PSF. They demonstrated that higher postoperative kyphosis in those undergoing segmental screw fixation, Ponte osteotomies and those using rigid stainless-steel rods. The present study only identified 14 patients with preoperative lordosis, with one returning to normokyphosis postoperatively, resulting in insignificant differences in preoperative and surgical parameters between the hypokyphotic and nomokyphotic groups. Nonetheless, this finding demonstrates that TK normalization is possible in patients with lordosis using alternate pedicle screw constructs without additional osteotomies or releases, although unlikely.

This study has certain limitations. First, given the retrospective design, some patients underwent surgery in the 2000s. Although no significant change was noted in the surgical protocol and techniques throughout the years, improvements in surgical implants with more rigid fixation may affect sagittal correction. Furthermore, this radiographical study did not analyze correlations with clinical outcomes. Lung function tests are not routinely performed for patients with AIS in Duchess of Kent Children's Hospital. However, patient-reported outcomes such as Scoliosis Research Society-22 scores were not introduced until the late 2000s and were not routinely assessed in patients undergoing surgery in the earlier years. Moreover, many patients were excluded because of unclear T5–12 TK on lateral view fulcrum bending films, as visualization of the coronal curve on fulcrum bending was the main concern. Finally, an arbitrary cutoff for thoracic hypokyphosis was used. This contradicts the increasing emphasis on using patient-specific TK targets calculated by spinopelvic parameters. However, this was limited by the older long cassette radiographs that did not fully expose the pelvis, hindering the measurement of these parameters. Future prospective studies can ensure clear visualization of T5–12 vertebral levels on lateral view fulcrum bending films, utilize spinopelvic parameters to set patient-specific kyphosis targets, and correlate radiographical outcomes with improvements in clinical and patient-reported outcomes.

Conclusions

To our knowledge, this is the first study that demonstrated the clinical utility of lateral view fulcrum bending radiographs to predict postoperative hypokyphosis. Low T5–12 kyphosis on fulcrum bending increases the risk of postoperative hypokyphosis at both the immediate and 2-year postoperative periods. A high convex side implant density was a risk factor for 2-year postoperative hypokyphosis, whereas other surgical factors did not affect kyphosis correction. The present findings suggest that T5–12 kyphosis of <12.5° on fulcrum bending is associated with a high risk of postoperative hypokyphosis; Ponte osteotomies, releases or a decrease in convex side implant density could improve kyphosis restoration in patients with hypokyphosis.

Key Points

- Lateral view fulcrum bending radiographs predict postoperative hypokyphosis in addition to its previously described capabilities to predict coronal correction.
- Low T5–12 thoracic kyphosis (TK) on lateral view fulcrum bending radiographs and high convex side implant density are significant risk factors for postoperative hypokyphosis.
- In patients with T5–12 TK <12.5° on lateral view fulcrum bending radiographs, Ponte osteotomies, releases or a decrease in convex side implant density should be considered to improve kyphosis restoration in patients who are hypokyphotic preoperatively (T5–12 TK <20°).

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

ORCID

Victoria Yuk Ting Hui: https://orcid.org/0009-0009-7210-577X;
Jason Pui Yin Cheung: https://orcid.org/0000-0002-7052-0875;
Prudence Wing Hang Cheung: https://orcid.org/0000-0002-3213-7373

Author Contributions

Conceptualization: all authors. Methodology: all authors. Data curation: VYTH. Formal analysis: VYTH. Investigation: VYTH. Project administration: PWHC. Resources: JPYC, PWHC. Visualization: all authors. Validation: JPYC, PWHC. Supervision: JPYC, PWHC. Writing–original draft: VYTH. Writing–review & editing: all authors. Final approval of the manuscript: all authors.

References

1. Illes T, Tunyogi-Csapo M, Somoskeoy S. Breakthrough in three-dimensional scoliosis diagnosis: significance of horizontal plane view and vertebra vectors. Eur Spine J 2011;20:135-43.
2. Grabala P, Kowalski P, Grabala M. The influence of increased pedicle screw diameter and thicker rods on surgical results in adolescents undergoing posterior spinal fusion for idiopathic scoliosis. J Clin Med 2024;13:2174.
3. Matsumoto H, Colacchio ND, Schwab FJ, Lafage V, Roye DP, Vitale MG. Flatback revisited: reciprocal loss of lumbar lordosis following selective thoracic fusion in the setting of adolescent idiopathic scoliosis. Spine Deform 2015;3:345-51.
4. Yu M, Silvestre C, Mouton T, Rachkidi R, Zeng L, Roussouly P. Analysis of the cervical spine sagittal alignment in young idiopathic scoliosis: a morphological classification of 120 cases. Eur Spine J 2013;22:2372-81.
5. Liu Y, Pan A, Hai Y, Li W, Yin L, Guo R. Asymmetric biomechanical characteristics of the paravertebral muscle in adolescent idiopathic scoliosis. Clin Biomech (Bristol) 2019;65:81-6.
6. Fabricant PD, Heath MR, Schachne JM, Doyle SM, Green DW, Widmann RF. The epidemiology of back pain in American children and adolescents. Spine (Phila Pa 1976) 2020;45:1135-42.
7. Young E, Regan C, Currier BL, Yaszemski MJ, Larson AN. At mean 30-year follow-up, cervical spine disease is common and associated with thoracic hypokyphosis after pediatric treatment of adolescent idiopathic scoliosis. J Clin Med 2022;11:6064.
8. Lin A, Skaggs DL, Andras LM, Tolo V, Tamrazi B, Illingworth KD. Increasing cervical kyphosis correlates with cervical degenerative disk disease in patients with adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 2024;49:486-91.
9. Kan MM, Negrini S, Di Felice F, et al. Is impaired lung function related to spinal deformities in patients with adolescent idiopathic scoliosis?: a systematic review and meta-analysis-SOSORT 2019 award paper. Eur Spine J 2023;32:118-39.
10. Winter RB, Lovell WW, Moe JH. Excessive thoracic lordosis and loss of pulmonary function in patients with idiopathic scoliosis. J Bone Joint Surg Am 1975;57:972-7.
11. Luk KD, Vidyadhara S, Lu DS, Wong YW, Cheung WY, Cheung KM. Coupling between sagittal and frontal plane deformity correction in idiopathic thoracic scoliosis and its relationship with postoperative sagittal alignment. Spine (Phila Pa 1976) 2010;35:1158-64.
12. Kokabu T, Sudo H, Abe Y, Ito M, Ito YM, Iwasaki N. Effects of multilevel facetectomy and screw density on postoperative changes in spinal rod contour in thoracic adolescent idiopathic scoliosis surgery. PLoS One 2016;11:e0161906.
13. Bowden D, Michielli A, Merrill M, Will S. Systematic review and meta-analysis for the impact of rod materials and sizes in the surgical treatment of adolescent idiopathic scoliosis. Spine Deform 2022;10:1245-63.
14. Fletcher ND, Hopkins J, McClung A, Browne R, Sucato DJ. Residual thoracic hypokyphosis after posterior spinal fusion and instrumentation in adolescent idiopathic scoliosis: risk factors and clinical ramifications. Spine (Phila Pa 1976) 2012;37:200-6.
15. Pesenti S, Clement JL, Ilharreborde B, et al. Comparison of four correction techniques for posterior spinal fusion in adolescent idiopathic scoliosis. Eur Spine J 2022;31:1028-35.
16. Feng J, Zhou J, Huang M, Xia P, Liu W. Clinical and radiological outcomes of the multilevel Ponte osteotomy with posterior selective segmental pedicle screw constructs to treat adolescent thoracic idiopathic scoliosis. J Orthop Surg Res 2018;13:305.
17. Pizones J, Sanchez-Mariscal F, Zuniga L, Izquierdo E. Ponte osteotomies to treat major thoracic adolescent idiopathic scoliosis curves allow more effective corrective maneuvers. Eur Spine J 2015;24:1540-6.
18. Shah SA, Dhawale AA, Oda JE, et al. Ponte osteotomies with pedicle screw instrumentation in the treatment of adolescent idiopathic scoliosis. Spine Deform 2013;1:196-204.
19. Cidambi KR, Glaser DA, Bastrom TP, Nunn TN, Ono T, Newton PO. Postoperative changes in spinal rod contour in adolescent idiopathic scoliosis: an in vivo deformation study. Spine (Phila Pa 1976) 2012;37:1566-72.
20. Harfouch EB, Bunyan RF, Al Faraidy M, et al. The effect of Ponte osteotomies on the sagittal shape of rods and spine derotation in adolescent idiopathic scoliosis: a single-center, retrospective cohort study. World Neurosurg X 2022;15:100125.
21. Halanski MA, Cassidy JA. Do multilevel Ponte osteotomies in thoracic idiopathic scoliosis surgery improve curve correction and restore thoracic kyphosis? J Spinal Disord Tech 2013;26:252-5.
22. Holewijn RM, Schlosser TP, Bisschop A, et al. How does spinal release and Ponte osteotomy improve spinal flexibility?: the law of diminishing returns. Spine Deform 2015;3:489-95.
23. Faldini C, Viroli G, Traversari M, et al. Ponte osteotomies in the surgical treatment of adolescent idiopathic scoliosis: a systematic review of the literature and meta-analysis of comparative studies. Children (Basel) 2024;11:92.
24. Wang F, Chen K, Ji T, et al. Do hypokyphotic adolescent idiopathic scoliosis patients treated with Ponte osteotomy obtain a better clinical efficacy?: a preliminary retrospective study. J Orthop Surg Res 2022;17:491.
25. Nash CL Jr, Moe JH. A study of vertebral rotation. J Bone Joint Surg Am 1969;51:223-9.
26. Cheung KM, Luk KD. Prediction of correction of scoliosis with use of the fulcrum bending radiograph. J Bone Joint Surg Am 1997;79:1144-50.
27. Cheung KM, Lam JW, Samartzis D, Lu WW, Luk KD. The use of a modified fulcrum for fulcrum bending radiographs: a technical note. J Orthop Surg (Hong Kong) 2014;22:248-51.

28. Luk KD, Cheung KM, Lu DS, Leong JC. Assessment of scoliosis correction in relation to flexibility using the fulcrum bending correction index. Spine (Phila Pa 1976) 1998;23:2303-7.
29. Luk KD, Don AS, Chong CS, Wong YW, Cheung KM. Selection of fusion levels in adolescent idiopathic scoliosis using fulcrum bending prediction: a prospective study. Spine (Phila Pa 1976) 2008;33:2192-8.
30. Shigematsu H, Cheung JP, Bruzzone M, et al. Preventing fusion mass shift avoids postoperative distal curve adding-on in adolescent idiopathic scoliosis. Clin Orthop Relat Res 2017;475:1448-60.
31. Schwab F, Blondel B, Chay E, et al. The comprehensive anatomical spinal osteotomy classification. Neurosurgery 2014;74:112-20.
32. Stagnara P, De Mauroy JC, Dran G, et al. Reciprocal angulation of vertebral bodies in a sagittal plane: approach to references for the evaluation of kyphosis and lordosis. Spine (Phila Pa 1976) 1982;7:335-42.
33. Cortina-Borja M. Handbook of parametric and nonparametric statistical procedures, 5th edn. J R Stat Soc Ser A Stat Soc 2012;175:829.
34. Cheung GW, Cooper-Thomas HD, Lau RS, Wang LC. Reporting reliability, convergent and discriminant validity with structural equation modeling: a review and best-practice recommendations. Asia Pac J Manag 2024;41:745-83.
35. Abelin-Genevois K, Estivalezes E, Briot J, Sevely A, Sales de Gauzy J, Swider P. Spino-pelvic alignment influences disc hydration properties after AIS surgery: a prospective MRI-based study. Eur Spine J 2015;24:1183-90.
36. Hwang SW, Samdani AF, Tantorski M, et al. Cervical sagittal plane decompensation after surgery for adolescent idiopathic scoliosis: an effect imparted by postoperative thoracic hypokyphosis. J Neurosurg Spine 2011;15:491-6.
37. Post M, Verdun S, Roussouly P, Abelin-Genevois K. New sagittal classification of AIS: validation by 3D characterization. Eur Spine J 2019;28:551-8.
38. Boeckenfoerde K, Schulze Boevingloh A, Gosheger G, Bockholt S, Lampe LP, Lange T. Risk factors of proximal junctional kyphosis in adolescent idiopathic scoliosis: the spinous processes and proximal rod contouring. J Clin Med 2022;11:6098.
39. Mannem A, Cheung PW, Kawasaki S, Shigematsu H, Cheung JP. What determines immediate postoperative coronal balance and delayed global coronal balance after anterior spinal fusion for Lenke 5C curves? Eur Spine J 2021;30:2007-19.
40. Ohrt-Nissen S, Cheung PW, Kawasaki S, Shigematsu H, Cheung JP. Curve overcorrection predicts coronal imbalance in selective thoracic fusion in adolescent idiopathic scoliosis. Global Spine J 2024;14:856-61.
41. Ohrt-Nissen S, Kamath VH, Samartzis D, Luk KD, Cheung JP. Fulcrum flexibility of the main curve predicts postoperative shoulder imbalance in selective thoracic fusion of adolescent idiopathic scoliosis. Eur Spine J 2018;27:2251-61.
42. Cheh G, Lenke LG, Lehman RA Jr, Kim YJ, Nunley R, Bridwell KH. The reliability of preoperative supine radiographs to predict the amount of curve flexibility in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 2007;32:2668-72.
43. Blondel B, Lafage V, Schwab F, Farcy JP, Bollini G, Jouve JL. Reciprocal sagittal alignment changes after posterior fusion in the setting of adolescent idiopathic scoliosis. Eur Spine J 2012;21:1964-71.
44. Lonner BS, Lazar-Antman MA, Sponseller PD, et al. Multivariate analysis of factors associated with kyphosis maintenance in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 2012;37:1297-302.
45. Angelliaume A, Ferrero E, Mazda K, et al. Titanium vs cobalt chromium: what is the best rod material to enhance adolescent idiopathic scoliosis correction with sublaminar bands? Eur Spine J 2017;26:1732-8.
46. Ohrt-Nissen S, Dahl B, Gehrchen M. Choice of rods in surgical treatment of adolescent idiopathic scoliosis: what are the clinical implications of biomechanical properties?: a review of the literature. Neurospine 2018;15:123-30.
47. Sudo H, Abe Y, Kokabu T, et al. Correlation analysis between change in thoracic kyphosis and multilevel facetectomy and screw density in main thoracic adolescent idiopathic scoliosis surgery. Spine J 2016;16:1049-54.
48. Larson AN, Polly DW Jr, Diamond B, et al. Does higher anchor density result in increased curve correction and improved clinical outcomes in adolescent idiopathic scoliosis? Spine (Phila Pa 1976) 2014;39:571-8.
49. Newton PO, Wu KW, Bastrom TP, et al. What factors are associated with kyphosis restoration in lordotic adolescent idiopathic scoliosis patients? Spine Deform 2019;7:596-601.