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Different kinematic strategies are adopted by AIS patients during walking depending on their Lenke type

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Abstract

Introduction Adolescent Idiopathic Scoliosis (AIS) is classically evaluated through static X-rays and health-related quality of life questionnaires that do not reflect the functional limitations of patients during daily life activities, such as walking. The aim was to investigate kinematic strategies in non-operated AIS with different types of curvature during walking using 3D gait analysis.

Methods 13 AIS with Lenke 5 (major Cobb: $23 \pm 8^\circ$), 30 AIS with Lenke 1 (major Cobb: $40 \pm 14^\circ$) in addition to 24 controls underwent biplanar X-rays followed by 3D gait analysis. The kinematic parameters of the head, trunk, spinal segments, pelvis and lower limbs were compared between groups.

Results AIS Lenke 5 had a lumbar segment bending while walking (T12L3-L3L5: $5 \pm 7^\circ$ vs. $-3 \pm 7^\circ$ in controls) to the concave side of the scoliosis. They walked with an increased pelvic frontal mobility ($12 \pm 3^\circ$ vs. $9 \pm 3^\circ$) and internal rotation of the right foot ($-2 \pm 6^\circ$ vs. $-11 \pm 8^\circ$; all $p < 0.05$). AIS Lenke 1 increased their thoracic & lumbar segment bending to the concave and to the opposite side respectively (T6T9-T9T12: $-4 \pm 9^\circ$ vs. $1 \pm 4^\circ$; T12L3-L3L5: $8 \pm 12^\circ$ vs. $-2 \pm 7^\circ$). However, they tended to reduce their lumbo-pelvic mobility ($7 \pm 5^\circ$ vs. $12 \pm 5^\circ$; all $p < 0.05$).

Conclusion In response to their inherent lumbar stiffness and bending, AIS Lenke 5 patients tended to increase their pelvic frontal mobility and to develop a homolateral internal foot rotation, ensuring a dynamic alignment during gait. AIS Lenke 1, by producing opposite bending movement at the thoracic and lumbar segments, tended to reduce their lumbo-pelvic mobility and ensure coronal dynamic alignment.

Keywords Adolescent idiopathic scoliosis · Lenke types · 3D gait analysis · Kinematics · Spine

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity primarily evaluated through static X-rays to measure the Cobb angle in the frontal plane [1]. The Lenke classification is used to differentiate between scoliotic deformities depending on the localization of the apical vertebrae and the flexibility of the scoliotic curve [2]. In addition to the spinal deformity, AIS patients might present a deterioration of their quality of life, mainly due to their

perception of the deformity, the severity of the spinal curve and other problems such as back pain, impaired spinal flexibility and postural malalignment [3, 4].

The scoliotic deformity is known to affect spinal mobility and trunk balance [5], thus, the position of the center of mass, leading to kinematic abnormalities during walking [6]. AIS patients were shown to present a reduced step length and cadence during walking, both correlated with the severity of the Cobb angle [7, 8]. Furthermore, it has been reported that AIS patients, with all Lenke types combined,

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exhibit a decreased mobility of the shoulders and the pelvis [9, 10]. Recent studies [11, 12] investigated global trunk kinematics during walking in AIS with thoracic and thoraco-lumbar/lumbar curvatures separately. The two groups exhibited a persistent overall trunk inclination to the convex side of the scoliosis while walking. However, the kinematics of the spinal segments in the trunk, the lower limbs and the possible compensatory mechanisms developed during gait are yet to be investigated.

This study aims to investigate kinematic strategies and compensatory mechanisms of the head, trunk, spinal segments, pelvis and lower limbs in non-operated AIS with different types of curvature during walking.

Methods

Study design

This is a cross-sectional study on AIS patients with different types of curvature, aged between 10 and 18 years old. Non-operated AIS patients were recruited through consecutive enrollment following their visit to the orthopedics department of our institution; they were referred for a radiographic imaging of the spine and 3D gait analysis which were conducted on the same day. The enrolled AIS patients presented a frontal Cobb angle $> 15^\circ$ with no previous spinal or musculoskeletal surgery. Patients with a structural lower limb discrepancy > 1 cm were excluded from this study. AIS patients were subdivided based on Lenke classification. Control subjects were recruited through community advertisements and local schools. They were asymptomatic, aged between 11 and 25 years old, with no musculoskeletal or neurological disorders. This study was approved by the ethical committee of our institution (CEHDF1770-2). All participants and their legal guardians signed an informed consent.

Demographics and radiographic data

Data on age, sex, height, and weight were collected for each participant.

All subjects underwent full-body low dose biplanar X-rays (EOS[®], EOS Imaging, Paris, France) in standing position. The spine, rib cage and lower limbs were reconstructed in 3D using SterEOS[®] (1.6.5.8188, EOS imaging, Paris). The following 3D radiographic parameters were then calculated (Fig. 1):

- Scoliosis parameters: coronal Cobb angle, apical vertebral rotation (AVR) and localization of the apical vertebra (coded such that its value increases progressively

from T1, localization of T1 = 1, to L5, localization of L5 = 17).

- Rib cage parameter: gibbosity and volumetric spine penetration index (VSPI) [13].
- Spino-pelvic parameters: thoracic kyphosis (T1T12, T4T12), lumbar lordosis (L1S1, L1L5), thoracolumbar junction angle (TLJ) (T10L2), pelvic incidence (PI), sacral slope (SS) and pelvic tilt (PT).
- Global postural parameters: sagittal vertical axis (SVA), T1 and T9 tilt, sagittal, coronal and 3D odontoid to hip axis (ODHA) angle [14].

Kinematic data

All participants underwent 3D gait analysis (8 Vero cameras 2.2; Vicon Motion Systems[®], Oxford, UK) in order to calculate full-body joint and segment kinematics during gait. Forty-two markers were placed on specific anatomical landmarks. The lower limbs markers were placed according to the conventional Davis protocol [15]. The modified Blondel protocol [16] was used for the trunk and spine marker set placement on the following landmarks (Fig. 2). The subjects performed several walking tests at self-selected speed in a 10 m length corridor. The following joint angles were calculated in the 3 planes and normalized to the gait cycle [17]: head (relative to the global reference), neck (head relative to thorax), segmental spine motion (L3L5 relative to T12L3, T12L3 relative to T9T12, T9T12 relative to T6T9, T6T9 relative to T3T6, T3T6 relative to C7T3, T12L5 relative to C7T12), thorax (relative to the global reference), shoulders (relative to the pelvis), pelvis (relative to the global reference), lumbo-pelvic joint (pelvis relative to L3L5 and T12L5), ODHA angle during walking measured in both the frontal and sagittal planes [18], hip (femur relative to the pelvis), knee (tibia relative to the femur), ankle (foot relative to the tibia), foot progression angle (foot relative to the global reference). Mean and range of motion (ROM) were calculated on the kinematic waveforms of the head, trunk, spinal segments, pelvis and lower limbs that were obtained during the normalized gait cycle in the three planes. The following spatio-temporal parameters were calculated: walking speed (m/s), cadence (steps/min), time of foot off (% of gait cycle), single and double support times (s) and step length (m).

HRQoL questionnaires

Both AIS and control groups filled out the following health-related quality of life (HRQoL) questionnaires: Hospital Anxiety and Depression Scale (HADS), Clinical Outcomes in Routine Evaluation (CORE-OM), Scoliosis Research Society-22 revised (SRS-22r) score.

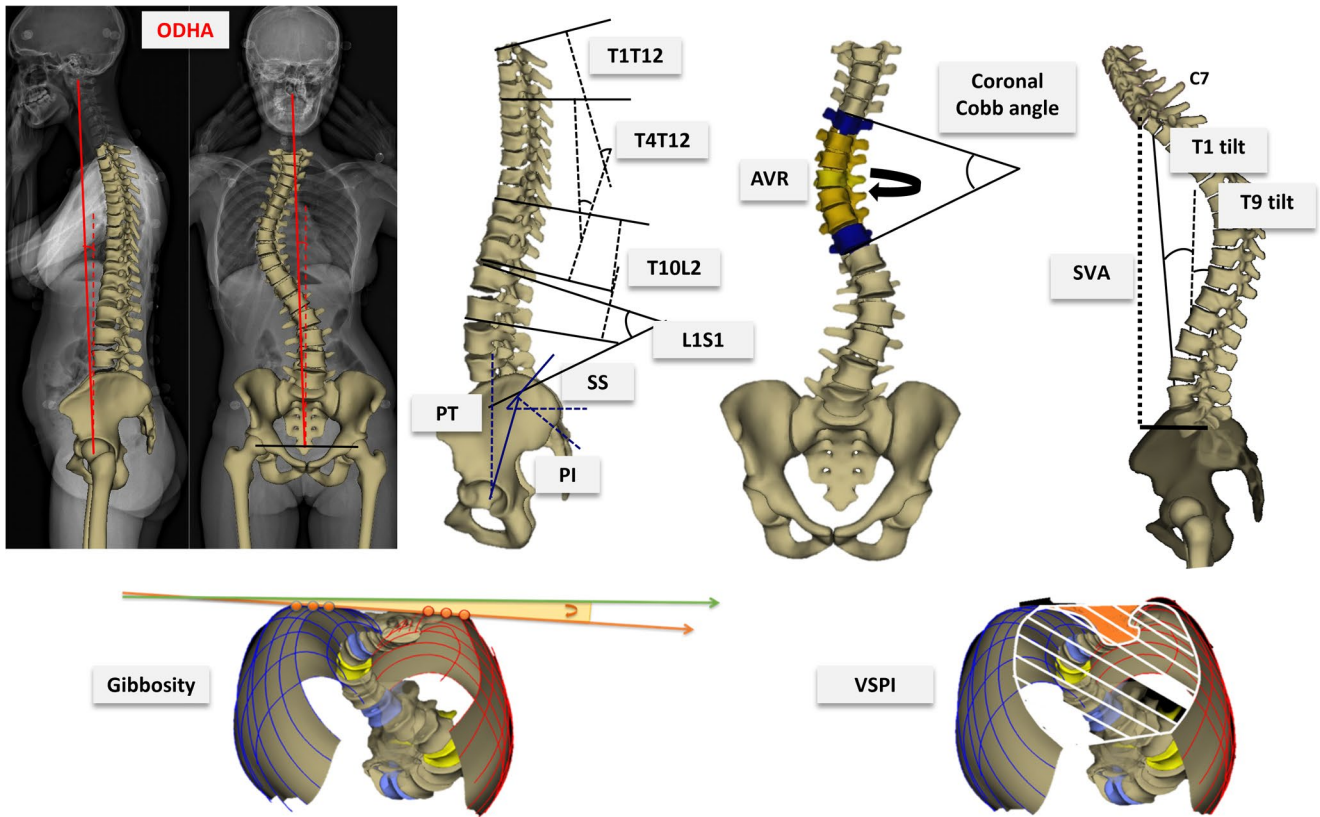


Fig. 1 3D reconstructions of the spine, ribcage and pelvis based on biplanar X-rays with calculation of radiographic parameters: coronal Cobb angle ($^{\circ}$), apical vertebral rotation AVR ($^{\circ}$), gibbosity ($^{\circ}$), VSPI ($^{\circ}$), T1T12 and T4T12 thoracic kyphosis ($^{\circ}$), L1S1 lumbar lordosis

($^{\circ}$), T10L2 thoracolumbar junction angle ($^{\circ}$), pelvic incidence PI ($^{\circ}$), sacral slope SS ($^{\circ}$), pelvic tilt PT ($^{\circ}$), sagittal vertical axis SVA (mm), T1 and T9 tilt ($^{\circ}$), sagittal and coronal ODHA angle ($^{\circ}$)

Statistical analysis

Demographics, spino-pelvic and global postural parameters, as well as HRQoL scores and kinematic parameters were compared between the AIS Lenke groups and controls using the Kruskal-Wallis test - assumptions of non-normal distributions were established beforehand - followed by Conover Iman for pairwise multiple comparisons. The Statistical Parametric Mapping (SPM) method was used to compare the kinematic waveforms between the 3 groups [19]. This technique was particularly suited to our analysis because it preserved the continuous structure of the data and provided a more comprehensive view of group differences than pointwise testing (such as mean, maximum, minimum or ROM). The relationships between radiographic parameters, gait kinematics and HRQoL scores were analyzed using Pearson's and Spearman's correlations for continuous and discrete variables respectively. Statistical analyses were conducted using XLSTAT (version 2018.3, Addinsoft, Paris, France). The level of significance was set at 0.05, and Bonferroni corrections were applied when multiple comparisons were computed.

Results

Demographics

In total, 43 patients formed the AIS group: 13 AIS had a Lenke 5 deformity with a main left thoracolumbar/lumbar convexity (13 F; major Cobb: $23 \pm 8^{\circ}$), and 30 AIS had a Lenke 1 deformity with a main right thoracic convexity (24 F; major Cobb: $40 \pm 14^{\circ}$). Additionally, 24 subjects formed the control group (12 F). The 3 groups had similar age (AIS Lenke 1 = 17 ± 3 , AIS Lenke 5 = 18 ± 4 , controls = 16 ± 2 years; $p=0.51$; Table 1).

Radiographic parameters

The coronal Cobb angle was greater in AIS Lenke 1 compared to AIS Lenke 5 ($40 \pm 13^{\circ}$ vs. $23 \pm 8^{\circ}$; $p < 0.001$). AIS Lenke 1 had a reduced thoracic kyphosis (T1T12: $32 \pm 13^{\circ}$ vs. $41 \pm 8^{\circ}$ in controls; $p=0.005$). They also showed a decreased T9 tilt ($8 \pm 5^{\circ}$ vs. $11 \pm 3^{\circ}$ in controls; $p=0.01$). Furthermore, the gibbosity and VSPI were increased in AIS Lenke 1 compared to controls ($8 \pm 5^{\circ}$ vs. $4 \pm 2^{\circ}$ and $6 \pm 2\%$ vs. $4 \pm 1\%$ respectively; both $p < 0.001$). AIS Lenke 5 had an

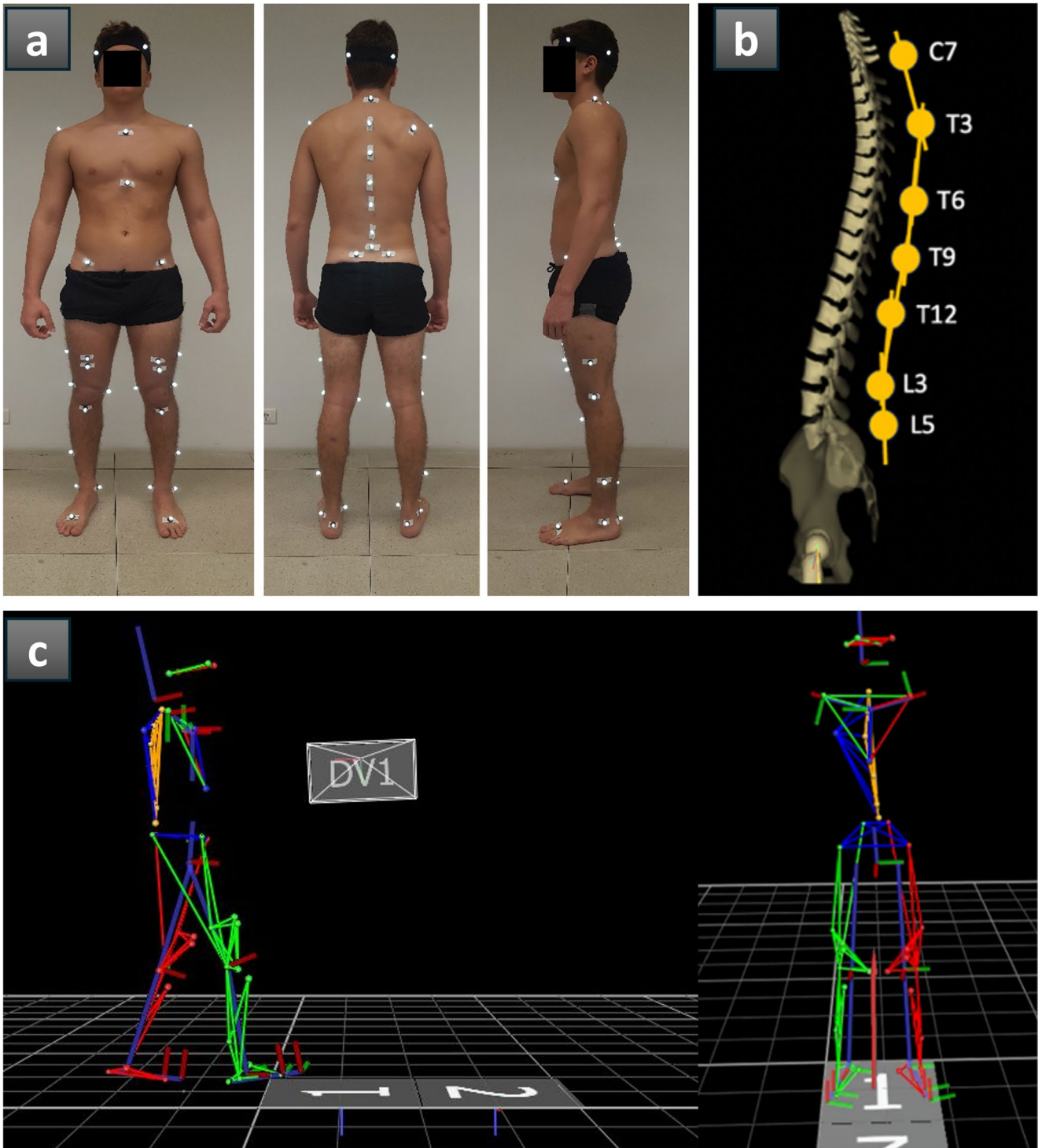
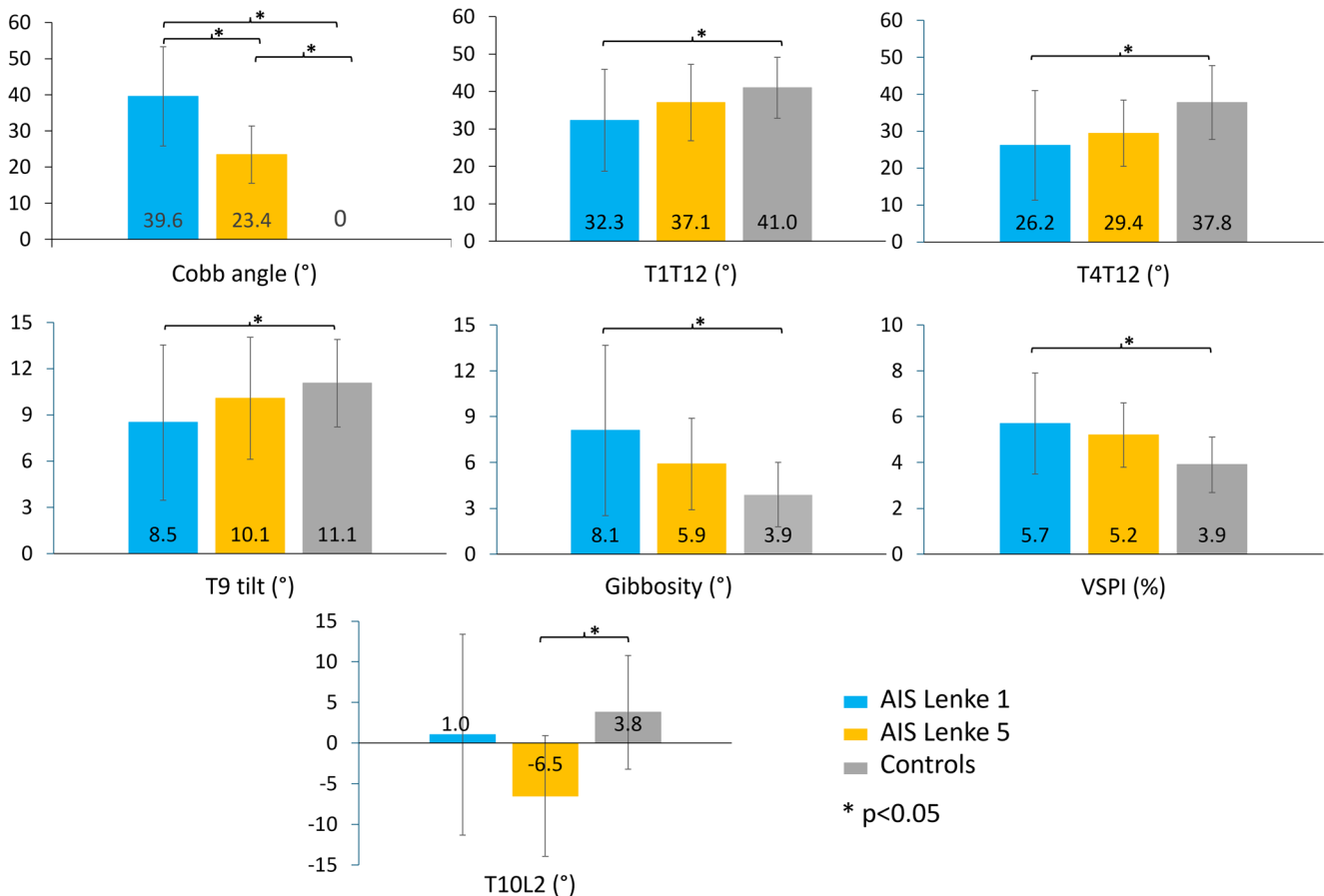


Fig. 2 (a) Marker set placement during gait acquisition based on the modified Davis and Blondel protocols. (b) Representation of spinal segments as described by Blondel et al. (c) Biomechanical modeling of the different segments during gait

Table 1 Comparison of demographic data between the 3 groups: Controls, AIS Lenke 1 and AIS Lenke 5

	AIS Lenke 1 (n=30)		AIS Lenke 5 (n=13)		Controls (n=24)		p-value
	Mean	SD	Mean	SD	Mean	SD	
Age (years)	17	3	18	4	16	2	0.51
Weight (kg)	53	12	55	10	66	17	0.004
Height (cm)	163	8	165	7	167	10	0.20
Gender (F/M)	24/6		13/0		12/12		0.002

**Fig. 3** Comparison of radiographic parameters between the 3 groups: Controls, AIS Lenke 1 and AIS Lenke 5

increased lordotic T10L2 thoracolumbar junction ($-7 \pm 7^\circ$ vs. $4 \pm 7^\circ$ in controls; $p=0.005$) (Fig. 3).

Kinematic parameters

AIS Lenke 5 patients had a lumbar segment bending to the concave side of the scoliosis (to the right) during gait compared to controls: (T12L3-L3L5: $5 \pm 7^\circ$ vs. $-3 \pm 7^\circ$; $p=0.003$) with an increased ROM ($10 \pm 4^\circ$ vs. $6 \pm 3^\circ$; $p=0.006$). Moreover, they exhibited a decrease of the mean dynamic thoracolumbar extension (C7T12-T12L5: $0 \pm 7.0^\circ$ vs. $-10 \pm 7^\circ$; $p=0.003$). Furthermore, they presented an increased ROM of the pelvic obliquity ($12 \pm 3^\circ$ vs. $8 \pm 3^\circ$ in controls; $p=0.009$) and an internal rotation of the right foot ($-2 \pm 6^\circ$ vs. $-11 \pm 8^\circ$; $p=0.001$).

In the frontal plane, AIS Lenke 1 patients increased their thoracic segment bending toward the concave side of the scoliosis (to the left) during gait: (T6T9-T9T12: $-4 \pm 8^\circ$ vs. $1 \pm 4^\circ$ in controls; $p=0.01$). However, they tended to bend the lumbar segment towards the opposite side (to the right) (T12L3-L3L5: $8 \pm 12^\circ$ vs. $-2 \pm 7^\circ$; $p<0.001$). They also showed a thoraco-lumbar segment bending to the right side (C7T12-T12L5: $5 \pm 5^\circ$ vs. $0 \pm 4^\circ$; $p=0.001$) and a lumbo-pelvic segment bending toward the opposite side (T12L5-Pelvis: $-4 \pm 5^\circ$ vs. $0 \pm 3^\circ$; $p=0.001$), coupled with a reduced L3L5-pelvis frontal ROM ($7 \pm 4^\circ$ vs. $12 \pm 5^\circ$; $p=0.001$). They exhibited an increased dynamic frontal ODHA ($2 \pm 1^\circ$ vs. $1 \pm 0.5^\circ$; $p=0.007$). In the sagittal plane, AIS Lenke 1 patients presented a reduced dynamic thoracic kyphosis during gait (T3T6-T6T9: $10 \pm 6^\circ$ vs. $15 \pm 5^\circ$ in controls;

$p=0.02$). In the axial plane, they showed an increased shoulder-pelvis rotation to the left ($7\pm 4^\circ$ vs. $0\pm 2^\circ$; $p<0.001$).

Differences in kinematic waveforms based on the SPM study related to the 3 groups were displayed in Fig. 4. Differences in kinematics at specific phases of the gait cycle were found in each group. For instance, the bending of the lumbar segment adopted by AIS Lenke 5 patients was significant

only at the start of the stance phase and during the swing phase, while the internal rotation of the right foot was significant throughout the whole gait cycle. In AIS Lenke 1 patients, the bending of the thoracic segment as well as the ODHA frontal deviation were significant from the terminal stance through the initial swing. They also presented their shoulder-pelvis rotation throughout the gait cycle.

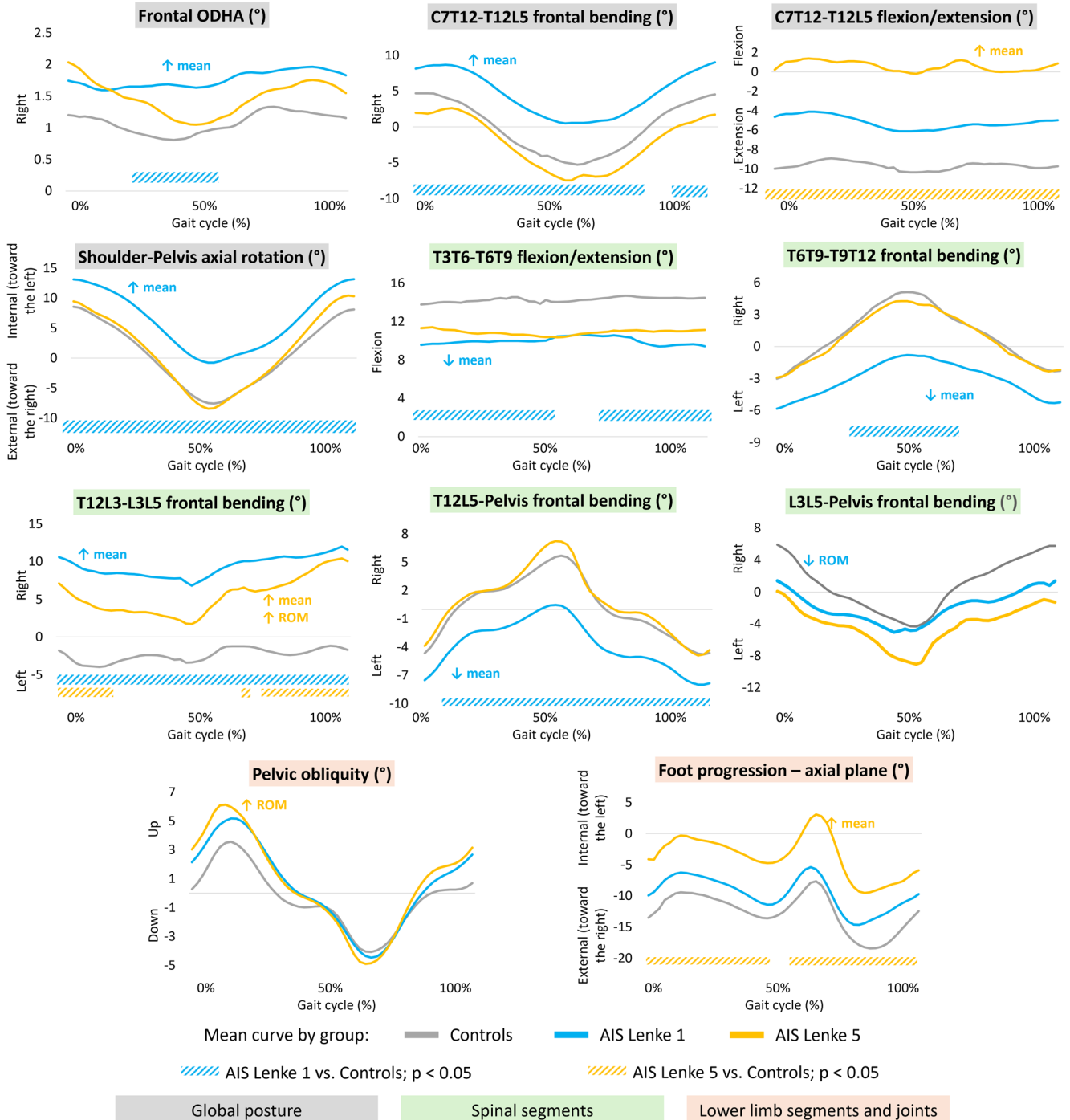


Fig. 4 Waveforms of gait kinematics for each group: comparison of the kinematic parameters between Controls, AIS Lenke 1 and AIS Lenke 5 using the SPM method

Table 2 Comparison of spatio-temporal parameters during walking between the 3 groups: Controls, AIS Lenke 1 and AIS Lenke 5

	Mean±SD			p-value
	Controls (n=24)	AIS Lenke 1 (n=30)	AIS Lenke 5 (n=13)	
Walking speed (m/s)	0.3±0.5	4.2±2.2	4.1±2.0	0.6
Cadence (steps/min)	0.8±0.3	0.9±0.8	1.0±0.6	0.4
Time of foot off (% of gait cycle)	0.8±0.5	1.0±0.9	1.1±0.8	0.5
Step length (m)	0.8±0.7	1.2±1.0	1.2±0.9	0.8
Single support time (s)	0.1±0.2	0.2±0.4	0.2±0.4	0.4
Double support time (s)	22.4±12.3	29.0±24.3	31.6±19.7	0.8

Table 3 Comparison of HRQoL scores between the 3 groups: Controls, AIS Lenke 1 and AIS Lenke 5

		Mean±SD			p-value	Controls vs. Lenke 1	Controls vs. Lenke 5	Lenke 1 vs. Lenke 5
		Controls (n=24)	AIS Lenke 1 (n=30)	AIS Lenke 5 (n=13)				
CORE-OM	Psychosocial function	0.8±0.3	0.9±0.8	1.0±0.6	0.56			
	Problems	0.8±0.5	1.0±0.9	1.1±0.8	0.53			
	Wellbeing	0.8±0.7	1.2±1.0	1.2±0.9	0.29			
	Risk	0.1±0.2	0.2±0.4	0.2±0.4	0.99			
	General score	22.4±12.3	29.0±24.3	31.6±19.7	0.53			
HADS	Anxiety	6.2±3.7	7.2±4.9	7.5±5.3	0.77			
	Depression	3.0±2.7	4.5±3.6	4.2±3.8	0.37			
SRS-22r	Pain	3.7±1.2	3.6±1.2	3.8±0.3	0.24			
	Function during daily-life activities	3.1±1.0	3.0±1.1	3.3±0.4	0.63			
	Self-image	3.9±1.3	3.2±1.2	3.8±0.9	0.002	*		
	Mental health	2.9±1.0	2.7±0.9	3.0±0.3	0.12			
	Total score	70.7±22.6	62.3±21.0	70.5±5.0	0.003	*		

***Bold**: statistically significant result

The spatio-temporal parameters were similar between the three groups (Table 2).

Quality of life

AIS Lenke 1 showed lower SRS-22r scores in terms of self-image and total score compared to controls (3±1 vs. 4±1 and 62±21 vs. 71±22, respectively; all $p < 0.01$; Table 3).

Correlation analysis

The bivariate analysis revealed numerous significant correlations between radiographic parameters, HRQoL scores, and kinematic alterations (Table 4). The internal rotation of the right foot during gait correlated positively to the apical vertebral localization ($\rho = 0.3$). The shoulder-pelvis rotation during gait was negatively correlated to T1T12 and positively correlated to the Cobb angle and the gibbosity ($r = -0.5$, $r = 0.6$ and $r = 0.4$ respectively). T6T9-T9T12 lateral bending during gait was positively correlated to T4T12 kyphosis ($r = 0.4$) and negatively correlated to the Cobb angle ($r = -0.4$). T12L3-L3L5 lateral bending during gait correlated positively to the Cobb angle ($r = 0.5$), while T12L5-Pelvis lateral bending correlated negatively to the Cobb angle ($r = -0.3$; all $p < 0.05$; Fig. 5).

Discussion

This is the first study investigating gait kinematics of the head, trunk, spinal segments, pelvis and lower limbs in AIS with Lenke 1 and Lenke 5 curvatures. The combination of radiographic parameters, 3D kinematic analysis, and HRQoL questionnaires provides a comprehensive understanding of both the biomechanical and quality of life aspects of AIS. Focusing on different Lenke types (Lenke 1 and Lenke 5) allows for a more refined analysis of how curvature type influences gait, addressing a gap in previous studies that treated AIS patients as a homogenous group. Results revealed that Lenke 5, characterized by a major thoracolumbar/lumbar deformity, tended to show lower limb compensations during gait. However, Lenke 1, characterized by a major main thoracic deformity, showed compensation at the lumbo-pelvic level.

In our study, we did not find spatio-temporal parameters differences between AIS Lenke 1, AIS Lenke 5 and controls. A previous study reported that a significant portion of Lenke 1 patients had an increased step length, cadence and single support time, and reduced double support time compared to other Lenke types [20]. However, this result could not be generalized on our population, as the groups in our study

Table 4 Correlations between gait kinematic parameters and radiographic parameters as well as HRQoL outcomes. Only significant correlations were reported ($p < 0.05$)

Correlation coefficient	Mean flex/ext C7T12-T12L5 (°)	Mean flex/ext T3T6-T6T9 (°)	Mean shoulder-rotation (°)	Mean pelvic axial rotation (°)	Mean foot progression (°)	Mean lateral bending T6T9-T9T12 (°)	Mean lateral bending T12L3-L3L5 (°)	Mean lateral bending C7T12-T12L5 (°)	Mean lateral bending T12L5-Pelvis (°)	Mean frontal ODHA (°)	ROM pelvic obliquity (°)	ROM lateral bending L3L5-Pelvis (°)	ROM lateral bending T12L3-L3L5 (°)
Frontal ODHA (°)										0.51			
T10L2 (°)	-0.57										-0.30		
T4T12 (°)	-0.44	0.51	-0.44			0.35						0.30	
T1T12 (°)	-0.34	0.52	-0.49			0.24						0.27	
Cobb angle (°)	0.24	-0.37	0.60			-0.35	0.52	0.35	-0.34	0.30		-0.39	
AVR (°)	0.34	-0.34	0.49			-0.42	0.25	0.30	-0.35	0.33		-0.34	
Apical localisation	0.39				0.33		0.39				0.34		0.28
Gibbosity (°)		-0.26	0.41		0.31	-0.32			-0.26			-0.29	
VSPI (%)	0.33	-0.33	0.39										
SRS-22r - Self-image													-0.32

included a wide array of scoliosis severity with homogeneous Lenke groups.

During gait, Lenke 5 patients showed an increased lumbar segment bending toward the concave right side of the scoliosis, according to their structural deformity. Consequently, their center of mass (CoM) was also shifted toward the same side, thus affecting the anterior progression of the full body during gait. This was in accordance with a previous study that showed an increased lateral displacement of the body's CoM in AIS during gait [21]. Therefore, in order to bring the projection of the CoM back within the base of support, AIS Lenke 5 patients exhibited an internal foot progression of the concave homolateral side during the gait cycle, coupled with an increase range of motion of the pelvic obliquity. This might help to ensure an appropriate translation of the CoM within the base of support during gait, and therefore to maintain stability [22, 23]. Notably, this internal foot progression is often observed in AIS during simple observation of gait. This compensation mechanism in AIS Lenke 5 patients has also been revealed in the positive correlation between the internal rotation of the right foot and a more caudal apical localization.

During gait, Lenke 1 patients showed an increased rotation of the shoulders relative to the pelvis to the left, as formerly observed in a previous study [11]. This increased rotation was correlated to the hypokyphosis (decreased T1T12) and increased gibbosity, which accounts for a more severe scoliotic deformity. They increased their thoracic segment bending toward the concave side of the scoliosis (to the left), thus shifting their CoM toward the same side. Given that altered CoM control affects the whole-body balance control [24], as a compensatory mechanism, AIS Lenke 1 tended to produce opposite bending movement at the lumbar segment in order to ensure a projection of the CoM within the base of support. Moreover, they tended to bend the lumbo-pelvic segment to the left side to maintain a frontally aligned pelvis. In this chain of frontal compensation due to the scoliotic deformity, AIS Lenke 1 patients had their head shifted to the right, as explained by the increased frontal ODHA.

This dynamic evaluation showed that AIS Lenke 1 patients seem to compensate at the lumbo-pelvic level, ensuring a dynamic alignment during forward gait progression. This lumbo-pelvic compensation chain in AIS Lenke 1 group has also been demonstrated in the correlation between Cobb angle and lateral dynamic bending toward the left side at the thoracic and lumbo-pelvic levels, and toward the right side at the lumbar level, in an attempt to keep a centered center of mass. However, Lenke 5 patients seem to use lower limb compensations during gait, as the thoracic segment is less flexible and cannot compensate for the coronal imbalance caused by the lumbar deformity [25]. These

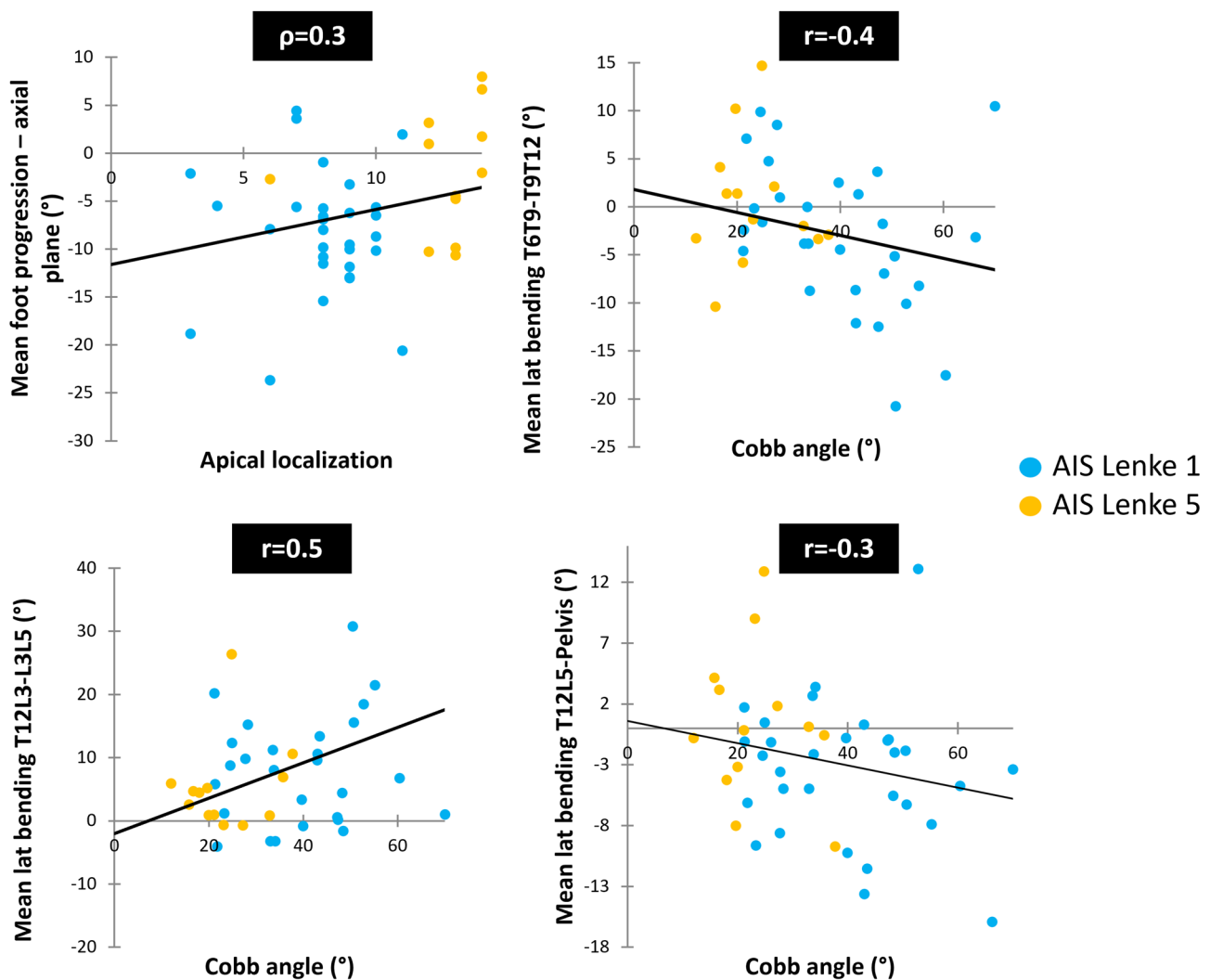


Fig. 5 Correlations between altered kinematic parameters and radiographic parameters

findings could be explained by the fact that curve location influences compensatory strategies in adjacent segments. For instance, Lenke 1 patients are characterized by a major main thoracic deformity, and compensation may occur more prominently in the lumbo-pelvic spine, with less involvement of the lower limbs. In contrast, Lenke 5 patients with a major thoracolumbar/lumbar deformity may show compensatory mechanisms at structurally flexible regions adjacent to the deformity, particularly the pelvis and lower limbs.

AIS Lenke 1 group seems to have a more deteriorated quality of life compared to AIS Lenke 5 group. The fact that AIS Lenke 1 group had a larger Cobb angle compared to AIS Lenke 5 group might account for the more affected HRQoL scores observed in the Lenke 1 group, as studies showed that an increase in Cobb angle affects quality of life in AIS [26].

The relatively small sample size (43 AIS patients, 13 Lenke 5 patients) limits the study's power and generalizability. Future studies involving multiple centers, including other Lenke types, with solely severe scoliotic deformity, would provide a wider understanding of the spectrum of kinematic strategies in AIS patients. Furthermore, potential confounding factors such as gender and body weight differences between groups may influence gait kinematics. For example, it is known that females typically exhibit greater pelvic obliquity during walking compared to males [27]. While weight and gender differences were found between Lenke groups and controls, an ANCOVA was computed to compare kinematics between the groups while controlling for weight and gender, and the same results were found as described when using the Kruskal-Wallis tests.

Moreover, tracking kinematic and compensatory mechanisms changes in post-surgery will provide more robust

conclusions about the effect of spinal fusion or bracing on gait, while including dynamic changes of the center of mass [28]. In a previous study conducted on a heterogeneous group of AIS, it was shown that spinal fusion did not affect lower extremity kinematics neither sagittal balance, while coronal spinal balance and transverse plane parameters showed improvement during gait [29]. Our exploratory study sets the foundation to a better understanding of gait patterns in non-operated AIS with different Lenke types and will serve as a benchmark to assess gait kinematics variations in post-operative settings for each Lenke type. However, we acknowledge that the use of 3D motion tracking systems presents practical limitations. These systems require specialized equipment as well as expertise in the associated analyses, which may not be accessible in all clinical settings. Future technologies should aim to simplify gait assessment protocols while retaining clinical relevance, to enable an easier implementation of functional analysis across diverse clinical practices such as physiotherapy or orthopedics.

Conclusion

In conclusion, this study showed that different curve types in AIS patients lead to different kinematic patterns during gait. Various strategies can be adopted either by recruiting compensatory mechanisms at the spine and pelvis levels or at the lower limbs, in order to ensure an appropriate anterior full body progression. These findings may hold crucial clinical implications. For instance, the recruitment of the lumbopelvic segment in Lenke 1 patients may suggest that rigidly fixing this region during spinal fusion could risk losing a valuable compensatory mechanism. While this remains a hypothesis, future comparative post-operative studies are needed to confirm and further elucidate its significance. The future of gait analysis and treatment in AIS patients lies in integrating physical therapy, bracing, and surgical interventions in a more personalized and dynamic manner. By focusing on gait patterns pre- and post-intervention, future studies can provide deeper insights into the best strategies for preserving mobility, improving posture, and enhancing overall quality of life.

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Author contributions MRK, MA, EW wrote the manuscript, performed statistics, prepared figures and tables and interpreted the findings. AM, MoK supervised operators, performed statistics and interpreted the findings. GEH, MB, MM, IH, GP, MoR, GA, JA, MaR, KH,

REH, EM, NN participated in data collection, processing, extraction and prepared figures. CV, HP conceptualized the study and reviewed findings and manuscript. RR, IG and AA supervised the work, participated in data interpretation, reviewed findings and manuscript. RR and EW contributed the same to this work. MRK and AA revised the manuscript after reviewers comments.

Data availability Data can be provided if needed.

Declarations

Competing interests The authors declare no competing interests.

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