https://doi.org/10.1007/s00586-022-07199-7

Assessment of dynamic balance during walking in patients with adult spinal deformity

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Abstract

Purpose To assess dynamic postural alignment in ASD during walking using a subject-specific 3D approach.

Methods 69 ASD (51 ± 20 years, 77%F) and 62 controls (34 ± 13 years, 62%F) underwent gait analysis along with full-body biplanar Xrays and filled HRQoL questionnaires. Spinopelvic and postural parameters were computed from 3D skeletal reconstructions, including radiographic odontoid to hip axis angle (ODHA) that evaluates the head's position over the pelvis (rODHA), in addition to rSVA and rPT. The 3D bones were then registered on each gait frame to compute the dynamic ODHA (dODHA), dSVA, and dPT. Patients with high dODHA (> mean + 1SD in controls) were classified as ASD-DU (dynamically unbalanced), otherwise as ASD-DB (dynamically balanced). Between-group comparisons and relationship between parameters were investigated.

Results 26 patients were classified as ASD-DU having an average dODHA of 10.4° (ASD-DB: 1.2°, controls: 1.7°), dSVA of 112 mm (ASD-DB: 57 mm, controls: 43 mm), and dPT of 21° (ASD-DB: 18°, controls: 14°; all $p < 0.001$). On static radiographs, ASD-DU group showed more severe sagittal malalignment than ASD-DB, with more altered HRQoL outcomes. The ASD-DU group had an overall abnormal walking compared to ASD-DB & controls (gait deviation index: 81 versus 93 & 97 resp., $p < 0.001$) showing a reduced flexion/extension range of motion at the hips and knees with a slower gait speed and shorter step length. Dynamic ODHA was correlated to HRQoL scores.

Conclusion Dynamically unbalanced ASD had postural malalignment that persist during walking, associated with kinematic alterations in the trunk, pelvis, and lower limbs, making them more prone to falls. Dynamic-ODHA correlates better with HRQoL outcomes than dSVA and dPT.

Keywords Adult spinal deformity · Gait analysis · Postural alignment · Spine · Biomechanics

Introduction

According to a United Nations' report in 2017, nearly 22% of the global population will have more than 65 years old by 2050 [1]. With this global aging process comes new prevalence of musculoskeletal disorders: around 68% of the general population aged more than 65 years develop spine pathology [2]. Thus, Adult Spinal Deformity (ASD) is currently defined as a growing issue for global health. In elderly patients, this pathology is identified according to the SRS-Schwab radiological classification [3].

Diagnosis and treatment of ASD are mainly assessed through the evaluation of postural alignment. In the presence of a spinal deformity, a chain of compensatory mechanisms is usually developed at the levels of the spine, pelvis, and knees in order to maintain the head above the pelvis and ensure a horizontal gaze [4, 5]. The current definition of ASD in the SRS-Schwab classification [6] uses both frontal and sagittal segmental malalignment based on the measurement of Pelvic Tilt (PT), Sagittal Vertical Axis (SVA), Thoracic Kyphosis (TK), and frontal Cobb angle. The alteration of these radiographic parameters was shown to be related to the deterioration of quality of life in ASD patients that are usually assessed through Health-Related Quality of Life (HRQoL) questionnaires [7].

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While the PT and SVA are important parameters to assess segmental and postural compensatory mechanisms in ASD, these parameters do not take into account the position of the head and its impact on overall balance. Recently, a new parameter has been described to quantify global alignment that takes into account the head position; the odontoid to hip axis angle (ODHA) measures the deviation of the line joining the hip axis center to the odontoid relatively to the vertical [8]. This parameter has been shown to be of interest in understanding the compensatory mechanisms used to maintain static balance [5].

While postural parameters are usually assessed on static X-rays, an evaluation of these parameters during daily life activities would be of interest in order to better evaluate the QoL concerns in these patients.

Previous studies have shown gait alterations in ASD subjects. Moreover, dynamic postural alterations were shown to be correlated to reduced quality of life [9]. ASD patients showed a preservation of static compensatory mechanisms during walking with a flexed attitude at the levels of the thorax, pelvis, and knees [10]. These alterations were associated with decreased mobility at the pelvis, hips, and knees [11] as well as an alteration in walking speed and step length [12]. While these studies had evaluated changes in joint kinematics and approximative postural assessment during walking, the variation of the head position above the pelvis during gait is yet to be described in ASD in order to better understand dynamic postural changes.

Thus, the aim of this study was to assess postural malalignment in ASD during walking by calculating postural parameters, such as SVA and PT but also the ODHA angle, using a subject-specific 3D approach based on image registration techniques.

Methods

This is an IRB-approved (CEHDF 1259) cross-sectional study where subjects with ASD consulting our center for radiographic assessment and control subjects were enrolled.

Population

In total, 69 primary ASD (51 ± 20 years, 77%F) and 62 asymptomatic subjects (34 ± 13 years, 62%F) were enrolled. ASD subject was included if they presented back pain and at least, one of the radiographic diagnostic criteria as defined by the International Spine Study Group: pelvic tilt (PT) > 25°, frontal Cobb angle > 20°, sagittal vertical axis (SVA) > 50 mm, or thoracic kyphosis (TK) > 60°. The exclusion criteria of the control group were any orthopedic history and/or back pain.

Data acquisition

All subjects filled the following health-related quality of life (HRQoL) questionnaires: Oswestry Disability Index (ODI), Short Form—36 (SF-36) item survey assessing general quality of life with both its physical (PCS) and mental (MCS) components, and the Visual Analog Scale for pain (VAS). Subjects were equipped with reflective markers on the head, spine, trunk, and lower limbs according to the modified Davis protocol [13] (Plug-In Gait model) and the Leardini protocol [14] (Fig. 1). They all underwent 3D gait analysis at self-selected speed using 7 infrared cameras MX3 (Vicon Motion Systems, Oxford, UK). A static trial was recorded at first. Then, each subject walked several trials that were compared for kinematic consistency using Polygon (Vicon Motion Systems, Oxford, UK). One representative trial was considered for the calculation of kinematics (of the trunk, pelvis, and lower limbs), the gait deviation index [15] and spatio-temporal parameters.

Additionally, subjects underwent full-body bi-planar X-rays (EOS Imaging, Paris, France) in the free-standing position [16] with gait reflective markers still in place (Fig. 2a). Then, 3D reconstructions of the spine, pelvis, lower limbs were performed by well-trained operators using a specific software (Arts et Métiers) [17].

The following spinopelvic and global alignment parameters were calculated using 3D reconstructions from static radiographs: Pelvic Tilt (rPT in °), Sagittal Vertical Axis (rSVA in mm), the Odontoid Hip Axis Angle (rODHA in ° in both 3D, frontal and sagittal planes): angle between the vertical reference line the line joining the summit of the odontoid (OD) and the center of the hip axis (HA), L1S1 (°), T1T12 & T4T12 (thoracic kyphosis in °), frontal Cobb angle (in °), pelvic incidence (PI in °) and PI-LL mismatch (in °) (Fig. 2b).

Skeletal segments were extracted as 3D points and meshes expressed in the X-ray booth coordinate system. The 3D location of reflective markers was also extracted. An image registration technique was applied using the computation of transformation matrix between the X-ray booth and the gait analysis environment for each segment at each time of the gait analysis [18, 19].

The ODHA, SVA, and PT were then computed on the moving skeletal segments in 3D during the gait cycle using Matlab (Mathworks, Nattwik, USA). Radiological value of SVA, PT, and ODHA were designated as rSVA, rODHA, and rPT while dynamical values were designated as dSVA, dODHA, and dPT.

Mean values and range of motion (ROM) of dynamic ODHA, SVA and PT were calculated during gait. The ROM of ODHA during gait presented the sway of the head above the pelvis during walking.

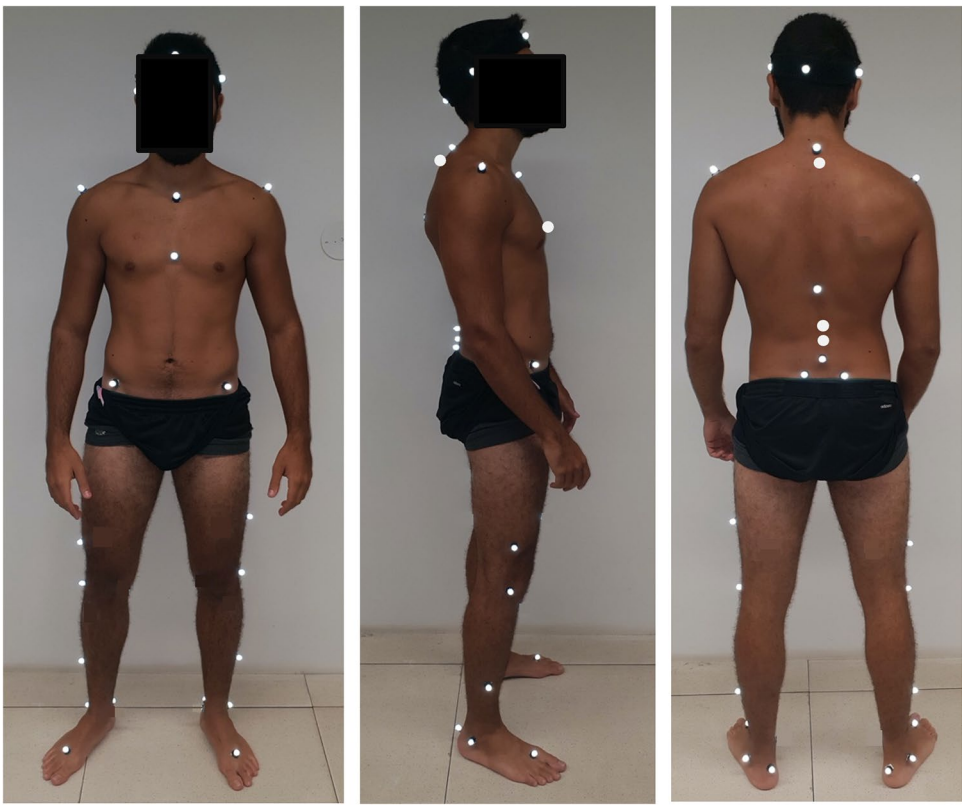

Fig. 1 Marker set for the modified Davis protocol (Plug-In Gait model) and Leardini protocol

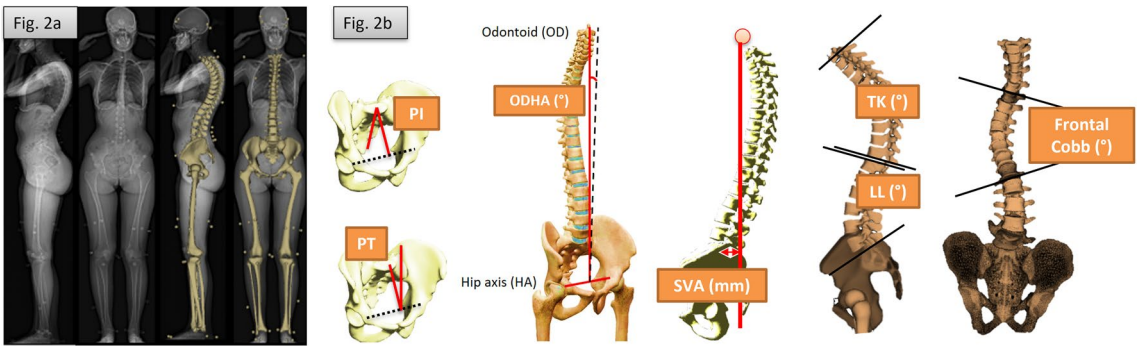

Fig. 2 **a** Frontal and lateral EOS radiographs with 3D reconstruction of the external markers, lower limb, pelvis, and spine. **b** Spinopelvic and global alignment 3D parameters: Pelvic Incidence (PI), Pelvic Tilt (PT), Sagittal Vertical Axis (SVA), Odontoïd to Hip axis Angle (ODHA), Thoracic Kyphosis (TK), Lumbar Lordosis (LL) & Frontal Cobb angle

Differences between dynamic and radiographic values were also computed: ΔODHA = dODHA-rODHA, the same for ΔSVA and ΔPT.

In order to evaluate postural malalignment during gait, especially sagittal imbalance, individuals that were outliers to the dODHA distribution in the control group were classified as ASD dynamically unbalanced (ASD-DU). The criterion was (dODHA in ASD > mean dODHA + 1SD in controls). ASD patients who had their ODHA inside the corridor of normality [ODHA-1SD; ODHA + 1SD in controls] were classified as dynamically balanced (ASD-DB).

Statistical analysis

Demographic, spinopelvic, and postural parameters were compared between groups using a Mann–Whitney test.

Spinopelvic and postural parameters as well as kinematic and spatio-temporal ones were compared between ASD-DU, ASD-DB, and controls using Kruskal–Wallis test.

The relationship between dynamic postural alignment and static ones, kinematics, and HRQOL outcomes were evaluated using Pearson's r correlation coefficient.

Statistical tests were run under Xlstat® (Addinsoft, Paris, France; version 2020.1.3.65336). The level of significance was set at 0.05.

Table 1 Radiological parameters between ASD and control population

	ASD	Control	*p*-value
3D ODHA (°)	3.7 (2.9)	1.3 (2.8)	**0.001**
Frontal ODHA (°)	3.3 (3.3)	0.2 (1.2)	**0.001**
Sagittal ODHA (°)	0.1 (4.5)	− 1.9 (2.2)	**0.02**
SVA (mm)	24.3 (50.1)	− 11.0 (21.4)	**0.001**
Frontal cobb (°)	22.4 (17.9)	4.4 (5.4)	**0.001**
TK: T1T12(°)	54.4 (20.2)	44.7 (9.0)	**0.002**
LL: L1L5 (°)	39.6 (19.4)	45.7 (10.2)	0.143
PT (°)	18.1 (10.3)	10.5 (6.2)	**0.001**
PI-LL (°)	− 2.9 (19.7)	− 12.8 (9.5)	**0.006**
PI (°)	50.1 (10.7)	47.7 (9.1)	0.107

Mean (SD) are displayed. Significant *p*-values are in bold

Results

Patients with ASD were older than control subject with an age of 51 (20) years (mean (SD)) compared to 34 (13) years ($p < 0.001$).

The radiological parameters between ASD patient and control subjects are presented in Table 1. ASD patient presented an altered radiographic global alignment (increased ODHA, SVA, PT, TK, frontal Cobb, and reduced LL) with reduced quality of life scores when compared to controls.

In dynamic, control subjects had a mean sagittal ODHA during gait of 1.7(3.5)°. In total, 26 over 69 ASD patients were classified as ASD-DU (66(13) years, 73%F) and 43 as ASD-DB (42(18) years, 79%F). ASD-DU had a dynamic sagittal ODHA during walking above the corridor of normality: 10.4 (4.8)° versus 1.2 (2.5)° for ASD-DB and 1.7 (3.5)° for controls ($p = 0.002$). The evolution of dynamic ODHA between groups during a gait cycle is represented in Fig. 3a.

The ASD-DU group had a slight increase in the sway of the head above the pelvis (3.9 vs. 2.9° for controls, Fig. 3b) and present a higher standard deviation (2.4 vs. 0.9° for controls) without exceeding the limit of statistical

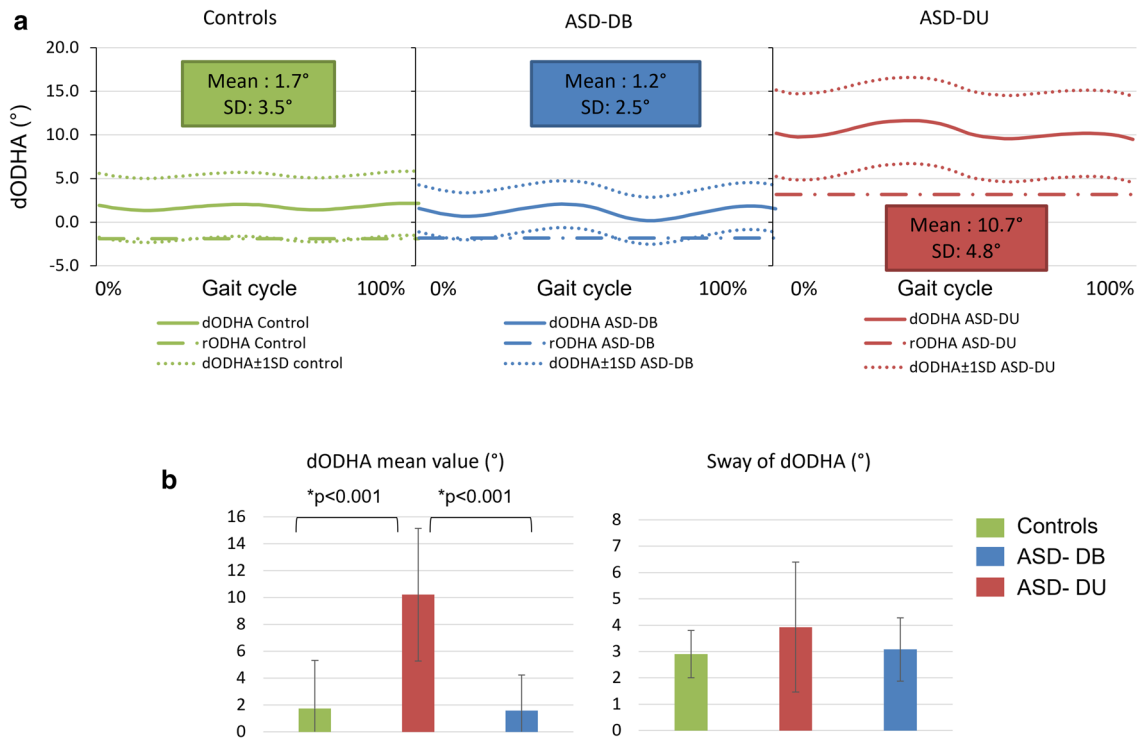

Fig. 3 **a** Dynamic value of ODHA during gait; **b** Sway and mean value of dODHA: control group in green, ASD-DB group in blue and ASD-DU group in red. Significantly different values are represented with * and the *p*-value of the statistical test

difference. In total, 42% of ASD-DU patients have a sway above the corridor of normality.

The evolution of dynamic SVA and PT during the gait cycle was displayed in Fig. 4a, b. The ASD-DU group presented an increased dynamic SVA with 111.9 (52.9) mm when compared to both controls and ASD-DB 56.7 (39.9) mm and 43.5 (28.4) mm respectively, ($p < 0.001$). Both ASD groups had their dynamic PT increased compared to controls: 21.3 (9.7) ° in ASD-DU and 18.2 (7.9) ° in ASD-DB versus 14.2 (5.7) ° in controls (both $p < 0.001$).

Moreover, ASD-DU group showed more altered HRQoL outcomes compared to ASD-DB and controls, both on the physical component of the SF-36 (37 vs. 43.5 and 53.8 resp.), VAS score for pain (6.4 vs. 5.0 and 3.5 resp.) and ODI (33.0 vs. 25.1 vs. 16.6 resp., all $p < 0.001$).

Radiological and dynamic parameters

The radiological parameters and their variation during walking as well as their between-group comparisons were detailed in Table 2. On static radiographs, patients in the ASD-DU group showed more severe postural and spinopelvic malalignment than ASD-DB patients and controls: increased 3D rODHA of 4.9° versus 3.1° (controls: 1.3°), sagittal ODHA of 3.2° versus −1.8° (controls: −1.9°), rSVA of 62.3 mm versus 1.4 mm (controls: −11 mm), radiographic knee flexion of 12.3° versus 1.7° (controls: 0°), rPT of 22.7° versus 15.2° (controls: 10.5°), and a reduced LL of 29.3° versus 45.9° (controls: 45.7°). The normalized projection of the odontoïd process on the axial plane was displayed in Fig. 5 showing the head-pelvis alignment in both groups of ASD and controls.

The difference between dynamic and radiological values showed that the ODHA increased from static to dynamic as well as the SVA. However, controls and ASD-DB seem to increase their pelvic tilt when going from the static position to walking posture, while patients in the ASD-DU seem to slightly decrease their pelvic tilt (Table 2).

Walking kinematics

The main joint kinematics that differed between groups during the gait cycle were displayed in Fig. 6. The ASD-DU group had an overall abnormal walking kinematics compared to both ASD-DB and controls: they walked with a reduced flexion/extension ROM at the hip (5.6° vs. 9.5° and 10.2° resp.), the knee (47.6° vs. 58.3° and 61.8° resp.) and reduced ROM of pelvic obliquity (5.6° vs. 9.5° and

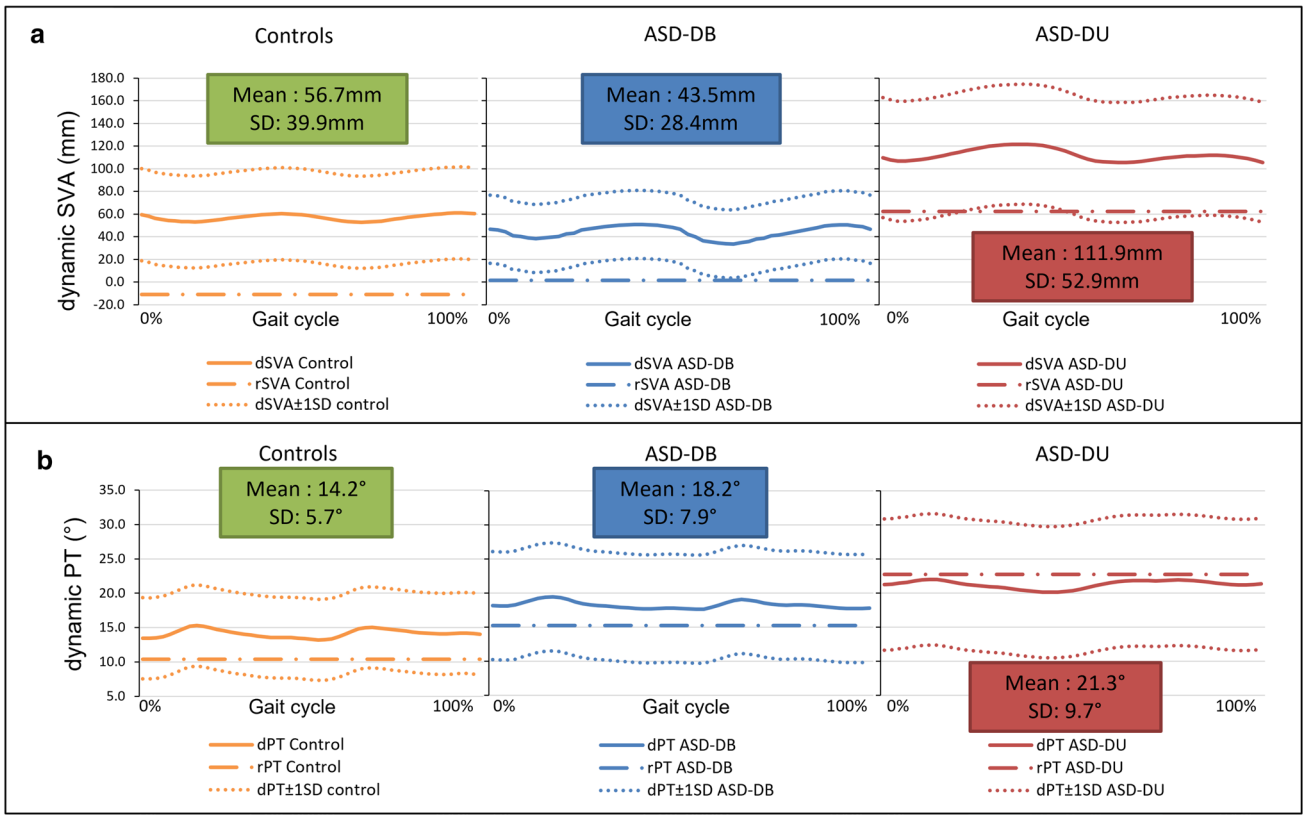

Fig. 4 **a** Mean value of SVA during gait; **b** Mean value of PT during gait: control group in green, ASD-DB group in blue and ASD-DU group in red

Table 2 Radiological parameters, dynamic mean value, range of motion (ROM) and difference (Δ) between dynamic and radiological value of ODHA, PT and SVA between groups

		Control	ASD-DB	ASD-DU	*p*-value	Control versus ASD-DB	Control versus ASD-DU	ASD-DB versus ASD-DU
Radiological	3D rODHA (°)	1.3 (2.8)	3.1 (1.7)	4.9 (4.1)	**< 0.001**	*	*	
	Frontal rODHA (°)	0.2 (1.2)	0.2 (1.9)	− 0.2 (1.8)	0.296			
	Sagittal rODHA (°)	− 1.9 (2.2)	− 1.8 (2.6)	3.2 (5.3)	**< 0.001**		*	*
	rSVA (mm)	− 11.0 (21.4)	1.4 (24.7)	62.3 (58.2)	**< 0.001**	*	*	*
	Cobb (°)	4.4 (5.4)	22.6 (15.9)	22.2 (21.1)	**< 0.001**	*	*	
	rTK: T1T12 (°)	44.7 (9.0)	53.2 (21.6)	56.4 (17.9)	**0.005**	*	*	
	rLL: L1L5 (°)	45.7 (10.2)	45.9 (14.4)	29.3 (22.4)	**0.01**		*	*
	L1S1 (°)	60.4 (9.1)	59.7 (16.1)	43.8 (20.7)	**0.01**		*	*
	rPT (°)	10.5 (6.2)	15.2 (10.0)	22.7 (9.2)	**< 0.001**	*	*	*
	PI-LL (°)	− 12.8 (9.5)	− 8.8 (15.1)	6.8 (22.6)	**< 0.001**		*	*
	PI (°)	47.7 (9.1)	50.9 (11.6)	50.6 (9.6)	0.270			
	Knee extention (°)	0.0 (6.0)	1.7 (8.9)	12.3 (12.3)	**< 0.001**		*	*
Dynamic	mean dODHA (°)	1.7 (3.6)	1.2 (2.5)	10.4 (4.8)	**< 0.001**		*	*
	mean dSVA (mm)	56.7 (39.9)	43.5 (28.4)	111.9 (52.9)	**< 0.001**		*	*
	mean dPT (°)	14.2 (5.7)	18.2 (7.9)	21.3 (9.7)	**0.002**	*	*	
	ROM dODHA (°)	2.9 (0.1)	3.0 (1.1)	3.9 (2.4)	0.234			
	ROM dSVA (°)	27.1 (9.7)	32.7 (20.1)	29.7 (15.6)	0.747			
	ROM dPT (°)	4.9 (2.5)	4.2 (1.9)	4.0 (2.1)	0.094			
Dynamic-Radiological	Δ ODHA (°)	− 3.7 (3.9)	− 3.0 (3.0)	− 7.2 (4.5)	**< 0.001**		*	*
	Δ SVA (mm)	− 67.8 (38.2)	− 42.2 (24.4)	− 49.6 (39.1)	**0.002**	*		
	Δ PT (°)	− 3.8 (4.6)	− 3.0 (4.1)	1.5 (5.6)	**< 0.001**		*	*

Mean (SD) are displayed. Significant differences between groups are presented with the * symbol or in bold

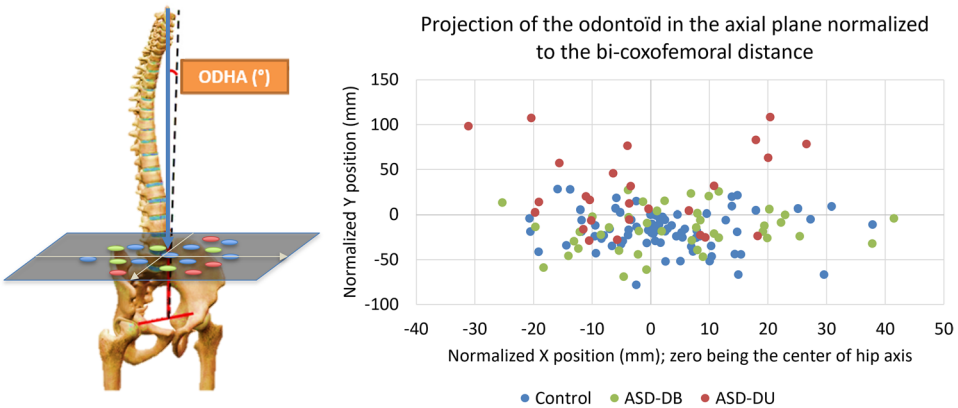

Fig. 5 Projection of the odontoid on the axial plane with the center of the bi-coxofemoral axis of each subject as the reference: for control group in green, ASD-DB group in blue and ASD-DU group in red. The projected *x* and *y* distance were multiplied by the ratio between the subject specific bi-coxofemoral distance and an arbitrary value of 200 mm, giving a normalised *x* and *y* in mm

10.2° resp.). ASD-DU group also presented a higher mean thorax flexion/extension angle (12.2°) compared to ASD-DB (3.5°) and controls (4.6°), associated with a lower mobility of thorax in the horizontal plane (ROM: 5.9° vs. 6.9° and 7.9° resp., all $p < 0.05$).

In the spine segments, the ASD-DU group showed lower dynamic lordosis at the L1L3-L3L5 level (− 9.0° vs. − 13.5° and − 12.4°, $p < 0.001$).

Moreover, patients in the ASD-DU group walked with a slower gait speed (0.8 m/s vs. resp. 1.0 and 1.2 m/s), shorter step length (0.5 m vs. 0.6 for ASD-DB and controls) and reduced cadence (98step/min vs 108step/min and 114step/min resp.). The overall gait deviation index showed an altered gait for the ASD-DU patients (81 vs. 93 in ASD-DB and 97 in controls, $p < 0.001$).

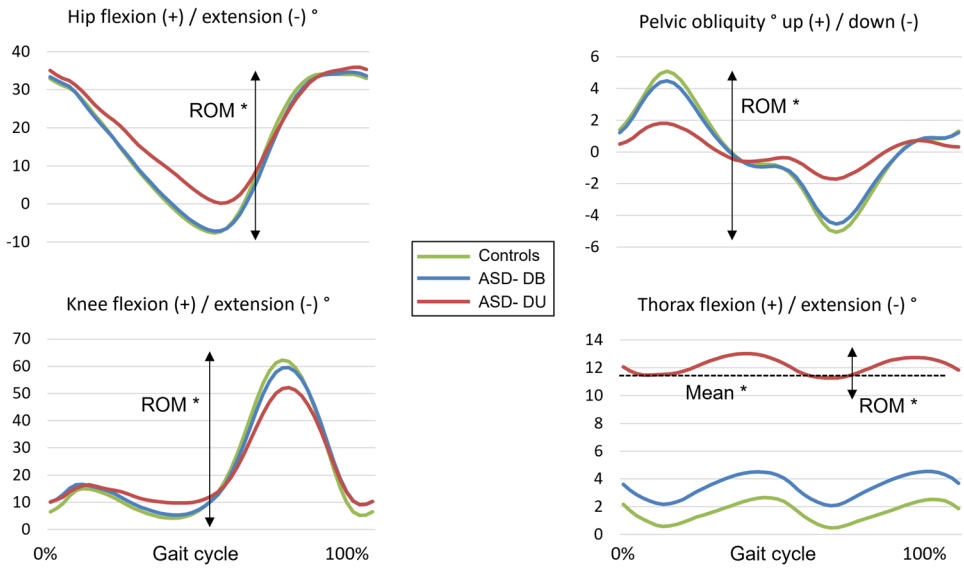

Fig. 6 Kinematic parameters during gait cycle with the hip flexion/extension angle, the pelvic obliquity, the knee flexion/extension angle and the thorax flexion/extension angle: for control group in green, ASD-DB group in blue and ASD-DU group in red

Correlation between radiographic, HRQoL outcomes and dynamic parameters

Correlation coefficient between radiographic, kinematic, and dynamic parameters were summarized in Table 3. Dynamic value of sagittal ODHA, SVA and PT was found to be highly correlated to the radiological ones, with a Pearson's r coefficient of 0.6 for ODHA, 0.67 for SVA, and 0.84 for PT.

The average dynamic sagittal ODHA (dODHA) during gait cycle was more correlated to ODI ($r=0.39$) compared to dPT ($r=0.33$) and dSVA ($r=0.19$). The same finding was found for the correlations with PCS-SF36 ($r=-0.41$, $r=-0.40$ and $r=-0.37$ resp.) and VAS scores ($r=0.34$, $r=0.26$ and $r=0.11$ resp., Table 3). The dODHA had similar to higher correlation with HRQOL scores than rODHA (ODI: $r=0.39$, PCS-SF36: $r=-0.38$, VAS: no significant correlation).

Table 3 Pearson's r correlation coefficients between dynamic sagittal ODHA (dODHA), Sagittal vertical axis (dSVA) and pelvic tilt (dPT), radiological parameters, HRQoL scores, kinematics and spatiotemporal parameters

	Parameters	dODHA	dSVA	dPT
Radiological parameters	Sagittal ODHA	0.59	0.54	0.13
	PI		0.19	0.51
	SS	−0.30	−0.21	−0.33
	PT	0.35	0.39	0.85
	SVA	0.62	0.67	0.49
	T1T12	0.22		
	Cobb angle	0.18	0.24	0.24
	L1S1	−0.31	−0.39	−0.43
	PI-LL	0.34	0.50	0.73
HRQoL scores	PCS	−0.41	−0.37	−0.40
	EVA/10	0.34		0.27
	ODI/100	0.39	0.19	0.33
Kinematics	Plevic obliquity ROM	−0.42	−0.42	−0.20
	Hip flexion/extension ROM	−0.42	−0.40	
	Knee flexion/extension ROM	−0.56	−0.48	−0.30
	Mean Thorax flexion/extension	0.43	0.31	0.30
Spatio—temporal	Walking Speed	−0.39	−0.47	−0.39
	Cadence	−0.35	−0.45	−0.34
	Step Length	−0.41	−0.45	−0.39
	Double support	0.51	0.42	0.29

Only significant correlations were displayed ($p<0.05$)

The dynamic ODHA was positively correlated to radiographic SVA (0.62), radiographic PT (0.36), radiographic mismatch PI-LL (0.35), radiographic knee flexion (0.36), and negatively correlated to LL (−0.32, Table 3).

The dODHA was also correlated to the ROM of knee flexion/extension ($r = -0.56$), the double support time ($r = 0.53$), the mean thorax flexion/extension ($r = 0.47$) and the maximum hip extension instance ($r = 0.35$, Table 3).

Discussion

Patients with ASD have a deteriorated QoL due to their spinal malalignment affecting both their standing posture and their daily life activities such as walking. While postural malalignment is usually assessed on static standing radiographs, this study computed postural malalignment in 69 ASD and 62 control subjects during walking with a patient-specific image registration technique allowing 3D bone representation during gait. Patients with severe spinal deformity showed unbalanced walking with more altered kinematics.

The population of ASD included in this study has shown typical spinal deformity along with compensatory mechanisms on static radiographs: pelvis retroversion with higher pelvic tilt, lower lumbar lordosis, higher thoracic kyphosis, sagittal vertical axis, and ODHA. Moreover, they showed a deteriorated QoL as expressed in the HRQOL outcomes.

In addition to the dynamic SVA and PT, the dynamic ODHA was also calculated, a new parameter that takes into account the global posture from the head to the hip axis. Patients who had their dynamic ODHA outside the corridor of normality were considered as dynamically unbalanced and further investigations on their dynamic and static posture as well as their gait kinematics were explored. While patients in the ASD-DU had both their SVA and PT increased in dynamic compared to controls, dynamically balanced ASD had also their PT increased, showing that patients in this latter group had sufficient recruitment of compensatory mechanisms in order to keep their head above their pelvis during walking, in contrary to patients in the ASD-DU group. Moreover, the sway of the head above the pelvis (ROM of the dODHA) was higher in the ASD-DU group compared to other groups without exceeding the significance limit. This result could reach the limit of significance when a larger group is considered.

As expected, patients in the ASD-DU group had more deteriorated quality of life scores: a decreased physical functionality in the SF-36 with increased pain and disability. Their dynamic postural alterations were consistent with the static ones. Patients in the ASD-DU group had increased radiographic ODHA, SVA, and PT in addition to an increased knee flexion used as a compensatory mechanism.

When analyzing the adaptation from static to dynamic by calculating the difference between the dynamic and static values of ODHA, SVA and PT, it was shown that control subjects as well as ASD-DB patient had a slight forward angulation of their trunk and head and retrovert their pelvis for achieving walking task. However, for ASD-DU subjects, the forward bending of the head is greater with an angulation of the head relatively to the pelvis twice higher than the one for the previous groups. This group also tends to antevert their pelvis to walk which could show a loss of ability to increase or even maintain the static pelvis compensation while walking.

The kinematics of the trunk and lower limbs were the most affected in the ASD-DU group. In fact, the ASD-DU group presented the same kinematic alterations during gait as the general ASD population reported in the literature [10–12] but to a higher extent: reduced walking speed and step length, cadence, range of motion of the knee &hip in flexion/extension, range of motion of pelvic obliquity and increased time of double support. Their reduced overall gait deviation index shows that these patients are more prone to falls [20].

Moreover, dynamic postural parameters were highly correlated to the static ones showing the importance of analyzing global postural parameters in dynamic. More importantly, this study showed that the dynamic ODHA, a newly calculated parameter in dynamic that takes into account the head position relative to the pelvis, showed higher correlations with HRQOL scores than both dynamic SVA and PT. The dODHA was also correlated to the static spinopelvic malalignment as well as kinematic alterations. The dODHA seems to be a functional score that can be complementary to the radiographic parameters. It is slightly better correlated than the radiological ODHA and when compared to other dynamic parameters it appears to be more correlated than dSVA both to PCS (0.41 vs. 0.37), EVA (0.34 vs. non-correlated), and ODI (0.39 vs. 0.19).

The major limitation of this study is the age difference between groups. The ASD-DU being older can present with higher degenerative spine and joints However, even when controlling for age (using ANCOVA model), the same results were obtained.

In conclusion, this study presented a new postural parameter that describes patient's balance during walking that is strongly related to HRQOL scores. Dynamically unbalanced ASD had postural malalignment that persist during walking associated with kinematic alterations in the trunk, pelvis, and lower limbs. Future studies should assess if postural malalignment is reduced in severe ASD during walking after corrective surgery.

Acknowledgments This research was funded by the University of Saint-Joseph (grant FM361), EUROSPINE (TFR2020#22), and ParisTech BiomecAM chair program on subject-specific musculoskeletal modeling (with the support of ParisTech and Yves Cotrel Foundations, Société Générale, Proteor and Covea). The funding sources did not intervene in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

Declarations

Conflict of interest Wafa Skalli holds patents related to the EOS system and associated 3D reconstruction methods, with no personal financial benefit (royalties rewarded for research and education). The other authors declare that they have no conflict of interest.

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