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Postural adjustments in adolescent idiopathic thoracic scoliosis during walking

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ABSTRACT

Introduction: Adolescent idiopathic scoliosis (AIS) is the most common type of three-dimensional spinal deformity. Identifying the postural adjustments or changes for different phases and events is needed for developing programs to improve the AIS gait, but such information has been limited. The current study aimed to fill the gap via three-dimensional motion analysis of quiet standing and level walking in patients with severe thoracic AIS.
Materials and Methods: Sixteen female adolescents with AIS (Lenke 1 or 2, age: 14.9 ± 1.7 years, height: 154.7 ± 5.0 cm, mass: 41.7 ± 7.2 kg) and sixteen sex-, age- and BMI-matched healthy controls (age: 14.8 ± 2.7 years, height: 154.9 ± 5.6 cm, mass: 44.7 ± 6.3 kg) participated in the current study with informed written consent. The kinematic and kinetic changes between the trunk, pelvis, and lower limb segments, and at the lumbosacral level at different gait events were measured during quiet standing and level walking.
Results: The homogeneity of the current patient group helped reduce the effects of the level and severity of spinal deformity on inter-subject variability that has been associated with controversies over reported gait variables in AIS. The current results support the hypothesis that postural adjustments involving the trunk, pelvis and lower limb segments were needed in severe thoracic AIS during both quiet standing and level walking, and differed between concave and convex sides at different key gait events during level walking.
Conclusions: Although scoliotic spinal deformity occurred mainly in the frontal plane, postural adjustments in all three planes were present at key events during level walking with associated joint loading changes in patients with severe thoracic AIS. Monitoring of such adjustments and the associated joint kinetic changes will be helpful for assessing the disease and treatment outcomes.

1. Introduction

Adolescent idiopathic scoliosis (AIS) is the most common type of three-dimensional spinal deformity during adolescence [1]. The typical curve is characterized by a lateral curvature beyond the normally straight spine as the consequence of an axial rotation with reduced kyphosis of the thoracic spine [2,3]. According to the Lenke classification system, six curve types can be defined depending on the spinal regions involved ([4]). The scoliotic curvature affects the body alignment, leading to altered whole body postural control and gait patterns [4–6]. Identifying the whole body postural adjustments or changes during standing and gait in patients with AIS relative to healthy controls is helpful for the management of these patients, aimed at improving their quality of life. Fig. 1.

Previous gait studies on AIS have focused mainly on the changes in individual gait variables, including temporal-distance parameters [7–11], ground reaction forces [9,12–15], and kinematics and kinetics of the lower limb joints [8,8,9,10,11,16–18]. Nishida et al. [19] is the only study to compare the asymmetrical trunk movement between patients with AIS with single thoracic curve and single lumbar curve, but the results were not compared to an age-matched healthy population. Studies reporting the motions of the trunk in relation to the other segments of the body are limited and focused on side-to-side asymmetry (e.g. [9,11],). Kramers-de Quervain et al. [11] found trunk rotational deviation to the concave side in relation to the pelvis during gait. Yang et al. [9] reported asymmetrical trunk motions in terms of side-to-side

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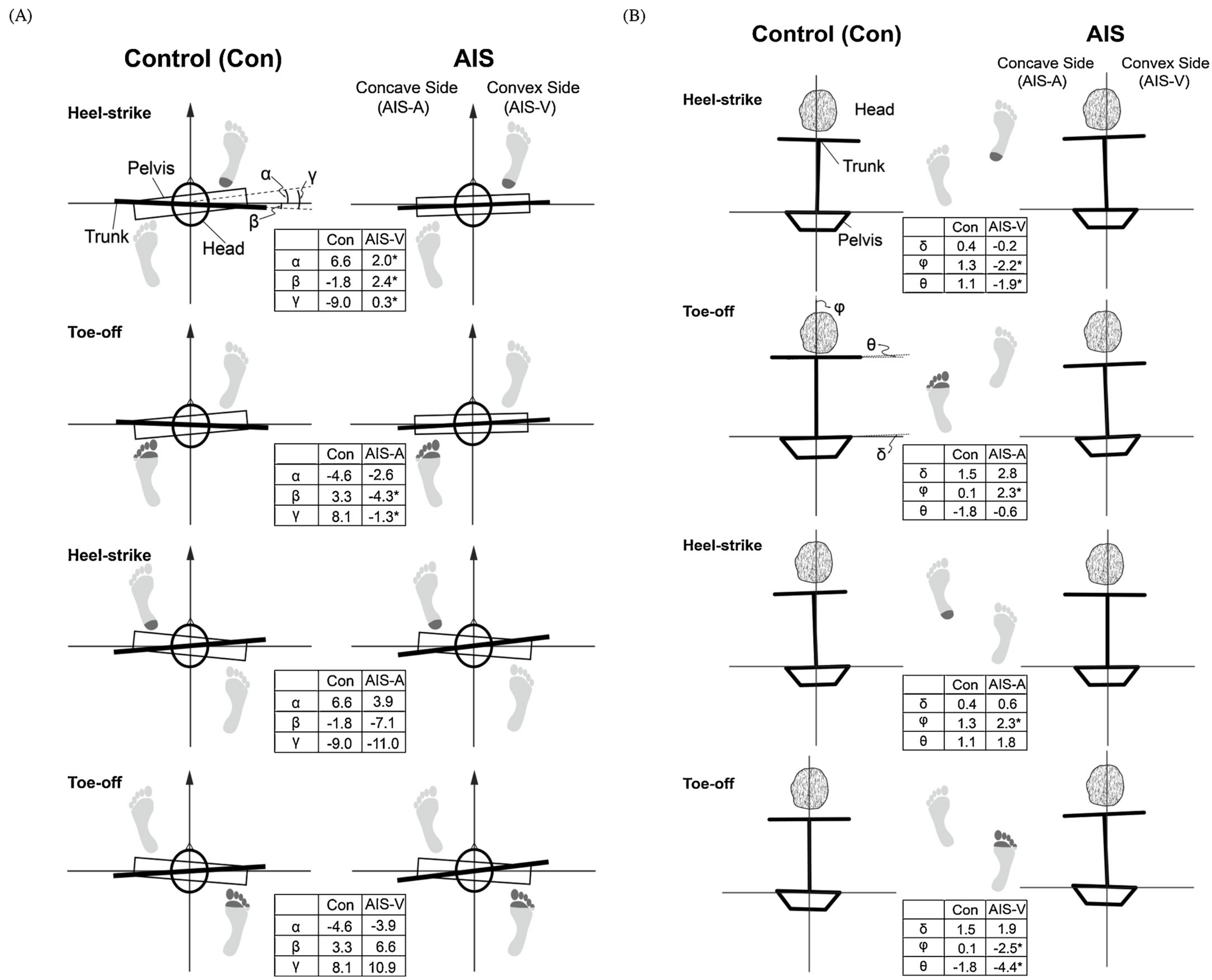

Fig. 1. Movements of the trunk and the pelvis in the transverse (A) and frontal (B) plane in the AIS (AIS-V: gait cycle on the convex side; AIS-A: gait cycle on the concave side) and Control groups during gait. The head (ellipse), trunk (thick line) and pelvic (thin rectangle) segments in the sub-figures were drawn according to the actual mean values. Positive values of α, β and γ are contralateral rotations of the pelvis, trunk and trunk/pelvis, respectively, indicating that the ipsilateral shoulder (hip) joint center is anterior to the contralateral shoulder (hip) for the trunk (pelvis). Positive values of δ, ϕ and θ are upward list of the pelvis and trunk, and side-bending of the trunk/pelvis, indicating that the contralateral shoulder (hip) joint center is higher than the ipsilateral shoulder (hip) for the trunk (pelvis). Foot prints with dark grey areas at the heel and toes indicate heel-strike and toe-off, respectively.

correlation coefficients during gait. These reports included patients with a variety of curve types and severity without considering the potential confounding effects of the curve characteristics. Park et al. [8] studied the coordination between the trunk and pelvis during the whole gait cycle using a vector coding technique. However, it is important to identify how the spinal deformity affects the instantaneous inter-segmental motions between the trunk, pelvis and the lower limb joints at different gait events for a better understanding of the postural adjustments and control strategies. To the best knowledge of the authors, such information has not been documented in the literature.

Diversity of the curve types of participants in the experimental groups appears to be an important factor contributing to the inconsistency in the reported gait analysis results [20]. Nearly all studies examining walking in scoliotic patients report some degree of gait deviation or altered whole body postural control. However, the findings are somewhat inconsistent [3,11,12,18,21]. For example, patients with AIS were shown to have about 7% shorter step length [18], but several authors do not agree that shorter step lengths are responsible for the decrease in gait velocity [9,11,17]. The AIS was shown to have altered whole body postural control in some studies [9,17,21], while several others found otherwise [3,11,12,18]. Note that most of these studies recruited subjects with a mixture of different curve types and severity [3–10,12–18,20–24]. Since the trunk is the biggest segment in the body, representing more than half of the body mass [25], the deformed spinal curve – and thus the altered shape and mass distribution of the trunk – is expected to affect its own motion and those of the other segments, especially the pelvis [17,26]. Therefore, it appears that homogeneity of the curve characteristics of the participants in the experimental groups is critical for identifying the gait deviations specific to the particular curve type.

The current study aimed to identify the whole body postural adjustments during quiet standing and level walking in patients with severe single thoracic AIS (Lenke 1), in terms of deviations from healthy controls in the three-dimensional kinematic and kinetic changes between the trunk, pelvis and lower limb segments, and at the lumbosacral level at different gait events. It was hypothesized that postural adjustments or changes involving multiple body segments on both sides were needed during both quiet standing and level walking, and that they differed between gait cycles of the concave and convex sides at different key events during level walking.

2. Materials and methods

2.1. Subjects

Sixteen female adolescents with AIS (AIS group, age: 14.9 ± 1.7 years, height: 154.7 ± 5.0 cm, mass: 41.7 ± 7.2 kg) participated in the current study with informed written consent signed by both them and their legal guardians. They were recruited from National Taiwan University Hospital between January 2009 and December 2011, scheduled for posterior spinal fusion. All the patients were determined radiographically to have a single thoracic curve (Lenke 1 [4]) with Cobb angles of 52.7 ± 10.5 °. Participants were excluded if they had leg length discrepancies greater than 1 cm or other musculoskeletal diseases, such as trauma, muscle atrophy or joint diseases, which would affect their gait performance. Sixteen healthy adolescents (Control group, age: 14.8 ± 2.7 years, height: 154.9 ± 5.6 cm, mass: 44.7 ± 6.3 kg) were selected to match with the AIS group for sex, age and BMI. An a priori power analysis based on pilot results using GPOWER [27] determined that five subjects for each group would yield a power of 0.8 at a significance level of 0.05. The study was approved by the Institutional Research Board.

2.2. Gait experiments

In a gait laboratory, each subject walked at a self-selected pace on a 10-meter walkway while 39 infrared retro-reflective markers were used to track the motions of the body segments, namely ASISs, PSISs, greater trochanters, mid-thighs, medial and lateral epicondyles, heads of fibulae, tibial tuberosities, medial and lateral malleoli, navicular tuberosities, fifth metatarsal bases, big toes and heels, and mandibular condylar processes, acromion processes, C7, medial and lateral humeral epicondyles, and ulnar styloids [28–30]. Three-dimensional trajectories of the markers were measured using an 8-camera motion analysis system (Vicon MX T-40, OMG, UK) at 120 Hz and the ground reaction forces were measured using two forceplates (OR6-7, AMTI, USA) at 1080 Hz. Data for three complete gait cycles for both the right and left lower limbs were obtained for each subject in the Control group. For the AIS group, data were obtained for three complete gait cycles of the lower limb on the convex side (denoted AIS-V or AIS-V cycle) and the lower limb on the concave side (denoted AIS-A or AIS-A cycle). Kinematic data were also collected for ten seconds for each subject while standing quietly with their feet shoulder-width apart as instructed.

2.3. Calculation of dependent variables

Each body segment was modeled as a rigid body embedded with an orthogonal coordinate system with the positive x-axis directed anteriorly, the positive y-axis superiorly and the positive z-axis to the right in accordance with the ISB recommendations [31]. The angular motions of the pelvis and trunk segments were described relative to the laboratory coordinate system, and that of the trunk relative to the pelvic system (here referred to as trunk/pelvis). A Cardanic rotation sequence of y-x-z was used to describe these rotational movements, and z-x-y for those of each of the lower limb joints [32]. Muscle moments at the lower limb joints and L5/S1 during stance phase were also calculated following the standard inverse dynamics analysis procedure from distal to proximal segments using the measured kinematic and GRF data. Effects of soft tissue artifacts of the pelvis-leg apparatus were reduced using a global optimization method that minimized the weighted sum of squared distances between measured and calculated marker positions, with ball-and-socket joint constraints [33]. Subject-specific body segmental inertial properties were obtained using an optimization-based method, which has been shown to reduce errors in the calculated center of mass motions and joint moments when compared to commonly used prediction methods [29]. Peak muscle moments were then extracted for subsequent statistical analysis. Spatio-temporal parameters of gait, namely stride length, stride time, step length, step width, cadence and gait speed were also obtained. The gait events of heel-strike and toe-off were determined from the forceplate and foot kinematic data [34].

2.4. Statistical analysis

For each calculated variable, means and standard deviations, and values at heel-strike, toe-off, and contralateral heel-strike and toe-off were obtained for each of the AIS-V and AIS-A gait cycles for the AIS group, while those for the Control group were obtained from gait cycles of both sides. Each of the calculated variables was first tested for normality using a Shapiro-Wilk test. For variables of normal distribution, independent *t*-tests were used to compare the differences between AIS-V and Control and between AIS-A and Control, while paired *t*-tests were used to compare between AIS-V and AIS-A. For those of non-normal distribution, Wilcoxon rank sum tests were used for between-group comparisons while Wilcoxon signed rank tests were used to detect the differences between AIS-V and AIS-A. A significance level of $\alpha = 0.05$ was set for all tests. All statistical analyses were performed using SAS version 9.2 (SAS Institute Inc., NC, USA).

3. Results

3.1. Posture during quiet standing and temporal-spatial parameters during walking

During quiet standing, when compared to the Control, the AIS group showed similar pelvic rotations but significantly less posterior tilt and greater left upward list of the trunk, with greater trunk/pelvis left rotation and side-bending (Table 1). There were no significant between-group differences in the walking speed, cadence, step length and step width (Table 1).

3.2. Kinematics

Compared to the Control, the AIS group showed similar pelvic rotations but significantly greater contralateral rotation at heel-strike and greater downward list of the trunk at heel-strike and toe-off during AIS-V (Table 2, Fig. S1). The AIS group also showed greater contralateral rotation of the trunk/pelvis at heel-strike and greater contralateral side-bending of the trunk/pelvis at both heel-strike and toe-off during AIS-V (Table 2, Fig. S1). During AIS-A, greater downward list of the trunk was found at heel-strike while greater ipsilateral rotation and upward list of the trunk were found at toe-off (Table 2, Fig. S1), with greater ipsilateral rotation of the trunk/pelvis at toe-off (Table 2, Fig. S1).

Compared to AIS-V, AIS-A showed greater ipsilateral rotation and upward list of the trunk at heel-strike and toe-off (Table 2, Fig. S1), with greater ipsilateral rotation and contralateral side-bending of the trunk/pelvis (Table 2, Fig. S1).

The AIS group showed greater lumbar flexion at toe-off during AIS-V, as well as at heel-strike and toe-off during AIS-A when compared to the corresponding values in the Control group (Table 2, Fig. S1). Significantly less lumbar ipsilateral side-bending at heel-strike but greater lumbar contralateral side-bending at toe-off were found during AIS-V (Table 2, Fig. S1). Compared to AIS-V, AIS-A showed greater lumbar flexion at heel-strike but reduced lumbar flexion at toe-off (Table 2, Fig. S1).

Compared to the Control, most significant differences in joint kinematics occurred during AIS-A, showing increased hip internal rotation, hip adduction, knee flexion and ankle internal rotation at heel-

Table 1
Means (standard deviations) of the spatiotemporal parameters during gait and the orientations of the pelvis and trunk relative to global, and those of the trunk relative to the pelvis (trunk/pelvis) during quiet standing in the subjects with adolescent idiopathic scoliosis (AIS) and healthy controls. The orientations were obtained following a y-x-z rotation sequence, giving rotation, list and tilt for the pelvis and trunk segments, and rotation, side-bending and flexion/extension for the trunk/pelvis, respectively.

	AIS	Control	P-value
Spatiotemporal Parameters During Gait			
Walking speed (m/s)	0.8 (0.3)	1.0 (0.3)	0.15
Step width (cm)	8.8 (2.9)	7.9 (2.6)	0.37
Cadence (1/s)	92.7 (25.0)	106.5 (24.6)	0.12
Convex Side Step length (cm)	50.0 (3.8)	51.9 (5.4)	0.27
Concave Side Step length (cm)	50.2 (4.5)	51.9 (5.4)	0.32
Pelvis and Trunk Orientations During Quiet Standing			
Trunk relative to the pelvis (trunk/pelvis)			
Flexion (+)/extension (-)	−14.1 (6.5)	−14.2 (8.6)	0.97
Right (+)/left (-) rotation	−9.0 (5.0)	−0.8 (2.4)	< 0.01*
Right (+)/left (-) SB	−2.0 (3.6)	1.8 (2.5)	< 0.01*
Trunk relative to global			
Anterior (+)/posterior (-) tilt	−1.7 (2.5)	−4.1 (2.5)	0.01*
Right (+)/left (-) rotation	−7.5 (8.6)	−1.9 (5.2)	0.03*
Right (+)/left (-) upward list	−2.5 (2.4)	1.0 (1.4)	< 0.01*
Pelvic relative to global			
Anterior (+)/posterior (-) tilt	12.3 (5.7)	10.1 (7.8)	0.37
Right (+)/left (-) rotation	2.8 (10.9)	−0.8 (6.4)	0.26
Right (+)/left (-) upward list	−0.2 (3.4)	−0.8 (2.0)	0.55

SB: side-bending; Right rotation (+) indicates that the left shoulder (hip) joint center is anterior to the right one for the trunk (pelvis); Right upward list (+) indicates that the left shoulder (hip) joint center is higher than the right one for the trunk (pelvis); Right (+) SB indicates that the right shoulder joint center is close to the right hip joint center in the frontal plane.

strike, and increased hip internal rotation, knee internal rotation and ankle internal rotation at contralateral toe-off (Tables 3 and 4, Fig. S2).

3.3. Kinetics

When compared to the Control, the AIS group showed a reduced peak knee extensor moment, peak ankle plantarflexor moment and peak ipsilateral lumbosacral lateral flexor moment, but greater peak lumbar extensor moment during AIS-A (Table 5). Compared to AIS-V, the AIS-A showed greater peak lumbar extensor moment but a reduced peak ipsilateral lumbosacral lateral flexor moment (Table 5)

4. Discussion

The current study aimed to identify postural adjustments in severe thoracic AIS in terms of deviations of inter-segmental motions during level walking. The homogeneity of the current patient group helped reduce the effects of the curve types of spinal deformity on inter-subject variability that has been associated with controversies over reported gait variables in AIS [20]. The current results support the hypothesis that postural adjustments involving the trunk, pelvis and lower limb segments were needed in severe thoracic AIS during both quiet standing and level walking, and differed between concave and convex sides at different key gait events during level walking.

In the transverse plane, the thoracic spinal deformity of the patients with AIS led directly to the observed trunk/pelvis malalignment in the standing posture – in agreement with previous studies [11,19] – which in turn contributed to the altered motions of the trunk relative to both the pelvis and the global coordinate system during gait. With about 9° of trunk/pelvis rotation to the left (concave side) during standing (Table 1), the patients showed a reduced total range of motion (AIS: 10°; Control: 19.4°) and an asymmetrical pattern in the trunk/pelvis rotations during walking. This limited the trunk/pelvis rotation to a range from neutral (about 0.3° at AIS-V heel-strike) to the left rotated position when in the standing posture, i.e., a close-to-normal value at heel-strike during AIS-A (Table 2). With the trunk/pelvis malalignment, the patients with AIS appeared to maintain a pelvic rotation as close as

Table 2
Means (standard deviations) of the angular motions (unit: degree) of the pelvis and trunk segments, as well as trunk/pelvis during walking in the subjects with adolescent idiopathic scoliosis (AIS; AIS-A: concave side; AIS-V: convex side) and healthy controls. The angular motions were obtained following a y-x-z rotation sequence, giving rotation, list and tilt for the pelvis and trunk segments, and rotation, side-bending and flexion/extension for the trunk/pelvis, respectively. P-values are also reported (P_A = AIS-A vs. Control; P_V = AIS-V vs. Control; P_S = AIS-A vs. AIS-V).

	Heel-Strike				Toe-off			
	AIS-V	AIS-A	Control	(P_V, P_A, P_S)	AIS-V	AIS-A	Control	(P_V, P_A, P_S)
Pelvis relative to global								
Anterior (+)/posterior(-) tilt	9.0 (5.9)	10.0 (5.7)	8.0 (7.2)	(0.66, 0.30, < 0.01)	9.7 (5.8)	9.5 (5.9)	7.5 (6.8)	(0.34, 0.34,0.55)
Contra (+)/Ispi(-) rotation	2.0 (3.4)*	3.9 (3.4)	6.6 (2.1)	(< 0.01, 0.20, 0.15)	−3.9 (3.3)	−2.6 (4.2)	−4.6 (2.7)	(0.53, 0.08, 0.43)
Upward (+)/downward (-) list	−0.2 (2.4)	0.6 (2.0)	0.4 (2.2)	(0.42, 0.26,0.39)	1.9 (2.0)	2.8 (2.6)	1.5 (2.4)	(0.67, 0.85, 0.33)
Trunk relative to pelvis								
Flexion (+)/extension (-)	−6.5 (7.0)	−7.0 (6.7)	−4.9 (8.2)	(0.56, 0.45, 0.08)	−7.6 (7.2)	−8.6 (7.3)	−6.5 (8.0)	(0.67, 0.43, < 0.01)
Contra (+)/Ispi (-) rotation	0.3 (5.6)*†	−11.0 (5.9)†	−9.0 (4.8)	(< 0.01, 0.80, < 0.01)	10.9 (5.3)†	−1.3 (5.9)*†	8.1 (4.0)	(0.10, < 0.01, < 0.01)
Ispi (+)/Contra (-) SB	−1.9 (3.0) *	1.8 (2.8)	1.1 (3.2)	(< 0.01, < 0.01, 0.01)	−4.4 (2.8)*†	−0.6 (2.7)†	−1.8 (3.1)	(0.02, 0.10, < 0.01)
Trunk relative to global								
Anterior (+)/posterior(-) tilt	2.5(3.4)	3.0 (3.5)	2.5 (3.6)	(0.99, 0.53, 0.11)	1.6 (4.0)	1.1 (3.8)	0.2 (4.3)	(0.34, 0.48, 0.06)
Contra (+)/Ispi(-) rotation	2.4 (4.1)*†	−7.1 (4.3)†	−1.8 (4.7)	(0.01,0.24, < 0.01)	6.6 (4.3)†	−4.3 (4.3)*†	3.3 (4.5)	(0.04, < 0.01, < 0.01)
Upward (+)/downward (-) list	−2.2(2.7)*†	2.3 (2.7)*†	1.3 (1.9)	(< 0.01, < 0.01, < 0.01)	−2.5 (2.8)*†	2.3 (2.4)*†	0.1 (1.5)	(< 0.01, < 0.01, < 0.01)
Lumbar flexion (+)/extension (-)	6.0(2.3)†	6.8 (2.6)*†	4.7 (3.2)	(0.19, 0.03, 0.04)	5.7 (2.7)*†	5.0 (2.7)*†	2.5 (3.6)	(0.01, 0.04, 0.02)
Lumbar Ispi (+)/Contra (-) SB	−1.5(1.8)	−0.4 (1.4)*	−2.0 (1.5)	(0.42, < 0.01, 0.14)	0.5 (1.8)	1.7 (1.4)*	0.9 (1.9)	(0.59, 0.05, 0.12)

Contra: contralateral; Ipsi: ipsilateral; SB: side-bending; *: significant difference from Control; †: significant difference between sides;
Contra rotation (+) indicates that the ipsilateral shoulder (hip) joint center is anterior to the contralateral shoulder (hip) for the trunk (pelvis); Upward list indicates that the contralateral shoulder (hip) joint center is higher than the ipsilateral shoulder (hip) for the trunk (pelvis); Ispi (+) SB indicates that the ipsilateral shoulder joint center is close to the ipsilateral hip joint center in the frontal plane.

Table 3
Means (standard deviations) of the angles (unit: degree) of the hip, knee and ankle joint during walking at heel-strike and contralateral heel-strike in the subjects with adolescent idiopathic scoliosis (AIS) and healthy controls. The calculated variables for the convex and concave side for the AIS group are denoted as AIS-V and AIS-A, respectively. P-values are also reported (P_V= AIS-V vs. Control; P_A= AIS-A vs. Control; P_S= AIS-A vs. AIS-V).

	Heel-Strike				Contralateral Heel-Strike			
	AIS-V	AIS-A	Control	(P_V, P_A, P_S)	AIS-V	AIS-A	Control	(P_V, P_A, P_S)
Hip flexion (+)	19.9 (5.2)	23.1 (4.2)	22.3 (6.3)	(0.06, 0.69, 0.01)	−9.2 (5.0)	−9.1 (4.6)	−10.2 (5.7)	(0.63, 0.53, 0.86)
Hip IR (+)	−3.1 (5.3)†	0.7 (3.2)*†	−5.0 (4.2)	(0.31, < 0.01, < 0.01)	3.3 (6.4)	3.9 (4.7)	1.3 (5.2)	(0.18, 0.16, 0.72)
Hip adduction (+)	4.5 (4.9)*	4.1 (5.6)*	−0.3 (5.8)	(< 0.01, 0.04, 0.83)	6.6 (4.0)†	3.5 (3.0)†	4.2 (4.0)	(0.19, 0.58, < 0.01)
Knee flexion (+)	9.0 (6.2)	11.6 (6.9)*	6.2 (8.1)	(0.55, 0.05, 0.06)	16.6(5.8)†	20.8(6.8)†	15.9(9.9)	(0.82, 0.12, 0.03)
Knee IR (+)	−0.5 (5.8)	1.3 (3.5)	−1.5 (3.2)	(0.56, 0.06, 0.36)	2.9 (3.6)	5.4 (5.2)	3.2 (1.0)	(0.85, 0.49, 0.15)
Knee adduction (+)	−2.8 (2.4)	−3.3 (2.3)	−3.1 (3.3)	(0.75, 0.15, 0.51)	−4.2 (2.7)	−4.8 (3.5)	−3.4 (3.8)	(0.77, 0.31, 0.44)
Ankle DF (+)	−1.8 (3.3)	−1.0 (3.7)	−1.4 (5.6)	(0.79, 0.80, 0.52)	5.6 (4.2)	6.0 (4.8)	5.9 (7.8)	(0.89, 0.51, 0.76)
Ankle IR (+)	4.0 (2.4)	2.4 (2.4)	1.7 (3.3)	(0.02, 0.50, 0.06)	4.4 (2.5)	5.3 (3.4)	4.1 (3.1)	(0.74, 0.06, 0.34)
Ankle adduction (+)	6.6 (5.7)	5.2 (5.0)	5.1 (6.1)	(0.25, 0.96, 0.21)	2.8 (5.9)	2.9 (5.6)	1.9 (4.8)	(0.63, 0.25, 0.91)

IR: internal rotation; DF: dorsiflexion; *: significant difference between AIS-V/AIS-A and Control; †: significant difference between AIS-A and AIS-V.

Table 4
Means (standard deviations) of the angles (unit: degree) of the hip, knee and ankle joint during walking at toe-off and contralateral toe-off in the subjects with adolescent idiopathic scoliosis (AIS) and healthy controls. The calculated variables for the convex and concave side for the AIS group are denoted as AIS-V and AIS-A, respectively. P-values are also reported (P_V= AIS-V vs. Control; P_A= AIS-A vs. Control; P_S= AIS-A vs. AIS-V).

	Toe-off				Contralateral Toe-off			
	AIS-V	AIS-A	Control	(P_V, P_A, P_S)	AIS-V	AIS-A	Control	(P_V, P_A, P_S)
Hip flexion (+)	−5.1(4.9)	−4.1(6.0)	−5.1(6.6)	(0.68, 0.68, 0.37)	16.7(5.5)	19.5(5.4)	20.1(7.3)	(0.15, 0.62, 0.02)
Hip IR (+)	−1.3(7.1)	−0.4(4.4)	−1.5(5.1)	(0.54, 0.53, 0.56)	1.8(5.0)	3.6(3.6)*	−1.3(3.8)	(0.06, < 0.01, 0.20)
Hip adduction (+)	1.3(4.1)*	−1.0(3.4)	−2.6(3.5)	(< 0.01, 0.21, 0.02)	8.8(4.1)*	7.7(5.5)	3.1(5.9)	(< 0.01, 0.28, 0.48)
Knee flexion (+)	38.7(9.6)	41.8(11.4)	40.7(8.8)	(0.55, 0.75, 0.18)	15.1(7.7)	19.0(7.4)	16.0(8.2)	(0.75, 0.21, < 0.01)
Knee IR (+)	−3.7(6.7)	−2.2(3.8)	−4.5(4.1)	(0.57, 0.11, 0.37)	−0.7(4.8)	2.2(4.0)*	−1.9(5.6)	(0.39, 0.03, 0.14)
Knee adduction (+)	−9.7(3.6)	−9.6(5.5)	−8.5(6.2)	(0.25, 0.62, 0.91)	−3.3(2.7)	−3.9(2.9)	−2.1(3.9)	(0.37, 0.15,0.41)
Ankle DF (+)	−7.1(6.5)*	−7.4(6.9)*	−14.7(9.0)	(< 0.01, 0.03, 0.87)	−1.4(3.9)	−0.6(4.2)	−3.8(5.2)	(0.18, 0.06, 0.48)
Ankle IR (+)	7.9(4.0)	8.0(3.7)	8.2(7.0)	(0.32, 0.93, 0.90)	1.3(2.4)	−0.1(3.9)	−1.4(3.4)	(0.02, 0.35, 0.11)
Ankle adduction (+)	8.1(6.5)	8.1(5.6)	6.0(7.6)	(0.52, 0.40, 0.97)	2.2(5.8)	0.8(4.5)	−0.5(5.4)	(0.33, 0.46,0.21)

IR: internal rotation; DF: dorsiflexion; *: significant difference between AIS-V/AIS-A and Control; †: significant difference between AIS-V and AIS-A.

Table 5
Means (standard deviations) of the peak muscle moments at the hip, knee, ankle and lumbosacral joints during walking in the subjects with adolescent idiopathic scoliosis (AIS) and healthy controls. The calculated variables for the convex and concave side for the AIS group are denoted as AIS-V and AIS-A, respectively. P-values are also reported (P_V= AIS-V vs. Control; P_A= AIS-A vs. Control; P_S= AIS-A vs. AIS-V).

	AIS-V	%GC	AIS-A	%GC	Control	%GC	(P_V, P_A, P_S)
Hip extensor (+)	8.9 (2.6)	2.8 (1.1)	9.7 (4.0)	3.0 (1.9)	9.8 (3.0)	2.1 (1.2)	(0.36, 0.96, 0.51)
Knee extensor (+)	5.7 (3.4)	12.3 (3.1)	5.3 (2.7)*	11.5 (2.4)	7.7 (4.1)	11.2 (2.2)	(0.14, 0.02, 0.63)
Ankle plantarflexor (+)	14.1 (2.0)	45.5 (3.6)	13.8 (1.9)*	45.1 (2.9)	16.1 (3.3)	46.8 (3.4)	(0.33, < 0.01, 0.17)
Lumbosacral extensor (+)	11.7 (3.2)†	1.5 (1.0)	14.2 (5.3)*,†	1.8 (0.9)	10.7 (3.3)	1.2 (0.8)	(0.42, 0.05, 0.02)
Lumbosacral lateral flexor #	−3.9 (2.7)†	6.5 (4.0)	0.7 (4.5)*,†	5.5 (3.7)	−5.1 (4.1)	8.3(3.2)	(0.53, < 0.01, 0.03)

Lateral flexor of contralateral side (+) /ipsilateral side (-).
* significant difference between AIS-V/AIS-A and Control.
† significant difference between AIS-V and AIS-A; %GC: % Gait Cycle.

possible to those of the controls, with unaltered step length and step width. The close-to-normal counter-rotation (rotation in the reverse direction) of the trunk relative to the pelvis about the vertical axis during AIS-A helped reduce the total body angular momentum, which has been suggested helps maintain the whole-body stability [26]. However, this mechanism appeared to be missing during AIS-V, suggesting that whole-body balance control may be more difficult during the stance phase of AIS-V. On the other hand, the slight reduction in the pelvic contralateral rotation and reduced hip external rotation at heel-strike during AIS-V (Table 3) will alter the foot progression angle and thus the base of support during walking (Table 1). Further study on the balance control of this patient population, such as via the body's center of mass (COM) motion relative to the dynamic base of support, i.e., center of pressure (COP) [15,35–38] will be needed to provide more insight into the control strategies adopted.

In the frontal plane, the patients with AIS showed an expected asymmetrical kinematic pattern of the trunk and pelvis during walking, predominantly as a result of the persistent trunk list of about 2.2°-2.5° towards the concave side. This includes greater trunk downward list and contralateral trunk/pelvis side-bending towards the concave side at heel-strike and toe-off during AIS-A, whether compared to Control or AIS-V (Table 2). Increased trunk list towards the concave side will shift the mass of the trunk in the same direction (Table 2), which will help decrease the peak ipsilateral lumbosacral lateral flexor moments during AIS-A but will increase around contralateral toe-off during AIS-V (Table 5). However, with the increased hip adduction around contralateral toe-off during AIS-V the patients successfully avoided the potentially excessive ipsilateral lumbosacral lateral flexor moments and maintained a value similar to Controls (Table 5). Increased hip adduction at heel-strike during both AIS-A and AIS-V may also help reduce ipsilateral lumbosacral lateral flexor moments (Table 5). These results suggest that the thoracic spinal deformity did not appear to increase the loadings at the lumbosacral joint level as one would have expected.

In the sagittal plane, asymmetrical kinematic patterns were found mainly in the lumbar joint and the lower limb joints during walking, with greater loadings in the lumbar extensor muscles, but reduced extensor muscle loadings in the knee and ankle during AIS-A (Table 5). To accommodate for the persistent trunk list towards the concave side, greater ipsilateral knee flexion but reduced contralateral knee flexion were found at heel-strike during AIS-A when compared with those at heel-strike during AIS-V (Table 3). These kinematic changes appeared to help reduce the knee extensor moments, but they increase the lumbar extensor moments around heel-strike during AIS-A (Table 5). These results suggest that, while scoliotic spinal deformity occurs mainly in the frontal plane, postural adjustments in the sagittal plane were also present at heel-strike of both limbs during level walking, with associated joint loading changes in patients with severe thoracic AIS. Therefore, it is suggested that monitoring postural adjustments and the associated kinetic changes of the trunk/pelvis and lower limbs is needed for assessing the disease and treatment outcomes.

The current study focused on patients with severe single thoracic AIS (Lenke 1), thus reducing the effects of diversity of curve types on inter-subject variability that may have been associated with controversies over reported gait variables in patients with AIS. For other curve types (single or double), locations of curves (thoracic and lumbar), and/or severity (Cobb angles), further studies will be needed. Longitudinal studies would also be helpful for investigating whether the observed postural adjustments have long term effects on the loadings of the spine and thus the progression of the spinal deformity. The results of the current study contribute to the understanding of the characteristics of motions between the trunk and pelvis and the lower limb joints in patients with severe thoracic AIS, which will be helpful in future development of rehabilitation programs and treatment plans for such patients.

5. Conclusions

Postural adjustments and/or deviations involving the trunk, pelvis and lower limb segments were identified in severe thoracic AIS during quiet standing and at key events of level walking. Although scoliotic spinal deformity appeared mainly in the frontal plane, postural adjustments and/or deviations with associated joint loading changes in all three planes were observed during level walking. These changes differed between the concave and convex sides at different gait events. Monitoring of such adjustments and the associated joint kinetic changes will be helpful for the assessment and management of the disease and treatment outcomes.

Conflicts of interest statement

None.

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