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A novel classification on degenerative thoracolumbar kyphosis based on sagittal spino-pelvic alignment: should the thoracolumbar segments be intervened?

Haoyuan Li[1†], Zhenqi Zhu[1†], Yuqiao Li[1†], Weiwei Xia[1], Chong Zhao[1], Chen Guo[1], Shuai Xu[1,2*] and Haiying Liu[1*]

Abstract

Purpose There are few researches on characterizing the sagittal alignment of degenerative thoracolumbar kyphosis (DTLK). In addition, the debate on the reasonable surgical strategies, for various patterns of DTLK, still continues. So, the study was to identify the features of DTLK, propose a novel classification of DTLK, and develop surgical strategies for this population.

Methods An overall 245 patients diagnosed with DTLK combined with lumbar stenosis performed surgeries (acquired satisfied) were selected from January 2016 to December 2022. The spino-pelvic measurements thoracic kyphosis (TK), thoracolumbar kyphosis (TLK), lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), sagittal vertical axis (SVA) as well as the severe osteoporosis were recorded. To identify groups with similar spino-pelvic sagittal alignment parameters and clinical features, a 2-step cluster analysis was performed.

Results Close relationships were found among the parameters. Four types of DTLK based on TLK and balance were classified with Type I: mild kyphosis and balance, Type II: mild kyphosis and imbalance, Type III: severe kyphosis and balance, Type IV: severe kyphosis and imbalance. The probability for imbalance with severe osteoporosis was 8.4 times higher than no osteoporosis (RR = 8.410). The probability for imbalance with PI-LL mismatch was 10 times higher than PI-LL matching (RR = 0.099 in Type II and RR = 0.103 in Type IV). For patients with DTLK, the TK was correlated with LL, PI-LL or PI in Type I to III group but not in Type IV group. Targeted treatment strategies for different types of patients was then addressed.

Conclusion We proposed a novel classifcation with four types of DTLK based on TLK and balance, followed by targeted treatment strategies for various types. Osteoporosis and lumbo-pelvic mismatch were risk factors for DTLK imbalance.

†Haoyuan Li, Zhenqi Zhu and Yuqiao Li are co-first authors.

*Correspondence:
Shuai Xu
xushuairmyy@pku.edu.cn
Haiying Liu
liuhaiying1131@sina.com

Full list of author information is available at the end of the article

Keywords Degenerative thoracolumbar kyphosis, Spino-pelvic alignment, Cluster analysis, Surgical strategy, Lumbar stenosis syndrome

Introduction

Degenerative thoracolumbar kyphosis (DTLK) is a structural deformity caused by spinal degeneration, often characterized by a reduction of normal anterior convexity angle in the sagittal plane [1], which significantly affects quality of patients' life. With the aging population, the number of patients with DTLK is expected to increase mainly due to skeletal disorders such as spinal deformation, intervertebral disc degeneration, osteoporosis and muscular atrophy [2]. DTLK is usually exposed accompanied with lumbar spinal stenosis in the elderly, leading to lower back pain, lower limb radiating pain, and intermittent claudication [3].

As the transitional area between the thoracic and lumbar vertebrae, the thoracolumbar junction plays an important role in both focal and entire sagittal balance [4]. Compared with the normal individuals, patients with DTLK are usually reported associated with reduced lumbar lordosis (LL), increased thoracic kyphosis (TK) as well as the modification of other parameters. Nevertheless, as the pattern of DTLK is not changeless, the classification of DTLK should be addressed to better characterize the sagittal alignment of DTLK and provide specific treatment strategies. However, few studies on this issue were searched. In 2005, Roussouly [5] firstly proposed a classification targeting normal spinal balance while still difficult to outline the patients with spinal degenerative diseases. Although the well-known SRS-Schwab classification was then proposed facing to adult spinal deformities [6], it mainly focused on scoliosis instead of sagittal malformation and hardly enabled to planning surgical strategies [7]. In 2017, Sebaaly et al. [8] firstly addressed a classification for sagittal alignment of spine with degenerative disorders, while it still failed to provided targeted treatment methods.

The sagittal alignment and spino-pelvic balance are fascinating in the field of adult spinal deformities. It was reported that the physiological spinal alignment are not stable but gradually varied with age. More specifically and obviously, the threshold of spino-pelvic parameters seems to be enlarged by increased age over 50 years, which has been demonstrated by Lafage et al., who established a formula linked the age with the pelvic incidence minus LL (PI-LL), pelvic tilt (PT) as well as sagittal vertical axis (SVA), based on more than 700 elderly population [9]. Although the hospitalized patients with DTLK are often combined with lumbar spinal stenosis, while there is still debate on whether the thoracolumbar kyphosis should be intervened during the surgical treatment for lumbar stenosis segments. Here, in order to identify the features of DTLK and summary targeted surgical strategies for this population, a novel classification of DTLK was to proposed.

Materials and methods

Participants and study design

A single-center retrospective study from January 2016 to December 2022 was conducted. The patients diagnosed with DTLK (Cobb angle > 15 degree) combined with lumbar stenosis performed surgical treatment were enrolled.The included criteria were DTLK participants: (1) with the age of over 50 years; (2) with surgical indication on lumbar stenosis and performed surgery by the same senior surgeon; (3) complete and clear preoperative full spine standing X-rays could be obtained; (4) with the follow up of at least one year and (5) the *health-related quality of life* was characterized by satisfied treatment, which was evaluated by t*he visual analogue scale (VAS) scores for the low back and leg, Oswestry disability index (ODI), and the Odom's criteria (excellent-good-fair-poor). The satisfaction was mainly quantified by* the ODI change larger than 25 scores and reaching *"good to excellent" grade of Odom's criteria*. The excluded criteria were participants: (1) with coronary imbalance malformations; (2) with incomplete or blurred X-ray data; (3) diagnosed as other spinal deformities such as scoliosis and ankylosing sopndylitis; (4) with lumbar spine tumors, infections, or spondylolisthesis; (5) performed thoracolumbar and lumbar spine surgery before; (6) performed arthroplasty on hip or knee joints; (7) *suffered from rheumatic diseases*, *coagulation abnormalities*, *systemic immune disorders*, *and surgical intolerance*.

All patients have signed informed consent and this study was approved by the Institutional Ethics Committee of our hospital. Eventually, a total of 245 patients (M: F = 64:181) were included the study with the mean follow up of 16.8 ± 4.3 months. The mean age of the cases was 67.1 ± 10.4 with the BMI of 25.4 ± 4.0 (kg/m^2) (Table 1).

Sagittal spino-pelvic alignment

Sagittal spino-pelvic alignment was characterized by the measurements containing TK, TLK and LL (spinal parameters), PI, PT and sacral slope (SS) (pelvic parameters), PI-LL (lumbo-pelvic parameter), and the balance status such as SVA and spino-sacral angle (SSA), where TLK, PI-LL, PT and SVA were regarded as the main parameters. The definition of all parameters were described in Fig. 1 (Fig. 1). All parameters were acquired on the picture archiving and communication system (PACS). In addition, the severe osteoporosis was also

Table 1 The demographics and spino-pelvic sagittal Paramters in DTLK patients at baseline

Parameters	M ± sd /(range)
M: F	64: 181
Age (y)	67.1 ± 10.4 (50 ~ 88)
BMI (kg/m^2)	25.4 ± 4.0 (18.7 ~ 35.6)
TLK (°)	26.1 ± 10.0 (15.1 ~ 64.2)
SVA (mm)	42.1 ± 43.4 (-61.8 ~ 200.0)
SSA (°)	66.4 ± 15.0
TK (°)	27.6 ± 13.9
LL (°)	31.7 ± 18.7
PI (°)	44.1 ± 10.9
PT (°)	19.8 ± 10.6
PI-LL (°)	11.1 ± 15.8
SS (°)	24.2 ± 11.1

Footnote: DTLK: degenerative thoracolumbar kyphosis; BMI: body mass index; TLK: thoracolumbar kyphosis; SVA: sagittal vertical axis; SSA: spino-sacral angle; TK: thoracic kyphosis; LL: lumbar lordosis; PI: pelvic incidence; PT: pelvic tilt; SS: sacral slope

Δ: The change of variable between postoperation and preoperation

evaluated based on the dual energy X-ray absorption as well as the intraoperative sensation of the senior operator.

In this study, TLK was stratified into mild kyphosis (Cobb angle ≤ 25) and severe kyphosis (Cobb angle > 25). There is currently no clear definition for mild to severe cases. Some studies suggest that the severe kyphosis of DTLK is defined as TLK greater than 25–30 degrees; [10] In addition, Katzman's study found that for every 10 degrees increase in thoracic or thoracolumbar kyphosis, there is a 22% increase in the risk of spinal fractures and significant changes in local biomechanics [11]. According to the DTLK definition, the degree of DTLK exceeds 15 degrees, and there will be changes after adding 10 degrees. Therefore, this study uses 25 degrees as the threshold.

PI was divided into two types named low PI (≤ 50) and high PI (> 50°) [8]. According to Schwab et al. [12], PI-LL, PT and SVA were regarded as the main sagittal spino-pelvic paramters. Then, Lafage developd age-related correction formulas on the main spino-pelvic parameters where PI-LL=(Age-55)/2 + 3, PT=(Age-55)/3 + 20 and SVA = 2×(Age-55) + 25. The three parameters based on cutoff vaule of Lafage formulas were also divided, where PI-LL, PT and SVA were respectively divided into matched and mismatched status, normal and retro-versional status, and balance and imbalance status.

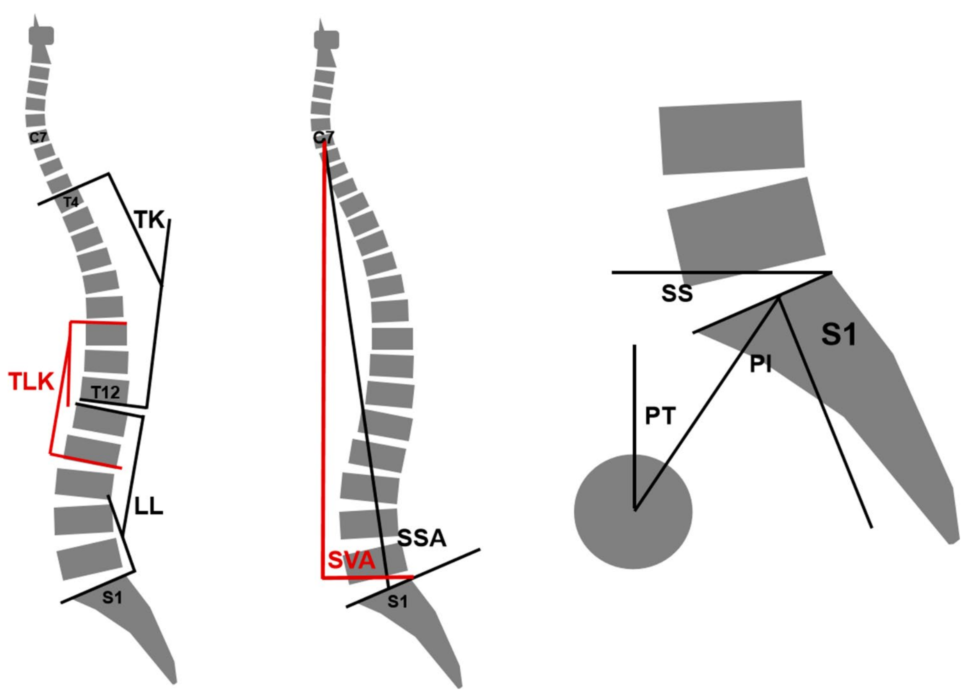

Fig. 1 The diagrams and definition of sagittal spino-pelvic parameters. TK: the angle between the upper endplate of T4 and the lower endplate of T12; TLK: the angle between upper endplate of T10 and lower endplate of L2; LL: the angle between upper endplate of L1 and upper endplate of S1; PT: the angle between a line drawn from the S1 endplate to the center of the femoral heads drawn intersecting the femoral heads; PI: the angle subtended by a line connecting the center of the femoral head to the center of the cephalad end plate of S1 and a second line drawn perpendicular to the S1 endplate at its center; SS: the angle between a line drawn parallel to the S1 endplate and the horizontal plane; PI-LL: the difference between PI and LL, a key parameter for quantifying sagittal balance used to determine whether the pelvis and lumbar match; SVA: the interval between C7 plumb line and the posterior upper corner of S1; SSA: the angle between a line connecting the midpoint of C7 to the midpoint of the sacral endplate and the upper endplate of the sacrum

Table 2 *The clinical indicators before and after surgery* and the postoperative complications of patients

	Preoperation point	End point	Δ
VAS-low back	5.3 ± 3.6	2.1 ± 1.9	3.1 ± 3.0
VAS-leg	7.5 ± 3.9	2.8 ± 1.5	4.8 ± 3.2
ODI	40.2 ± 13.0	8.7 ± 4.7	31.3 ± 7.6
Odom's criteria (excellect-good-fair-poor)	0-8-63-174	158-67-18-2	
Complications			
PJK (proximal junctional kyphosis)	3 (none with obvious symptoms)		
Internal fixation loosening or fracture	0		
Dural rupture	8 (with routine conservative treatment)		
ASD (adjacent segment degeneration)	13 (all with conservative treatment)		
SSI (*surgical site infection)*	3 (the wound promptly cleaned)		
Reoperation	4 (three for cervical spine surgery and one for thoracic MISS)		

Δ: The change of variable between postoperation and preoperation

Statistical analysis

To identify groups of DTLK patients with similar spino-pelvic sagittal alignment parameters, a 2-step cluster analysis was performed using a combination of hierarchal cluster and k-mean cluster analysis for all participants. Of note, the 2-step cluster analysis is a natural way to select the number of groups and criteria for groups within a dataset, where measurement data were automatically standardized. The distance was calculated with the log-likelihood method and the number of clusters was determined automatically with use of the Bayesian information criterion. The clustering average contour value was addressed by Silhouette value, which larger than 0.5 means the clustering was reasonable.

The measurement data was expressed as mean ± standard deviation. Pearson correlation analysis was utilized among spine-pelvic sagittal parameters in DTLK patients. The one-way analysis of variance method was used to compare all parameters among different clusters (groups). And then, the multinomial logistic regression analysis was performed to identify the disparities of these parameters for these clusters. The multiple linear regression analysis (TK as the dependent variable) was conducted to determine the influencing factors for proximal spine and distal spino-pelvic alignment. Notably, as PI was regard as the intrinsic anatomical parameters and LL was regarded as the initial region of the change of biomechanical compensatory chain for sagittal alignment, so the post-hoc analysis mainly depended on the relationship between TK and PI or PI-LL, where the latter was usually regarded as the independent variable. The statistical analysis was performed using SPSS 22.0 (International Business Machines Corporation, Armonk, NY, USA) and statistical significance was defined as P value < 0.05.

Results

The mean TLK was 26.1 ± 10.0 and the mean PI-LL, PT and SVA was respectively 11.1 ± 15.8, 19.8 ± 10.6 and 42.1 ± 43.4 (Table 1). All patients' health-related quality of life has improved, with the mean change VAS-low back of 3.1 ± 3.0,the mean change VAS-leg of 4.8 ± 3.2, and the mean change ODI of 31.3 ± 7.6. Odom's criteria (excellect-good-fair-por) improves from 0-8-63-174 to 158-67-18-2. Only two patients reached poor grade of Odom's criteria, respectively due to cervical spine and knee disorders. *The rate of complications was 12.6%, mainly including proximal junctional kyphosis, internal fixation loosening or fracture, dural rupture*, adjacent segment degeneration. *The result of complications was shown in* (Table 2).

Among these sagittal parameters, SVA was positively correlated to SSA and PI-LL ($P < 0.001$), while it negatively correlated to LL and SS ($P < 0.01$). TK was positively correlated to LL, PI and SS ($P < 0.001$), while negatively correlated to PI-LL ($P < 0.001$). PT was positively correlated to PI and PI-LL ($P < 0.001$), while negatively correlated to SS ($P < 0.001$) (Table 3).

Then the 2-step cluster analysis was performed for the sagittal parameters. Eventually, TLK and SVA (both seen as dichotomous mentined above) were detected as the 2 main dependent variables for cluster formations. Here,

Table 3 The correlation analysis among spino-pelvic sagittal Paramters in DTLK patients

	SVA	SSA	TK	TLK	LL	PI	PT	PI-LL
SSA	0.433***							
TK	-0.133*	-0.178*						
TLK	0.003	0.005	0.162*					
LL	-0.496***	-0.617***	0.522***	-0.002				
PI	-0.038	-0.388***	0.205**	-0.038	0.466***			
PT	0.145*	0.341***	-0.024	0.008	-0.360***	0.462***		
PI-LL	0.537***	0.475***	-0.389***	-0.06	-0.717***	0.121	0.566***	
SS	-0.172**	-0.663***	0.227***	-0.038	0.792***	0.535***	-0.490***	-0.416***

Notefoot: DTLK: degenerative thoracolumbar kyphosis; SVA: sagittal vertical axis; SSA: Spino-sacral angle; TK: thoracic kyphosis; TLK: thoracolumbar kyphosis; LL: lumbar stenosis; PI: pelvic incidence; PT: pelvic tilt; SS: sacral slope four unique clusters of subjects based on TLK and balance were formed, which included cluster I (Type I): mild kyphosis and balance; cluster II (Type II): mild kyphosis and imbalance; cluster III (Type III): severe kyphosis and balance; cluster IV (Type IV): severe kyphosis and imbalance, which was verified with the Akaike information criterion.The silhouette measure of cohesion was larger than 0.5, indicating a good fit for our clusters. A scatterplot detailing the spread of each cluster in terms of TLK and balance is shown in Fig. 2 (Fig. 2). Among the four clusters, TK was smaller in small TLK groups (Type I and Type II) ($P=0.002$). SSA and PI-LL were smaller in balance groups (Type I and Type III) ($P=0.003$ and $P<0.001$, respevtively). The loss of LL was found in imbalance groups ($P<0.001$) and retroversional pelvis mainly happened in Type IV. Other information was detailed in Table 3; Fig. 3 (Table 4; Fig. 3).

When Type I group was set as the internal reference by multinomial logistic regression analysis, it showed that the probability for emerging imbalance in patients with severe osteoporosis was 8.4 times higher than patients without osteoporosis ($P=0.001$, RR = 8.410 [2.424,29.146]). The probability for imbalance status in patients with lumbo-pelvic mismatch was almost 10 times higher than that in patients with spino-pelvic matching ($P=0.001$, RR = 0.099 [0.027,0.369] in Type II; $P=0.002$, RR = 0.103[0.024,0.437] in Type IV). There were no statistical differences in terms of gender ratio, age

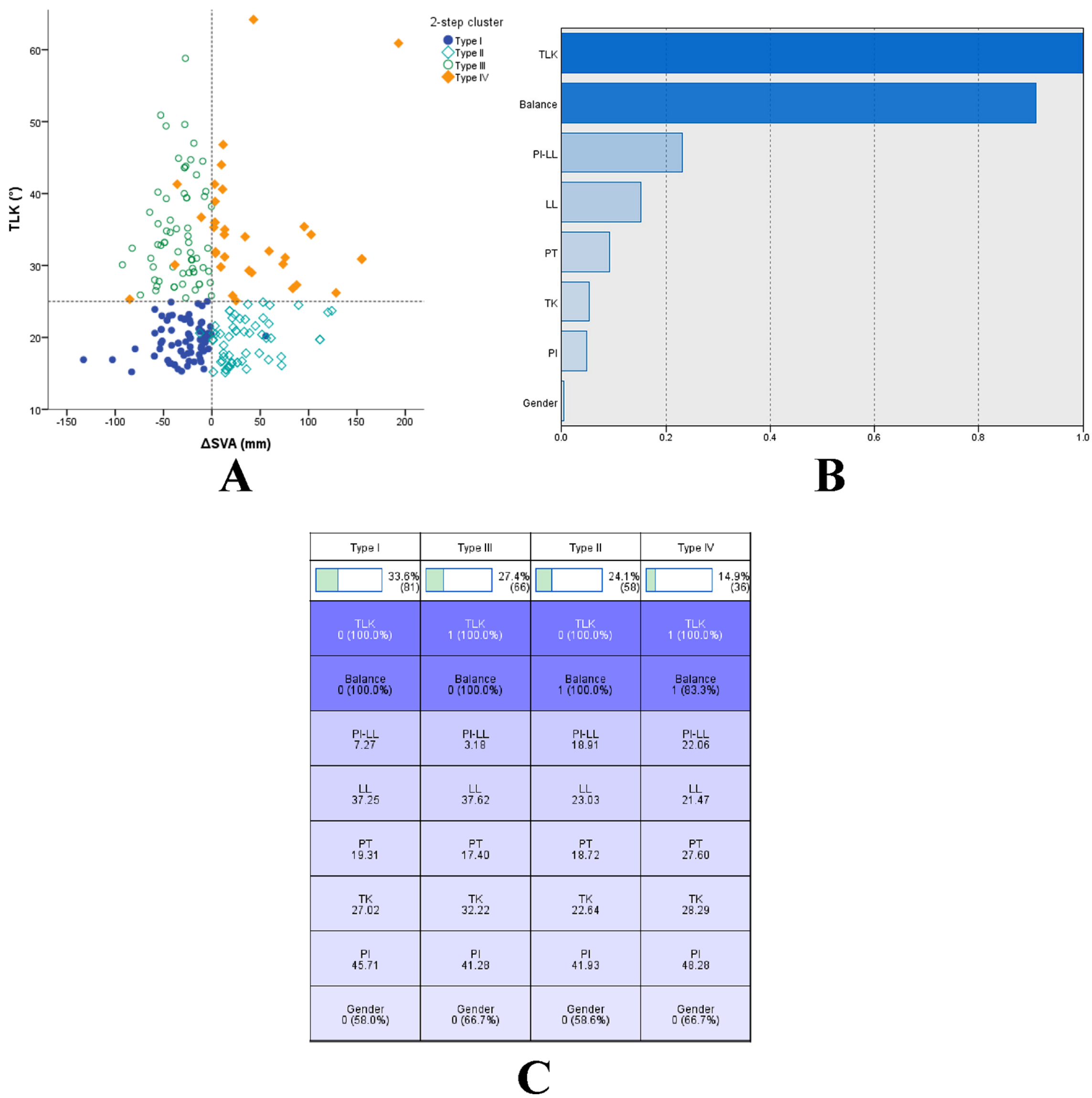

Fig. 2 The 2-step cluster analysis for the classifications on DTLK. (**A**) the scatter diagram for the 4 clusters based on TLK and balance status; (**B**) the predicted ranking of importance for various variables (TLK and balance status were the top two); (**C**) the predicted ranking of importance for various variables among four clusters

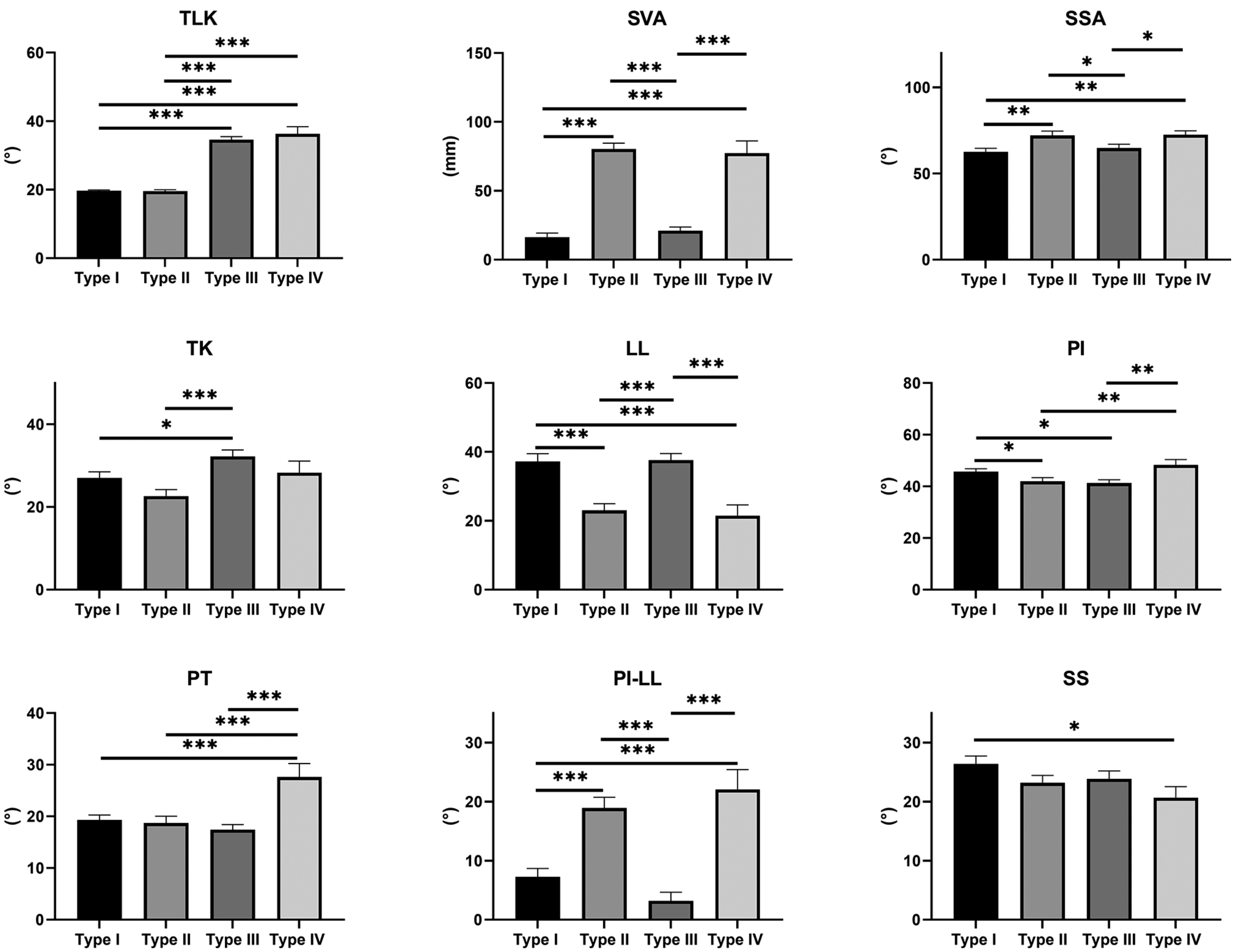

Fig. 3 Comparisons on the spino-pelvic parameters of DTLK patients in 4 cluster groups. (The data was expressed by the mean and standard error. *: $P<0.05$; **: $P<0.01$; ***: $P<0.001$)

Table 4 The spino-pelvic parameters of DTLK patients in 4 cluster groups

	Type I ($n=81$)	Type II ($n=58$)	Type III ($n=66$)	Type IV ($n=36$)	*P*
M: F	17:64	17:41	19:47	11:25	0.577
Age (y)	66.3 ± 8.0	66.7 ± 13.4	70.6 ± 7.0	62.5 ± 13.0	0.001
BMI (kg/m^2)	25.1 ± 3.1	25.2 ± 4.7	25.6 ± 3.4	25.6 ± 5.1	0.834
TLK (°)	19.7 ± 2.5	19.6 ± 2.9	34.6 ± 7.3	36.3 ± 12.3	< 0.001
SVA(mm)	16.4 ± 26.6	80.4 ± 32.0	21.0 ± 21.3	77.3 ± 53.4	< 0.001
SSA (°)	62.7 ± 15.7	72.1 ± 15.1	64.8 ± 13.6	72.5 ± 10.8	0.003
TK (°)	27.0 ± 13.6	22.6 ± 12.1	32.2 ± 13.0	28.3 ± 16.9	0.002
LL (°)	37.2 ± 19.9	23.0 ± 15.0	37.6 ± 15.5	21.5 ± 18.8	< 0.001
PI (°)	45.7 ± 9.9	41.9 ± 11.1	41.3 ± 10.4	48.3 ± 12.7	0.003
PT (°)	19.3 ± 8.4	18.7 ± 9.8	17.4 ± 8.3	27.6 ± 15.8	< 0.001
PI-LL (°)	7.3 ± 12.7	18.9 ± 13.8	3.2 ± 12.0	22.1 ± 20.2	< 0.001
SS (°)	26.4 ± 12.0	23.2 ± 9.5	23.9 ± 10.9	20.7 ± 11.1	0.063

Notefoot: DTLK: degenerative thoracolumbar kyphosis; SVA: sagittal vertical axis; SSA: Spino-sacral angle; TK: thoracic kyphosis; TLK: thoracolumbar kyphosis; LL: lumbar stenosis; PI: pelvic incidence; PT: pelvic tilt; SS: sacral slope

group, and the value of PI and PT among the four clusters (Table 5).

In the Type I group, the linear regression analysis showed that PI and PI-LL were the influencing factors for TK with the formula of $TK=0.25\times PI-0.40\times(PI-LL)$. For Type II group, LL and PT were key factors for adjustment of TK with $TK=14.6+0.79\times LL+0.49\times PT$. For Type III group, LL, PI and PT were the influencing factors for TK with $TK=21.7+1.89\times LL-1.30\times PI+0.60\times PT$. In the Type IV group, there was no definite influencing factors for TK (Table 6).

Since all cases with satisfied treatment were included, the rough operation strategies, to an extent, could be outlined. For patients in type I, the short-segment fixation for stenosis, instead of the kyphotic segment, was recommended. Then, more segmental operation may be performed for type II and type III. For patients in type IV, the operation with decompensation and long-segment fixation for lumbar stenosis, kyphosis and imbalance may be requested. Hence, the details of sagittal biomechanical

Table 5 The risk factors of various clusters compared to type I group by multinomial logistic regression analysis

	Type II			Type III			Type IV		
	B	P	RR (95% CI)	B	P	RR (95% CI)	B	P	RR (95% CI)
BMI(kg/m^2)	0.076	0.247	1.079[0.949,1.228]	0.130	0.082	1.139[0.983,1.320]	-0.013	0.825	0.987[0.880,1.107]
OP (Y vs. N)	2.129	0.001	8.410[2.424,29.146]	0.321	0.558	1.378[0.471,4.035]	0.787	0.231	2.198[0.606,7.972]
Gender (M vs. F)	0.115	0.863	1.122[0.305,4.130]	0.116	0.840	1.123[0.363,3.472]	0.699	0.346	2.011[0.470,8.608]
Age (y)									
50~	-1.095	0.192	0.335[0.065,1.731]	-1.168	0.143	0.311[0.065,1.484]	0.136	0.883	1.145[0.190,6.912]
60~	-1.005	0.142	0.366[0.096,1.401]	-0.655	0.255	0.519[0.168,1.606]	-0.138	0.860	0.871[0.188,4.041]
70~	0[a]	-	-	0[a]	-	-	0[a]	-	-
PI (°) (L vs. H)	0.884	0.174	2.421[0.677,8.665]	0.817	0.147	2.264[0.751,6.823]	-1.072	0.085	0.342[0.101,1.157]
PI-LL (°) (B vs. IB)	-2.309	0.001	0.099[0.027,0.369]	0.820	0.175	2.272[0.694,7.439]	-2.273	0.002	0.103[0.024,0.437]
PT (°) (B vs. IB)	1.190	0.079	3.286[0.869,12.416]	0.671	0.289	1.956[0.565,6.767]	-0.274	0.675	0.760[0.211,2.737]

Footnote: BMI: body mass index; OP: osteoporosis; SVA: sagittal vertical axis; LL: lumbar stenosis; PI: pelvic incidence; L: low PI; H: high PI; PT: pelvic tilt; B: balance; IB: imbalance

[a]: the data of "70~" subgroup was seen as the control subgroup among all age groups

Table 6 Compensatory mechanism of proximal spine (TK) and distal spinal-pelvic alignment for 4-cluster DTLK patients

Clusters	Coefficient	Unstandardized		Standardized	t	P
		B	SE	Beta		
Type I	(constant)	12.338	6.973		1.769	0.081
	PI	0.348	0.153	0.251	2.269	0.026
	PI-LL	-0.434	0.136	-0.404	-3.192	0.002
	PT	0.101	0.194	0.062	0.520	0.605
Type II	(constant)	14.64	5.627		2.602	0.012
	LL	0.644	0.165	0.794	3.893	< 0.001
	PI	-0.433	0.266	-0.394	-1.627	0.110
	PT	0.604	0.275	0.488	2.197	0.032
Type III	(constant)	21.674	4.466		4.853	< 0.001
	LL	1.580	0.394	1.887	4.014	< 0.001
	PI	-1.623	0.379	-1.301	-4.286	< 0.001
	PI-LL	0.563	0.410	0.520	1.372	0.175
	PT	0.936	0.176	0.600	5.329	< 0.001
Type IV	(constant)	16.14	12.173		1.326	0.194
	PI1	0.398	0.339	0.299	1.176	0.248
	PI-LL	-0.203	0.163	-0.243	-1.245	0.222
	PT1	-0.094	0.264	-0.088	-0.356	0.724

Footnote: TK: thoracic kyphosis; DTLK: degenerative thoracolumbar kyphosis; B: regression coefficient; SE: standard error; PI: pelvic incidence; LL: lumbar stenosis; PT: pelvic tilt

compensatory and the surgical strategie could be summarized in Table 6 (Table 7; Fig. 4).

Discussion

It should be emphasized that DTLK is hotspot in the field of adult spinal deformities, and there has been no consensus on the classifications and treatment strategies for this issue. This study enrolled Chinese subjects with DTLK combined with lumbar spinal stenosis underwent surgery and conducted the classifications of DTLK as well as separate sagittal compensatory mechanisms based on spino-pelvic sagittal alignment. We eventually identified the influencing factors and the surgical treatment strategies in four different types of patients.

The changes of lumbar spine alignment and its kinematics are important signals and initials of the disorders of sagittal alignment [13]. It has been found interaction among spino-pelvic sagittal parameters based on lumbar spinal stenosis patines in the elderly with the fitting formula of PI-LL = 0.5 × PT-0.2 × TK, [14] which provided evidence for evaluation of spino-pelvic sagittal alignment and intrinsic biomechanical compensation.Wang et al. [15] addressed that the coordination of the spine and pelvis would reduce in elderly patients with lumbar degenerative diseases, with the movement forward of center of gravity and the increased retroversion of the pelvis in such cases. They also verified that lumbar lordosis and the matching of lumbar spine and pelvis were core parameters in correlation with various sagittal alignment.

Table 7 The characteristics and operation strategies for DTLK patients based on the classification

Classification	Classification basis	Features and risk factors	Biomechanical compensatory	Operation strategies
Type I	Small TLK Balance	Normal LL Normal PT Proper PI-LL	Compensation	Short-segment operation for LSS
Type II	Small TLK Imbalance	Lower LL Normal PT Mismatched PI-LL Severe OP	Partial	Multi-segment operation for LSS and mild imbalance (rigid fixation for case with severe OP)
Type III	Large TLK Balance	Normal LL Normal PT Proper PI-LL	Compensation	Multi-segment operation for LSS and kyphosis
Type IV	Large TLK Imbalance	Lower LL Retroversional PT Mismatched PI-LL	Decompensation	Long-segment operation for LSS, kyphosis and imbalance with I-IV osteotomy

Footnote: DTLK: degenerative thoracolumbar kyphosis; TLK: thoracolumbar kyphosis; SVA: sagittal vertical axis; SSA: Spino-sacral angle; TK: thoracic kyphosis; LL: lumbar lordosis; PT: pelvic tilt; OP: osteoporosis; LSS: lumbar stenosis syndrome

Our data also found close correlations among sagittal parameters in DTLK populations where the overall trend of spino-pelvic mismatching and sagittal imbalance would increased accompanied with the malalignment of lumbar spine, which was consistent with previous studies.

Sagittal alignment and balance status were reported significantly correlated with health-related quality of life, and treatment would be varied for different conditions of DTLK. In that case, it could enable surgeons to develop targeting surgical treatments by clarifying the characteristics of the spino-pelvic sagittal alignment. Therefore, the morphology of DTLK was classified here and the severity of thoracolumbar kyphosis and whole balance status were detected the two main factors in the procedure of cluster analysis. The ultimate goal of spinopelvic balance is to maintain the center of gravity near to the hips [16]. In our study, we found not all sagittal parameters of patients in the balance groups were within normal range but maintained balance through compensatory mechanisms. In patients with DTLK, the anterior flexion of the trunk was usually found with lumbar lordosis reduction. In that case, the coordination of muscle and bone system were activated with the reduction of the thoracic kyphosis [17], lumbar hyperextension and pelvic anteversion to maintain the overall balance [18], which was corresponded to the type I and type III in our study. For patients with excessive imbalance and kyphosis, like type IV, insufficient compensation was sometimes accompanied, where the lumbar hyperextension and even posterior spondylolisthesis were sometimes experienced with the increased risk of segmental instability and spinal stenosis.

Our study also found that the imbalance was more susceptible in patients with severe osteoporosis, wich was reflected by Zhao et al. [19] that osteoporosis had an adverse effect on proximal junctional kyphosis after long-segmental thoracolumbar fusion. By the bone mass reduction, the stress of cortical bone and intervertebral disc would simultaneously increase, significantly accelerating the probability of proximal junctional kyphosis. Another study found that osteoporotic patients showed worse sagittal alignment and decreased quality of life [20]. In total, it was emphasized that the elderly need to moniter the bone mineral density timely in case to be trapped with sagittal imbalance. *Meanwhile, it is recommended to provide strong fixation for type II patients with severe osteoporosis, such as preserving tissue as much as possible, using screws with dense patterns, and taking oral anti-osteoporosis drugs during the perioperative period to prevent the occurrence of osteoporosis related instrumental complications.*

For most degenerative spinal pathologies with surgical indications, surgeons were advised to cautiously tailor individualised surgical plans for each patient with distinctive malformations [21]. Zeng et al. [22] recommended that apical segment resection osteotomy with biaxial rotation orthopedics was an optional method to treat moderate to severe kyphosis. In addition, Yukawa et al. [23] noted the elderly had smaller LL and more adaptable PI-LL compared to the younger individuals. Liang et al. [24] also found that excessive recovery of LL might cause the expansion of TK, consequently leading to a high incidence rate of proximal junction kyphosis. Therefore, LL should be properly recovered to avoid complications. Pan et al. [25] addressed that surgeons should not only pay attention to the focal lumbar segment, but also to the matching relationship between the lumbar spine and pelvis, which could be helpful for orthopedic strategies. Our study suggested that lumbo-pelvic matching

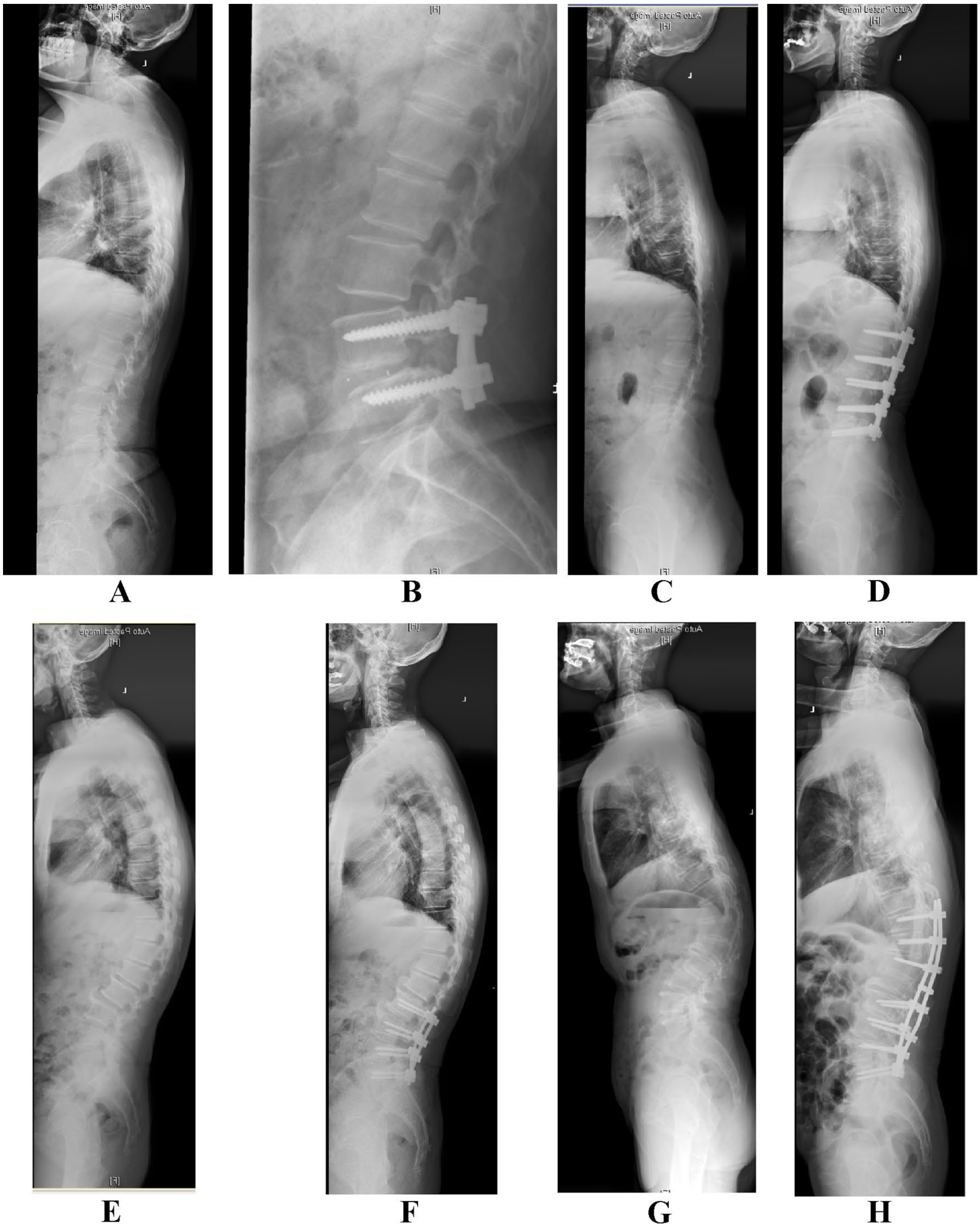

Fig. 4 The cases for the surgical strategy for four types of DTLK. (**A**-**B**) Type I: A 61-year-old female with SVA of -7.3 mm and TLK of 20.5, she was performed L4-5 PLIF with the change of ODI of 33 at the 13-month follow up; (**C**-**D**) Type II: A 76-year-old male with SVA of 32.5 mm and TLK of 44.9, he was performed L2-5 PLIF&PLF with the change of ODI of 38 at the 15.5-month follow up; (**E**-**F**) Type III: A 65-year-old female with SVA of 73.9 mm and TLK of 20.6, she was performed L1-5 PLIF&PLF with the change of ODI of 28 at the 16-month follow up; (**H**-**I**) Type IV: A 69-year-old male with SVA of 96 mm and TLK of 64.2, he was performed T10-L5 PLIF&PLF with the change of ODI of 40 at the 13-month follow up

was the key for preserving the balance status in DTLK patients. Where there is the mismatch, the risk of sagittal imbalance would sharply increase, together with the difficulty of operation. Hence, PI-LL played an important role in maintaining the sagittal balance, regulating proximal sequence with biomechanical compensatory and affecting surgical fixation segments in DTLK patients.

The significance of this study lied that the basic features of DTLK was summarized and characterized by stratifying this population, where the importance of sagittal parameters and overall balance in DTLK was emphasized again. Then, the sagittal compensatory mechanisms for different types was clarified, of whom the consolidation of bone mineral density as well as regular functional exercise for proper sagittal alignment was recommended to maximally prevent the occurrence of type IV. Furthermore, this procedure was not only the morphological classification, but provided specific treatment strategies for various types, as well as probably supplemented the manage plans in the field of adult spinal deformities. The current research has several limitations. Firstly, only the single-center study was designed here and it was necessary to conduct multi-center study with longer follow-up time. Secondly, the cases with scoliosis was excluded in our study and whether the conclusion was applicable to patients with DTLK combined with scoliosis could be further investigated. Then, the surgical strategies were depended on comprehensive factors such as the segmental stability, the physical conditions of patients and the dynamic balance, instead of the sagittal parameters, so we just provided one of the methods for characterizing DTLK. Finally, the patients with DTLK combined with lumbar stenosis who required surgery, rather than the pure DTLK, was collected. To be honest, although patients with pure DTLK are in perfect condition, it is relatively rare for the pure DTLK elderly without stenosis exposed at hospital.

Conclusions

In this study, close relationships among the sagittal spinopelvic parameters of DTLK were found, where the spinopelvic mismatch and the overall imbalance coordinated with the loss of lumbar alignment. More significantly, DTLK patients were classified into four types based on kyphotic severity and balance status. The sagittal mechanism chain could be modified with compensation in type I, type II and type III mainly depending on PI-LL and LL, while it was not in type IV. In addition, osteoporosis and lumbo-pelvic mismatch were risk factors for DTLK imbalance, and the latter was as high as 10 times to be induced imbalance compared to PI-LL matching cases. Finally, targeted treatment strategies for different types of patients was mentioned as follows: for type I, short-segment fixation for stenosis was adequate; for type II and III, multi-segment operation, for stenosis with imbalance and for stenosis with kyphosis, was respectively recommended; for type IV, long-segment operation for stenosis, kyphosis and imbalance with more iatrogenic interference was recommended.

Abbreviations

DTLK	Degenerative thoracolumbar kyphosis
LL	Lumbar lordosis
TK	Thoracic kyphosis
PI	Pelvic incidence
PT	Pelvic tilt
SVA	Sagittal vertical axis
ODI	Oswestry disability index
SS	Sacral slope
SSA	Spino-sacral angle
PACS	Picture archiving and communication system

Author contributions

Conceptualization: Haoyuan Li, XS, LYQ; Data Curation: Haoyuan Li, XS, LYQ; Formal Analysis: XS, ZZQ, Haiying Liu; Investigation: Haoyuan Li, LYQ; Methodology: XS, ZC, GC; Project Administration: Haoyuan Li, XS; Resources: XS, LYQ; Software: XS, GC, XWW; Validation: XWW, GC, Haiying Liu; Visualization: ZZQ; Writing & Editing: Haoyuan Li, XS, GC, ZZQ.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study has obtained ethics approval and consent of the ethics committee in our hospital.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Spinal Surgery, Peking University People's Hospital, Peking University, No. 11 Xizhimen South Street, Xicheng District, Beijing 100044, P.R. China
[2]Beijing HuaSheng Rehabilitation Hospital, No.1 Guangcai Road, Fengtai District, Beijing 100075, P.R. China

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