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Bilateral asymmetry in kinematic strategies for obstacle-crossing in adolescents with severe idiopathic thoracic scoliosis

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ABSTRACT

Introduction: Adolescent idiopathic scoliosis (AIS) is the most common three-dimensional spinal deformity pathology during adolescence, often accompanied with sensory integration and proprioception problems, which may lead to abnormal postural control and altered end-point control during functional activities. This paper identifies the effects of AIS on the end-point control and on angular kinematics of the trunk and pelvis-leg apparatus during obstacle-crossing for both the concave- and convex-side limb leading.

Materials and Methods: Sixteen adolescents with severe Lenke 1 AIS (age: 14.9 ± 1.7 years, height: 154.7 ± 5.0 cm) and sixteen healthy controls (age: 14.8 ± 2.7 years, height: 154.9 ± 5.6 cm) each walked and crossed obstacles of 3 heights with either the concave- (AIS-A) or convex-side (AIS-V) limb leading. Angular motions of the trunk, pelvis and lower limbs, and toe-obstacle clearances were measured. Two-way analyses of variance were used to study between-subject (group) and within-subject (limb and height) effects on the variables. Whenever a height effect was found, a polynomial test was used to determine the linear trend. $\alpha = 0.05$ was set for all tests.

Results: Patients with AIS significantly reduced pelvic downward list but increased dorsiflexion in both stance and swing ankles at leading limb crossing when compared to controls ($p < 0.05$). During AIS-A, additional kinematic modifications were observed, i.e., increased stance hip adduction (4.2 ± 0.8°, p = 0.005) and increased swing knee flexion (12.6 ± 1.4°, p = 0.106), with significantly decreased leading toe-clearance (AIS-A: 121.4 ± 6.7 mm, controls: 140.1 ± 5.6 mm, p = 0.031).

Conclusions: Patients with AIS adopted an altered kinematic strategy for successful obstacle-crossing. With the concave-side limb leading, more joint kinematic modifications with reduced toe-clearance were found when compared to those during the convex-side limb leading, suggesting an increased risk of tripping. Further studies on the kinematic strategies adopted by different types of AIS will be needed for a more complete picture of the functional adaptations in such patient group.

1. Introduction

Adolescent idiopathic scoliosis (AIS), characterized by a lateral spinal curvature with an axial rotation and loss of sagittal kyphosis of the thoracic spine, is the most common three-dimensional spinal deformity pathology during adolescence, with a prevalence of 2% - 4% among those aged from 10 to 16 [1–3]. The asymmetrical trunk anatomy in AIS limits the capacity and functional biomechanics of the chest [4], exercise capacity [5–7], general fitness and ability to work [8]. The degrees of limitations depend on the type and severity of the deformity. Problems with sensory integration and proprioception may also lead to abnormal postural control in these patients, affecting their performance of activities of daily living [9,10]. Patients with AIS have been shown to develop adaptive strategies to compensate for postural changes and standing and/or locomotion instability accompanied with the scoliotic deformity during upright stance, side stepping, walking and when seated on a see-saw [11–15]. These dynamic adaptive motor processes have also been found to be associated with an increase in the asymmetry of the dynamics between the lower limbs [16,17]. Identifying these postural adjustments and gait deviations in patients with AIS is helpful for a better understanding of strategies adopted by these patients in coping with activities of daily living.

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Among the activities of daily living, negotiating obstacles places more neuromechanical demand on the locomotor system than level walking does, and has been identified as an environmental risk factor for falling [18]. A safe and efficient obstacle-crossing task requires precise end-point (foot) position control while maintaining body balance through highly coordinated joint movements of the stance and swing limbs. With asymmetrical trunk anatomy and compromised proprioception and sensory integration [19–22], patients with AIS may have more difficulties than healthy peers in dealing with the neuromechanical challenges during obstacle-crossing. The extent of the challenge depends on the type and severity of the disease and also on the limb that is leading. Therefore, specific kinematic strategies may be required or developed to overcome the challenge. Knowledge of these kinematic strategies in terms of changes in joint angular motions and toe-obstacle clearances will be helpful for a better understanding of the performance of obstacle-crossing in AIS and for better management of the disease. However, to the best knowledge of the authors, no study has reported how AIS affects the kinematic performance of obstacle-crossing and how such performance might be affected by the obstacle height and/or choice of leading limb.

The purpose of this study was to identify the kinematic changes of the pelvis-leg apparatus in patients with AIS as compared to healthy controls when crossing obstacles of three different heights. It was hypothesized that increased toe-obstacle clearance with bilateral changes in joint kinematics in the pelvis-leg apparatus would be needed in patients with AIS; that different kinematic strategies would be adopted for obstacle-crossing with the convex side vs. the concave side as the leading limb, and that these strategies would be affected by obstacle height.

2. Methods

2.1. Subjects

Sixteen adolescents with right thoracic AIS without compensatory lumbar curves (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 the subjects and their legal guardians. They were recruited from National Taiwan University Hospital between January 2009 and December 2011 and had been scheduled for posterior spinal fusion. All the patients were determined radiographically to have a Lenke 1 thoracic curve [23] with Cobb angles of 54.6 ± 14.5° and kyphosis angles of 28.2 ± 9.1°. They were of normal lower limb muscle strength, with corrected vision and right leg dominance without limitations in performing daily or sports activities. The only treatment received was wearing a brace during the daytime. All indicated studies were performed without wearing the brace. 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 that would affect their gait performance. Sixteen healthy adolescents (Control group; age: 14.8 ± 2.7 years, height: 154.9 ± 5.6 cm, body mass: 44.7 ± 6.3 kg) were selected to match with the AIS group for sex, age and BMI. The study was approved by the Institutional Research Board (Permit Number: 201306013RINB).

2.2. Gait experiments

Each subject walked at a self-selected pace on a 10-meter walkway and crossed a height-adjustable obstacle that was composed of a 1.5 m long tube with a diameter of 1.5 cm placed horizontally across a metal frame [24]. Three obstacle heights (i.e., 10%, 20% and 30% of leg length) were tested with either leg leading. Thirty-nine infrared retro-reflective skin markers were used to track the motions of the head and neck, trunk, pelvis, upper arms, forearms, thighs, shanks and feet [25,26]. Three-dimensional marker trajectories were measured at 120 Hz using an 8-camera motion analysis system (Vicon MX T-40, OMG, UK), and the ground reaction forces (GRF) were measured at 1080 Hz using two forceplates (OR6-7, AMTI, USA) placed on either side of the obstacle in the middle of the walkway. Data for three complete crossing cycles for both the right and left lower limbs were obtained for each subject in the Control group. For the AIS group, data of three complete crossing cycles were obtained each for crossing with the lower limb on the convex side leading (denoted AIS-V) and for crossing with the lower limb on the concave side leading (denoted AIS-A). For the crossing limb conditions (AIS: convex side (AIS-V) vs. concave side (AIS-A); Control: right vs. left) a counterbalanced measures design was used, while the sequence of the obstacle conditions was decided by a random number table.

2.3. Calculation of dependent variables

Crossing speed was calculated as the ratio of the distance traveled by mid-ASISs in the walking direction and the time spent from leading toe-off immediately before crossing to trailing heel-strike immediately after crossing. Toe-clearance for both the leading and trailing limb was calculated as the vertical distance between the toe marker of the swing limb and the obstacle when the swing toe was directly above the obstacle. The trailing toe-obstacle distance was defined as the horizontal distance between the obstacle and the toe marker of the trailing limb during stance immediately before stepping over the obstacle. The leading heel-obstacle distance was defined as the horizontal distance between the obstacle and the heel marker of the leading limb during stance immediately after stepping over the obstacle.

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 ISB recommendations [27]. The angular motions of the pelvis 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 [28]. 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 [29]. Values of the calculated angular motions when the leading and trailing toes were above the obstacle, here called crossing angles, were extracted for subsequent statistical analysis [24].

2.4. Statistical analysis

For statistical comparisons between AIS and Control, a two-way mixed-design analysis of variance (ANOVA) was used to compare the differences in all the calculated variables with one between-subject factor (i.e., AIS-V vs. Control, and AIS-A vs. Control) and one within-subject factor (obstacle height). For between-side comparisons in AIS, a two-way repeated-measures ANOVA was used to compare the differences with one within-subject factor (AIS-V vs. AIS-A) and another within-subject factor (obstacle height). Whenever an obstacle height effect was found, a post hoc analysis was performed using a polynomial test to determine the linear trend. For all the statistical analyses, data of each calculated variable were averaged across crossing cycles for each subject, and data from both sides were further averaged for the Control group. All the calculated variables were determined to be normally distributed by a Shapiro-Wilk test and the homogeneity of variance across groups was confirmed by the Levene's test. A significance level of $\alpha = 0.05$ was set for all test conditions. An power analysis based on pilot results using GPOWER [30] determined that a projected sample size of eleven subjects for each group would be needed with a power of 0.8 and a large effect size ($\eta^2 = 0.2$) at a significance level of 0.05. Thus, 16 subjects for each group were more than adequate for the main objectives of the current study. All statistical analyses were performed

Table 1
Means (standard deviations) of the crossing speeds and end-point variables of the patients with adolescent idiopathic scoliosis (AIS) and healthy controls (Control) when crossing obstacles of heights of 10%, 20% and 30% of the subjects' leg length (LL).

Variables	Obstacle Height (%LL)	AIS-V		AIS-A		Control		P_V	P_A	P_H	P_S
Crossing speed (mm/s)	10	1000.9	(133.8)	1012.8	(126.7)	940.7	(84.2)			0.000↓	0.473
	20	945.1	(106.4)	953.3	(118.6)	888.3	(85.6)	0.095			
	30	899.5	(101.6)	904.7	(12 7.9)	850.3	(101.0)	0.065			
Leading toe-clearance (%LL)	10	16.5	(4.7)	15.5	(5.0)	16.2	(2.4)			0.173	0.014†
	20	16.1	(5.4)	14.7	(4.1)	16.9	(3.1)	0.314	0.016*		
	30	15.5	(3.8)	13.8	(18.5)	18.0	(4.3)				
	Trailing toe-clearance (%LL)	10	13.4	(4.1)	13.6	(2.3)	16.9		(3.1)		
		20	14.4	(5.6)	13.3	(5.7)	18.0	(4.3)	0.049*		
30		15.7	(5.5)	14.4	(5.8)	17.6	(3.2)	0.023*	0.490	0.490	0.394
Trailing toe-obstacle distance (mm)	10	192.7	(22.9)	178.2	(17.9)	187.0	(19.4)		0.394	0.000↑	0.014†
	20	227.2	(17.3)	220.0	(21.6)	220.3	(17.7)	0.236			
	30	288.4	(17.4)	284.5	(13.1)	284.5	(15.3)	0.469			
Leading heel-obstacle distance (mm)	10	187.0	(25.0)	179.6	(22.8)	154.4	(28.6)			0.000↑	0.889
	20	200.1	(15.4)	203.0	(17.4)	178.9	(24.5)	0.007*			
	30	236.5	(24.1)	239.4	(19.6)	225.6	(26.3)	0.011*			
Leading toe-obstacle distance (mm)	10	630.3	(61.9)	629.8	(39.2)	660.1	(39.4)			0.000↑	0.976

AIS-V: crossing cycle with the convex-side limb leading; AIS-A: crossing cycle with the concave-side limb leading; P_H = p-value for obstacle height; P_V = AIS-V vs. Control; P_A = AIS-A vs. Control; P_S = AIS-A vs. AIS-V. With increasing obstacle heights, ↑ indicates a linearly increasing trend and ↓ indicates a linearly decreasing trend ($P_H < 0.05$); * indicates a significant group effect ($P_V < 0.05$ or $P_A < 0.05$).

using SPSS version 20 (SPSS Inc., Chicago, IL, USA).

3. Results

Compared to the Control, the AIS group showed significantly decreased leading toe-clearance during AIS-A but no significant difference was found during AIS-V (Table 1). Compared to AIS-V, significantly decreased leading toe-clearance and trailing toe-obstacle distance were found during AIS-A. During trailing crossing, both AIS-A and AIS-V showed significantly decreased trailing toe-clearance and leading toe-obstacle distance but increased leading heel-odstacle distance (Table 1).

Compared to the Control, when the leading toe was above the obstacle during AIS-A, significantly increased hip adduction in the stance limb and increased knee flexion in the swing limb (Table 2) were noted. For AIS-V, significantly increased knee flexion in the stance limb and contralateral trunk/pelvis side-bending were found. Both AIS-A and AIS-V showed significantly increased ankle dorsiflexion in the swing and stance limbs but decreased pelvic downward list, without significant differences in the other kinematic components of the pelvis and the lower limb joints (Table 2). When compared to AIS-V, significantly increased ipsilateral trunk/pelvis side-bending and contralateral hip adduction but decreased contralateral knee flexion were found in AIS-A (Tables 2 and 4).

Compared to the Control, when the trailing toe was above the obstacle during AIS-V, significantly increased hip adduction in the stance limb and pelvic downward list (becoming a downward list in the 10% and 20% conditions) were found (Table 3). For AIS-A, significantly increased ankle dorsiflexion and knee flexion in the stance limb, and increased ipsilateral trunk/pelvis side-bending and decreased swing hip flexion were found (Tables 3 and 4). When compared to AIS-V,

Table 2
Means (standard deviations) of the crossing angles of the pelvis and those at the hip, knee and ankle in the patients with adolescent idiopathic scoliosis (AIS) and healthy controls (Control) when the leading toe was above the obstacles of heights of 10%, 20% and 30% of subjects' leg length (LL).

Variables	Obstacle Height (%LL)	AIS-V		AIS-A		Control		P_V	P_A	P_H	P_S
Ipsilateral limb											
Hip flexion (+)	10	50.9	(6.0)	52.6	(7.2)	50.3	(2.8)			0.000↑	0.550
	20	60.2	(6.7)	60.7	(6.1)	58.4	(2.8)	0.163			
	30	70.5	(6.9)	70.3	(6.4)	65.8	(3.0)	0.062			
Knee flexion (+)	10	86.4	(9.4)	88.9	(14.4)	81.6	(7.6)			0.000↑	0.157
	20	100.9	(10.6)	103.1	(12.1)	94.5	(5.2)	0.053			
	30	110.7	(9.6)	113.9	(11.7)	103.6	(6.3)	0.017*			
Ankle DR (+)	10	19.3	(7.6)	20.2	(8.9)	10.7	(7.8)			0.000	0.600
	20	21.0	(6.7)	22.3	(9.0)	13.3	(7.6)	0.018*			
	30	22.8	(7.1)	23.0	(9.1)	14.9	(7.6)	0.024*			
Contralateral limb											
Hip flexion (+)	10	−0.3	(5.9)	−1.4	(6.2)	−2.5	(3.9)			0.010	0.052
	20	0.8	(5.5)	−0.8	(6.2)	−2.2	(3.4)	0.069			
	30	2.8	(7.0)	−0.5	(6.8)	−2.5	(3.7)	0.434			
Hip Adduction (+)	10	3.4	(3.6)	5.9	(2.9)	1.8	(2.4)			0.000↓	0.013†
	20	2.0	(3.8)	3.8	(3.5)	0.4	(2.9)	0.149			
	30	0.4	(4.8)	2.9	(3.3)	−1.8	(3.6)	0.004*			
Knee flexion (+)	10	14.3	(7.2)	11.7	(5.9)	8.6	(4.5)			0.007	0.046†
	20	15.2	(7.9)	13.1	(5.6)	8.9	(4.3)	0.013*			
	30	16.1	(7.3)	13.0	(5.4)	9.3	(4.9)	0.074			
Ankle flexion (+)	10	8.9	(4.7)	8.8	(4.4)	3.8	(3.3)			0.000	0.944
	20	7.8	(5.2)	7.9	(4.5)	2.9	(3.4)	0.012*			
	30	6.7	(5.3)	6.9	(5.5)	2.4	(3.4)	0.008*			

AIS-V: crossing cycle with the convex-side limb leading; AIS-A: crossing cycle with the concave-side limb leading; P_H = p-value for obstacle height; P_V = AIS-V vs. Control; P_A = AIS-A vs. Control; P_S = AIS-A vs. AIS-V. With increasing obstacle heights, ↑ indicates a linearly increasing trend and ↓ indicates a linearly decreasing trend ($P_H < 0.05$); *: significant group effect.

Table 3
Means (standard deviations) of the crossing angles of the pelvis and those at the hip, knee and ankle in the patients with adolescent idiopathic scoliosis (AIS) and healthy controls (Control) when the trailing toe was above the obstacles of heights of 10%, 20% and 30% of the subjects' leg length (LL).

Variables	Obstacle Height(%LL)	AIS-V		AIS-A		Control		P_V	P_A	P_H	P_S
Contralateral limb											
Hip flexion (+)	10	22.8	(5.5)	19.7	(4.5)	23.1	(2.5)			0.000↑	0.011†
	20	25.7	(4.5)	22.3	(4.7)	26.4	(2.9)	0.691			
	30	28.6	(5.1)	25.9	(6.5)	29.0	(5.2)	0.030*			
Knee flexion (+)	10	99.1	(9.8)	96.1	(9.9)	99.4	(6.3)			0.000↑	0.235
	20	112.0	(10.9)	108.3	(9.9)	112.3	(5.3)	0.909			
	30	124.6	(11.9)	123.1	(9.0)	123.0	(5.2)	0.387			
Ankle DR (+)	10	−1.4	(12.4)	3.2	(10.8)	−1.1	(10.0)			0.000↑	0.415
	20	4.5	(15.0)	6.9	(11.0)	2.7	(6.1)	0.349			
	30	16.3	(11.2)	15.5	(9.5)	9.5	(4.3)	0.130			
Ipsilateral limb											
Hip flexion (+)	10	9.4	(7.1)	12.6	(7.5)	7.5	(5.0)			0.004	0.073
	20	9.7	(6.7)	11.8	(7.3)	8.0	(4.7)	0.368			
	30	11.6	(7.0)	12.5	(8.1)	9.5	(4.2)	0.069			
Hip adduction (+)	10	8.9	(2.9)	6.5	(4.2)	5.9	(1.8)			0.000↓	0.077
	20	7.3	(3.1)	5.2	(4.3)	3.6	(2.1)	0.006*			
	30	4.2	(3.8)	3.4	(4.8)	−0.2	(2.1)	0.158			
Knee flexion (+)	10	12.7	(8.7)	18.1	(9.2)	9.9	(6.8)			0.094	0.001†
	20	13.1	(8.3)	15.8	(8.8)	8.4	(7.0)	0.234			
	30	11.5	(6.6)	15.4	(9.0)	8.4	(6.0)	0.018*			
Ankle flexion (+)	10	4.8	(6.0)	6.0	(5.0)	0.8	(3.9)			0.452	0.163
	20	5.6	(6.5)	6.3	(4.8)	0.8	(4.2)	0.060			
	30	4.6	(5.5)	6.5	(4.4)	1.2	(4.4)	0.008*			

AIS-V: crossing cycle with the convex-side limb leading; AIS-A: crossing cycle with the concave-side limb leading; P_H = p-value for obstacle height; P_V = AIS-V vs. Control; P_A = AIS-A vs. Control; P_S = AIS-A vs. AIS-V. With increasing obstacle heights, ↑ indicates a linearly increasing trend and ↓ indicates a linearly decreasing trend ($P_H < 0.05$); *: significant group effect; †: significant difference between sides ($P_S < 0.05$).

Table 4
Means (standard deviations) of the crossing angles of the trunk relative to pelvis in the patients with adolescent idiopathic scoliosis (AIS) and normal controls (Control) when the leading or trailing toe was above the obstacles of heights of 10%, 20% and 30% of the subjects' leg length (LL).

Variables	Obstacle Height(%LL)	AIS-V		AIS-A		Control		P_V	P_A	P_H	P_S
Leading swing limb											
Pelvis relative to global											
Anterior (+)/posterior (−) tilt	10	8.5	(6.8)	9.9	(7.4)	10.4	(4.5)			0.001	0.214
	20	7.6	(6.8)	8.5	(7.1)	9.3	(4.0)	0.568			
	30	7.8	(6.5)	7.4	(7.5)	7.7	(3.6)	0.790			
Upward (+)/downward (−) list	10	−3.0	(2.0)	−2.0	(2.6)	−4.8	(1.5)			0.000↑	0.475
	20	−4.5	(1.9)	−4.1	(3.5)	−6.4	(2.0)	0.014*			
	30	−6.3	(2.8)	−5.5	(3.6)	−8.6	(2.5)	0.004*			
Trunk relative to pelvis											
Flexion (+)/ extension(-)	10	−2.5	(8.7)	−2.9	(9.0)	−6.1	(4.7)			0.000	0.836
	20	−0.9	(7.5)	−0.5	(8.6)	−4.3	(4.6)	0.105			
	30	1.3	(7.4)	0.9	(8.3)	−2.8	(4.4)	0.111			
Ipsi (+)/Contr (-) SB	10	−1.6	(3.1)	4.5	(3.3)	3.0	(1.8)			0.000↑	0.000†
	20	−0.7	(3.6)	6.0	(4.0)	4.7	(2.0)	0.000*			
	30	0.4	(3.7)	7.3	(4.2)	6.5	(2.6)	0.205			
Trailing swing limb											
Pelvis relative to global											
Anterior (+)/posterior (-)	10	14.2	(6.8)	13.6	(6.1)	15.5	(5.0)			0.000↑	0.032
	20	15.9	(7.5)	15.2	(6.6)	17.5	(4.5)	0.618			
	30	19.1	(6.9)	17.0	(6.7)	19.4	(4.1)	0.274			
Upward (+)/downward (-) list	10	−2.2	(2.5)	−0.7	(2.2)	−0.2	(1.7)			0.000↑	0.240
	20	−0.3	(2.6)	1.0	(2.1)	2.0	(2.1)	0.032*			
	30	3.3	(4.0)	3.7	(3.1)	5.8	(2.0)	0.137			
Trunk relative to pelvis											
Flexion (+)/extension (-)	10	−8.2	(8.9)	−7.4	(7.5)	−11.7	(5.1)			0.853	0.061
	20	−8.2	(7.7)	−7.2	(7.8)	−11.8	(5.0)	0.061			
	30	−8.0	(7.6)	−7.0	(8.1)	−11.5	(4.7)	0.022*			
Ipsi (+)/contra (-) SB	10	0.0	(4.0)	5.0	(2.3)	2.0	(2.1)			0.000↓	0.001†
	20	−2.0	(4.6)	4.0	(2.5)	0.1	(2.4)	0.096			
	30	−5.0	(4.1)	2.1	(4.1)	−3.3	(2.1)	0.000*			

AIS-V: crossing cycle with the convex-side limb leading; AIS-A: crossing cycle with the concave-side limb leading; P_H = p-value for obstacle height; P_V = AIS-V vs. Control; P_A = AIS-A vs. Control; P_S = AIS-A vs. AIS-V. With increasing obstacle heights, ↑ indicates a linearly increasing trend and ↓ indicates a linearly decreasing trend ($P_H < 0.05$); *: significant group effect; †: significant difference between sides. Ipsi: ipsilateral, Contra: contralateral.

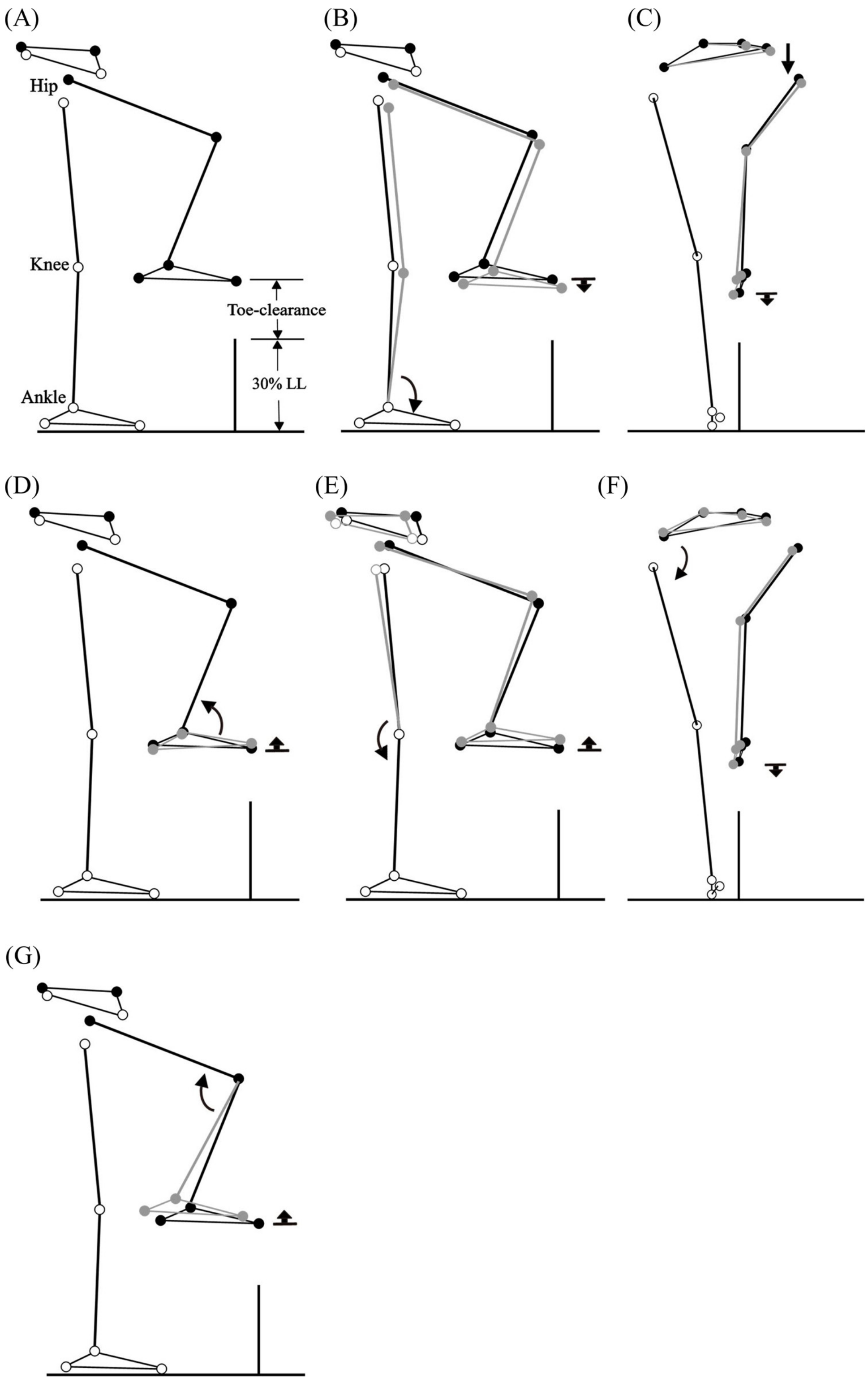

Fig. 1. Effects of the observed significant angular changes at individual joints on the leading toe-clearance in the AIS group (grey stick figure) compared with the mean Control (A, black stick figure) when the leading swing toe was above an obstacle of 30% LL. When the convex side was leading, the AIS group showed increased ankle dorsiflexion in the stance limb (B), decreased pelvic downward list (C), increased ankle dorsiflexion in the swing limb (D) and increased knee flexion in the stance limb (E). As indicated by the grey stick figure, while (B) and (C) tended to reduce the leading toe-clearance, (D) and (E) gave the opposite effect, leading to the observed normal toe-clearance. When the concave side was leading, additional angular changes were also found, namely increased hip adduction in the stance limb (F) and increased knee flexion in the swing limb (G). While (D) and (G) tended to increase the toe-clearance, the opposite effects produced by (B) (C) and (F) appeared to be more dominant, thus leading to the observed reduction in the leading toe-clearance. The segments with open circles at joints are away from the viewer while the solid black circles are closer to the viewer. The stick model was drawn using marker positions of a typical subject. With the stance foot fixed to the ground, only one joint was rotated at a time according to the mean angular change reported in Table 2 while keeping the other joints fixed, and the segments of the stance limb distal to the current joint stationary.

significantly decreased leading stance knee flexion and increased ipsilateral trunk/pelvis side-bending were found during AIS-A (Tables 3 and 4). The observed significant angular changes at individual joints showed different effects on the leading and trailing toe-clearances in the AIS group when compared with the Control, some tending to increase the toe-clearance while others showing opposite effects (Figs. 1 and 2).

There were no interactions found between the group and height factors for all the calculated variables. With increasing obstacle height, both AIS and Control linearly increased their crossing speeds, trailing toe-obstacle distances and leading heel-obstacle distances (Table 1). When the leading toe was above the obstacle, both AIS and Control groups linearly increased the pelvic downward list, contralateral trunk/pelvis side-bending, and hip and knee flexion of the swing limb, but linearly decreased the hip adduction in the stance limb (Tables 2 and 4). On the other hand, when the trailing toe was above the obstacle, both groups linearly increased the pelvic upward list, as well as hip flexion, knee flexion and ankle dorsiflexion of the swing limb, but

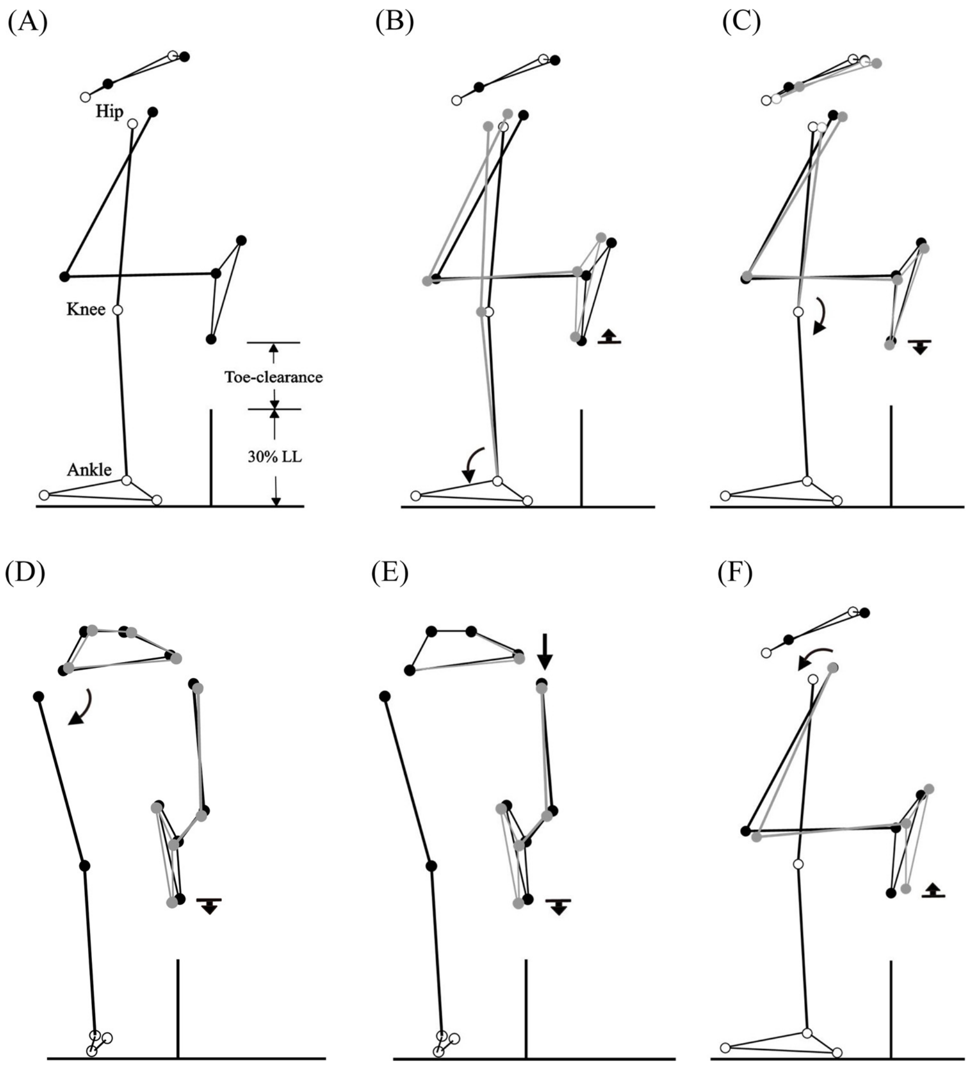

Fig. 2. Effects of the observed significant angular changes at individual joints on the trailing toe-clearance in the AIS group (grey stick figure) compared with the mean control (A, black stick figure) when the trailing swing toe was above an obstacle of 30% LL. When the concave side was trailing, the AIS group showed increased hip adduction in the stance limb (D) but decreased pelvic upward list (E). As indicated by the grey stick figure, (D) and (E) lead to the observed reduction in the trailing toe-clearance. When the convex side was trailing, the AIS group showed increased ankle dorsiflexion (B) and knee flexion (C) but decreased hip flexion in the swing limb (F). While (B) and (F) tended to increase the toe-clearance, the opposite effect produced by (C) appeared to be more dominant, thus leading to the observed reduction in the trailing toe-clearance. The segments with open circles at joints are away from the viewer while the solid black circles are closer to the viewer. The stick model was drawn using marker positions of a typical subject. With the stance foot fixed to the ground, only one joint was rotated at a time according to the mean angular change reported in Table 3 while keeping the other joints fixed, and the segments of the stance limb distal to the current joint stationary.

linearly decreased the ipsilateral trunk/pelvis side-bending and hip adduction of the stance limb (Table 3).

4. Discussion

The current study aimed to identify the kinematic strategies of the pelvis-leg apparatus in patients with AIS when crossing obstacles of three different heights. Compared to healthy controls, patients with AIS were found to adopt altered kinematic strategies for successful obstacle-crossing, depending on whether led with the convex or concave side. These altered strategies did not appear to be affected by obstacle heights.

The altered kinematic strategies enabled the AIS group to maintain a normal toe-clearance during AIS-V but led to a decreased toe-clearance during AIS-A. An appropriate toe-clearance was essential for a safe and successful obstacle-crossing. Decreased toe-clearance is an indication of increased risk of tripping as toe-obstacle contact is more likely to occur [31,32]. The normal toe-clearance during AIS-V appeared to be achieved by increasing the knee flexion in the stance limb and the ankle dorsiflexion in the swing limb to neutralize the potential decrease in the toe-clearance caused by decreased pelvic downward list and increased ankle dorsiflexion in the stance limb (Table 2, Fig. 1D and E). Higher knee flexion during gait has also been found in patients with severe deformity [6,33,34]. Compared to AIS-V, significantly reduced knee flexion in the contralateral stance limb during AIS-A was also found. The observed increase in the contralateral trunk/pelvis side-bending during AIS-V corresponding to the curve of the spinal deformity shifted the trunk closer to the stance limb, which would be helpful for better balance control.

During the leading crossing phase of AIS-A, kinematic changes similar to those of AIS-V were also found, but with normal knee flexion in the stance limb and significant changes in additional kinematic components, namely increased hip adduction in the stance limb and increased knee flexion in the swing limb (Fig. 1F and G). The additional changes in the hip adduction and knee flexion in the stance limb all contributed to the observed decrease of the leading toe-clearance during AIS-A (Fig. 1F). These additional changes were presumably related to the shape and pose changes of the trunk as a result of the spinal deformity or the imbalance of the activation of the lumbar and/or pelvic muscles, which are associated with a restriction in the range of motion of the pelvis and hip in the frontal plane, and the knee in the sagittal plane [34]. Without an increase in the contralateral trunk/pelvis side-bending as found in AIS-V, the trunk was further away from the stance limb when compared to AIS-V, placing a greater challenge on the stance limb for balance control [35]. Further studies on the body's COM and trunk motion will be needed to provide more insight into this phenomenon. The current results suggest that patients with AIS should cross obstacles with the limb of the convex side leading in order to avoid an increased risk of tripping over the obstacles.

During trailing limb crossing, both AIS-A and AIS-V showed decreased toe-clearance but with altered kinematic strategies when compared to healthy controls. Decreased trailing toe-clearance may increase the risk of tripping, especially because neither the swing limb, nor the obstacle are within the subject's visual field while crossing [36,37]. During AIS-V, the significantly increased hip adduction of the leading stance limb and the pelvic downward list contributed to the reduced trailing toe-clearance (Fig. 2D and E). During AIS-A, more joint kinematic changes were found, namely increased ipsilateral trunk/pelvis side-bending and increased ankle dorsiflexion and knee flexion of the stance limb, but decreased hip flexion of the swing limb (Fig. 2B, C and F). The increased knee flexion in the leading stance limb appeared to be the main contributor to the observed decrease in the trailing toe-clearance during AIS-A (Fig. 2C). The current results showed that bilateral asymmetric kinematic strategies of the pelvis-leg apparatus were adopted for successful obstacle-crossing in adolescents with severe scoliotic deformity of the thoracic spine, but with an increased risk of tripping except during the leading crossing phase of AIS-V.

The observed differences in the changes in the end-point and pelvis-leg kinematics between AIS-A and AIS-V cycles, and between leading and trailing phases may be attributed to the differences in the neuromechanical challenges. The neuromechanical challenge for balance control is greater during leading-limb crossing than during trailing-limb crossing, as the body is moving away from the trailing stance limb during leading-limb crossing, while moving towards the leading stance limb during trailing-limb crossing. An even greater challenge was present during the leading crossing phase of AIS-A when the trunk shifted away from the stance limb in the frontal plane as a result of the spinal deformity. Under such an increased neuromechanical challenge, the additional compensatory angular changes may be needed in order for the stance limb to provide the necessary stability and for the swing limb to provide the precision control of the end-point as it traverses the obstacle. However, it appears that the observed compensatory changes did not completely normalize the end-point control as indicated by the decreased toe-clearance, exposing the patients to an increased risk of tripping over the obstacle. Further studies will be needed to evaluate the possible roles of factors such as degraded balance control and proprioception commonly found in patients with AIS [10,38–41], resulting in their failure to maintain normal toe-clearance. On the other hand, further study is also needed to test whether the compensatory changes would help with the stability of the stance limb and whole body balance.

The current study was limited to patients with Lenke 1 AIS. Further studies on patients with different curve types and severities of AIS would be needed to determine whether kinematic strategies for obstacle-crossing would change with different curve types or with progression of the disease. Possible effects of the observed kinematic strategies on balance control during obstacle-crossing will also require further studies.

5. Conclusions

The current study identified the kinematic strategies of the pelvis-leg apparatus in patients with AIS when crossing obstacles of three different heights. Compared to healthy controls, patients with AIS were found to adopt altered kinematic strategies for successful obstacle-crossing, depending on whether they led with the convex or concave side. End-point control with significantly decreased toe-clearance was observed when the limb on the concave side was leading. These results suggest that patients with severe Lenke 1 AIS should rather not cross obstacles with concave-side limb leading to reduce the risk of tripping during obstacle-crossing. Further studies on the kinematic strategies adopted by different types of AIS will be needed for a more complete picture of the functional adaptations in such patient group.

Conflicts of interest

None.

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