Kinematic adaptations from self-selected to fast speed walking in patients with adult spinal deformity

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Abstract

Purpose To investigate kinematic adaptations from self-selected to fast speed walking in ASD patients.

Methods 115 primary ASD and 66 controls underwent biplanar radiographic X-rays and 3D gait analysis to calculate trunk, segmental spine and lower limb kinematics during self-selected and fast speed walking. Kinematic adaptation was calculated as the difference (Δ) between fast and self-selected speed walking. ASD with 7 or more limited kinematic adaptation parameters were classified as ASD-limited-KA, while those with less than 7 limited kinematic adaptation parameters were classified as ASD-mild-KA.

Results 25 patients were classified as ASD-limited-KA and 90 as ASD-mild-KA. ASD-limited-KA patients walked with a lesser increase of pelvic rotation (Δ = 1.7 vs 5.5°), sagittal hip movement (Δ = 3.1 vs 7.4°) and shoulder–pelvis axial rotation (Δ = 3.4 vs 6.4°) compared to controls (all $p < 0.05$). ASD-limited-KA had an increased SVA (60.6 vs − 5.7 mm), PT (23.7 vs 11.9°), PI–LL (9.7 vs − 11.7°), knee flexion (9.2 vs − 0.4°) and a decreased LL (44.0 vs 61.4°) compared to controls (all $p < 0.05$). Kinematic and radiographic alterations were less pronounced in ASD-mild-KA. The limited increase of walking speed was correlated to the deteriorated physical component summary score of SF-36 ($r = 0.37$).

Discussion Kinematic limitations during adaptation from self-selected to fast speed walking highlight an alteration of a daily life activity in ASD patients. ASD with limited kinematic adaptations showed more severe sagittal malalignment with an increased SVA, PT, PI–LL, and knee flexion, a decreased LL and the most deteriorated quality of life. This highlights the importance of 3D movement analysis in the evaluation of ASD.

Keywords Adult spinal deformity · 3D gait analysis · Kinematic adaptations · Sagittal malalignment · Quality of life

Introduction

The occurrence of degenerative pathologies affecting the musculoskeletal system and limiting the function of the spine is increasing throughout the years [1]. Pathologies affecting the spine, pelvis or lower limbs, such as adult spinal deformity (ASD), result in postural imbalance of the subject [2, 3] where skeletal malalignment extends from the cervical spine to the lower limbs [4, 5].

ASD as defined by the International Spine Study Group (ISSG) [6] requires the presence of at least one of these radiographic criteria: sagittal vertical axis (SVA) ≥ 50 mm, Cobb angle ≥ 20°, T1–T12 thoracic kyphosis (TK) ≥ 60°, pelvic tilt (PT) ≥ 25° and the mismatch between pelvic incidence and lumbar lordosis (L1–S1) PI–LL ≥ 10°. Due to these radiographic alterations, ASD patients experience limitations in their daily living activities [7, 8], thus altering their quality of life [9]. Evaluation of spinal deformity is based on the clinical examination and radiographic assessment [10]. However, evaluating the functional limitations in ASD patients remains important. Recent studies have reported that ASD patients present spine and lower limb kinematic alterations during several functional daily tasks such as walking, sitting and standing [7, 11, 12].

Fast walking is a highly demanding activity that is often adopted in daily life such as crossing the streets, walking in

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crowded places or at the same pace of a companion [13]. Therefore, its assessment in ASD patients might reveal further disabilities. In addition, fast walking is sensitive at evaluating risk of falls in adults [14]. Therefore, any morbidity altering changes in walking speed might affect the level of physical independence [13].

Thus, the aim of this study was to investigate kinematic adaptations from self-selected to fast speed walking and their relationship with spino-pelvic deformities and quality of life scores in ASD patients.

Materials and methods

Study design

This is a cross-sectional study, approved by the ethics committee of our institution (CEHDF1259). Standing radiographic parameters were studied in primary ASD patients and compared to a group of asymptomatic subjects. All participants signed an informed consent prior to the study.

Patients above 20 years old referred by physicians for experiencing back pain and/or discomfort while also having at least one of the following radiographic parameters specific to ASD were enrolled: SVA ≥ 50 mm, PT ≥ 25°, PI–LL ≥ 10°, TK ≥ 60° or Cobb angle ≥ 20°. The inclusion criteria are based on those reported by the International Spine Study Group (ISSG) [15]. Control subjects above 20 years old recruited from our institution were selected upon the following criteria: absence of back pain and not meeting the ISSG radiographic criteria. Patients and control subjects with neurological disorders, deformities in the lower limbs, who underwent prior surgery in the spine or lower limbs, or presenting any other pathology (tumors, rheumatic diseases, etc.) that could affect the motor function were excluded.

Data acquisition

Demographics

The demographic data of patients and control subjects were collected: age, sex, height and weight.

Radiographic acquisition

Low-dose full-body biplanar radiographs of ASD and control subjects in a standing position were collected (EOS Imaging®, Paris, France). The three-dimensional reconstructions of the spine and pelvis are performed by experienced operators using the SterEOS® software (EOS Imaging, Paris, France). The following spino-pelvic parameters were calculated: Pelvic incidence PI (°), Pelvic tilt PT (°), L1–S1 lumbar lordosis LL (°), PI–LL (°), T1–T12 thoracic kyphosis TK (°), and frontal Cobb angle (°). The global postural parameters calculated are the sagittal vertical axis SVA (mm) and the center of auditory meatus to hip-axis plumbline CAM-HA (mm) (Fig. 1).

Quality of life questionnaires

The following quality of life questionnaires were answered by all participants: Oswestry Disability Index (ODI), 36-Item Short Form Health Survey (SF-36) with its both physical and mental components (PCS and MCS, respectively), and Beck's Depression Inventory (BDI). Pain was assessed by all participants using the visual analog scale (VAS).

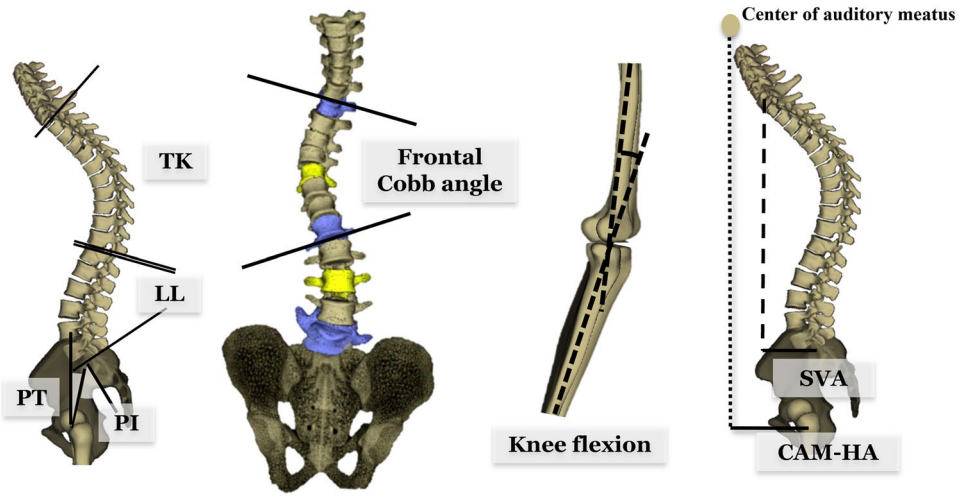

Fig. 1 Spinopelvic and postural parameters: pelvic incidence PI (°), pelvic tilt PT (°), L1–S1 lumbar lordosis LL (°), T1–T12 thoracic kyphosis TK (°), knee flexion (°), frontal Cobb angle (°), sagittal vertical axis SVA (mm) and plumbline from center of auditory meatus plumb line to hip-axis CAM-HA (mm)

Gait analysis

Three-dimensional gait analysis was performed for all participants (8 Vero 2.2 cameras, Vicon Motion Systems®, Oxford, UK). Markers of the lower limbs were placed according to Davis' protocol [16], and those of the trunk and spine according to Leardini's protocol [17]. The trunk and spine markers are placed on the following anatomical points: right and left acromion, suprasternal notch, xiphoid process, and spinous processes of C7, T2, T10, L1, L3 and L5 vertebrae.

First, all subjects were asked to walk at their own self-selected speed on a path of 10 m for several trials. Then, during the second set of acquisitions, subjects had to walk at the fastest possible speed without running. Three acquisitions for each gait speed were recorded. The Polygon software (Vicon Motion Systems®, Oxford, UK) was used for the data processing of all the captured trials where all waveforms were displayed. The consistency across the three trials was tested by examining the kinematic waveforms plotted on the same graphs. The most repeatable trial was selected. Joint angles formed by the movement of the different segments relative to each other were calculated in the 3 planes using Nexus and ProCalc software (Vicon®, Oxford, UK): inter-segmental movements of the spine (L3L5–L1L3, L1L3–T10L1, T10L1–T2T10 and T2T10–T2C7), trunk (thorax relatively to the global reference), pelvis (pelvis relatively to the global reference), pelvis–L3L5, hip (femur relatively to the pelvis), knee (tibia relatively to the femur), ankle (foot relatively to the tibia), foot (foot relatively to the global reference in the horizontal plane) and shoulder–pelvis axial rotation range of motion (ROM) as the shoulder relatively to the pelvis axis in the horizontal plane. Time–distance parameters were also calculated: gait speed (m/s), cadence (steps/min), foot off (in %), single and double support times (s), as well as the step length (m). All the parameters mentioned above were calculated during both self-selected and fast speed walking.

In order to study the kinematic adaptations from self-selected to fast speed walking, the difference between the values obtained for each parameter during the two gait acquisitions was calculated and represented by the symbol Δ (Δ = fast speed walking – self-selected speed walking).

Statistical analysis

The mean ± 1 standard deviation (SD) of the kinematic adaptations (Δ) in control subjects was considered as normative kinematic adaptation from self-selected to fast speed walking. Kinematic adaptation was collected for all ASD patients of the study and analyzed in order to define the groups. ASD patients having a Δ outside this normative range were considered as having an abnormal kinematic adaptation from self-selected to fast speed walking for this specific kinematic parameter. For each ASD patient, the number of abnormal Δ was collected. The distribution of the frequency of abnormal Δ was plotted (Fig. 2). Patients who have 7 or more abnormal kinematic adaptations formed the ASD-limited-KA group, presenting limited kinematic adaptations from self-selected to fast speed walking. Those who have less than 7 abnormal kinematic adaptations formed the ASD-mild-KA group, presenting mild or normal kinematic adaptations from self-selected to fast speed walking.

Demographics, radiographic parameters, health-related quality of life (HRQOL) and spine, pelvis and lower limbs kinematic adaptations were compared between the groups using Kruskal–Wallis test followed by Conover Iman pairwise multiple comparison. Correlations between variables were calculated using Pearson and Spearman coefficients.

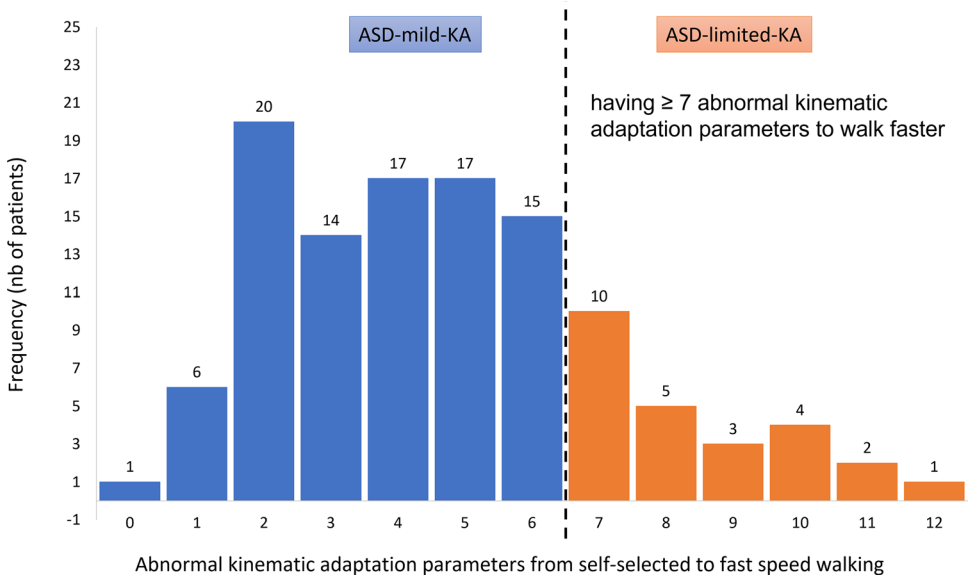

Fig. 2 Histogram showing the total number and the frequency of abnormal kinematic parameters in subdivision of ASD sub-groups: ASD-limited-KA and ASD-mild-KA

Statistical analysis was performed using XLSTAT® software (Addinsoft, Paris, France; version 2019). The significance level was set at 0.05 and adjusted by a Bonferroni correction for multiple comparisons.

Results

Demographics

The ASD group included 115 patients and was subdivided into ASD-limited-KA which included 25 (19F) patients and ASD-mild-KA (67F) which included 90 patients. The control group included 66 subjects (40F). The three groups were comparable in weight and height as well as in sex (all $p > 0.05$). ASD-limited-KA patients were older compared to ASD-mild-KA and control subjects (59.4 ± 17.1 years vs 48.7 ± 18.9 years and 47.4 ± 10.4 years, respectively).

Kinematic adaptations from self-selected to fast speed walking

During the transition from self-selected to fast speed walking, control subjects increased their pelvic obliquity ROM (from 10.5° to 14.6°; $p = 0.014$; $\Delta = 4.1°$), pelvic rotation ROM (from 11.9° to 17.4°; $p = 0.005$; $\Delta = 5.5°$) as well as their shoulder–pelvis axial rotation ROM (from 18.0° to 25.1°; $p = 0.009$; $\Delta = 7.1°$). Control subjects also increased their hip sagittal ROM (from 52.5° to 45.1°; $p < 0.001$; $\Delta = 7.4°$). These kinematic adaptations were observed along with an increased walking speed (from 1.2 to 1.8 m/s; $p < 0.001$; $\Delta = 0.6$ m/s) and step length (from 0.6 to 0.8 m; $p < 0.001$; $\Delta = 0.2$ m).

ASD-limited-KA population presented a less pronounced increase in pelvic obliquity ROM ($\Delta = 1.7°$ vs 4.1°; $p = 0.001$) and pelvic rotation ROM ($\Delta = 1.7°$ vs 5.5°; $p = 0.006$) as well as a significantly inferior increase in hip sagittal ROM ($\Delta = 3.1°$ vs 7.4°; $p = 0.001$) and hip frontal ROM ($\Delta = 1.5°$ vs 3.7°; $p = 0.03$) compared to controls. ASD-limited-KA patients did not sufficiently extend their knee in stance phase ($\Delta = 0.6°$ vs $-1.7°$; $p = 0.006$) compared to controls when walking faster. ASD-limited-KA patients did not sufficiently increase their shoulder–pelvis axial rotation ROM ($\Delta = 3.4°$ vs 6.4° in controls; $p < 0.001$). This was associated with a more pronounced flexion of the thorax ($\Delta = 3.3°$ vs 0.1° in controls; $p = 0.003$). Full-body kinematic adaptations were displayed in Table 1.

As for the time–distance parameters, the ASD-limited-KA patients showed a significantly lesser increase in their speed ($\Delta = 0.38$ vs 0.64 m/s controls; $p < 0.001$) and cadence ($\Delta = 22.3$ vs 32.5 step/min; $p = 0.002$) during the transition of walking from self-selected to fast speed (Table 2).

Radiographic parameters

ASD-limited-KA had an increased SVA (60.6 mm vs − 5.7 mm; $p < 0.001$), CAM-HA (31.7 mm vs -23.4 mm; $p < 0.001$), PT (23.7° vs 11.9°; $p < 0.001$), PI–LL (9.5° vs − 11.7°; $p < 0.001$) and knee flexion (9.2° vs − 0.4°; $p < 0.001$) when compared to controls. They had an increased thoracic kyphosis TK (53.7° vs 46.5°; $p = 0.02$) and frontal Cobb angle (18.5° vs 3.3° in controls; $p < 0.001$). ASD-limited-KA also showed a significantly decreased lumbar lordosis LL (44.0° vs 61.4°; $p = 0.003$) when compared to controls.

ASD-mild-KA showed an increased SVA (15.9 mm vs -5.7 mmm; $p < 0.001$), CAM-HA (− 1.3 mm vs − 23.4 mm; $p < 0.001$), PT (16.8° vs 11.9°; $p < 0.001$) and knee flexion (3.8° vs − 0.4°; $p < 0.001$) compared to controls. ASD-mild-KA also had an increased thoracic kyphosis TK (54.4° vs 46.5°; $p = 0.02$) and Cobb angle (20.7° vs 3.3°; $p < 0.001$) when compared to controls (Fig. 3).

SVA, CAM-HA, PT, PI–LL and knee flexion were significantly higher in ASD-limited-KA compared to ASD-mild-KA (all $p < 0.001$).

Quality of life scores

ASD-limited-KA patients had the most severe alterations compared to controls (Table 3). They had a lower PCS score (35.6 vs 51.1; $p < 0.001$) and an increased ODI (42.4 vs 16.0; $p < 0.001$), compared to controls. Moreover, ASD-limited-KA had a higher VAS (7.1 vs 3.6; $p < 0.001$). Similarly, ASD-mild-KA had altered quality of life scores but to a lesser degree with a decreased PCS score (41.7 vs 51.1 $p < 0.001$), an increased ODI (26.1 vs 16.0; $p < 0.001$) and VAS (5.5 vs 3.6 $p < 0.001$) when compared to controls. Moreover, ASD-limited-KA had a significantly increased PCS, VAS and ODI compared to ASD-mild-KA.

Correlation analysis

Significant correlations were found between radiographic parameters and kinematic alterations during adaptation from self-selected to fast speed walking.

Δ pelvic rotation was negatively correlated with SVA ($r = -0.27$). Δ hip frontal ROM was also negatively correlated with SVA ($r = -0.30$) and Δ hip sagittal ROM with PT ($r = -0.28$). As for the time–distance parameters, Δ walking speed was negatively correlated with PT, PI–LL, ($r = -0.32$, $r = -0.28$, respectively) and positively correlated with PCS ($r = 0.37$) and the body pain score (Bodily pain) estimated from SF-36 ($r = 0.28$) (Table 4, Fig. 4).

Table 1 Comparison of the kinematic adaptation parameters from self-selected to fast speed walking among the 3 groups

	Mean ± SD			*p*-value	Controls vs ASD-limited-KA	Controls vs ASD-mild-KA	ASD-limited-KA vs ASD-mild-KA
	Controls	ASD-limited-KA	ASD-mild-KA				
Trunk							
Δ Mean thorax flexion/extension (°)	0.1 ± 1.6	3.3 ± 5.6	0.5 ± 3.9	**0.003**	*		*
Δ ROM thorax flexion/extension (°)	− 0.2 ± 1.2	0.1 ± 1.5	0.2 ± 1.2	0.142			
Δ ROM shoulder–pelvis axial rotation (°)	7.1 ± 3.8	3.4 ± 5.0	6.1 ± 4.7	**0.02**	*		*
Δ Mean pelvis–L3L5 flexion/extension (°)	1.2 ± 1.9	1.3 ± 2.2	1.2 ± 1.9	0.990			
Δ ROM pelvis–L3L5 flexion/extension (°)	1.4 ± 2.6	− 0.5 ± 3.7	1.2 ± 4.1	0.155			
Pelvis							
Δ Mean pelvic tilt (°)	1.0 ± 1.9	0.7 ± 5.9	0.9 ± 2.1	0.332			
Δ ROM pelvic tilt (°)	0.9 ± 1.4	0.6 ± 2.0	0.9 ± 1.6	0.605			
Δ Mean pelvic obliquity (°)	− 0.2 ± 1.0	0.1 ± 2.6	− 0.2 ± 1.1	0.448			
Δ ROM pelvic obliquity (°)	4.1 ± 3.3	1.7 ± 2.3	2.6 ± 2.5	**0.001**	*	*	*
Δ Mean pelvic rotation (°)	0.2 ± 1.8	− 1.0 ± 2.0	0.1 ± 2.0	**0.046**			
Δ ROM pelvic rotation (°)	5.5 ± 5.7	1.7 ± 6.5	4.1 ± 4.4	**0.006**	*		*
Hip							
Δ Mean hip flexion/extension (°)	1.6 ± 2.2	1.6 ± 6.8	1.5 ± 2.6	0.723			
Δ ROM hip flexion/extension (°)	7.4 ± 5.3	3.1 ± 5.0	7.1 ± 4.7	**0.001**	*		*
Δ ROM hip abduction/adduction (°)	3.7 ± 4.3	1.5 ± 3.3	3.5 ± 2.6	**0.026**	*		*
Knee							
Δ knee flexion in stance (°)	7.2 ± 5.3	3.6 ± 6.0	6.7 ± 4.5	**0.018**	*		*
Δ knee extension in stance (°)	− 1.7 ± 3.2	0.6 ± 3.3	− 0.3 ± 3.2	**0.006**	*	*	
Δ knee flexion in swing (°)	2.7 ± 4.2	3.6 ± 5.1	3.1 ± 3.9	0.881			
Δ knee flexion/extension (°)	2.9 ± 2.2	2.8 ± 2.9	3.2 ± 2.4	0.345			
Δ ROM knee flexion/extension (°)	2.8 ± 5.8	2.2 ± 6.8	3.0 ± 5.0	0.843			
Ankle and foot							
Δ Mean dorsiflexion/plantar flexion (°)	− 0.2 ± 2.6	− 0.6 ± 2.2	0.0 ± 3.0	0.313			
Δ ROM dorsiflexion/plantar flexion (°)	1.3 ± 7.0	3.8 ± 7.1	2.3 ± 7.9	0.147			

*or bold: significant *p*-values (adjusted according to the Bonferroni correction in case of multiple comparisons)

Table 2 Comparison of the kinematic adaptation of time–distance parameters from self-selected to fast speed walking among the 3 groups

	MeanSD			*p*-value	Controls vs ASD-limited-KA	Controls vs ASD-mild-KA	ASD-limited-KA vs ASD-mild-KA
	Controls	ASD-limited-KA	ASD-mild-KA				
Δ Walking speed (m/s)	0.6 ± 0.3	0.4 ± 0.3	0.5 ± 0.2	**< 0.001**	*		*
Δ Cadence (step/min)	32.5 ± 12.5	22.3 ± 15.7	30.6 ± 11.3	**0.04**	*		*
Δ Foot off (%)	− 2.9 ± 2.3	− 3.4 ± 3.9	− 2.6 ± 2.7	0.480			
Δ Step length (m)	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.21			
Δ Single support (s)	− 0.1 ± 0.1	0.0 ± 0.0	-0.1 ± 0.1	0.76			
Δ Double support (s)	− 0.1 ± 0.1	− 0.2 ± 0.1	-0.1 ± 0.1	0.121			

*or bold: significant *p*-values (adjusted according to the Bonferroni correction in case of multiple comparisons)

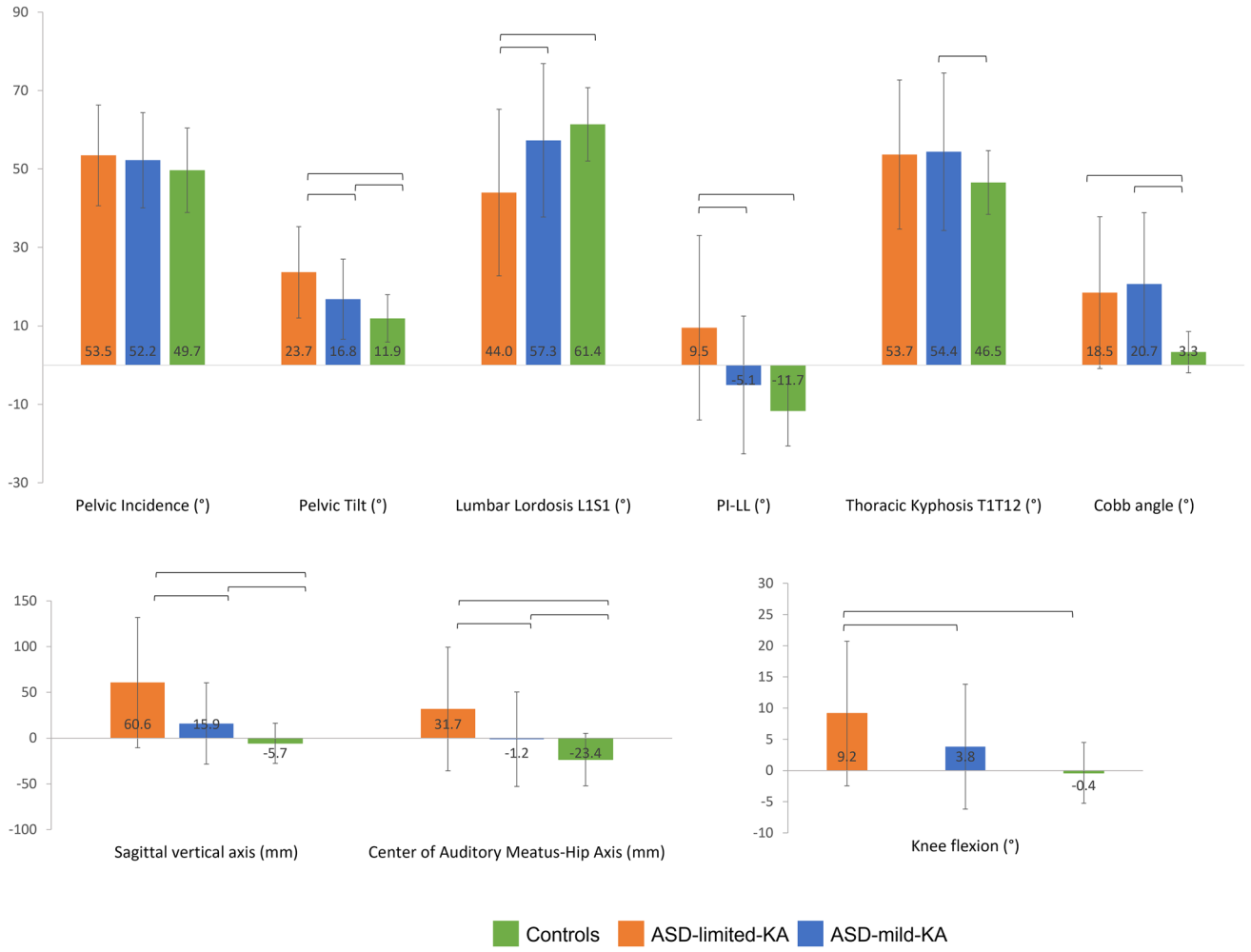

Fig. 3 Comparison of radiographic parameters between the three groups

Table 3 Quality of life scores compared between the 3 groups

		Mean SD			*p*-value	Controls vs ASD-limited-KA	Controls vs ASD-mild-KA	ASD-limited-KA vs ASD-mild-KA
	SF-36	Controls	ASD-limited-KA	ASD-mild-KA				
	PCS	51.1 ± 7.7	35.6 ± 8.8	41.7 ± 8.9	**< 0.001**	*	*	*
	MCS	53.9 ± 6.7	48.9 ± 9.1	50.9 ± 9.0	**0.045**			
	Physical functioning	50.9 ± 11.8	35.6 ± 13.0	43.6 ± 11.4	**< 0.001**	*	*	*
	Role physical	48.7 ± 8.8	36.8 ± 3.8	38.0 ± 5.1	**< 0.001**	*	*	
	Bodily pain	54.8 ± 5.8	40.5 ± 9.6	45.7 ± 9.3	**< 0.001**	*	*	*
	General health	53.5 ± 8.6	41.5 ± 9.9	47.0 ± 9.9	**< 0.001**	*	*	*
	Vitality	52.9 ± 10.3	41.7 ± 12.0	47.4 ± 11.2	**< 0.001**	*	*	
	Social functioning	54.7 ± 6.9	45.5 ± 12.7	49.8 ± 10.4	**0.00**	*	*	
	Role emotional	50.2 ± 7.6	41.1 ± 4.8	41.4 ± 4.6	**< 0.001**	*	*	
	Mental health	54.9 ± 9.4	49.9 ± 10.5	53.8 ± 11.4	0.25			
ODI		16.0 ± 10.9	42.4 ± 18.4	26.1 ± 17.5	**< 0.001**	*	*	*
VAS for pain		3.6 ± 1.9	7.1 ± 2.2	5.5 ± 2.7	**< 0.001**	*	*	*
BDI		6.5 ± 4.1	11.9 ± 9.7	10.4 ± 8.0	**0.004**	*	*	

*or bold: significant *p*-values (adjusted according to the Bonferroni correction in case of multiple comparisons)

Table 4 Significant correlations between kinematic adaptations, spino-pelvic parameters and health-related quality of life outcomes

	SVA	PT	PI–LL	PCS	Bodily pain BP
Δ ROM pelvic rotation		**– 0.270**			
Δ ROM hip flexion/extension		**– 0.275**			
Δ ROM hip abduction/adduction	**– 0.304**				
Δ Walking speed		**– 0.323**	**– 0.279**	**0.374**	**0.282**

Bold: significant correlations

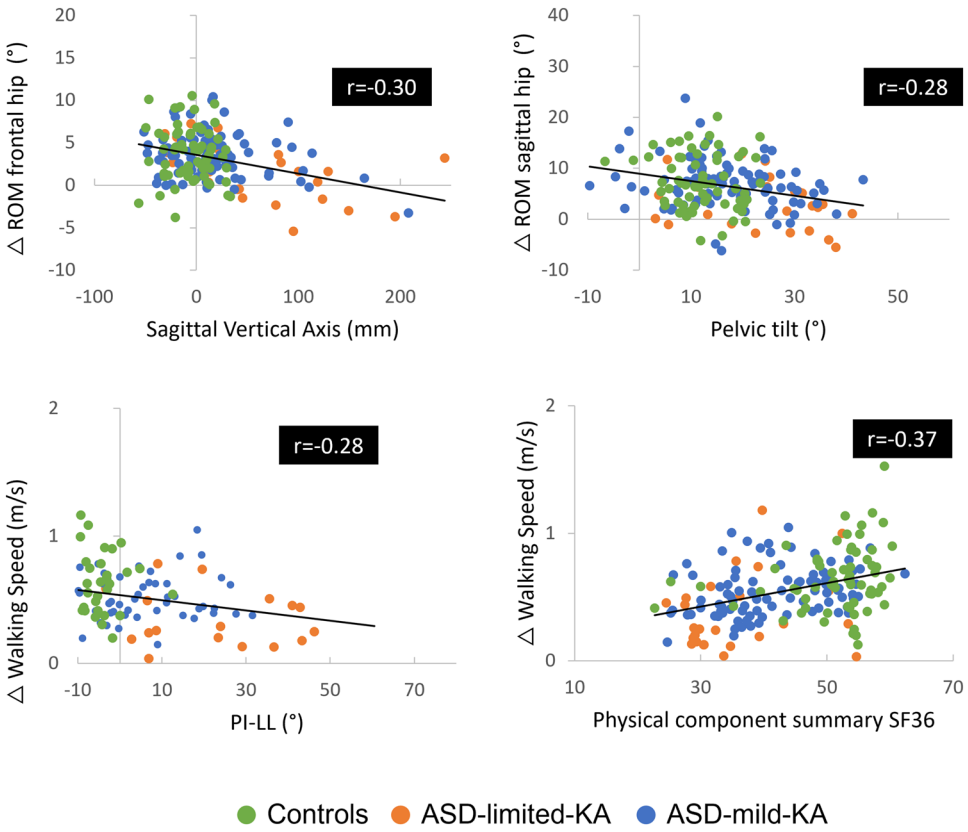

Fig. 4 Correlation between kinematic adaptation parameters, radiographic parameters and quality of life scores

Discussion

Spinal deformity is known to be responsible of quality of life deterioration. Recent studies reported kinematic alterations in ASD population during functional tasks such as walking, sitting and standing [7, 11, 12]. The aim of this study was to investigate the inability to adapt from self-selected to fast speed walking in ASD subjects. A group of ASD patients (ASD-limited-KA) who have limited kinematic adaptations from self-selected to fast speed walking was compared to ASD with mild kinematic adaptations (ASD-mild-KA) and control subjects. ASD-limited-KA did not sufficiently increase their range of movement at the pelvis, hip and knee levels. They had more severe sagittal malalignment with more deteriorated quality of life scores.

Patients in group ASD-limited-KA were unable to sufficiently increase their pelvic range of motion in both frontal and horizontal planes, along with a less pronounced increase of range of motion of the hips in both sagittal and horizontal planes. These limitations might be related to joints stiffness in these patients. Moreover, ASD-limited-KA were unable to increase knee extension in stance phase, which is a crucial step in the propulsion of the center of gravity during fast walking. In addition, ASD-limited-KA tended to increase their thorax flexion when asked to walk faster most probably to ensure an anterior projection of the center gravity, therefore an appropriate propulsion. ASD-limited-KA also showed a less pronounced increase range of motion of the shoulder–pelvis axial rotation, which is an evidence of spine rigidity in this population. This dissociation between the

shoulder and the pelvic girdles is a key component in leading the walking momentum, further limiting the capacity of ASD-limited-KA to adapt to fast gait. These kinematic alterations might be caused by the exhaustion of compensation mechanisms in ASD-limited-KA population as previously described [18], which consequently limit their capacity to properly adapt their gait pattern when asked to walk faster.

When the radiographic parameters of these patients were investigated, it was shown that ASD-limited-KA had a sagittal imbalance with an increased SVA, PT, PI–LL, TK but also an increased frontal Cobb angle. They showed a decreased LL, resulting in a forward shift of the trunk. Therefore, they tended to retrovert the pelvis and bend the knees in an attempt to reposition the trunk and their center of mass above the support polygon [5]. ASD-mild-KA showed TK and Cobb angle alterations comparable to ASD-limited-KA. However, they had significantly less altered SVA, PT and PI–LL compared to ASD-limited-KA. These findings emphasizes that sagittal spinal malalignment seems to be the main determinant of non-adaptation to fast walking in adult spinal deformity.

Moreover, ASD-limited-KA had the most altered quality of life scores compared to the other groups, thus affecting their daily life activities [19]. The highest correlation was found between the ability of ASD patient to increase their walking speed and the physical component summary (PCS) estimated from SF-36, knowing that this component includes the patients' abilities to climb stairs and to achieve daily life activities such as carrying groceries, lifting objects, bathing and dressing. This emphasizes the importance of assessing the capacity of ASD population to adapt their walking speed.

The discrepancies described in ASD during the adaptation from self-selected to fast speed walking were related to spino-pelvic and global malalignment. In fact, the limited increase in ROM of pelvic rotation, sagittal hip movement and walking speed were related to the increase of SVA, PT and PI–LL.

While it is known that a decreased physical strength, a reduced muscular mass, as well as joints stiffness might also affect the gait kinematics [20], these features were not considered in this study forming its limitation. Further investigations should take into consideration the physical examination outcomes in order to better understand the impact of muscle force and joint mobility on gait and other daily life functions in ASD population.

Conclusion

This study showed that sagittal malalignment is the leading factor limiting kinematic adaptations to walk faster in ASD. ASD patients who were unable to adapt from self-selected to fast speed walking showed the most severe sagittal malalignment along with the most deteriorated quality of life scores. This highlights the importance of adopting a functional and comprehensive analysis to evaluate adults with spinal deformities, using motion analysis, as a functional assessment which simulates challenges faced during daily life activities.

Further studies should consider the impact of surgical intervention, in particular the spinal fusion, on patient's functionality.

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Declarations

Conflict of interest None.

Ethical approval This is an IRB-approved study (University of Saint-Joseph-CEHDF1259).

References

1. Aebi M (2005) The adult scoliosis. Eur Spine J 14:925–948. https://doi.org/10.1007/s00586-005-1053-9
2. Dubousset J (1994) Three-dimensional analysis of the scoliotic deformity. The Pediatric Spine 1994:479–496
3. Roussouly P, Gollogly S, Noseda O, Berthonnaud E, Dimnet J, (2006) The Vertical Projection of the Sum of the Ground Reactive Forces of a Standing Patient Is Not the Same as the C7 Plumb Line. Spine (Phila Pa 1976) 31:E320–E325. https://doi.org/10.1097/01.brs.0000218263.58642.ff
4. Barrey C, Roussouly P, Perrin G, le Huec J-C (2011) Sagittal balance disorders in severe degenerative spine. Can we identify the compensatory mechanisms? Eur Spine J 20:626–633. https://doi.org/10.1007/s00586-011-1930-3
5. Lafage V, Schwab F, Skalli W, Hawkinson N, Gagey P, Ondra S, Farcy J (2008) Standing Balance and Sagittal Plane Spinal Deformity Analysis of Spinopelvic and Gravity Line Parameters. 33:1572–1578
6. Schwab F, Ungar B, Blondel B, Buchowski J, Coe J, Deinlein D, DeWald C, Mehdian H, Shaffrey C, Tribus C, Lafage V, (2012) Scoliosis Research Society-Schwab adult spinal deformity classification: a validation study. Spine (Phila Pa 1976) 37:1077–1082. https://doi.org/10.1097/BRS.0b013e31823e15e2
7. Kawkabani G, Saliby RM, Mekhael M, Rachkidi R, Massaad A, Ghanem I, Kharrat K, Kreichati G, Saad E, Lafage V, Lafage R, Skalli W, Assi A (2021) Gait kinematic alterations in subjects

with adult spinal deformity and their radiological determinants. Gait Posture 88:203–209. https://doi.org/10.1016/j.gaitpost.2021.06.003
8. Yagi M, Ohne H, Konomi T, Fujiyoshi K, Kaneko S, Takemitsu M, Machida M, Yato Y, Asazuma T (2017) Walking balance and compensatory gait mechanisms in surgically treated patients with adult spinal deformity. The Spine Journal 17:409–417. https://doi.org/10.1016/j.spinee.2016.10.014
9. Pellisé F, Vila-Casademunt A, Ferrer M, Domingo-Sàbat M, Bagó J, Pérez-Grueso FJS, Alanay A, Mannion AF, Acaroglu E (2015) Impact on health related quality of life of adult spinal deformity (ASD) compared with other chronic conditions. Eur Spine J 24:3–11. https://doi.org/10.1007/s00586-014-3542-1
10. Smith JS, Shaffrey CI, Fu KMG, Scheer JK, Bess S, Lafage V, Schwab F, Ames CP (2013) Clinical and radiographic evaluation of the adult spinal deformity patient. Neurosurg Clin N Am 24:143–156. https://doi.org/10.1016/j.nec.2012.12.009
11. Semaan K, Rachkidi R, Saad E, Massaad A, Kawkabani G, Saliby RM, Mekhael M, Abi Karam K, Fakhoury M, Jaber E, Ghanem I, Skalli W, Lafage V, Assi A (2022) Alterations of gait kinematics depend on the deformity type in the setting of adult spinal deformity. Eur Spine J 31:3069–3080. https://doi.org/10.1007/s00586-022-07348-y
12. Saad E, Semaan K, Massaad A, Fakhoury M, Karam KA, Jaber E, Lafage V, Skalli W, Rachkidi R, Assi A (2021) Alteration of the sitting and standing movements in adult spinal deformity. Gait Posture 90:215–216. https://doi.org/10.1016/J.GAITPOST.2021.09.111
13. Baudendistel ST, Schmitt AC, Stone AE, Raffegeau TE, Roper JA, Hass CJ (2021) Faster or longer steps: maintaining fast walking in older adults at risk for mobility disability. Gait Posture 89:86–91. https://doi.org/10.1016/j.gaitpost.2021.07.002
14. Abdul Jabbar K, Seah WT, Lau LK, Pang BWJ, Ng DHM, Tan QLL, Chen KK, Mallya Ullal J, Ng TP, Wee SL (2021) Fast gait spatiotemporal parameters in adults and association with muscle strength – The Yishun study. Gait Posture 85:217–223. https://doi.org/10.1016/j.gaitpost.2021.01.001
15. Schwab F, Ungar B, Blondel B, Buchowski J, Coe J, Deinlein D, DeWald C, Mehdian H, Shaffrey C, Tribus C, Lafage V (2012) Scoliosis Research Society—Schwab Adult Spinal Deformity Classification. Spine (Phila Pa 1976) 37: 1077–1082. https://doi.org/10.1097/BRS.0b013e31823e15e2
16. Davis RB, Ounpuu S (1991) A gait analysis data collection and reduction technique. Hum Mov Sci 10:575–587
17. Leardini A, Biagi F, Merlo A, Belvedere C, Benedetti MG (2011) Multi-segment trunk kinematics during locomotion and elementary exercises. Clin Biomech 26:562–571. https://doi.org/10.1016/J.CLINBIOMECH.2011.01.015
18. Lafage V, Schwab F, Patel A, Hawkinson N, Farcy J-P (2009) Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine (Phila Pa 1976) 34:E599–E606. https://doi.org/10.1097/BRS.0b013e3181aad219
19. Kawkabani G, Saliby RM, Mekhael M, Saad E, el Rachkidi R, Ghanem I, Kharrat KE, Lafage V, Lafage R, Skalli W, Assi A (2020) P16. Spinopelvic deformities and postural malalignment affect gait patterns in ASD patients. The Spine J. https://doi.org/10.1016/j.spinee.2020.05.414
20. Lattouf NA, Tomb R, Assi A, Maynard L, Mesure S (2021) Eccentric training effects for patients with post-stroke hemiparesis on strength and speed gait: A randomized controlled trial. NeuroRehabilitation 48:513–522. https://doi.org/10.3233/NRE-201601