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Sagittal Plane Lumbar Responses after Anterior Selective Thoracic Fusion for Main Thoracic Adolescent Idiopathic Scoliosis

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Study Design: A retrospective radiographic study.

Purpose: To verify the correlation of sagittal and coronal plane changes after selective thoracic fusion in main thoracic (MT) adolescent idiopathic scoliosis (AIS).

Overview of Literature: Sagittal plane deformity is known to be essential in the evolution of scoliosis.

Methods: Twenty-eight MT AIS patients treated by anterior selective thoracic fusion were evaluated after minimal follow-up of two years. The unfused lumbar area was divided into proximal and distal parts by the lumbar apex in the coronal plane, and into proximal and distal lumbar lordosis by L2 in the sagittal plane. Surgical motion (the difference between pre-operative and postoperative values) and follow-up motion (the difference between postoperative and the last follow-up values) were compared.

Results: Immediately after surgery, as thoracic kyphosis increased, lumbar lordosis decreased ($r=0.734$); proximal lumbar lordosis increased, and distal lumbar lordosis decreased. The proximal lumbar area was mobilized in the sagittal plane, and was straightened in the coronal plane. However, the distal lumbar area was stabilized in the sagittal plane, and showed resistant motion against MT translation in the coronal plane. The surgical motion was correlated to the follow-up motion, *i. e.*, was regulated during follow-up, and the regulatory motion was more precise in the distal than proximal lumbar area in both sagittal and coronal planes.

Conclusions: Sagittal and coronal motions were co-related; optimal sagittal motions were necessary for optimal coronal motions after anterior selective thoracic fusion for MT AIS. Proximal and distal lumbar motions were different for different roles; the proximal lumbar area played a role as a bumper to absorb the MT translatory force, and the distal lumbar area played a role of resistance against MT translation.

Key Words: Sagittal plane, Selective thoracic fusion, Anterior spinal fusion, Adolescent idiopathic scoliosis

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Introduction

Dickson et al.[1] reported that the sagittal plane was important in the evolution of scoliosis, and there were two kinds of spinal deformities, kyphotic and lordotic. A kyphotic spinal column is stable, and presents as uniplanar kyphotic deformity. However, a lordotic or hypokyphotic thoracic spine is rotationally unstable, and prone to rotate[2]. Coronal uniplanar asymmetry is already present in the normal population[3]. The physiological flexion force in the sagittal plane and translatory force in the coronal plane evoke uneven distribution of disc pressure, that is, higher pressure in the ventral and concave sides. At this moment, the only way of gaining even distribution of disc pressure is by twisting, that is, rotation of the vertebra, which is the concept of biplanar

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asymmetry. If the sagittal plane change is so important in the evolution of scoliosis, it should play an important role in the resolution of scoliosis after corrective surgery.

Recent posterior surgery for idiopathic scoliosis cannot correct sagittal plane sufficiently, and correct the curve by *en bloc* relocation of the coronal curve to the sagittal plane rather than real vertebral derotation[4-7]. Increased coronal correctability without sufficient sagittal and axial correction induces coronal decompensation after selective thoracic fusion[8-12]. The essence of anterior surgery is the removal of discs, which are the most resistant structures against rotation[13]. By removing discs, the spine becomes derotated naturally, and more kyphotic. In addition, shorter fusion is possible from end vertebra to end vertebra. Theoretically, anterior scoliosis surgery would cause less decompensation because of optimal three-dimensional correction and more availability of mobile transitional segments for compensation.

There are few reports concerning the lumbar response in the sagittal plane after selective thoracic correction in adolescent idiopathic scoliosis (AIS). The purpose of this study is to verify the different responses in proximal and distal lumbar areas, and to verify the effect of sagittal plane changes on coronal plane changes in the resolution of lumbar curves after anterior selective thoracic fusion in patients with main thoracic (MT) AIS.

Materials and Methods

Radiographs of 28 patients with MT AIS treated by anterior selective thoracic fusion were evaluated retrospectively. The images contain curves with Lenke's lumbar modifier A, B, and C. To minimize the selection bias, the following cases were excluded: cases with proximal thoracic Cobb angles of more than 25° on side-bending (Lenke type 2 curves), cases with lumbar modifier A in which the body center of lumbar apex did not cross the center sacral vertical line (CSVL), and cases where distal fusion exceeded more than one level distal to the lower end vertebra of the MT curves.

Patients underwent surgery between September 1994 and May 2004 in Klinikum Karlsbad-Langensteinbach, Germany. The mean age at surgery was 14 years 8 months (range, 11.4~18.4 years). Of the patients, 23 were female and 5 were male. The mean follow-up was 50.1 months (range, 25~116 months). All of the MT curves were right-sided. A senior surgerns (JH) performed surgery by the standard surgical approach of one incision, double thoracotomy to obtain access to the whole MT vertebrae and occasionally up to the first lumbar vertebra[14]. Instrumentation used was a Moss Miami Spine System (Depuy Spine, Raynham, MA, USA) in 23 patients and a Moss Spine System (Depuy Spine) in 5 patients. All patients were operated one time without revision.

Measurement was performed by one of the investigators (KHN). Eight radiographs were measured in each patients; posteroanterior and lateral long cassette standing radiographs without brace in the preoperative, immediate postoperative and the last follow-up periods, and long cassette preoperative supine active side bending radiographs. Immediate postoperative radiographs were checked on postoperative 7 to 14 days in all cases.

In the coronal plane, three types of coronal parameters were measured; positions, tilt angles, and Cobb angles. Position parameters were the position of the C7 plumb line (C7 PL), and positions or translations of MT and lumbar apical vertebrae (AV). Position parameters were described as (+) if they lay on the right side from the CSVL, and (-) if on the left side, and their changes were described as (+) if they moved to the right side, and (-) if they moved to the left side. Tilt angles were angles of lower instrumented vertebra (LIV) tilt, lumbar AV tilt, and lumbar lower end vertebra (EV) tilt, which were measured at the lower endplates. Tilt angles or angle changes were described as (+) if the left edge of the lower endplate was up or upward, and (-) if down or downward. The motion of tilt parameters was also described as motion to the right or left side like the motion of the position parameters. For example, if lumbar AV tilt motion was left downward, we described it as "moved to the left side". Coronal Cobb angles with side-bending Cobb angles were measured in MT and lumbar curves. According to the result of our findings and the literature describing that most coronal motion occurs between the LIV and lumbar apex after selective thoracic fusion[9], the unfused lumbar coronal curve (LIV-EV) was divided by the lumbar AV into the proximal lumbar Cobb angle (the lower endplate of LIV to that of AV) and distal lumbar Cobb angle (the lower endplate of AV to that of EV). From our findings, the mean lumbar apex was 14.5 between L2 (14) and L3 (15), and the mean lumbar distal EV was 16.0. Coronal balance was measured as the distance of the C7 PL from the CSVL.

In the sagittal plane, the thoracic kyphosis (T5-T12), transitional angle (T10-L2), fused transitional angle (T10-LIV), lumbar lordosis (T12-S1), and sacral slope were measured. Segmental lordosis angles of (LIV-L1), (L1-L2), (L2-L3), (L3-L4), and (L4-S1) were measured. According to the results of segmental lordosis angle changes, the unfused lumbar sagittal curve (LIV-S1) was divided by L2 vertebra into proximal lumbar lordosis (the lower endplate of LIV to that of L2), and distal lumbar lordosis (the lower endplate of L2 to the upper endplate of S1). Sagittal angles or angle changes were described as (+) if they were or became kyphotic, and (-) if lordotic. Sagittal balance (the position of the C7 plumb line from the postero-superior cornor of the S1 body) was measured; (+) indicates anterior deviation, (-) posterior deviation.

Statistical analysis was performed using SPSS 12.0 for Windows (SPSS Inc., Chicago, IL, USA). The motions of sagittal and coronal parameters were analyzed using Pearson's correlation and linear regression analysis, and explained by the mean values. The change from preoperative to immediate postoperative values was described as a “surgical change,” and the change from immediate postoperative to final values as a “follow-up change.” For a comparision with the sagittal angle difference, the coronal angle difference was used instead of the correction rate.

Results

At the last follow-up, the MT and lumbar coronal Cobb angle was 65.2% and 61.1% corrected, respectively (Table 1). Finally, three cases were decompensated by the definition of trunk shift more than 20 mm, and nine cases by 10 mm. Distal fusion (11.8) was performed at the 0.5 level distal to MT lower EV (11.3), and the same as neutral vertebra (11.8). An average of 6.8 levels were fused. Thoracic kyphosis increased 18.4°, and lumbar lordosis increased 4.7°.

Surgical changes

Immediately after surgery, as thoracic kyphosis increased 9.5°, lumbar lordosis decreased 3.7° (flattened) (Table 1). Therefore, sagittal balance was aggrevated from +12.6 mm to +41.5 mm, even though sacrum was verticalized. Thoracic correction showed a high correlation to lumbar correction only in the sagittal plane (r=0.734, Pearson's correlation) (Fig. 1). The correlation between MT and lumbar coronal correction was moderate (r=0.448). Few findings have been reported about immediate postoperative thoracic kyphosis angle changes[15,16]. Our results showed 9.5° of thoracic kyphosis increased after surgery.

Another important finding was the different segmental motions of the unfused lumbar area in the sagittal plane: segments of (LIV-L1) and (L1-L2) became lordotic, and segments of (L2-L3), (L3-L4), and (L4-S1) became kyphotic (Table 2). Following segmental motion differences, we divided unfused lumbar lordosis (LIV to S1) into proximal and distal areas by the borderline vertebra of L2. Proximal lumbar lordosis (LIV-L2) increased 3.1°, and distal lumbar lordosis (L2-S1) decreased 4.9°. To the change of lumbar

Table 1. Thoracic and lumbar profiles

		Main thoracic (°)				Lumbar (°)			
		SB	Pre	IPO	Last	SB	Pre	IPO	Last
Coronal Cobb angle	Mean	26.2	52.0	14.0	18.1	2.9	35.0	14.2	13.6
	Minimum	7	38	- 1	5	- 20	18	4	3
	Maximum	49	72	30	32	25	49	28	31
	SD	10.7	9.2	8.4	7.4	10.6	7.0	6.3	8.4
			Thoracic kyhosis (T5 - T12) (°)				Lumbar lordosis (T12 - S1) (°)		
			Pre	IPO	Last		Pre	IPO	Last
Sagittal angle	Mean		18.0	27.5	36.3		- 58.1	- 54.4	- 62.8
	Change			+ 9.5	+ 8.9			+ 3.7	- 8.5
	Minimum		0	14	17		- 33	- 35	- 39
	Maximum		35	49	59		- 83	- 75	- 85
	SD		10.3	9.0	11.3		12.6	11.8	13.1

SB: sibe-bending, Pre: preoperative, IPO: immediate postoperative, Last: last follow-up, change: angle difference from preoperative angle at IPO, and angle difference from IPO angle at last follow-up, (+) means kyphtic change, and (-) means lordotic change, SD: standard deviation.

Table 2. Sagittal motions

	C7 plumb line from S1 (mm)			Proximal lumbar lordosis (LIV-L2) (˚)			Distal lumbar ordosis (L2-S1) (˚)			Unfused lumbar lordosis (LIV-S1) (˚)		
	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last
Mean	+ 12.6	+ 41.5	+ 11.9	- 3.9	- 7.0	- 7.5	- 53.3	- 48.4	- 55.9	- 57.2	- 55.4	- 63.4
Change		+ 28.9	+ 29.5		- 3.1	- 0.6		+ 4.9	- 7.5		+ 1.9	- 8.1
Motion			58.4			3.7			12.4			10.0
	Segmental sagittal angle (LIV-L1) (˚)			Segmental sagittal angle (L1-L2) (˚)			Segmental sagittal angle (L2-L3) (˚)			Segmental sagittal angle (L3-L4) (˚)		
	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last
Mean	- 0.4	- 1.9	- 2.9	- 3.5	- 5.0	- 4.7	- 9.4	- 7.9	- 12.4	- 10.5	- 10.1	- 12.0
Change		- 1.5	- 0.9		- 1.6	+ 0.4		+ 1.5	- 4.5		+ 0.3	- 1.9
Motion			2.4			2.0			6.0			2.2
	Segmental sagittal angle (L4-S1) (˚)			Sacral slope (˚)			Transitional angle (T10-L2) (˚)			Fused transitional angle (T10-LIV) (˚)		
	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last
Mean	- 33.5	- 30.4	- 31.5	- 45.6	- 43.4	- 43.0	- 1.1	- 2.2	0.6	2.8	4.8	8.2
Change		+ 3.1	- 1.1		+ 2.2	+ 0.4		- 1.0	+ 2.8		+ 2.0	+ 3.4
Motion			4.2			2.6			3.8			5.4

C7 plumb line from S1: position of C7 plumb line from posterosuperior cornor of S1 body, (+) means anterior position or motion, (-) means posterior position or motion, motion: total motion of parameter by summation of surgical motion and follow-up motion, change in sacral slope, (+) means verticalization of sacrum, LIV: lower instrumented vertebra, Pre: preoperative, IPO: immediate postoperative, Last: last follow-up.

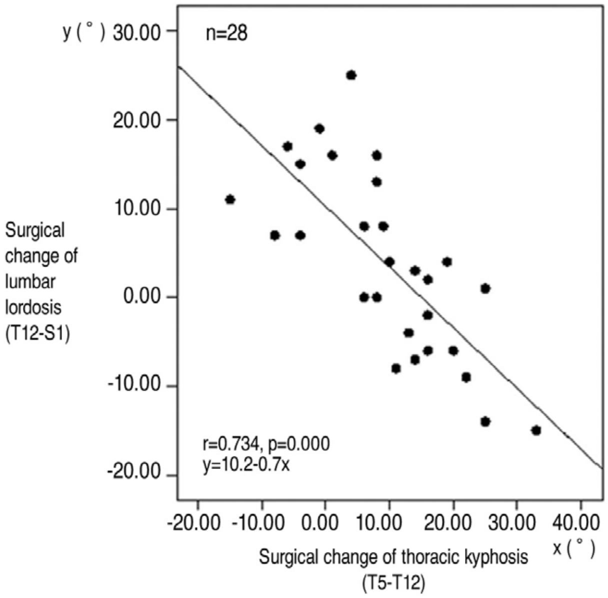

Fig. 1. Thoracic to lumbar correlation in sagittal plane immediate postoperatively. (Pearson's correlation, Linear regression)

lordosis (T12-S1), the distal lumbar lordosis change was more correlated (r=0.771) than the proximal lumbar lordosis change (r=0.471). Also, to the change of unfused lumbar lordosis (LIV-S1), the distal lumbar lordosis change was more correlated (r=0.906) than the proximal lumbar lordosis change (r=0.628).

In the coronal plane, most of lumbar coronal correction occurred in the proximal lumbar area; the proximal lumbar Cobb angle decreased 13.0˚, and the distal lumbar Cobb angle decreased 5.5˚ (Table 3). As the MT apex translated 38.5 mm to the left side, parameters including LIV tilt, lumbar AV tilt, and lumbar AV translation moved to the left side; LIV tilt decreased 17.5˚, lumbar AV tilt decreased 3.9˚, and lumbar AV translated 1.4 mm to the left. We called this change "coronal block motion." Only the lumbar EV tilt increased 1.6˚, which indicates that this distal lumbar parameter, lumbar EV tilt, was resistant against the MT apical translation. We called this motion "lumbar EV tilt resistance" or "distal lumbar coronal resistance". Among the 28 cases, lumbar EV tilt increased in 18 cases, decreased in 8 cases, and did not change in 2 cases.

Follow-up changes

During follow-up, thoracic kyphosis became 8.9˚ further

Table 3. Coronal motions

	C7 plumb line from CSVL (mm)			MT apex translation (mm)			Lower instrumented vertebral tilt (˚)			Proximal lumbar Cobbs (LIV-AV) (˚)		
	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last
Mean	- 4.3	- 1.9	- 6.6	39.5	1.0	8.6	23.1	6.3	6.2	23.7	10.7	8.7
Change		+ 2.4	- 4.7		- 38.5	+ 7.6		- 16.9	- 0.1		- 13.0	- 2.0
Motion			7.1			46.1			17.0			15.0

	Lumbar apex translation (mm)			Apical vertebral tilt (˚)			Distal lumbar Cobbs (AV-EV) (˚)			End vertebral tilt (˚)		
	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last	Pre	IPO	Last
Mean	- 14.8	- 16.1	- 13.1	- 0.6	- 4.4	- 2.5	8.6	3.2	4.5	- 9.2	- 7.6	- 7.0
Change		- 1.4	+ 3.0		- 3.9	+ 1.9		- 5.5	+ 1.3		+ 1.6	+ 0.6
Motion			4.4			5.8			6.8			2.2

C7 plumb line from CSVL: position of C7 plumb line from center sacral vertical line, (+) means right position or motion, (-) means left position or motion, MT: main thoracic, AV: apical vertebral, EV: end vertebral, Pre: preoperative, IPO: immediate postoperative, Last: last follow-up, LIV: lower instrumented vertebra.

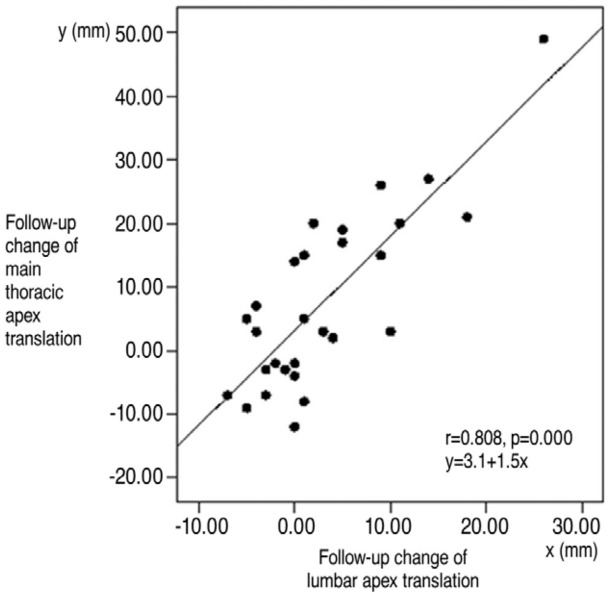

Fig. 2. Coronal block motion during follow-up. As lumbar apex translated medially to right side, main thoracic apex also translated to the same side.

kyphotic, and lumbar lordosis increased 8.5˚. The follow-up change of thoracic kyphosis showed no significant correlation with that of lumbar lordosis (r=0.491). Meanwhile, the sacrum remained in a vertical position, and sagittal balance was restored from +41.5 mm to +11.9 mm. Most of lumbar lordosis occurred in the distal lumbar area; proximal lumbar lordosis increased only 0.6˚, while distal lumbar lordosis increased 7.5˚.

Coronal parameters from MT apex translation to lumbar EV tilt moved to the right side during follow-up (coronal block motion) (Table 3). In addition, there was a high tendancy that MT and lumbar apecies translated following the motion of lumbar EV tilt (r=0.748, and r=0.690 respectively). The correlation of lumbar EV tilt motion to MT apex motion was moderate after surgery (r=0.489), but was high during follow-up (r=0.748). The correlation of lumbar apex translation to MT apex translation was similarly moderate after surgery (r=0.467), but was high during follow-up (r=0.808) (Fig. 2). Coronal block motion was more obvious during follow-up than after surgery.

Self-regulation

Surgical motions were regulated during follow-up; the directions of follow-up motions of parameters were grossly opposite to the directions of surgical motions. For example, lumbar kyphotic surgical motion was followed by a lordotic follow-up motion, which indicates that lumbar surgical motion was regulated during follow-up (Table 4). The correlation coefficients indicates the degree of precision of regulatory motion. Strictly speaking, the direction of follow-up motion was not always opposite to the direction of surgical motion as it followed a certain equation, where the constant of the equation was not zero. In the sagittal plane, distal lumbar lordosis was highly regulated (r=0.702) (Fig. 3A), whereas proximal lumbar lordosis was nearly not regulated (r=0.019) (Fig. 3B). Furthermore, in the coronal plane, distal lumbar motion was precisely regulated, but proximal

Table 4. Self-regulation in coronal and sagittal planes

Coronal plane parameter	C7 plumb line from CSVL (mm)	MT apex translation (mm)	LIV tilt (˚)	Proximal lumbar Cobbs (LIV-AV) (˚)	Lumbar AV tilt (˚)	Lumbar AV translation (mm)	Distal lumbar Cobbs (AV-EV) (˚)	EV tilt (˚)
r	0.544	0.443	0.277	0.275	0.341	0.540	0.653	0.661
Sagittal plane parameter	C7 plumb line from S1 (mm)			Proximal lumbar lordosis (LIV-L2) (˚)			Distal lumbar lordosis (L2-S1) (˚)	Unfused lumbar lordodsis (LIV-S1) (˚)
r	0.725			0.019			0.702	0.728

r: Pearson's correlation coefficients between surgical and follow-up change in each parameter, CSVL: position of C7 plumb line from center sacral vertical line, (+) means right position or motion, (-) means left position or motion, MT: main thoracic, AV: apical vertebral, EV: end vertebral, LIV: lower instrumented vertebra.

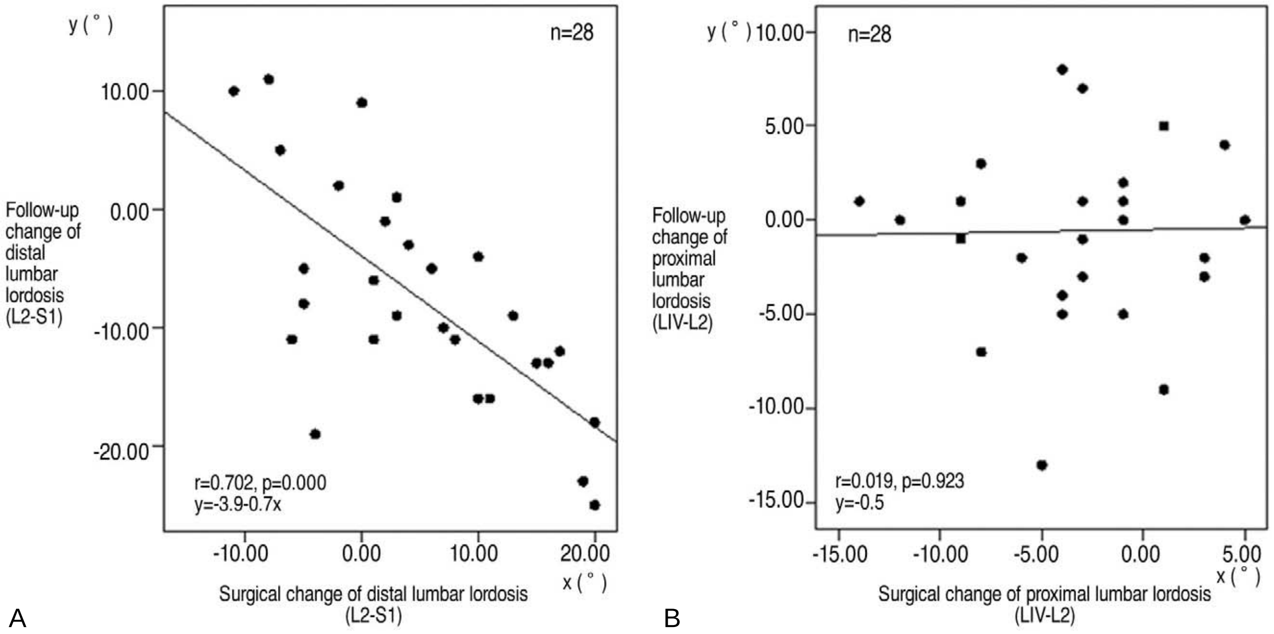

Fig. 3. Self-regulation is the correlation between surgical motion and follow-up motion. Distal lumbar lordosis were obviously regulated (**A**), but proximal lumbar lordosis was nearly not regulated (**B**).

lumbar motion was not regulated well; the distal lumbar Cobb angle (r=0.653), and the proximal lumbar Cobb angle (r=0.275).

Most lumbar sagittal motion occurred in the distal lumbar area; 3.7° in the proximal lumbar area, and 12.4° in the distal lumbar area. However, most lumbar coronal motion occurred in the proximal lumbar area; proximal lumbar motion was 15.0˚, and distal lumbar motion was 6.8˚.

Discussion

The material corrected by anterior scoliosis surgery should be a better model to show the lumbar responses after selective thoracic correction than that corrected by posterior scoliosis surgery as anterior scoliosis surgery results in more natural three-dimensional correction. Coronal C7 PL motion and MT apex motion were highly correlated after surgery (r=0.727), and during follow-up (r=0.808). Therefore, for easy understanding, we ignored the influence of proximal thoracic motion in this study, and analyzed the lumbar motion compared with MT apex motion instead of C7 PL motion.

Decompensation is an excessive left translation of C7 PL in the coronal plane[8-12]. We analyzed sagittal motion related with coronal motion. After surgical correction of the MT curve, proximal and distal lumbar motions were different. The proximal lumbar area was mobilized in the sagittal plane, and was straightened in the coronal plane. However, the distal lumbar area was stabilized in the sagittal plane, and was resistant against MT translation. Through the motion of the mobilized proximal lumbar area, the MT apex could translate medially. It seemed to be rational for the proximal lumbar area to become mobile for these motions. Apparently, the proximal lumbar area (the unfused trasitional area) seems to play a more important role for coronal balance than the distal lumbar area as the gross postsurgical coronal and rotational changes occur in this area[6-14]. Against the MT apex translational force, the counter-force in the coronal plane should occur in the unfused lumbar area. For the counter-force to be effective, and for the proximal lumbar area to move following the MT force, the distal lumbar area should become kyphotic (stabilized) in the sagittal plane. Distal lumbar sagittal stabilization looks like a rational response. We believe that the proximal lumbar area played a passive role as a bumper to absorb MT translatory force, and distal lumbar area played an active role of resistance against MT translation.

During follow-up, the MT area was only a fused mass, and most of the proximal lumbar motion had occurred already after surgery. Therefore, the MT fused mass and proximal lumbar area were passive components. They should follow active distal lumbar motion. Surgical motion was self-regulated during follow-up, which was more precise in the distal lumbar area. Coronal motions of the MT apex and lumbar apex was left-sided after surgery and right-sided during follow-up, which indicates that they moved as a block. This block motion was more obvious during follow-up than after surgery. Passive straightening of the proximal lumbar area seemed to the cause of the low correlation of block motion after surgery. Block motion is the relationship between MT motion and lumbar motion. In our opinion, block motion is not the problem of post-fusional rigidity. It looks like a process of compensation. The distal lumbar area could control the fused MT mass gradually; actively resisting control after surgery, and actively controlling the fused MT mass during follow-up. The combined motion of these step-by-step processes was regulation. Self-regulation is the relationship between surgical motion and follow-up motion in each parameter. The results of regulatory motions were well-controlled medialization of the MT and lumbar apices.

Lumbar coronal motion was different from lumbar sagittal motion. Most coronal Cobb angle change occurred in the proximal lumbar area, but most sagittal angle change occurred in the distal lumbar area. In addition, most proximal lumbar coronal Cobb angle change occurred after surgery. However, distal lumbar sagittal angle change occurred evenly after surgery and during follow-up. Moreover, distal lumbar motion was also more precisely regulated than proximal lumbar motion in both coronal and sagittal planes. We believe that distal lumbar sagittal motions after surgery and during follow-up occur for active regulation. It seemed to be clear that proximal lumbar motion was passive, and distal lumbar motion was active.

This study has some limitations. First, the borderline vertebra in the sagittal plane (L2, 14.0) was different from that in the coronal plane (lumbar apex, 14.5). Reasonably thinking, the two should be the same. Similar results were obtained using the lumbar apex instead of L2 as the sagittal borberline vertebra. However, the regulation of distal lumbar lordosis was lower using the lumbar apex; approximately 0.5 by lumbar apex (14.5) and 0.7 by L2 (14.0). A further study would be required. Second, distal lumbar sagittal motions were measured from L2 to S1, but distal lumbar coronal motions were measured from lumbar apical vertebra to lumbar lower end vertebra. The curve configurations in the coronal and sagittal planes are different. In the coronal plane, the distal end of the lumbar curve is the lumbar lower end vertebra, but in the sagittal plane, it should be the S1 upper end plate. We feel that the two planes have different motion-boimechanics, and chage following their own motion-boimechanics.

Conclusions

We conclude that the distal and proximal lumbar motions are different for different roles. The sagittal and coronal motions are co-related; that is, an optimal sagittal motion is necessary for an optimal coronal motion. A further study about rotation is required to understand further about the lumbar responses.

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