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Investigation of in vivo three-dimensional changes of the spinal canal after corrective surgeries of the idiopathic scoliosis

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Abstract

Objective: To determine the three-dimensional (3D) changes of the spinal canal length (SCL) after corrective surgeries and their association with the radiographic and clinical outcomes of idiopathic scoliosis patients. The length of the spinal cord has been demonstrated to be strongly correlated with the SCL. Understanding the changes in SCL could help determine the morphologic changes in the spinal cord to prevent spinal cord injury.

Methods: Twenty-seven scoliotic patients' 3D spinal canal were investigated using computed tomography images. The SCL between the upper and lower end vertebrae (U/L-EV) was measured at five locations. The radiographic parameters of each patient and the patient-reported outcomes (PROs) scores were also collected. The correlations of the changes of the SCLs with the other factors were analyzed.

Results: The SCL between the U/L-EV changed non-uniformly at different locations. The post-operative SCLs were significantly elongated by 7.5 ± 3.5 mm (6.0 ± 2.5%, $P < .001$) at the concave side and compressed by −2.6 ± 2.6 mm (−1.9 ± 1.9%, $P < .001$) at the convex side. The elongations of the SCL at the concave and posterior locations were correlated with the radiographic parameters including the pre-operative main Cobb angles ($r = .511$, $P = .006$; $r = .613$, $P = .001$) and apical vertebral translation (AVT) ($r = .481$, $P = .011$; $r = .684$, $P = .000$). No PRO scores were found to correlate with the SCL changes.

Conclusion: The corrective surgeries elongated the spinal canal mainly at the concave side and compressed at the convex side. The main thoracic Cobb angle, the changes of AVT, and Cobb angles were moderately associated with the changes of the SCLs, but no PRO score was found to associate with the changes of the SCLs. The data could be instrumental for the improvement of corrective surgeries that are aimed to maximize the correction of scoliosis and minimize the negative effect on the spinal cord to prevent neurological complications.

KEYWORDS
idiopathic scoliosis, spinal canal, spinal cord injury, spine, spine deformity, three-dimensional reconstruction

1 | INTRODUCTION

Idiopathic scoliosis is a three-dimensional (3D) structural deformity of the spine.[1] The abnormal spinal curve of the idiopathic scoliosis could be corrected surgically by using screw insertion, rod placement, derotation, cantilever technique, local distraction and compression.[2-4] However, intraoperative over-stretch of the spinal cord due to correction of the spine deformity could result in spinal cord injury (SCI).[5-8] The morbidity of neurological complications, although has been reported to be around 1%, could result in serious consequences such as damages to the spinal cord of the patients.[9-13] Therefore, it is critically important to control the negative effects of corrective surgeries on spinal cord deformation.

Many studies have investigated the injury conditions of the spinal cord.[5,6,14,15] Studies using living animal models measured the maximum elongation lengths of the spinal cord that could result in neurological signal changes.[6,14] It is evidenced that overstretching the spinal canal results in the SCI, and the changes of spinal canal length (SCL) is correlated with spinal cord legnth.[6,14] Therefore, measuring changes in the length of the spinal canal accurately predicts changes in the length of the spinal cord. Few retrospective studies of the scoliotic patients have measured the changes of the central SCL based on pre- and post-operative X-ray[16] or computed tomography (CT) images[17] of the patients. Due to variations in patient conditions and measurement techniques, inconsistent data have been reported on the SCL changes among these studies. For example, Bridwell et al conducted a study using X-rays to measure the changes of SCL. Basically, the measurements on X-rays contains ratio mismatch, artificial measurements error which conduces to unperfect results; Yahara et al using CT images measured the length of SCL by connecting the central points of each vertebrae on selected planes. Ideally, the spinal cord could be considered as a cylinder and its deformation is 3D rather than linear. Therefore these results of 2D measurements cannot exactly demonstrate the morphological deformation of the operated spine in different locations such as in the concave and convex side; These studies demonstrated that the SCL changes measured at one location, such as at the central spinal cord, could provide insufficient data on the 3D spinal cord deformation. Further, clinical studies that used the somatosensory evoked potentials (SSEPs) to monitor the spinal cord have reported that SSEPs could decline fractionally only on one side of the spinal cord[18] and pathological damages to the spinal cord could vary across the spinal cord cross section.[15] To understand that which side of the spinal cord is more liable to be injured is critical to prevent SCI in operations. To our knowledge, no studies have measured the SCL changes in 3D in different locations of the spinal cord. It is unknown how the corrective surgeries could affect the changes of the SCL across the spinal canal cross section.

Previously, we have investigated 3D geometries of the human spinal canal by reconstruction of the 3D spinal canal volume.[19,20] Using this technique, we investigated the SCL changes of a group of scoliotic patients before and after corrective surgeries and the relationship between the SCL changes and clinical outcomes after the surgery. It was hypothesized that the spinal canal of idiopathic scoliosis experiences inhomogeneous deformation in 3D space after the corrective surgeries and the SCL changes are correlated to the clinical outcomes.

2 | MATERIALS AND METHODS

2.1 | Patients

This is an observational, retrospective study of 27 patients (5 males and 22 females) with idiopathic scoliosis operated between 2015 and 2018 in our hospital (Table 1). This study was approved by the Beijing Chao-Yang hospital, Capital Medical University ethics committee on August 31, 2019. The mean age of the patients was 18.9 ± 5.1 years (range 13-30 years) at the surgery. Their Risser signs are IV or V, implying that the skeleton is nearly or already mature and could be treated using fusion techniques. Since the spinal cord normally does not extend below L2 level, we selected patients with Lenke I or II scoliosis (indicating the spinal deformity at the thoracic segment and not involving the lumbar segment) in this retrospective study. Sixteen patients were with Lenke I scoliosis and 11 with Lenke II scoliosis. All patients were operated by one medical team. To compare with the data reported in literature,[16,17] we further stratified the patients into two groups with one having main thoracic Cobb angles between 40° and 80° ($n = 17$) and the other between 80° and 120° ($n = 10$). No patient had previous history of surgical treatments. Pre- and post-operative full spine X-ray and 3D CT images (Siemens, Germany, with a 1 mm thickness and a resolution of 512 × 512 pixels) of the whole spine of each patient acquired for surgical planning and treatments were obtained for this study. Patient reported outcomes (PRO) scores, including Scoliosis Research Society Outcomes-22 (SRS-22), Short Form Healthy Survey (SF-36), Japanese Orthopaedic Association (JOA) and visual analogue scale (VAS) questionnaires, were obtained. Each patient was clinically followed up at 3, 6, 12, 24 and 36 months post-operatively. The PRO scores at the last available follow up of all patients were analyzed in this study.

2.2 | Surgical methods

All patients were treated using a standard corrective surgical procedure. Under general anesthesia, the patient was positioned in prone

TABLE 1 Demographic and radiographic parameters of the Patients

	Mean ± SD			
Characteristics	**All cases (n = 27)**	**40°-80° (n = 17)**	**80°-120° (n = 10)**	***P* value**
Age at operation (years)	18.9 ± 5.1	18.6 ± 5.1	19.2 ± 5.3	.857
Height (cm)	157.4 ± 9.3	160.5 ± 7.0	152.6 ± 10.5	<.05 (57.0%)
Weight (kg)	48.3 ± 9.5	51.7 ± 10.1	43.2 ± 6.0	.491
BMI	19.5 ± 3.3	20.0 ± 3.6	18.6 ± 2.6	.302
Risser (grade)	4 ± 1	4 ± 1	4 ± 1	.517
Follow up (m)	12.4 ± 8.3	11.5 ± 4.6	10.2 ± 5.7	.725
Pre-op radiographic factors				
Cobb angle (°)				
Proximal thoracic	36.2 ± 12.1	29.4 ± 7.4	48.2 ± 9.0	<.00001 (100.0%)
Main thoracic	77.3 ± 21.8	62.9 ± 8.9	101.9 ± 12.7	<.00001 (100.0%)
Thoracolumbar/lumbar	33.8 ± 11.5	32.0 ± 11.5	37.8 ± 11.2	.249
Flexibility (%)	31.0 ± 11.1	32.0 ± 14.0	22.9 ± 7.0	<.05 (50.9%)
Kyphosis (°)	22.0 ± 17.7	15.4 ± 12.2	33.4 ± 20.4	<.01 (73.3%)
AVT (mm)	59.3 ± 27.8	44.0 ± 20.3	85.4 ± 17.5	<.00001 (100.0%)
SRS-22	85.2 ± 5.0	87.4 ± 4.1	81.6 ± 4.3	<.01 (91.4%)
SF-36	90.2 ± 3.8	90.3 ± 3.7	90.0 ± 4.3	.840
JOA	26.5 ± 1.8	26.6 ± 1.8	26.2 ± 1.9	.632
VAS	2.8 ± 1.3	2.7 ± 1.4	3.0 ± 1.2	.639

Note: Statistical powers obtained from post hoc power analysis (using the software of G*Power 3.1) were shown in parentheses along with *P* values <.05.
Abbreviations: JOA, Japanese Orthopaedic Association; SF-36, Short Form Healthy Survey; SRS-22, Scoliosis Research Society Outcomes; VAS, visual analogue scale.

with a posterior middle incision. Subperiosteal exposure of posterior elements of the spine was performed. Pedicle screws were inserted at both sides, and pre-curved titanium rods were inserted. The scoliosis was then preliminary realigned using rod-derotation techniques. A direct segmental derotation technique was used to enhance the vertebral derotation outcome around the apical vertebra. Correction outcomes were finally enhanced by conventional correction techniques including distraction, compression and translation. If the deformity was rigid, an asymmetrical Ponte osteotomy averaged by four levels would be performed and a sequential segmental compression and cantilever maneuver were used to close the osteotomies and correct the kyphosis. SSEPs were used to monitor the neurological response of the spinal cord during the entire operation for each patient.

2.3 | Radiographic parameters

All patients had full spine X-rays and CT scans taken within 1 month before and after the surgery. In this study some common and clinical relative radiographic parameters such as main thoracic Cobb angle, kyphosis, apical vertebral translation (AVT) and flexibility index were measured on the X-ray images. The Cobb angle[21] is defined as the angle between the most two tilting vertebrae on cranial and caudal. The AVT[22] is defined as the distance between the central point of apex and the C7 plumbline. The flexibility index is defined as the difference between the Cobb angle in standing position and the Cobb angle in bending position divided by the Cobb angle at standing position. The correction rate of Cobb angles is defined as the difference between the post- and pre-operative angles divided by the pre-operative angle.

2.4 | 3D model analysis

The CT images of each patient were input into the 3D-Slicer software (V.4.10.1) to reconstruct a 3D model of the entire spine (Figure 1A). The model was then input into the Rhinoceros software (V. 5.5.2) for measurements of the geometric parameters of the spine (Figure 1B). Different vertebrae were marked using different colors to ease geometric measurements in the software (Figure 1C). As the spinal cord generally reaches to the L2 level and the upper instrumented vertebra is normally not above the T2 level, the spinal canal was analyzed between the L2 to T2 vertebrae and between the U/L-EV. To do this, each selected vertebra was cut in a plane that is parallel to the upper endplate and passing through the center points of both pedicles in the axial direction to create a cross section of the spinal canal (Figure 1D). The cross section of the canal was outlined using a closed curve. The area centroid of the cross section was defined as the center point of the spinal canal. Using the anatomic landmarks on the canal, the anterior, posterior, left and right points of the canal were specified

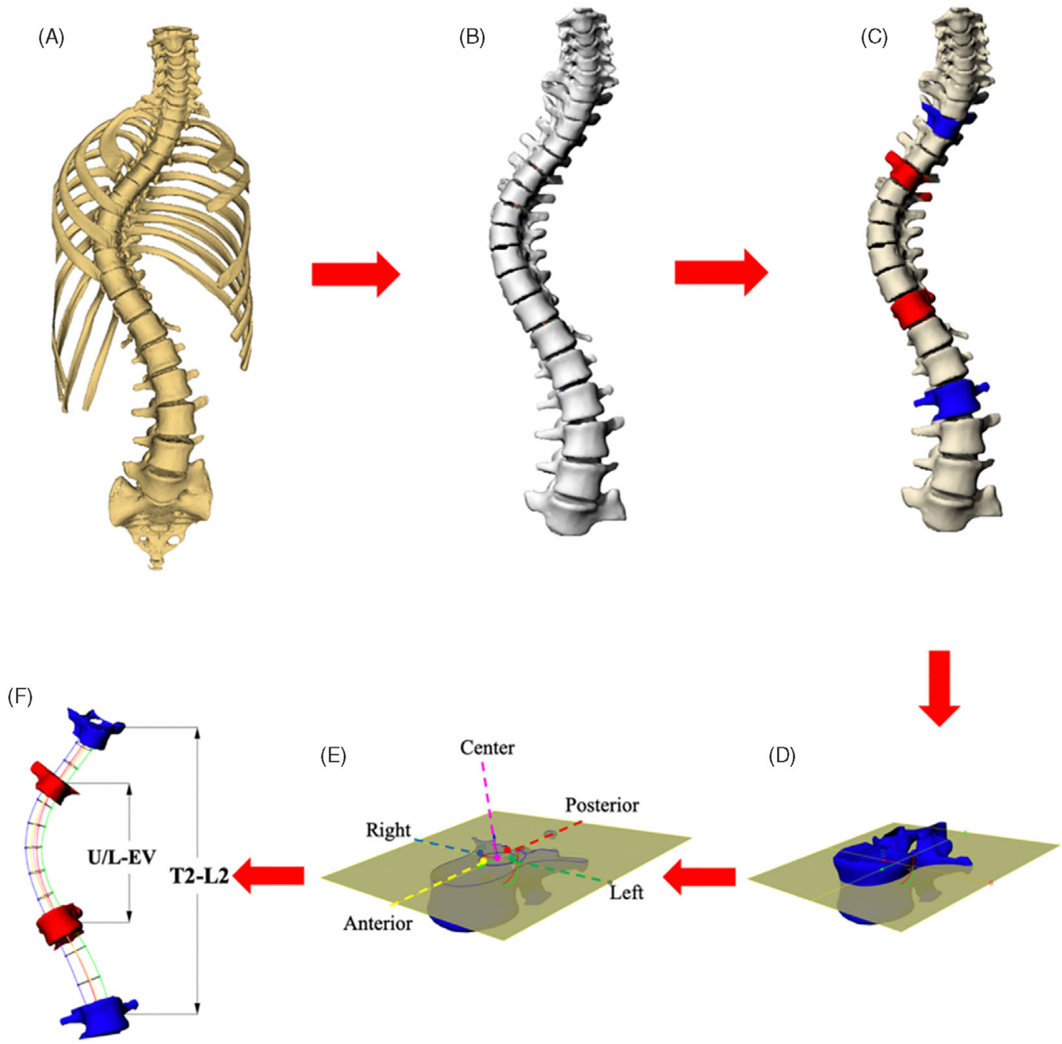

FIGURE 1 A, A 3D raw model of the spine reconstructed using computed tomography (CT) images. B, The 3D spine model. C, The vertebrae were colored for scoliosis analysis: T2 and L2 in dark blue, upper and lower end vertebrae (U/L-EV) in red, and the rest of the spine in butter; D, the cross-section cut on a vertebra for the determination of the spine canal outline. The plane is parallel to the upper endplate and passes the center points of both pedicles in the axial direction. E, Outline of the spinal canal and the definition of different locations on the canal cross-section. F, The surface shape of the spine canal. The longest line was defined as the convex side and the shortest was define as the concave side. The spinal canal length (SCL) was measured between the U/L-EV and T2-L2 segments

(Figure 1E). The same locations on all canal sections were connected by curved lines to represent the length of the canal at different locations of the spinal canal (Figure 1F). The length of the spinal canal at each selected location on the canal cross section was measured using the Rhinoceros software. The location having the shortest SCL was defined as the concave side, and the opposite side was defined as the convex side (Figure 2).

2.5 | Statistical analysis

All results were expressed using mean values and SDs (mean ± SD). Paired *t* test was used to compare the changes of patient outcome scores and radiographic parameters of the spine before and after surgeries. A repeated measure analysis of variance (ANOVA) with a Tukey post hoc test was performed to compare the SCL changes after the surgeries at the concave, center, convex, anterior and posterior locations of the spinal canal. A significant difference was defined when $P < .05$. Pearson's coefficient test was used to calculate the correlations of the changes of the SCL with the radiographic parameters and post-operative PROs scores. A comparison of the changes of the SCL was also performed between the Lenke I and II patients of this cohort. All statistical analyses were performed using the SPSS 22.0 software.

3 | RESULTS

The patients' demographic data were shown in Table 1. The main thoracic Cobb angle was 77.3° ± 21.8 (48.3°-123.0°) and the follow-up

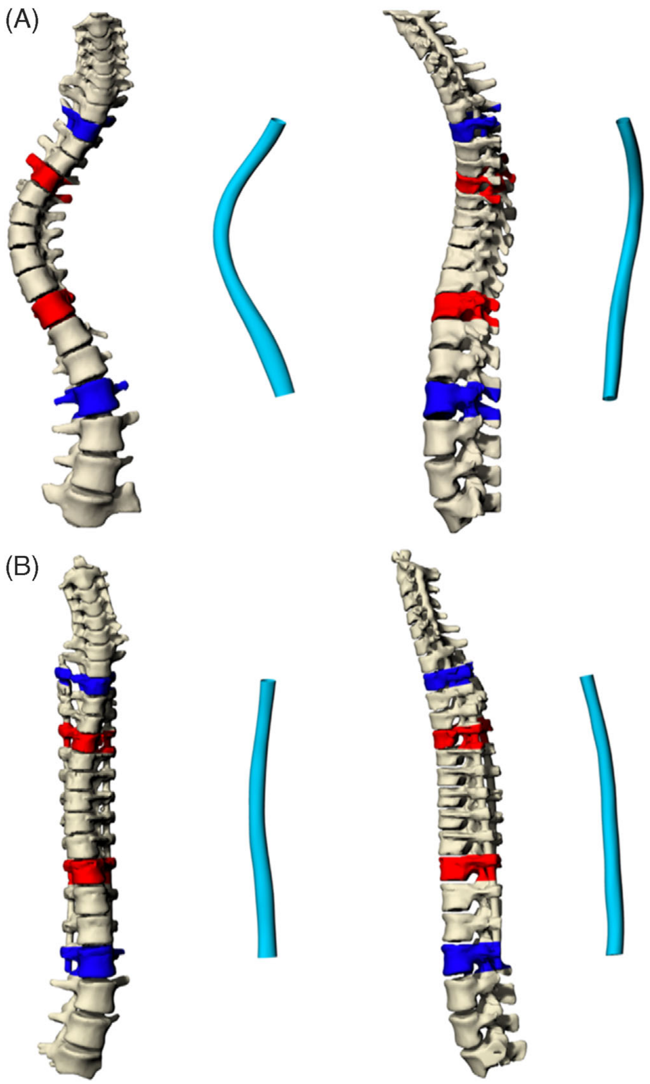

FIGURE 2 The spine vertebra and canal models of a typical patient constructed A, before and B, after the surgery

time was 12.4 ± 8.3 months (6-36 months). By stratifying the patients into moderate (40°-80°) and severe (80°-120°) scoliosis groups, there were significant differences in body heights, proximal Cobb angles, main thoracic Cobb angles, flexibility, kyphosis and AVT between the two groups ($P < .05$) (Table 1). There were significant differences in post-operative Cobb angles (17.0 ± 9.2° vs 39.9 ± 12.7°, $P < .00001$), Cobb angle changes (45.9 ± 10.6° vs 62.0 ± 8.2°, $P < .001$), correction rates (73.1 ± 13.1% vs 61.4 ± 9.5%, $P < .05$) and post-operative AVT (14.0 ± 12.8 mm vs 32.2 ± 7.4 mm, $P < .001$) between the two groups (Table 2).

The SCL between the U/L-EV changed non-uniformly at different locations of the spinal canal after the surgery (Table 3). On average, the SCL was elongated the most by 7.5 ± 3.5 mm (6.0 ± 2.5%) at the concave side ($P < .001$), followed by 3.1 ± 3.5 mm (2.1 ± 2.5%) at the posterior side ($P < .001$), 2.4 ± 2.6 mm (1.6 ± 1.8%) at the center point ($P < .001$), and 1.75 ± 1.97 mm (1.24 ± 1.37%) at the anterior side ($P < .001$). However, the convex side was shortened by −2.6 ± 2.6 mm (−1.9 ± 1.9%) ($P < .001$). The SCL changes at the concave (elongation) and the convex (compression) sides were significantly different from those at other locations ($P < .001$). No significant difference was detected among the changes of the SCL at the anterior, center, and posterior locations. The SCL change at the concave side in the 40° to 80° patient group (6.1 ± 2.9 mm) was significantly smaller than that in the 80° to 120° group (10.0 ± 3.0 mm) ($P < .01$). A significant difference was also detected at the posterior (1.6 ± 3.2 mm vs 5.6 ± 2.7 mm) ($P < .01$), but not at the convex (−2.9 ± 2.1 mm vs −2.1 ± 2.9 mm) ($P = .101$) sides of the spinal canal between the two patient groups. There was no significant difference of the changes of the SCLs between the Lenke I and II patient groups in the five locations on the spinal canal cross section (Table 4).

The PRO scores were all improved after the surgery ($P < .05$). There were significant differences in SRS-22 scores before and after the surgeries between the two groups of patients but no differences in other outcome scores. The elongations of the SCL at the concave and posterior sides were moderately correlated with the radiographic parameters including main Cobb angle ($r = .511$, $P = .006$; $r = .613$, $P = .001$), pre-operative AVT ($r = .481$, $P = .011$; $r = .684$, $P = .000$) and Cobb angle changes of the apical vertebral levels. No outcome score, such as SRS-22, SF-36, JOA and VAS, was found to correlate with the changes of SCLs (Figure 3) (Table 5).

4 | DISCUSSION

Ischemic spinal cord injuries of idiopathic scoliosis patients due to over-stretch of the spinal cord during corrective surgeries have been reported in literatures.[5,7,8,23] Experimental measurements using animal models have reported the maximum distractions of the spinal canal that could result in spinal cord injuries.[6,14] In a porcine model, a mean elongation of 20.2 mm (3.6% to thoracolumbar length) of the spine was found to cause histological spinal cord injuries.[6] While in a goat model,[14] the spinal cord was found to be injured at an average elongation of 11.8 mm. Few studies have also reported on the changes of the SCLs of clinically successful patients.[16,17] Bridwell et al found that the center of the spinal canal of the scoliosis patients was elongated by an average of 8.4 mm (3.7-12.7 mm) after corrective surgeries, while Yahara et al found that the center of the SCL was changed by a mean of 10.1 mm (3.6% to T2-L2 canal length, range between 2.3 and 28.8 mm) between the T2 and L2 vertebrae. A comparison of the data reported between the animal models and the clinically successful patients in literature showed that a portion of the patients would have the spinal canal elongated more than the injury levels found in the animal models.[6,14] However, in our data, the changes of the SCLs were shown to be much smaller than the data observed in the animal models[6,14] and living patients reported previously.[16,17] For example, for patients with Cobb angles in the range of 40° to 80°, our measurements showed an average of 1.8 mm elongation of the center canal between the U/L-EV, but an average elongation of 8.4 mm was reported in literature.[16] Between T2 and L2 segments, our patients showed a mean of 6.5 mm (2.5-10.5 mm,

TABLE 2 Postoperative results of the patients

	Mean ± SD			
	All cases (n = 27)	40°-80° (n = 17)	80°-120° (n = 10)	*P* value
Post-op radiographic				
Cobb angle (°)				
Main thoracic	25.5 ± 15.4	17.0 ± 9.2	39.9 ± 12.7	<.00001 (100.0%)
Cobb change	51.8 ± 12.4	45.9 ± 10.6	62.0 ± 8.2	<.001 (98.4%)
Correction rate (%)	68.7 ± 13.0	73.1 ± 13.1	61.4 ± 9.5	<.05 (69.4%)
Kyphosis (°)	20.1 ± 6.7	18.8 ± 5.4	22.3 ± 8.4	.199
AVT (mm)	20.7 ± 14.2	14.0 ± 12.8	32.2 ± 7.4	<.001 (98.7%)
SRS-22	96.0 ± 5.2	97.9 ± 4.3	92.9 ± 5.4	<.05 (69.5%)
SF-36	97.2 ± 4.3	98.2 ± 4.0	95.4 ± 4.4	.129
JOA	27.8 ± 1.3	27.8 ± 1.3	27.6 ± 1.4	.813
VAS	1.1 ± 0.9	1.1 ± 1.0	0.9 ± 0.8	.661

Note: Statistical powers obtained from post hoc power analysis (using the software of G*Power 3.1) were shown in parentheses along with *P* values <0.05.
Abbreviations: JOA, Japanese Orthopedic Association; SF-36, Short Form Healthy Survey; SRS-22, Scoliosis Research Society Outcomes; VAS, visual analogue scale.

TABLE 3 3D Measurements of the SCL between U/L-EV segments

	Mean ± SD					
	All cases		40°-80° group		80°-120° group	
	Delta change (mm)	Correction rate (%)	Delta change (mm)	Correction rate (%)	Delta change (mm)	Correction rate (%)
Concave (1)	7.54 ± 3.47[2,3,4,5]	5.98 ± 2.51	6.07 ± 2.89	4.99 ± 1.83	10.04 ± 2.98	7.67 ± 2.69
Center (2)	2.40 ± 2.57[1,3]	1.63 ± 1.75	1.77 ± 2.36	1.22 ± 1.64	3.46 ± 2.67	2.34 ± 1.80
Convex (3)	−2.59 ± 2.62[1,2,4,5]	−1.91 ± 1.88	−2.91 ± 2.08	−2.24 ± 1.86	−2.06 ± 2.90	−1.36 ± 1.88
Anterior (4)	1.75 ± 1.97[1,3]	1.24 ± 1.37	1.44 ± 1.78	1.08 ± 1.28	2.28 ± 2.27	1.51 ± 1.52
Posterior (5)	3.08 ± 3.53[1,3]	2.08 ± 2.49	1.62 ± 3.18	1.09 ± 2.33	5.55 ± 2.69	3.77 ± 1.79

Note: Multiple comparison (one-way ANOVA + post hoc Tukey correction): different sites were represented by numbers 1 to 5 in parentheses; the significant differences of the SCL changes at a site compared with other sites were indicated by superscript numbers ($P < .05$). For the SCL changes at different locations considering all cases (ie, the first column), post hoc power analysis (G*Power 3.1) shows that the statistical power of the one-way ANOVA is 100.0%.
Abbreviations: SCL, spinal canal length; U/L-EV, upper and lower end vertebrae.

TABLE 4 The change of SCL between Lenke I and II

	Lenke I		Lenke II	
Side	Delta change (mm)	Correction rate (%)	Delta change (mm)	Correction rate (%)
Concave	6.00 ± 3.66	4.58 ± 2.55	8.20 ± 3.53	6.46 ± 2.29
Center	1.91 ± 2.73	1.34 ± 1.92	2.40 ± 2.81	1.59 ± 1.98
Convex	−2.61 ± 2.62	−1.86 ± 1.79	−3.11 ± 3.19	−2.35 ± 2.30
Anterior	1.51 ± 2.38	1.11 ± 1.73	1.51 ± 1.74	1.02 ± 1.19
Posterior	2.35 ± 3.45	1.58 ± 2.39	3.54 ± 3.99	2.38 ± 2.99

Note: There was no significant difference of the change of SCL between Lenke I and II.
Abbreviation: SCL, spinal canal length.

2.4%) elongation of the canal length at the center of the canal, but an average elongation of 10.1 mm (2.3-28.8 mm, 3.6%) was reported in literature.[17] The differences between our data and those reported in the literature could be explained by the differences in measurement methods of the SCLs. Most of the reported studies measured the SCL at the center of the canal using 3D CT images or X-ray images,[16,17] and no studies have directly measured the 3D spinal canal morphologic changes after corrective surgeries. In our study, we

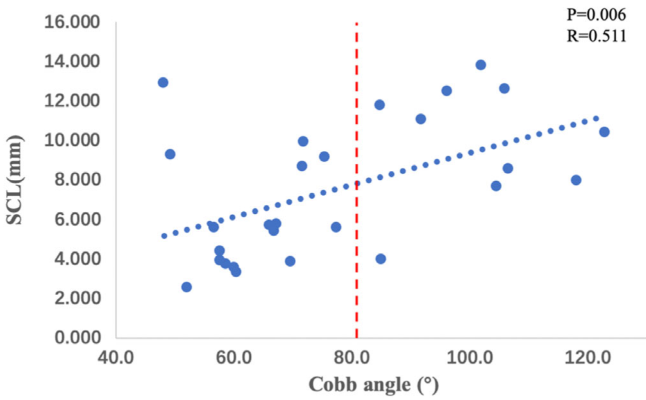

FIGURE 3 The correlation of the changes of spinal canal length (SCL) with the main Cobb angle

reconstructed the 3D-models of the spinal canals using high-resolution CT images acquired before and after the surgery using a previously validated method (Figure 2).[24] 3D-reconstruction is the gold standard in measuring spine.[25] Therefore, we were able to accurately determine the 3D morphologic changes of the spinal canal after the surgery.

In contemporary corrective surgeries of scoliosis, the intraoperative neurological damage of the axial spinal cord has been found at different locations across the spinal cord cross section,[15] and SSEPs always showed unilateral spectrum deteriorations.[18,26] SCI was found not simply in the center location of the cord. Therefore, it could provide incomplete information on spinal cord conditions if the SCL changes are only measured at the center of the spinal canal. As the concave side of the tense spinal cord of scoliosis patients has the shortest length in the canal,[27,28] the concave side of the spinal

TABLE 5 Correlation coefficients/*P* values (*R*/*P*) between the changes of the SCL in five locations and the clinical factors

	SCL				
Clinical factors	Concave	Center	Convex	Anterior	Posterior
Age	.038/.849	.089/.660	.229/.251	.120/.293	.101/.617
Height	.051/.807	.126/.550	.200/.337	−.006/.978	−.136/.516
Post-height	.119/.057	.212/.309	.183/.381	.025/.905	.094/.656
Delta height	*.471/.017*	.057/.786	.039/.854	.022/.916	.040/.849
Weight	−.197/.346	−.011/.959	.125/.552	−.066/.755	−.373/.066
BMI	−.268/.295	−.116/.580	−.002/.992	−.080/.706	−.348/.088
Risser	.135/.504	.036/.859	−.059/.770	.246/.217	−.066/.742
Pre-op radiographic factors					
Proximal curve	.208/.340	.011/.960	.109/.621	.145/.508	.057/.272
Main thoracic	*.511/.006*	.296/.134	.172/.402	.235/.248	*.613/.001*
Thoracolumbar/lumbar	.298/.158	.157/.452	.004/.984	.035/.873	.151/.481
Kyphosis	.219/.283	.122/.543	.302/.133	.227/.266	.263/.194
flexibility	−.370/.063	−.240/.227	−.074/.719	−.111/.590	−.347/.083
AVT	*.481/.011*	*.390/.044*	.232/.255	.205/.315	*.684/.000*
EV distance	*.493/.009*	.379/.051	.080/.699	.168/.411	.160/.426
TL distance	−.056/.783	−.100/.620	−.075/.717	−.151/.462	*−.444/.020*
Post-op radiographic factors					
Post cobb	.146/.477	.250/.209	.273/.177	.082/.690	.318/.114
Delta cobb angle	*.387/.046*	.210/.292	−.049/.812	.282/.163	*.520/.005*
Correction rate	.220/.280	−.132/.513	−.245/.227	.091/.658	−.136/.509
Delta AVT	*.550/.003*	.014/.943	.095/.643	.191/.350	*.622/.001*
Delta kyphosis	−.124/.548	−.139/.498	−.244/.229	−.131/.525	−.192/.349
Delta EV distance	*.489/.010*	.300/.128	.242/.234	*.396/.041*	*.406/.036*
Delta TL distance	*.474/.012*	.226/.257	.099/.632	.203/.320	*.417/.030*
SRS-22	.029/.893	.081/.708	−.136/.866	.026/.906	.007/.975
SF-36	.115/.594	.001/.098	−.011/.959	.205/.377	−.128/.551
JOA	.005/.982	.201/.346	.208/.330	.275/.194	.156/.467
VAS	.171/.426	−.138/.520	.000/.999	.027/.899	−.216/.312

Note: The italic values emphasis the correlation.

Abbreviations: AVT, apical vertebral translation; JOA, Japanese Orthopaedic Association; SCL, spinal canal length; VAS, visual analogue scale.

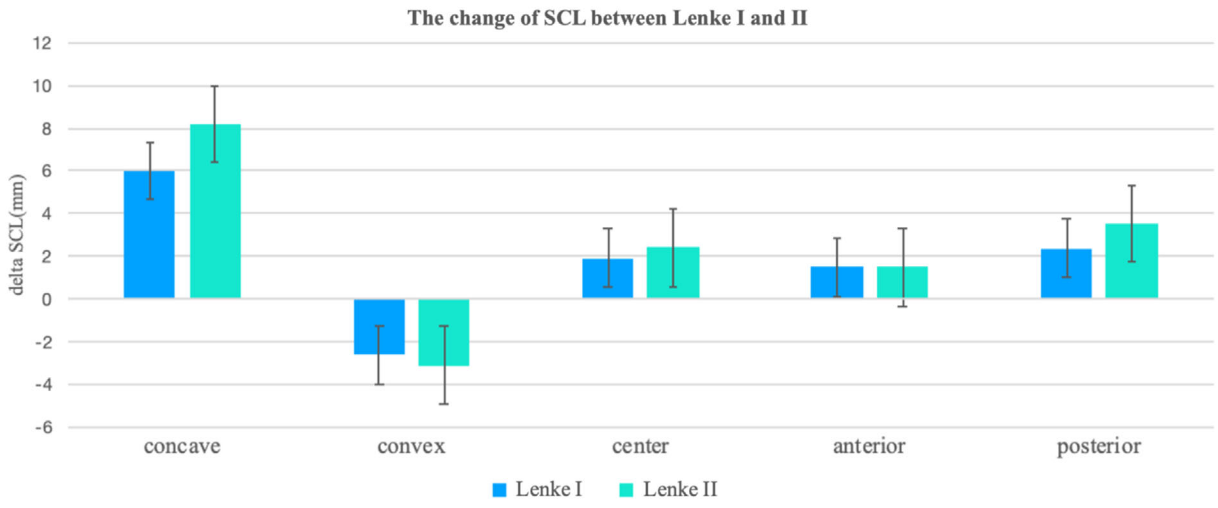

FIGURE 4 The changes of spinal canal length (SCL) between Lenke I and II

cord could be more prone to over-stretch during corrective surgeries that could lead to spinal cord damages. Between the U/L-EV, we found that the SCL in the concave side was changed in average by 7.5 mm (2.5-13.8 mm, 6.0%), that is almost 3 times of that at the center canal (2.4 mm, −2.3-7.3 mm, 1.6%). Since the patients of our study were with improved PROs and radiographic outcomes (without post-operative neurological complications), the SCL elongations of these patients caused by the corrective surgeries could be within a safe region of the spinal cord deformation.

Our data also showed that there were moderate correlations between the radiographic parameters (such as the main thoracic Cobb angles, pre-AVT, the change of AVT and Cobb angles) and the changes of the SCL at the concave side (Figure 3). By stratifying the patients into two groups (with Cobb angles of 40°-80° and 80°-120°), we further found that there was a significant difference in the changes of the SCLs in the concave side between the two patient groups (average 6.1 vs 10.0 mm, $P = .002$) but not in the center and convex sides of the canal. These data indicate that patients of larger Cobb angles could experience larger SCL changes during the corrective surgeries. Therefore, it should be cautious when conducting local distractions in the concave side of the spine during corrective surgeries of patients with severe scoliosis. An excessive SCL elongation of patients with severe scoliosis could be liable to impair the spinal cords.[29]

It is interesting to find that there was no significant difference in the changes of the SCLs between patients of Lenke I and II across the canal sections (Figure 4). Corrections of the spine deformities of these patients were performed by a rod-rotation (with or without osteotomy) at the apical vertebrae, and the proximal thoracic curve which rarely affects the correction was passively corrected secondary to the main cure. Therefore, the changes of the SCLs were not affected by the types of spinal deformity curves.

There were some limitations in this study. First, the patient population is relatively small. Therefore, this study could not make a comparison between patients operated using Ponte osteotomy and those using simple corrections. Future study should examine how different surgical techniques could affect the spinal canal during operations. Second, the follow-up time was short (in a mean of 12.4 months, range from 6 to 36 months) since it is difficult to follow patients with severe scoliosis in a longer time. The spinal canal geometry could change with post-operative time due to the post-operative correction lost. Future studies should collect patient data in longer follow up terms. Third, the CT images of the spine were taken in a supine position for all patients. Therefore, the data could not be used to represent the changes of the SCL under weightbearing conditions. In addition, this retrospective study included patients without clinical complications. Therefore, the measured SCL changes represent the safe zone data of spinal cord deformation. Future study should investigate the maximal changes of the SCL by evaluating the SCL changes of scoliotic patients combing with SSEPs' abnormal potential and(or) Multi-shot echo-planar diffusion tensor imaging (MS-DTI) that could evaluate the conditions and functions of the spinal cord on each side to investigate when and where the spinal cord could be injured and what is the safe maximum elongation of the SCL. At last we did not take vertebral rotation and height into consideration cause we did not find an accurate method to evaluate these factor, we will try a 3D-measurements on models in the next step study.

5 | CONCLUSION

This study measured the changes of the SCLs of scoliotic patients after corrective surgeries for spine deformity. The increasing in SCLs was mainly found at the concave side and decreasing in the convex side of the spinal canal. The main thoracic Cobb angle, the changes of AVT and Cobb angles were moderately associated with the SCL changes. No outcome scores were found to associate with the changes of the SCL in this study. The data of this study demonstrated that the 3D analysis of the spinal canal is a valuable method for evaluation the SCL changes of scoliotic patients before and after corrective surgeries. These data could be instrumental for future improvement of corrective surgeries that are aimed to maximize the correction of the spine deformity and minimize the negative effect on spinal cord to prevent neurological complications.

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CONFLICT OF INTEREST

The authors declare that no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Guoan Li and **Yong Hai:** Conceived and conducted the study. **Chaofan Han:** Carried out the reconstuctions and segmentations of 3D-models, data collection and analysis of this study. **Chaochao Zhou** and **Wei Wang:** Performed statistical analysis and data collection. **Peng Yin**, **Ruisheng Guo**, and **Thomas Cha:** Contributed to revision. **Chaofan Han:** Drafted this manuscript. The authors read and approved the final manuscript.

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