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ORIGINAL ARTICLE

Spinal correction surgery improves asymmetrical trunk kinematics during gait in adolescent idiopathic scoliosis with thoracic major curve

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Abstract

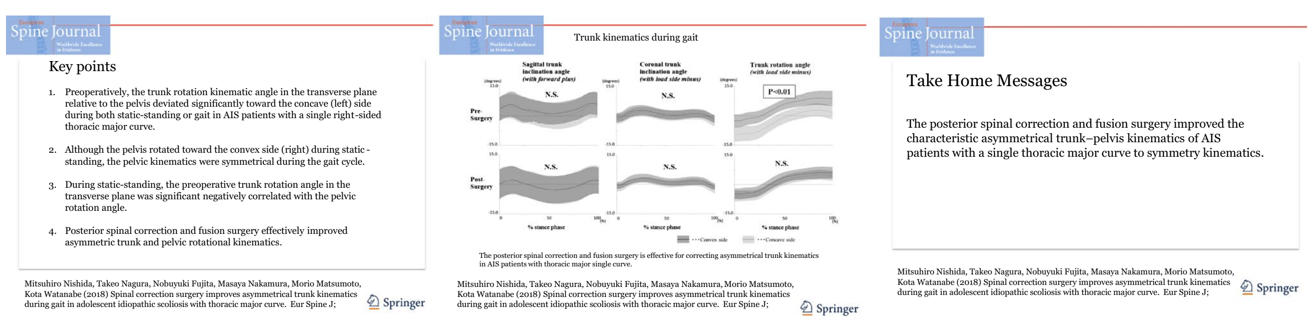
Purpose To clarify the effect of posterior correction and fusion surgery on the trunk–pelvic kinematics during gait in adolescent idiopathic scoliosis (AIS) patients with single thoracic major curve.

Methods Among preoperative AIS patients who planned correction surgery, 18 patients with Lenke type 1A or B were selected for this study. All patients were female. The patients' trunk and pelvic kinematics during gait were measured three-dimensionally and dynamically using reflective markers, optoelectronic motion capture system. The gait analysis was performed before and 1–2 years after surgery. The trunk and pelvic symmetry during gait was evaluated at coronal, sagittal, and transverse planes between concave and convex sides.

Results The trunk and pelvic angles in sagittal and coronal planes were equivalent between concave and convex sides before and after surgery. Preoperatively, transverse trunk rotation angles were significantly deviated toward the concave (left) side during both static standing ($4.3 \pm 2.0°$) and gait ($8.8 \pm 0.6°$, $p < 0.01$). Preoperative transverse pelvic rotation angles were significantly deviated toward the convex side during static standing ($4.0 \pm 3.8°$). However, pelvis displayed with symmetric rotational kinematics during gait. Postoperatively, the deviated transverse trunk rotation angle significantly decreased ($1.6 \pm 0.3°$), and the transverse rotational kinematics of both trunk and pelvis improved to symmetric.

Conclusions Posterior correction and fusion surgery have improved preoperative asymmetric global rotational kinematics of trunk and pelvis in transverse plane to symmetric postoperatively in AIS patients with thoracic single major curve.

Graphical abstract These slides can be retrieved under Electronic Supplementary Material.



Keywords Adolescent idiopathic scoliosis · Three-dimensional gait analysis · Trunk–pelvic kinematics · Thoracic major curve · Trunk position

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Introduction

Adolescent idiopathic scoliosis (AIS) will impact negatively on self-image, may cause osteoarthritic changes, and may cause respiratory and circulatory dysfunction in severely progressed cases [1–4]. Basically, the current treatments for AIS are decided based on the Cobb angle, which is the static radiographic assessments of the spinal deformity, and the assessment of spinal deformity from the stand point of spinal kinematics still remains unclear. Previously [5], we have reported that the trunk kinematics during gait in preoperative patient with Lenke type 1 curve [6] (single thoracic major curve) displayed characteristic asymmetric trunk kinematics. However, the influence of the correction and fusion surgery on the trunk kinematics also remains unclear. The previously reported influences of correction surgery on AIS were reduction in the sway of gravity center of the trunk during gait [7], restriction in range of motion of the trunk [8], decrease in gait speed [9], and decrease in step length, while a few of them investigated the merits of surgery from a kinematic perspective, and the previous evaluations included the variety of curve types such as single thoracic or lumbar curve, or double major curve. Since the global postural control strategy supposed to be differed according to each curve pattern in AIS patients, the effect of the correction surgery for the trunk kinematics should be discussed in each curve pattern.

Thus, we evaluated pre- and postoperative trunk kinematics of AIS patients with thoracic single major curve and hypothesized that the posterior correction and fusion surgery would improve the asymmetry trunk kinematics during gait.

Methods

Among 122 preoperative patients diagnosed with AIS who were scheduled for posterior correction and fusion surgery between December 2011 and June 2014, 18 patients with Lenke type 1A or B (single major thoracic curve) were selected for this study. All patients were female. In our previous study [5], since the trunk kinematics under 30 years old did not differ from adolescence, we included the patients aged between 10 and 30 years old in the present study. The trunk and pelvis kinematics of the patients were measured a few days before surgery and 1–2 years after surgery. To analyze the influences of spinal deformity on trunk kinematics, none of the patients were neurologically disturbed, and none had back significant pain which may affect the trunk kinematics of spine before and after surgery. The convexities of thoracic curves located on the right side in all patients. At the time of preoperative measurements, the mean age was 17.4 ± 4.4 (range 13–28) years, the mean weight was 46.9 ± 5.4 (range 36.5–60) kg, and the mean height was 155.9 ± 5.6 (range 148.7–167) cm. At the time of postoperative measurements, the mean weight was 46.9 ± 6.0 (range 35.3–60) kg and the mean height was 158.2 ± 5.6 (range 150.5–168.7) cm (Table 1).

Table 1 Demographic and radiological data for 18 AIS patients

Patient no.	Age at surgery	Body height (cm)		Body weight (kg)		Main Cobb angle (°)		Lenke classification	Fusion level
		Pre-surgery	Post-surgery	Pre-surgery	Post-surgery	Pre-surgery	Post-surgery		
1	18	156	157.3	43	43	43.3	17.3	1B-	T6-T11
2	15	167	168	46	45	41.9	3	1AN	T5-L1
3	15	166.5	168.7	52.6	53.8	49.4	7	1A-	T5-L1
4	14	151	154	39	38.35	72.2	1.6	1B-	T5-L2
5	17	157	157.7	60	60	39.2	24.2	1AN	T6-L1
6	18	148	150.5	45.5	45.6	53.7	19.5	1BN	T5-T12
7	14	157	160.3	45	43.05	54.2	14.5	1AN	T6-L1
8	26	150	151	51	52.6	41.2	10.3	1AN	T6-L1
9	15	149	152.5	42.9	42	46.9	14.9	1BN	T6-L2
10	14	157	159.2	45	44.1	40.7	3.6	1BN	T7-L2
11	13	153	155.5	46	45.1	60.6	14.3	1BN	T5-L1
12	24	160	162.2	50	50.2	58.1	14	1A-	T5-L1
13	19	159.8	164.1	44.3	47.1	65.3	22.7	1BN	T3-L1
14	28	148	151.4	50	51.1	53.4	16.7	1B+	T6-T12
15	19	156	156.9	49	49.8	44.7	11.0	1BN	T6-T12
16	14	158	162.1	45	45.4	53.9	10.4	1BN	T5-T12
17	14	160	161.9	52.8	53.4	52.8	14.5	1AN	T6-L1
18	16	153	154.2	36.5	35.3	45.3	19.9	1AN	T6-T12

Gait analysis system and method of marker affixation

In order to measure the gait kinetically and three-dimensionally, we used an optoelectronic motion capture system (Oqus, Qualysis, 8 cameras, 120 Hz, Gothenburg, Sweden) and two floor reaction force plates (Frequency 600 Hz, Type 4060-10, Bertec, Columbus, OH, USA) synchronized with the camera system. We affixed reflective markers to 31 locations as anatomical markers for the trunk and limb surfaces (Table 2).

Method of assessing trunk and pelvic kinematics

Trunk kinematics were calculated using Visual 3D software (C-Motion, Inc., Rockville, MD, USA) as follows. First, we evaluated the kinematics of the pelvis. We set the coordinate in the measurement space as reference (the virtual laboratory's coordinate) and then measured the motion of the coordinate axis of pelvis. The coordinate axis of the pelvis was determined using the marker on the S1 spinous process. We defined the "sagittal pelvic inclination angle," "coronal pelvic inclination angle," and "pelvic rotation angle" as the pelvic tilt in the each sagittal, coronal, and transverse planes (Fig. 1).

Then, we measured the kinematics of the trunk in association with pelvis. The "sagittal trunk inclination angle" and "coronal trunk inclination angle" were defined as the angle between the vertical axis and a line connecting the markers on the C7 and S1 spinous processes in the sagittal and coronal plane. The "trunk rotation angle" was defined as the angle between the line connecting markers on the two acromion processes and the axis of coordinates in the transverse plane. These definitions were based on methods in our previous study [5].

Measurement of trunk and pelvic kinematics during standing and gait

First, trunk and pelvic positions were measured for 5 s while patients standing with their both upper limbs hanging downwards. And we analyzed the correlation between the trunk and pelvic positions during standing.

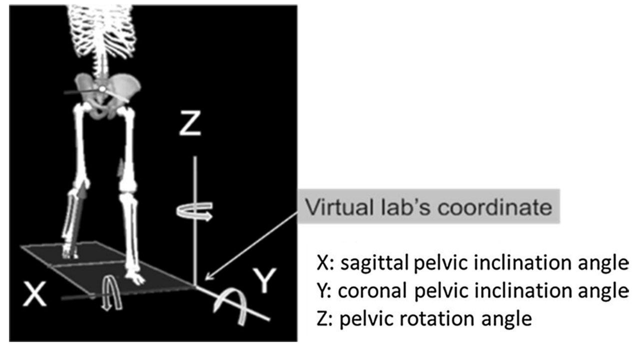

Fig. 1 Method for assessing the pelvic angle. We set the virtual laboratory's coordinates in the measurement space as a reference and measured the motion of the coordinate axis of the pelvis using the marker on the S1 spinous process. We defined the "sagittal pelvic inclination angle" as the pelvic tilt in the sagittal plane, the "coronal pelvic inclination angle" as the tilt in the coronal plane, and the "pelvic rotation angle" as the tilt in the transverse plane

Next, measured trunk and pelvic kinematics during gait on a 10-m straight path with normal walking speed. The patients required to step on the two ground reaction force plates affixed on the path to analyze each stance phase of the concave and convex sides. Prior to measuring, each patient walked several times as a warmup.

In order to detect the asymmetric kinematics of the trunk and pelvis during gait, we extracted data of the stance phases from the gait cycle, from each concave and convex side, and compared between the concave and convex sides at 1% intervals, normalized by each stance phase time and each height. This method can detect the asymmetric kinematics between the concave and convex sides during whole gait cycle. The data were also compared between before and after surgery.

Table 2 Reflective surface markers' positions

Segments or vertebrae	Markers
Trunk	Bilateral acromion, C7 and Th10 spinous process
Upper extremity	Bilateral epicondyles of the humerus and wrist
Pelvic	Outermost borders of both wings of the ilium, S1 spinous process
Lower extremity	Bilateral greater trochanters of the femur
	Anterior surface of the thigh, mediolateral knee joint
	Anterior surface of the lower leg, mediolateral ankle joint
	Posterior surface of the calcaneal bone
	The heads of the 1st and 5th metatarsal bones

Correlation between radiograph findings and trunk posture measurement results

In order to investigate the correlation between trunk kinematics and radiograph findings, we measured the parameters including Cobb angle, sagittal balance, coronal balance, apical translation, thoracic kyphosis angle (T5-12), lumbar lordosis angle (T12-S1), pelvic obliquity, and sacral obliquity (a tilt in the sacral endplate secondary to an intrinsic sacral deformity) on pre- and postoperative standing full-length spine radiographs. We further measured pelvic rotation, apex vertebral rotation (major curve), apex vertebral rotation (upper minor curve) using CT images. Then, we analyzed the correlation between the above-mentioned radiographic parameters and maximum angles of trunk kinematics in all planes during the stance phases of both concave and convex sides at pre- and postoperative status.

Statistical analysis methods

PASW software version 17.0 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. The paired *t* test was used to make comparisons between the concave and convex sides. A Pearson product moment correlation coefficient (R) was used to determine whether respective relationships existed between the static image parameters and the maximum angles of trunk kinematics in all planes. For all tests, a p value below 0.05 was considered significant.

Ethics

The ethical review board of the hospital approved the study. All patients and their parents were given an explanation of the study, covering its purpose, content, risks, and safety. The study was only conducted after the patient provided their consent in writing.

Results

Trunk and pelvic position during standing (Table 3)

During standing, the mean sagittal trunk inclination angles were $-10.2 \pm 6.0°$, indicating backward inclination, before surgery, and decreased significantly to more neutral position after surgery (mean angle $-5.7 \pm 8.0°$). The trunk coronal inclination angles were not significantly different between pre- and postoperatively, indicating the trunks were maintained at the center of pelvis in the coronal plane. The mean trunk rotation angles were significantly deviated to the left (concave) side preoperatively with a mean angle of $4.1 \pm 2.2°$ and decreased significantly to $0.8 \pm 2.1°$ after surgery, indicating the trunk positions in the transverse plane were corrected to neutral position by the surgeries.

The preoperative pelvic positions were inclined to the front with the mean sagittal pelvic inclination angle of $5.1 \pm 4.5°$, which significantly decreased to $0.9 \pm 6.4°$ after surgery. The preoperative coronal pelvic inclination angles during standing located at the center of the virtual laboratory's coordinate and were maintained after surgery. The mean pelvic rotation angles were deviated $4.0 \pm 3.8°$ to the convex (right) side preoperatively and significantly decreased to $-1.6 \pm 2.7°$ after surgery (Table 3).

The preoperative trunk rotation angle was negatively correlated with the preoperative pelvic rotation angle ($R = -0.64$, $p < 0.01$) (Fig. 2). This result indicated that the pelvis rotated to the opposite side to the truncal rotation to keep the trunk toward the front.

Trunk and pelvic kinematics during gait (Fig. 3a, b)

Sagittal trunk inclination angle Preoperative patients were walking with forward-tilted posture in all stance phase with the mean angle of $4.9 \pm 3.6°$, which postoperatively decreased to $-1.8 \pm 3.5°$ ($p > 0.05$). No statistically significant differences were noted preoperatively and

Table 3 Standing trunk and pelvic posture

Trunk angle	Sagittal trunk inclination angle (with forward plus)	Coronal trunk inclination angle (with right side plus)	Trunk rotation angle (with left rotation plus)
Pre-surgery	− 10.2 ± 6.0	0.9 ± 2.1	4.1 ± 2.2
Post-surgery	− 5.7 ± 8.0*	0.7 ± 1.9	0.8 ± 2.1*
Pelvic angle	**Sagittal pelvic inclination angle (with forward plus)**	**Coronal pelvic inclination angle (with right side plus)**	**Pelvic rotation angle (with left rotation plus)**
Pre-surgery	5.1 ± 4.5	0.9 ± 1.6	− 4.0 ± 3.8
Post-surgery	0.9 ± 6.4*	− 1.1 ± 1.5	− 1.6 ± 2.7*

*Significantly different between pre- and post-surgery

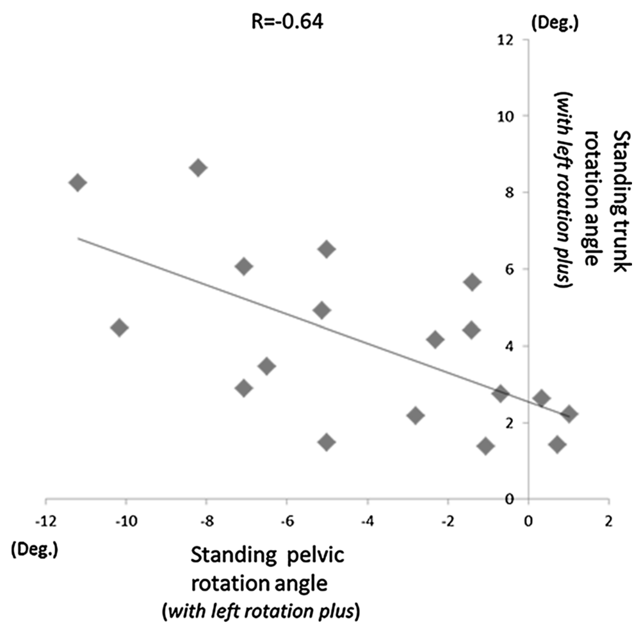

Fig. 2 Correlation between standing trunk rotation angle and standing pelvic rotation angle ($R=-0.64$; $p<0.05$)

postoperatively between the concave and convex sides in sagittal plane.

Coronal trunk inclination angle No statistically significant differences were also noted preoperatively and postoperatively between the concave and convex sides in coronal plane in all stance phase.

Trunk rotation angle The preoperative mean trunk rotation angle of 7.2 ± 0.3° indicated that the trunk was significantly rotated to the concave (left) side in all stance phase. Thus, the left shoulder was maintained to the backward during gait. The mean trunk rotation angle significantly decreased to 1.6 ± 0.3° postoperatively, and no statistically significant differences were noted between the concave and convex sides after surgery ($p>0.08$) which indicating the bilateral shoulder recovered to more symmetric movement.

The pelvic angle The pelvis displayed with symmetric kinematics during gait. No statistically significant differences of pelvic angles were noted between the concave and convex sides for all planes in the stance phase preoperatively and postoperatively.

Correlation between radiographic parameters and trunk kinematics during gait (Table 4)

The preoperative radiographic parameters which significantly correlated with the maximum values of the coronal trunk inclination angle during gait were coronal parameters including major Cobb angle ($R=0.53$), apical translation ($R=0.49$), and pelvic obliquity ($R=0.52$). The significant correlation between the postoperative radiographic parameters and the maximum angles of postoperative trunk kinematics during gait were only observed between the vertebral rotation angles at the apex of major and minor curve and the coronal trunk inclination angles.

Discussions

The asymmetrical trunk–pelvic kinematics of the AIS patients with right-sided thoracic major single curve became symmetric kinematics in transverse plane after the posterior spinal correction and fusion surgery.

The preoperative trunk rotation angle in relation to the pelvis displayed rotation deviation to the concave (left) side in the gait cycle. This is consistent with previous studies [10, 11]. Our previous gait analysis [5] demonstrated that type 1 AIS patients showed significant trunk rotation with the mean rotation angle of 8.8° during entire gait phase and type 5 (single lumbar major curve) AIS patients showed symmetric trunk rotational kinematics. Thus, the trunk rotation to the concave side appeared to be the characteristic trunk kinematics in AIS patient with major thoracic curve.

During standing, the rotational deviations of trunks were compensated by the pelvic rotation to the opposite side of trunk rotation. This enabled the trunk facing straight to the front while standing. However, during gait the pelvis kinematics became symmetric and the motion of the pelvis did not compensate the trunk rotation, resulting in marked trunk rotational deviation toward concave side. Park et al. [11] reported that AIS patients with thoracic major curve had the less thorax–pelvis coordination than age-matched controls in the transverse plane. Wong-Chung et al. [12] reported that AIS patients with double major curves had more asymmetrical trunk motions during gait in the transverse plane than that in the patients with single thoracic curve. These results supported that the coordination of the lumbar spine and pelvis had an important role in compensating the asymmetric rotational trunk kinematics caused by the thoracic curve to maintain the stability of the entire body.

However, the result that preoperatively asymmetric kinematics of the trunk and pelvis changed to symmetric kinematics postoperatively demonstrated that the posterior correction surgery improved the asymmetric trunk rotational kinematics. This change of postoperatively trunk kinematics was in range of the previous study [12].

In the sagittal plane, previous studies [8, 9] reported that AIS patients did not show any differences between before and after surgery on the radiographic, standing postural, and gait analysis. They suggested that it might be related to the fact that none of these patients had a significant preoperative sagittal malalignment. Our study demonstrated that the patients tilted slightly forward (4.9 ± 3.6°) during gait before surgery. Khoo et al. [13] reported that the healthy volunteers

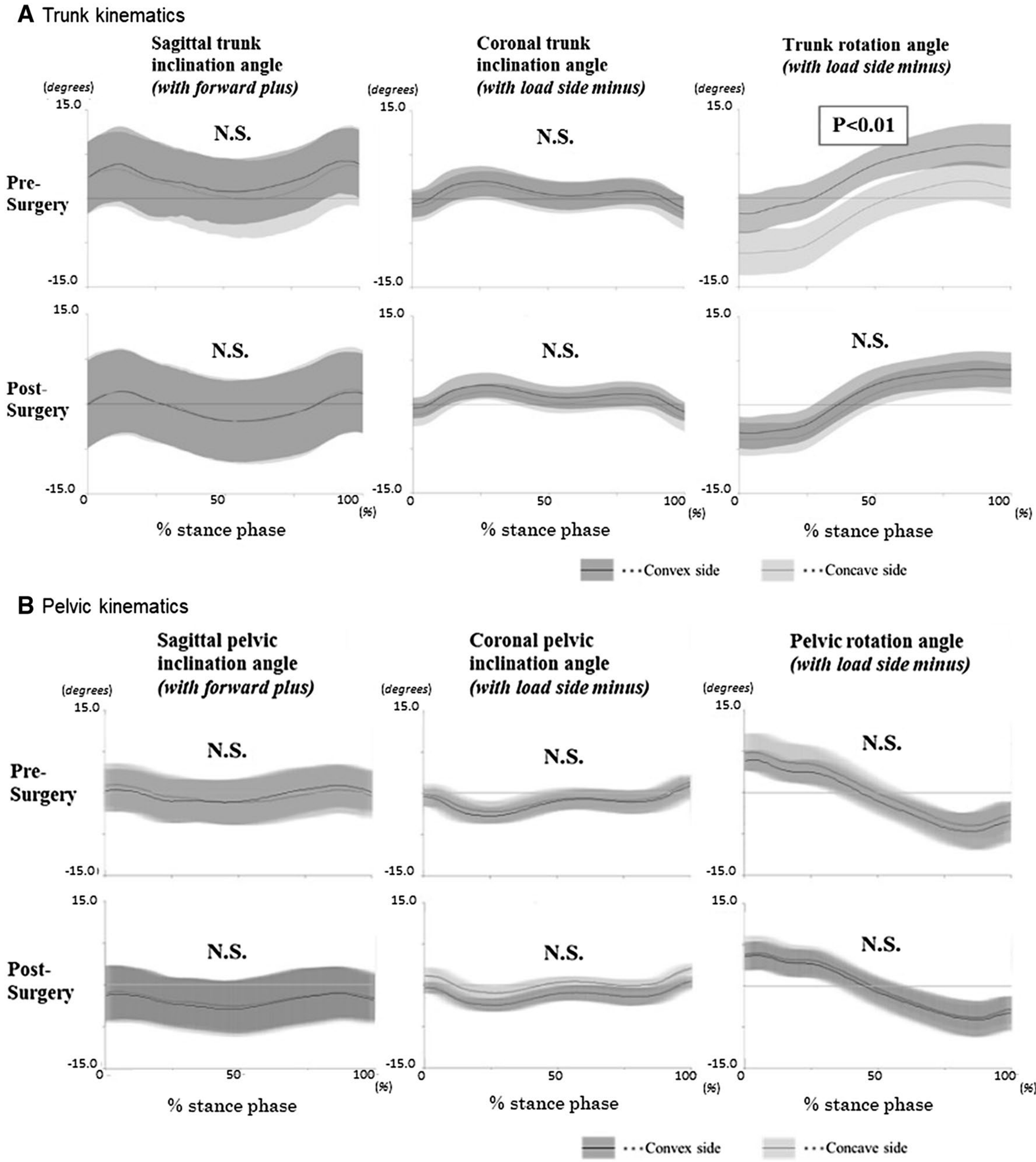

Fig. 3 Pre- and postoperative trunk and pelvic kinematics during the gait cycle. Graphs show the trunk balance during the stance phase of the gait cycle, standardized to 100%. The dark gray line shows the trunk position angle on the convex side under load, and the light gray line shows the angle on the concave side under load. The thin solid line shows the shift in the median value, and the width of each gray line shows the standard error of the mean

also shifted their center of gravities to the front during gait, which indicated that the forward-bend posture was not the characteristics of AIS, while posture of the patients in our study tended to be in vertical position ($-1.8 \pm 3.5°$) during gait after surgery. Mahaudens et al. [14] analyzed energy expenditure during gait in AIS patients using electromyogram and expired gas analysis. They found that AIS patients expended less motion energy in comparison with healthy individuals in spite of having higher oxygen consumption requirements, showing that they utilized their energy inefficiently. To compensate the inefficient energy consumption, AIS patients will be tended to be forward tilting posture to increase their movement efficiency. The correction surgery may have balanced the trunk kinematics and required no forward tilting posture during gait after surgery.

In the coronal plane, type 1 patients display symmetric kinematics in both the trunk and the pelvic and at both before and after surgery. In a previous study [5], we reported

Table 4 Correlation between radiographic static image parameters and trunk kinematics during gait

Trunk kinematics during gait	Sagittal trunk inclination angle		Coronal trunk inclination angle		Trunk rotation angle	
	R max	*L* max	*R* max	*L* max	*R* max	*L* max
Radiographs						
Pre-surgery						
Major Cobb angle (°)	−0.09	−0.11	0.53*	−0.37	0.16	0.09
Upper minor Cobb angle (°)	−0.18	−0.18	−0.31	0.36	0.09	−0.45
Lower minor Cobb angle (°)	0.17	0.14	0.4	−0.37	0.16	0.28
Sagittal balance (mm)	0.13	0.09	−0.24	0.3	−0.01	−0.12
Coronal balance (mm)	−0.3	−0.24	0.27	−0.23	−0.17	0.14
Apical translation (mm)	−0.25	−0.21	0.49*	−0.19	0.27	−0.04
Thoracic sagittal profile T5-12 (°)	0.23	0.24	−0.01	−0.04	−0.2	0.13
Lumbar lordosis T12-S1 (°)	0.16	0.2	0.42	−0.38	0.26	−0.02
Pelvic Obliquity (°)	−0.21	−0.28	0.52*	−0.1	0.35	−0.07
Sacral Obliquity	−0.22	−0.21	−0.12	−0.05	−0.42	0.23
Pelvic rotation (°)	−0.37	−0.33	0.08	0.26	−0.32	−0.35
Apex vertebral rotation (major curve)	−0.04	−0.03	−0.38	0.31	−0.29	−0.18
Apex vertebral rotation (upper minor curve)	−0.01	0	−0.28	0.04	−0.09	−0.34
Post-surgery						
Major Cobb angle (°)	0.11	0.16	−0.42	−0.28	0.31	0.2
Upper minor Cobb angle (°)	−0.06	−0.04	−0.28	−0.02	−0.19	0.15
Lower minor Cobb angle (°)	0.18	0.24	−0.14	−0.38	0.43	0.29
Sagittal balance	−0.14	−0.19	−0.11	0.02	0.35	−0.38
Coronal balance	0.1	0.08	0.08	−0.23	0.2	−0.12
Apical translation (mm)	0.27	0.26	−0.4	−0.11	0.44	−0.38
Thoracic sagittal profile T5-12 (°)	−0.13	−0.12	−0.15	0.35	0.14	0.11
Lumbar lordosis T12-S1 (°)	0.22	0.26	−0.13	0.02	−0.12	0.51*
Pelvic Obliquity (°)	−0.22	−0.25	0.43	−0.07	−0.02	−0.38
Sacral Obliquity	−0.05	−0.08	−0.15	0.06	0.08	−0.19
Pelvic rotation (°)	0.07	0.07	−0.18	−0.04	−0.04	0.05
Apex vertebral rotation (major curve)	−0.09	−0.1	−0.19	0.59*	−0.13	0.14
Apex vertebral rotation (upper minor curve)	−0.11	−0.1	−0.48*	0.21	0.04	−0.05

*Significant correlation by Pearson correlation analysis ($p < 0.05$)

that preoperative type 1 patients were able to maintained symmetric kinematics during gait, since the coronal balance was compensated by the lumbar spine, which was more flexible than the thoracic spine. Thus, the correction surgeries, which were only performed at the thoracic spine, had no influences on coronal kinematics.

We identified only significant correlations between the coronal radiographic parameters and coronal trunk inclination angle during gait. The preoperative correlations between the coronal radiographic parameters and coronal trunk inclination angle have disappeared postoperatively because that radiographic parameters significantly improved and became too small values for analysis. There are a few reports evaluating vertebra rotation using static images [15–19]. In the present study, we could not have demonstrated the correlation between vertebral rotation angles measured on CT images and trunk rotational kinematics during gait. The reason might be the differences in the position of evaluation, that is, CT images were obtained in the supine position, while the trunk kinematics were evaluated in standing position.

The limitation of the present study was that we did not compare with healthy individuals assumed to walk symmetrically. Trunk–pelvic kinematics analysis of the age-matched healthy population will increase the clinical impact of the abnormalities observed in AIS patients. And the kinematics we analyzed by the skeletal models simulated from the reflective surface markers might have been slightly different from real spinal alignments and kinematics. To lower the error, we affixed markers at the points where subcutaneous tissues were thin. However, since the present study analyzed exclusively the AIS patients with thoracic single major curve, we clarified the effect of correction surgery for AIS patients from the stand points of biomechanics.

Conclusions

We analyzed the trunk–pelvic kinematics of AIS patients with single right-sided thoracic major curve before and after surgery. Postoperatively, the characteristic rotational trunk–pelvic kinematics were improved symmetrical. A better understanding of trunk–pelvic kinematics and the effect of surgery for the kinematics of AIS patients will provide additional insights that may assist in considering the meaning of surgery.

Compliance with ethical standard

Conflict of interest All authors state that there are no conflicts of interest that might have influenced the preparation of this manuscript.

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