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ORIGINAL ARTICLE

Characterization of trunk motion in adolescents with right thoracic idiopathic scoliosis

Sébastien Pesenti[1,2,3] · Solenne Prost[1,2,3] · Vincent Pomero[2] · Guillaume Authier[2] · Mathieu Severyns[1] · Elke Viehweger[1,2,3] · Benjamin Blondel[1,2,3] · Jean-Luc Jouve[1,2,3]

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Abstract

Background Although standard radiography is currently used for deformity assessment in AIS patients, it is performed in a constrained position and probably not reflective of spinal balance during daily-life activities. Our main objective was to compare trunk motion in Lenke 1 and 2 AIS patients to healthy volunteers, using gait analysis.

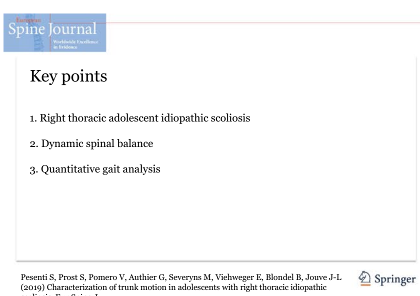
Material and methods Lenke 1 or 2 AIS patients planned for surgery were included. The day before surgery, they underwent radiographic evaluation and gait analysis. Among the gait parameters, sagittal vertical axis (Dyn-SVA), shoulder line rotation (Dyn-SL rotation), pelvis rotation (Dyn-P rotation) and acromion pelvis angle (Dyn-APA) were measured. AIS patients were compared to 25 asymptomatic controls.

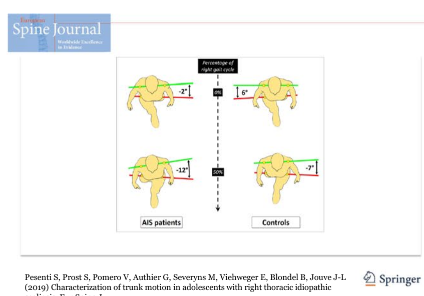
Results A total of 57 patients were included in the study, with a mean Cobb angle of 55.4°. AIS patients had a lower Dyn-SVA when compared to controls (47.0 vs. 62.9 mm, $p=0.012$). Dyn-APA and Dyn-SL rotation were negative in AIS patients, meaning that shoulder line was rotated towards the left (−6.4 vs. 7.8° and −7.5 vs. −0.4°, $p<0.001$, respectively). On the other hand, Dyn-P rotation was positive, meaning that pelvis was rotated towards the right side during gait (1.1 vs. −0.5, $p=0.026$).

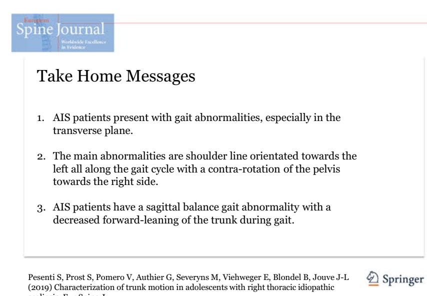
Discussion This is one of the largest series of gait analysis in AIS patients. We demonstrated that AIS patients have an abnormal gait pattern, with a decreased anterior tilt of the trunk and transverse plane abnormalities. We found that gait deviation was not related to radiographic measurements, pointing out that dynamic assessment provides new data about spinal posture.

Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.







Keywords Adolescent idiopathic scoliosis · Gait analysis · Shoulder line rotation · Sagittal balance

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✉ Sébastien Pesenti
seb.pesenti@gmail.com

Extended author information available on the last page of the article

Introduction

Adolescent idiopathic scoliosis (AIS) is a common three-dimensional deformity, associating vertebral rotation, coronal deviation of the spine and modification of the sagittal profile. The onset occurs in late childhood or adolescence, with curve worsening during pubertal growth [1]. Negative effects of spine deformity in adulthood on daily-life activity have been reported, especially when Cobb angle was over 40° to 50° at skeletal maturity [1–3]. However, in adolescents, the impact of spinal deformity is currently thought to be minor [4].

Standard radiography is currently used for deformity assessment is these patients, allowing the measurement of local curves (Cobb angle, thoracic kyphosis and lumbar lordosis) or global balance of the spine (coronal vertical axis, sagittal vertical axis). Nevertheless, this measurement method is probably biased because it is performed in a restrained environment and in a constrained position [5]. Therefore, radiographic assessment is probably not reflective of spinal balance during daily-life activities, making difficult to draw conclusions from such limited assessment.

Since the last three decades, quantitative gait analysis has been developed, providing new dynamic data [6–8]. In addition to the assessment of the lower limbs, some authors have reported the use of gait analysis for trunk motion assessment [9–12]. In 2012, we developed a protocol able to capture spine motion using a limited number of markers [13, 14]. Used in a static position, this protocol has shown good reliability to usual radiographic parameters in AIS patients [15].

Some studies have reported gait abnormalities in AIS patients when compared to normative controls, such as changes in spatio-temporal parameters, lower limbs kinematics or trunk balance [16–19]. However, most of authors reported their results with a limited set of patients. Furthermore, no segmental analysis of the spine in these patients has been reported to date.

Our main objective was to compare segmental spinal motion in AIS patients with a main thoracic curve to healthy volunteers, using gait analysis. Our secondary objective was to explore the influence of coronal deformity on gait pattern in AIS patients.

Material and methods

Study design

After approval from our local ethics committee, we conducted a single-centre prospective study. Prior to inclusion, we obtained the consent from every patients and legal representatives. Our hypothesis was that AIS patients presented with gait pattern abnormalities when compared to controls.

Study population and inclusion criteria

Patients from our department who were planned for corrective surgery were recruited. The inclusion criteria were (1) diagnosis of juvenile 3 or adolescent idiopathic scoliosis and (2) right thoracic curve, classified Lenke 1 or 2. Our protocol calls for surgery proposal in AIS Lenke 1 or 2 when main Cobb angle exceeds 45°. Patients with a transitional vertebrae or history of spine surgery or major spine or lower limbs trauma were excluded from the study. Gait data of the inclusion population were compared to a database of 25 asymptomatic volunteers of the same age.

Study protocol

The day before surgery, patients underwent standing biplanar low-dose radiographs (EOS, Paris, France). Then, they underwent gait analysis. According to Blondel et al. protocol, 36 retroreflective markers were placed on the skin. Six markers were used for spine description (C7, T6, T9, T12, L3 and S1), 2 for shoulder grid description (acromioclavicular joints), and 3 for pelvis description (S1 and the 2 antero-superior iliac spines) (Fig. 1). The position of the markers was caught by 6 high-resolution infrared cameras at the frequency of 100 Hz. Patients were asked to walk at a self-selected speed, barefoot, on a 9-m walkway.

Evaluation criteria

Radiographic parameters were measured with a semi-automated method using a dedicated software (Surgimap, Nemaris, USA). On AP view, we measured upper-thoracic (UT) and mid-thoracic (MT) Cobb angles and the coronal vertical axis (CVA). On lateral view, we measured C2–C7 cervical lordosis (CL), T4–T12 thoracic kyphosis (TK), L1–S1 lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT) and sacral slope (SS), as well as sagittal vertical axis (SVA). Patients were classified according to Lenke classification [20].

During gait analysis, different parameters were measured from markers position (Fig. 1). In coronal plane, we measured the dynamic thoracic Cobb angle (Dyn-Cobb angle), defined as the coronal angle between the C7–T6 line and the T9–T12 line; the dynamic shoulder line inclination (Dyn-SL inclination), defined as the angle between the bi-acromion line and a horizontal line and the dynamic coronal vertical axis (Dyn-CVA). In sagittal plane, we measured the dynamic thoracic kyphosis (Dyn-TK), defined as the sagittal angle between the C7–T6 and the T9–T12 lines; the dynamic lumbar lordosis (Dyn-LL), defined as the sagittal angle between the T12–L3 and L3–S1 lines; the dynamic pelvic tilt (Dyn-PT) as defined in the Helen Hayes protocol [21]; and the dynamic sagittal vertical axis (Dyn-SVA). Finally, in transversal plane, we measured the dynamic shoulder line rotation (Dyn-SL rotation), defined as the angle between the bi-acromion line and a line perpendicular to the axis of gait; the dynamic pelvic rotation (Dyn-P rotation), defined as the

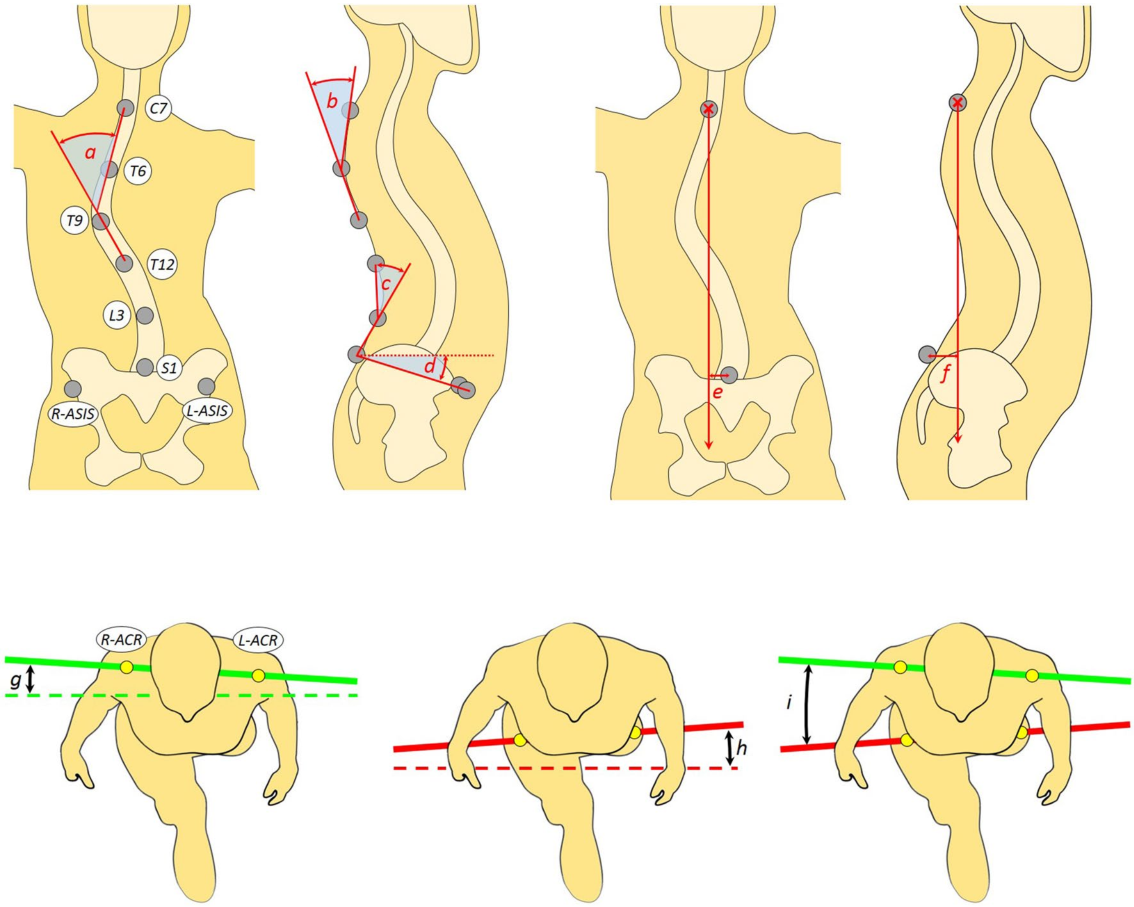

Figure 1 Markers protocol and gait parameters. **a** Dyn-Cobb angle; **b** Dyn-TK; **c** Dyn-LL; **d** Dyn-PT; **e** Dyn-CVA; **f** Dyn-SVA; **g** Dyn-SL rotation; **h** Dyn-P rotation; **i** APA. *R-ASIS* right antero-superior iliac spine, *L-ASIS* left antero-superior iliac spine, *R-ACR* right acromion, *L-ACR* left acromion

angle between the 2-ASIS line and a line perpendicular to the axis of gait; and the acromion pelvis angle (Dyn-APA), defined as the angle between the bi-acromion line and the ASIS line.

Statistical analysis

Values are presented as means, standard deviations and ranges. Gait data were recorded for the whole right gait cycle, and values were obtained for each percentage of gait cycle. For comparison between study population and control group, data were analysed in 2 fashions: comparison of data at each percentage of gait cycle and comparison of the mean value of each parameter. Range of motion (ROM) for gait parameters was calculated and compared between the 2 groups. Comparisons of means were made using a Student *T* test for independent samples. The relations between radiographic parameters and their dynamic equivalent were explored using the Pearson correlation coefficient. Finally, the influence of Dyn-Cobb angle on other gait parameters was assessed using Pearson correlation tests. Threshold for statistical significance was set at 5% ($p < 0.05$).

Results

Study population

From July 2014 to May 2018, 478 patients were operated on in our department for adolescent idiopathic scoliosis correction. Among them, 57 fitted inclusion criteria and were enrolled into our study. Mean age was 15.2 years (± 2, from 12 to 20 years), mean weight was 51.4 kg (± 8, from 36 to 76 kg), mean height was 162.0 cm (± 7, from 155 to 183 cm), and mean BMI was 19.5 kg m^{-2} (± 2, from 15 to 23 kg m^{-2}). Patients were not statistically different from controls regarding demographic parameters (Table 1). Fifty patients (88%) had a single-thoracic curve (Lenke 1) and 7 (12%) a double-thoracic curve (Lenke 2). The average Cobb angle was 55.4°. Radiographic data are summarized in Table 2.

Table 1 Statistical comparison of demographic data between AIS patients and controls

	AIS patients ($n=57$)			Controls ($n=25$)			p
	Mean	SD	Range	Mean	SD	Range	
Age (year)	15.2	2	12–20	16.1	6	11–31	0.29
Weight (kg)	51.4	8	36–76	52.4	16	32–87	0.81
Height (cm)	162	7	155–183	160	14	137–180	0.58
BMI (kg m^{-2})	19.5	2	15–23	20.0	3	16–28	0.58

Table 2 Summary of radiographic parameters for inclusion population

	Mean	SD	Range
Main Cobb angle	55.4	12	45–100
UT Cobb angle	29.9	11	8–62
MT Cobb angle	54.7	12	27–100
CVA (mm)*	3.0	16	−27–35
Cervical lordosis**	−7.9	14	−42–23
Thoracic kyphosis	19.0	12	−2–59
Lumbar lordosis	52.0	13	13–72
Pelvic incidence	49.4	11	21–30
Pelvic tilt	5.9	9	−13–25
Sacral slope	43.5	9	15–63
SVA (mm)	14.3	21	−20–87

UT upper thoracic, *MT* mid-thoracic

*Negative values indicate deviation towards the left

**Negative values indicate kyphosis

Gait analysis: comparison to control group

The results of gait parameters analysis are summarized in Table 3.

In coronal plane, gait analysis showed no differences between AIS patients and controls, except for Dyn-Cobb angle that was greater in AIS patients (15.1° vs. 4.5°, $p<0.001$). Surprisingly, Dyn-SL inclination was not greater in AIS patients (0.2° vs. 0.1°, $p=0.821$). Range of motion of Dyn-SL inclination was greater in AIS patients when compared to controls (4.9° vs. 3°, $p<0.001$). Range of motion of Dyn-CVA was lower in AIS patients (26.9 vs. 36.1 mm, $p=0.02$).

In sagittal plane, Dyn-SVA was significantly lower in AIS patients when compared to controls (47.0 vs. 62.9 mm, $p=0.012$) (Fig. 2). Otherwise, sagittal parameters were not different between AIS patients and controls. Range of motion of Dyn-TK was greater in AIS patients (5.1° vs. 3.1°, $p=0.003$).

Every transversal parameter was different between AIS patients and controls. Mean APA and Dyn-SL rotation were negative in AIS patients, meaning that shoulder line was rotated towards the left during gait (Figs. 2 and 3). On the other hand, mean Dyn-P rotation was positive in AIS patients, meaning that pelvis was rotated towards the right side during gait.

Correlation analysis

Except for SVA, every radiographic parameter was significantly correlated with its dynamic equivalent (Table 4). Dyn-SL rotation and APA were neither correlated with UT

Table 3 Comparison of gait parameters (means and ROM) between AIS patients and controls

	AIS patients		Controls		p mean	p ROM
	Mean	ROM	Mean	ROM		
Dyn-SL inclination	0.2	4.9	0.1	3.0	0.851	**< 0.001**
Dyn-P inclination*	−0.1	7.6	−0.2	8.4	0.821	0.278
Dyn-CVA*	−1.1	26.9	−1	36.1	0.980	**0.02**
Dyn-Cobb angle	15.1	7.2	4.5	7.3	**< 0.001**	0.924
Dyn-TK	28	5.1	28.1	3.1	0.953	**0.003**
Dyn-LL	19.7	4.5	17.3	4.9	0.144	0.464
Dyn-PT	9.4	2.9	10.9	3	0.432	0.513
Dyn-SVA	47.0	26.9	62.9	25.4	**0.012**	0.445
APA*	−7.5	11.6	−0.4	15.8	**< 0.001**	**0.003**
Dyn-SL rotation*	−6.4	7.8	−0.8	8.9	**< 0.001**	0.09
Dyn-P rotation*	1.1	8.3	−0.5	11.0	**0.026**	**0.01**

Bold values indicate statistical significance

*Negative values indicate deviation towards the left

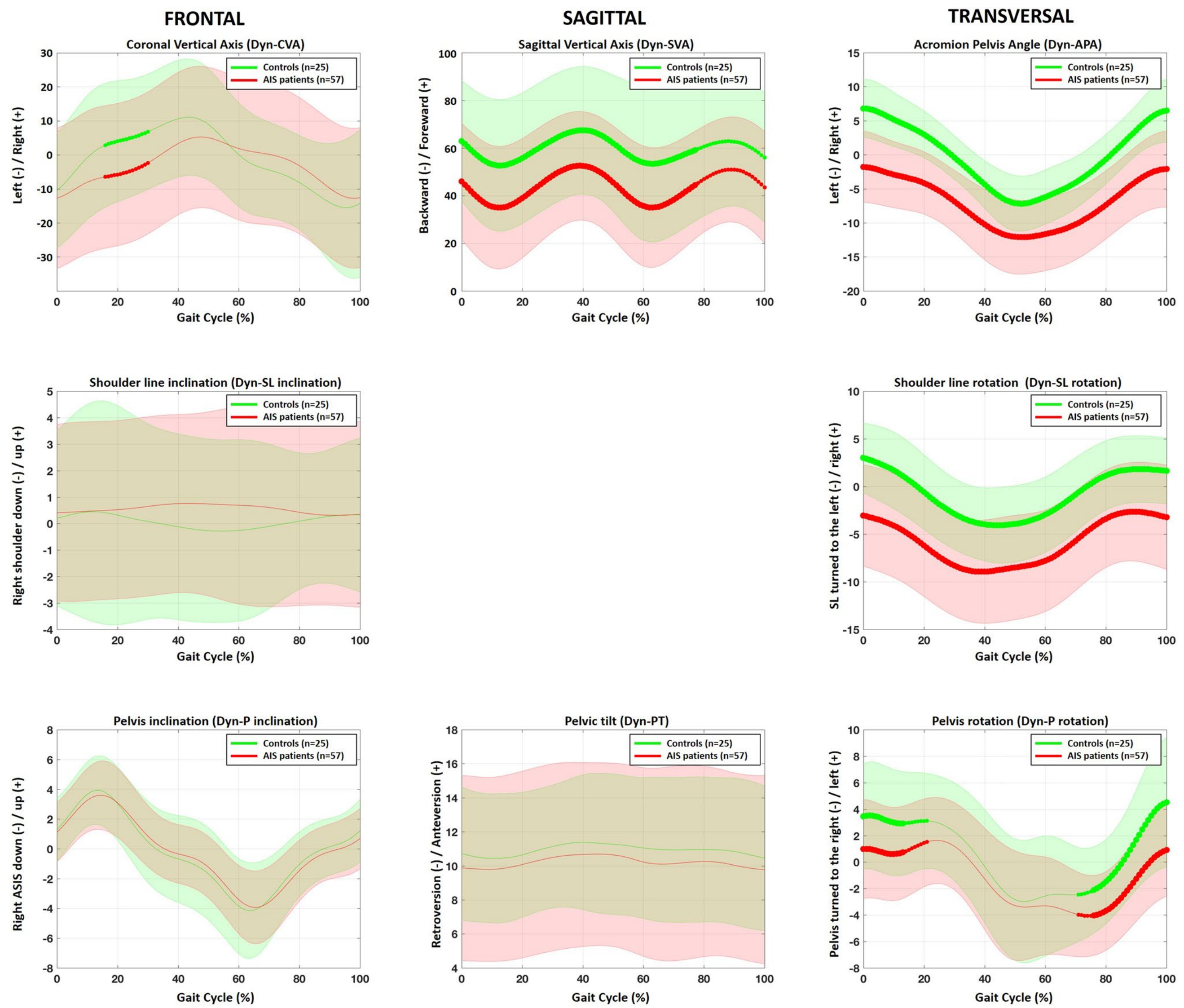

Figure 2 Comparison of AIS patients (red curves) and controls (green curves). Bold points indicate statistical significance ($p<0.05$)

Cobb angle nor to MT Cobb angle. Dyn-Cobb angle was significantly correlated with Dyn-SL rotation and APA ($R=-0.392$ and $R=-0.317$, $p=0.002$ and $p=0.017$, respectively) (Fig. 4). On the other hand, Dyn-P rotation and Dyn-Cobb angle were not significantly correlated ($R=0.174$, $p=196$). Dyn-SL rotation and Dyn-P rotation were significantly correlated ($R=0.445$, $p<0.001$).

Discussion

In previous studies, some authors have found that AIS spinal deformity had a clear influence on gait [16, 22–24]. Most of gait deviations were described in transverse plane. Our results are in line with the previously reported studies and confirm the asymmetrical gait pattern with shoulder line turned towards the left and in a lesser proportion and a contra-rotation of the pelvis towards the right. In addition, we found a decreased anterior tilt of the trunk when walking.

Using our protocol, we were able to describe segmental trunk motion with the following parameters: Dyn-Cobb angle, Dyn-TK and Dyn-LL. In a previous study, we reported significant correlations between gait and radiographic, demonstrating that our protocol was efficient in describing spinal shape in AIS patients [15]. Our protocol was especially efficient for thoracic spine description. In the present study, dynamic parameters were significantly correlated with their radiographic equivalents, except for SVA measurement. Dyn-SVA was largely greater than radiographic SVA. Obviously, SVA is probably more anterior when walking, explaining the difference with SVA measured on radiographs. However, the absence of correlation

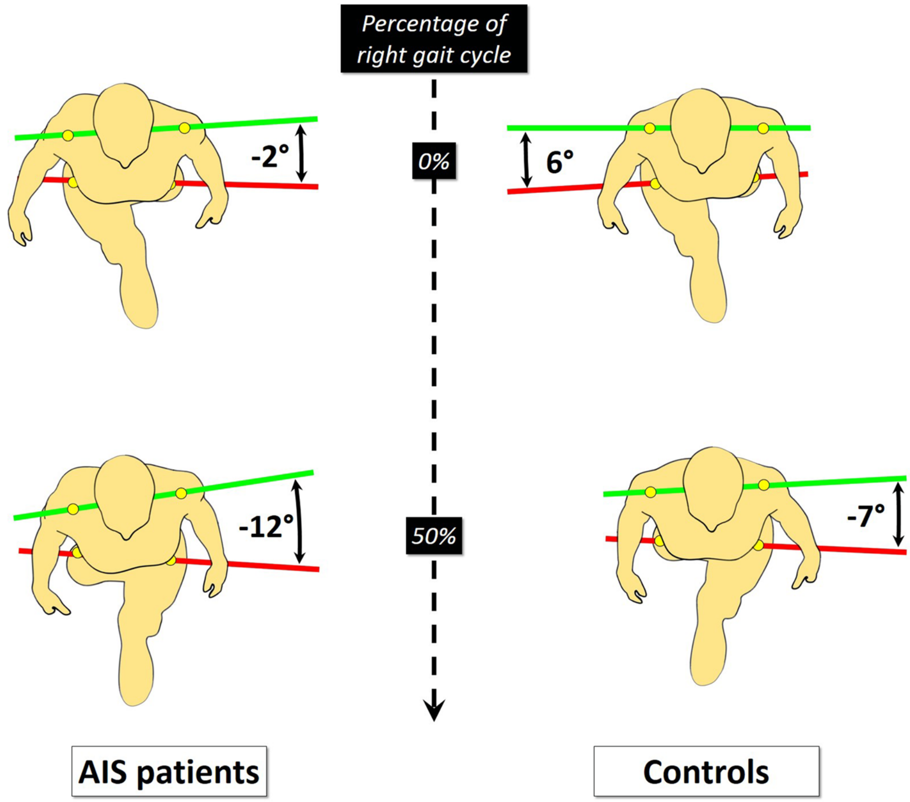

Figure 3 Comparison of gait in transverse plane between AIS patients and controls. In AIS patients, shoulders were turned to the left throughout the gait cycle

Table 4 Correlation analysis between radiographic and dynamic parameters

Radiographic parameter	Dynamic parameter (mean)	*R*	*p*
MT Cobb angle	Dyn-Cobb angle	0.294	**0.026**
CVA	Dyn-CVA	0.356	**0.007**
Thoracic kyphosis	Dyn-TK	0.606	**< 0.001**
Lumbar lordosis	Dyn-LL	0.365	**0.005**
Pelvic tilt	Dyn-PT	− 0.377	**0.004**
SVA	Dyn-SVA	0.164	0.228
MT Cobb angle	Dyn-SL rotation	− 0.047	0.727
MT Cobb angle	Dyn-P rotation	− 0.038	0.780
MT Cobb angle	APA	− 0.08	0.570
UT Cobb angle	Dyn-SL rotation	0.106	0.434
UT Cobb angle	Dyn-P rotation	0.071	0.602
UT Cobb angle	APA	0.167	0.215

Bold values indicate statistical significance

between radiographic SVA and Dyn-SVA points out that static measurements may not be a reliable assessment of spinal balance in daily-life activities. Therefore, gait analysis is able to provide additional data about spinal balance and its dynamic aspect.

AIS spinal deformity usually involves loss of thoracic kyphosis. However, concerning the overall balance, AIS patients are usually known to present with a normal sagittal alignment [25]. On the other hand, in a study by Roussouly *et al.*, the authors reported a more posterior sagittal alignment of the spine based on radiographic evaluation [26]. Based on gait analysis, we found contradictive results, with Dyn-SVA significantly lower in AIS patients when compared to controls (47.8 vs. 62.9 mm, $p = 0.012$). This result suggests that when walking, the sagittal balance of AIS patients is altered, pointing out that dynamic evaluation of these patients provides additional info that may help to understand the functional disability induced by the spinal deformity. Applied to post-operative assessment, gait analysis could help, through dynamic assessment of sagittal balance, to understand phenomenon that is not well explained by the simple radiographic evaluation, such as proximal junctional kyphosis.

Abnormalities of transverse plane have been previously reported on smaller sets of patients [16, 18, 22–24]. With 57 AIS patients with right thoracic curves, our sample is the largest ever reported and confirms the previously reported results. Correlation analysis between gait parameters showed that SL rotation and Pelvis rotation were significantly linked to each other. Dyn-Cobb angle was correlated with Dyn-SL rotation and to Dyn-APA, but not with Dyn-P rotation. These results suggest that spinal deformity mainly influences the shoulder line direction. Therefore,

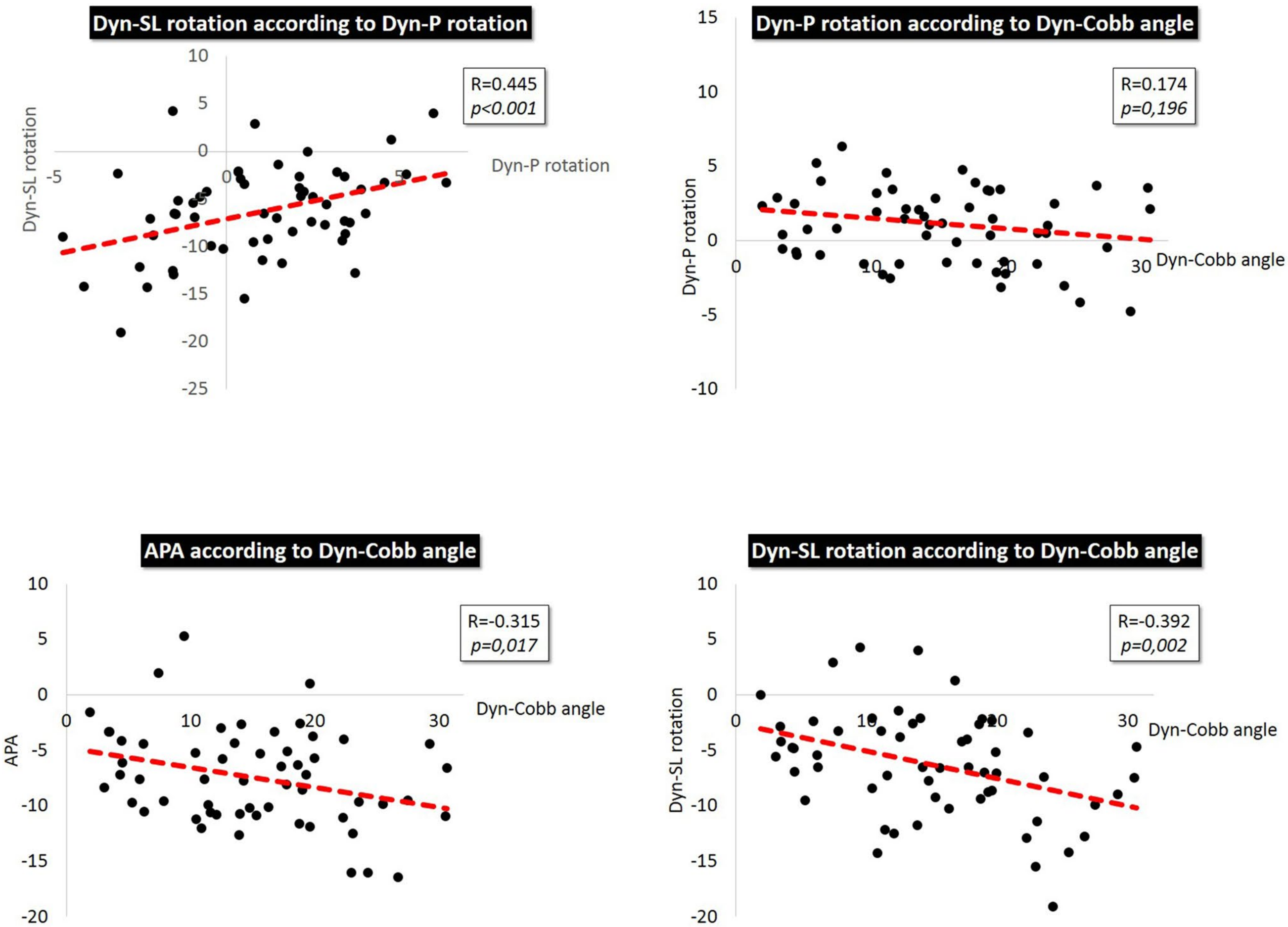

Figure 4 Correlation analysis between gait parameters in AIS patients

pelvis rotation appears as a compensatory mechanism in order to keep the body facing gait direction.

Otherwise, the direction of rotation deviation is surprising. Indeed, in right thoracic scoliosis, vertebral rotation occurs towards the right. However, shoulders are turned in the opposite direction. Patel et al. suggested that SL rotation direction was due to the presence of an upper-thoracic curve, in which vertebral rotation was towards the left [24]. However, in our study, Dyn-SL rotation was neither correlated with UT Cobb angle nor with MT Cobb angle, suggesting that SL rotation was independent of vertebral rotation of the upper-thoracic spine. As suggested by Kramers de Quervain et al., we believe that transverse plane abnormalities may not be directly related to spinal deformity itself [23].

So far, the current research has not permitted yet to determine the exact cause of spinal curvature in idiopathic scoliosis. The literature suggests that AIS patients had an erroneous perception of their body position [27]. In the light of our results, we could hypothesize that the specific gait pattern of shoulders line could be the major abnormality that will secondarily lead to the onset of spinal deformity. However, this is highly hypothetical and further studies, especially in patients with lower Cobb angles, are needed to elucidate this specific point.

Conclusion

This study is one of the largest reported series of gait analysis in right thoracic AIS patients. We demonstrated that AIS patients have an abnormal gait pattern, with a decreased anterior tilt of the trunk when walking and transverse plane abnormalities. Shoulder line orientation towards the left throughout gait cycle appears to be the most abnormal gait parameter. Our results also suggest that gait deviation was not related to radiographic measurements, pointing out that dynamic assessment provides new data about spinal posture that standard radiographic assessment is not able to catch. Therefore, gait analysis may become a cornerstone of preoperative assessment in these patients. Otherwise, with further studies, gait analysis could allow for a better understanding of mechanisms leading to spinal deformity in AIS patients.

Compliance with ethical standards

Conflict of interest Authors declare no conflict of interest related to this work.

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Affiliations

Sébastien Pesenti[1,2,3] · Solenne Prost[1,2,3] · Vincent Pomero[2] · Guillaume Authier[2] · Mathieu Severyns[1] · Elke Viehweger[1,2,3] · Benjamin Blondel[1,2,3] · Jean-Luc Jouve[1,2,3]

1 Paediatric Orthopaedics , Hopital d'enfants de la Timone, Aix Marseille University , 264 rue Saint Pierre, 13005 Marseille, France

2 Gait Analysis Platform , Timone, Aix Marseille University , Marseille, France

3 Orthopédie pédiatrique, APHM, CNRS, ISM , Hôpital de la Timone, Aix Marseille University , Marseille, France