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Kinematic limitations during stair ascent and descent in patients with adult spinal deformity

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ABSTRACT

Background: Adults with spinal deformity (ASD) are known to have spinal malalignment, which can impact their quality of life and their autonomy in daily life activities. Among these tasks, ascending and descending stairs is a common activity of daily life that might be affected.

Research question: What are the main kinematic alterations in ASD during stair ascent and descent?

Methods: 112 primary ASD patients and 34 controls filled HRQoL questionnaires and underwent biplanar X-from which spino-pelvic radiographic parameters were calculated. Patients were divided into 3 groups: 44 with sagittal malalignment (ASD-Sag: PT $> 25°$, SVA$>$5 cm or PI-LL$>10°$), 42 with isolated thoracic hyperkyphosis (ASD-HyperTK: TK $> 60°$), 26 with isolated frontal spine deformity (ASD-Front: Cobb$>20°$). All participants underwent 3D motion analysis of the whole body while ascending and descending a stair step from which kinematic waveforms were extracted.

Results: During stair ascent, ASD-Sag exhibited an increased thorax flexion (20 vs 5°), a decreased lumbar lordosis L1L3-L3L5 (7 vs 14°), and an increased ROM of lumbo-pelvic joint (15 vs 10°, all $p < 0.05$), compared to controls. Similar compensations were shown while descending the stairstep. ASD-HyperTK had similar kinematic limitations as ASD-Sag but to a lesser extent. ASD-Front had normal kinematic patterns. PCS-SF36 correlated to thorax flexion ($r = -0.45$) and ODI was correlated to pelvic tilt ROM ($r = 0.46$).

Discussion and conclusion: ASD subjects with sagittal malalignment tend to ascend and descend stairs with increased thorax flexion, making them more prone to falls. Compensation mechanisms occur at the head and lumbo-pelvic levels to maintain balance and avoid falling forward.

1. Introduction

Adult spinal deformity (ASD) includes different types of posture and spino-pelvic alterations of the lumbar or thoracolumbar spine. These alterations can occur in one or more of the three planes (Glassman et al., 2005; Pellisé et al., 2015).The prevalence of ASD is rising as a result of better medical treatment, a longer life expectancy, and an increase in the number of healthy senior subjects (United Nations and Department of Economic and Social Affairs PD, 2017). ASD is defined based on the presence of back pain and/or discomfort, combined with alterations of one or more of the following radiographic parameters: Pelvic Tilt (PT) $\geq 25°$, Sagittal Vertical Axis (SVA) $\geq$ 50 mm, coronal Cobb angle $\geq 20°$, pelvic incidence – lumbar lordosis PI-LL mismatch $\geq 10°$ and Thoracic Kyphosis (TK) $\geq 60°$ (Lafage et al., 2016; Schwab et al., 2012a).

In an attempt to counteract the repercussions generated by the spino-pelvic alterations, compensation mechanisms at the level of the spine, pelvis and lower limbs are encountered, most often leading to an overall postural imbalance (Le Huec et al., 2019; Kim et al., 2017), therefore affecting patients' quality of life (Glassman et al., 2005; Pellisé et al., 2015; Bess et al., 2016). Usually, HRQoL (Health Related Quality of Life) questionnaires are used to assess quality of life as well as autonomy of the patients through functional daily tasks, such as walking, climbing

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stairs, etc.

In fact, recent studies showed that functional assessment based on 3D kinematic evaluation in ASD can better predict quality of life scores than radiographic analysis (Mekhael et al., 2023). Recent works were interested in studying the impact of the spino-pelvic skeletal deformities in ASD population on functional tasks, such as walking (Abi Karam et al., 2024; Kawkabani et al., 2021; Semaan et al., 2022) and transition from sitting to standing (Saad et al., 2022), showing the kinematic limitations in each of these movements depending on the spinal deformity and its severity. These kinematic patterns can contribute to better understanding of the underlying mechanisms behind mechanical complications that can occur after spinal fusion in ASD patients.

The activity of ascending and descending stairs is known to be a crucial activity of daily life and important for patient's autonomy (Novak and Brouwer, 2011; Protopapadaki et al., 2007). However, kinematic limitations while performing this task have never been investigated in ASD patients.

Therefore, the aim of this study was to investigate the spine and lower limbs kinematics during the ascent and descent of stairs and their relationship with radiographic deformities and HRQoL scores outcomes in ASD patients.

2. Methods

2.1. Population

This cross-sectional study enrolled ASD subjects who consulted their physicians for back pain and/or discomfort. Subjects were included if they met at least one of the following radiographic criteria: PT $> 25°$, SVA >50 mm, PI-LL $>10°$, T1T12 thoracic kyphosis TK $> 60°$, and/or coronal Cobb angle $>20°$ (Lafage et al., 2016; Schwab et al., 2012b). The inclusion criteria are based on those reported by ISSG.

ASD subjects were subdivided into three groups: subjects with sagittal malalignment (ASD-Sag) presenting an SVA >50 mm and/or PT $> 25°$ and/or PI-LL $> 10°$ regardless of the presence of other deformities, subjects only with frontal deformity (ASD-Front) presented a Cobb angle $>20°$ and subjects with only a thoracic hyperkyphosis (ASD-HyperTK), having only a TK $> 60°$.

Subjects with a history of lower limb or spine surgery, or with other motion-altering diseases were excluded.

A control group was enrolled upon the following criteria: absence of back pain, spinal or lower limbs surgeries, and not meeting any of the ISSG radiographic criteria.

This study was approved by the ethics committee of our institution (CEHDF 1259). Informed consent was obtained from all the subjects prior to the study.

2.2. Data acquisition

2.2.1. Demographics

Demographic data such as age (year), sex (F/M), height (cm) and weight (kg) were collected.

2.2.2. Radiographic parameters

All subjects underwent a full-body biplanar X-ray in a free-standing position (EOS Imaging, Paris, France) (Fig. 1A) (Chaibi et al., 2012). Three-dimensional reconstructions of spines, pelvis, and lower limbs were performed using Stereos (v1.8.99.20R) (Fig. 1B). Radiographic PT, PI, L1S1 lumbar lordosis (LL), PI-LL mismatch, coronal Cobb angle, T1T12 thoracic kyphosis (TK), SVA, distance from center of auditory meatus plumb line to hip-axis (CAM-HA) and knee flexion were computed on the 3D reconstructions (Fig. 1C).

2.2.3. HRQoL questionnaires

All participants filled the following HRQoL questionnaires: physical (PCS) and mental (MCS) components of the SF-36 survey that decrease with severity; on a scale from 100 to 0; Oswestry Disability Index (ODI) that increases with disability on a scale of 0–100; Beck's Depression Inventory (BDI) that increases with depression on a scale of 0–63; Visual Analog Scale (VAS) for pain that increases with the level of pain from 0 to 10 (Bess et al., 2016; Schwab et al., 2003).

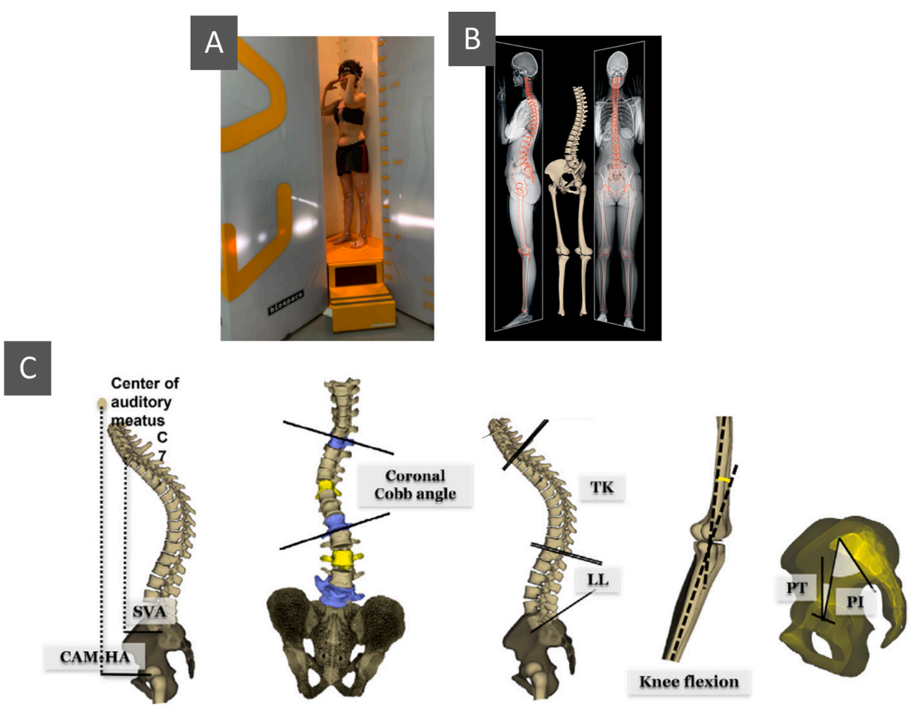

Fig. 1. (A) Biplanar X-ray acquisition in standing position using EOS®. (B) 3D reconstruction of the spine and pelvis. (C) Postural and spino-pelvic parameters: Pelvic Incidence (PI), Pelvic tilt (PT), Coronal Cobb angle, T1T12 Thoracic kyphosis (TK), L1S1 Lumbar lordosis (LL), Sagittal vertical axis (SVA), Distance from center of auditory meatus plumb line to hip-axis (CAM-HA) and knee flexion (KF).

2.2.4. Motion analysis

For the three-dimensional motion analysis, eight infrared cameras (Vero 2.2, 200 Hz; from Vicon Motion Systems in Oxford, UK) were utilized. The trunk and spine measurements followed a modified version of Leardini's protocol (Davis et al., 1991; Leardini et al., 2011), marking specific body points: four markers were attached to a band around the head (two in front and two at the back), markers were also placed on the left and right acromion, suprasternal notch, xiphoid process, and spinous processes at the neck (C7), upper back (T2, T10), and lower back (L1, L3, L5 vertebrae; Fig. 2A). For lower limbs analyzing, Davis' protocol was used for the placement of markers on key anatomical points: antero-superior and postero-superior iliac spines, distal third of the femur, lateral knee condyles, distal third of the tibia, lateral malleoli, calcaneum, and base of second metatarsal.

All subjects ascended a standard 15 cm stair step and then descended with the same leg.

The ascending and descending sequences are presented in Fig. 2B.

Using Nexus and ProCalc (Vicon®, Oxford, UK), segmental movements of the spine (L3L5 relative to L1L3, L1L3 relative to T10L1, T10L1 relative to T2T10 and T2T10 relative to T2C7), trunk (pelvis relative to the thorax), thorax, head and pelvis (all 3 relative to the global reference), lumbo-pelvic joint (pelvis relative to L3L5), hip (femur relative to pelvis), knee (tibia relative to femur), ankle (foot relative to tibia) and foot (foot relative to the global reference) were calculated in the 3 planes.

A cycle for each of stair step ascent and descent was delimited. The ascent frame started just before the initial hip flexion, until bipodal standing position was reached on the stair step and where no movements are detected along the trajectories of the markers. The subject was asked to stay still for 3 s before descending the stair step. The second frame started straight after the double support detection on the stair step and ended when the double support was detected on the ground. Each frame was normalized between 0 and 100%, representing one movement cycle.

We extracted the mean values and the range of motion (ROM) – difference between the highest and lowest values – both during ascending and descending transitions, using Matlab (Mathworks, Natick, USA; R2016a).

2.3. Statistical analysis

We compared demographic data between ASD subjects and controls using the Mann-Whitney *U* test for continuous variables and the chi-squared test for categorical variables. Health-related quality of life HRQoL scores, along with radiographic and kinematic parameters (including maximum, minimum, mean values, and ROM) during ascending and descending the stair step were compared between the 4 ASD groups and controls using Kruskal-Wallis test. The association between kinematics, radiographic parameters and HRQoL scores was determined using Pearson's correlation coefficient. All statistical tests were conducted using XLSTAT software (2019 version, Addinsoft, Paris, France), and findings were presented as mean $\pm$ 1 standard deviation. A significance threshold was set at $p < 0.05$, with Bonferroni correction applied to account for multiple testing.

3. Results

3.1. Demographics

The ASD group included 112 patients (52 $\pm$ 20 years [20–81]; 84 F and 28 M) and 34 subjects formed the control group (48 $\pm$ 14 years [22–76]; 20 F and 14 M). ASD and control groups were comparable in age and sex ($p = 0.12$ and $p = 0.07$, respectively), as well as in weight (ASD = 71.8 $\pm$ 14.9 kg vs controls = 71.2 $\pm$ 12.7 kg, $p = 0.87$). ASD subjects were 4.5 cm shorter than the control group (162.2 $\pm$ 9.93 cm vs 166.7 $\pm$ 7.27 cm, $p = 0.002$). The ASD group was divided as follows: 44 ASD-Sag, 42 ASD-HyperTK and 26 ASD-Front.

3.2. Radiographic parameters

PI was comparable between the 4 groups (51.5 $\pm$ 10.5°). When compared to controls, ASD-Sag group showed an increased SVA (71.2 vs −3.7 mm; $p < 0.001$), CAM-HA (37.5 mm vs −18.7 mm; $p < 0.001$), PT (27.8° vs 10.6°; $p < 0.001$) and PI-LL (18.6° vs −10.6°; $p < 0.001$). These

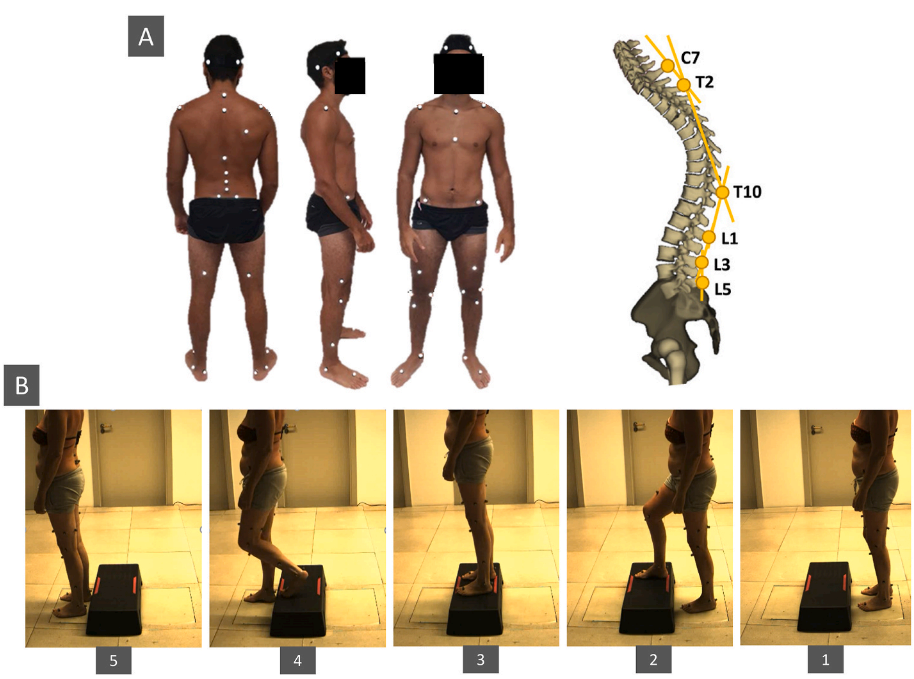

Fig. 2. (A) Marker set according to the modified Davis and Leardini protocols for the head, trunk, spine, pelvis and lower limbs. (B) Patient's stair ascent and descent acquisition: (1) standing with double support on the ground (2) lower limb reaches the stair step (3) standing with double support on the stair step (4) lower limb reaches the ground (5) standing with double support on the ground.

subjects had a significantly decreased LL (36.4° vs 61.6°; $p < 0.001$) and increased knee flexion (12.6° vs 0.2°; $p < 0.001$). ASD-HyperTK patients had an increased TK and LL (TK: 71.6° vs 46.0° and LL: 68.9° vs 61.6° respectively; $p < 0.001$). Furthermore, ASD-Front had an increased coronal Cobb angle (38.5° vs 6.5°, $p < 0.001$) (Fig. 3).

3.3. Quality of life scores

All HRQoL scores were significantly different in ASD groups compared to controls (Table 1). ASD-Sag exhibited the most altered scores with the lowest PCS (ASD-Sag: 36.2 vs. 49.6, $p < 0.001$) and MCS (ASD-Sag: 51.2 vs. 55.1, $p = 0.016$) compared to controls. They had the greatest level of depression (BDI: 11.3 vs 2.5, $p < 0.001$), an increased level of disability (ODI: 38.0 vs 3.2, $p < 0.001$) and presented with the highest level of pain (VAS: 6.7 vs 1.3, $p < 0.001$; Table 1).

3.4. Spine and lower limb kinematics while ascending a stair step

During the stair ascent movement, the ASD-Sagittal group presented a head hyperextension (−26.5° vs −8.0°; $p < 0.001$) and an increased trunk flexion (20.0° vs 4.9°; $p < 0.001$) when compared to controls. In addition, they showed a reduced L1-L3/L3-L5 ROM and an increased L1-L3/L3-L5 extension (6.1° vs 7.4° and −7.2° vs −14.1°; respectively, $p < 0.001$). They also presented an increased ROM of pelvic tilt (11.4° vs 8.2°; $p = 0.004$) and pelvis-L3L5 flexion/extension (14.6° vs 10.1°, $p = 0.001$). Furthermore, they showed an increased hip rotation ROM (29 vs 23°, $p = 0.28$) and a reduced knee flexion (76° vs 87°, $p<0.001$) and ankle dorsiflexion (18.7° vs 23.7°, $p < 0.01$).

ASD-HyperTK group showed an increased mean flexion between T2T10 and T10L1 (35.3° vs 22.5° $p < 0.01$) and between C7T2 and T2T10 (31.4° vs 24.6°, $p < 0.001$).

Spine and lower limbs kinematics in ASD-Front group were comparable to the control group (Fig. 4; Supplement 1).

3.5. Spine and lower limb kinematics while descending a stair step

During the stair descent movement, the ASD-Sagittal group had an increased thorax flexion (15° vs 0.8°, $p < 0.001$) when compared to controls. At the spinal level, they presented a reduced L1L3-L3L5 and T10L1-L1L3 extension (−7.4° vs −14.8°, $p = 0.002$ and −2.3° vs −7.9°, $p < 0.001$; respectively). They showed an increased ROM of hip adduction/abduction and internal/external rotation (14.1° vs 10.8°, $p = 0.038$ and 33.8° vs 26.5°, $p = 0.006$; respectively), as well as an increased hip flexion (13° vs 9°, $p = 0.035$). A reduced knee ROM in the sagittal plane was also noticed in this group (44.5° vs 50.2°, $p = 0.001$).

Similar to ASD-sagittal group, the ASD-HyperTK group presented an increased thorax flexion (7.3° vs 0.8°, $p < 0.001$) and head extension (−11.7° vs −4.6°, $p < 0.001$) as well as a hyperextension of T10L1-L1L3

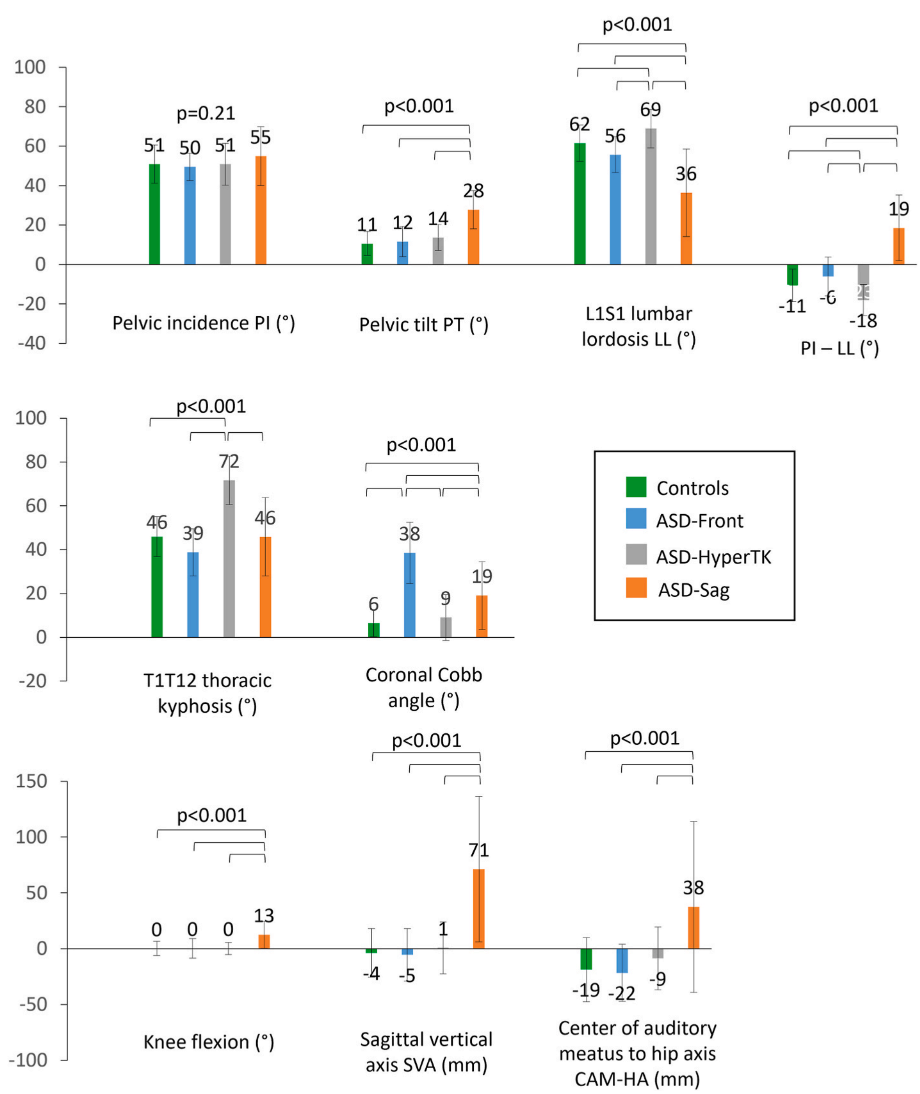

Fig. 3. Comparison of spino-pelvic and postural parameters between the four groups.

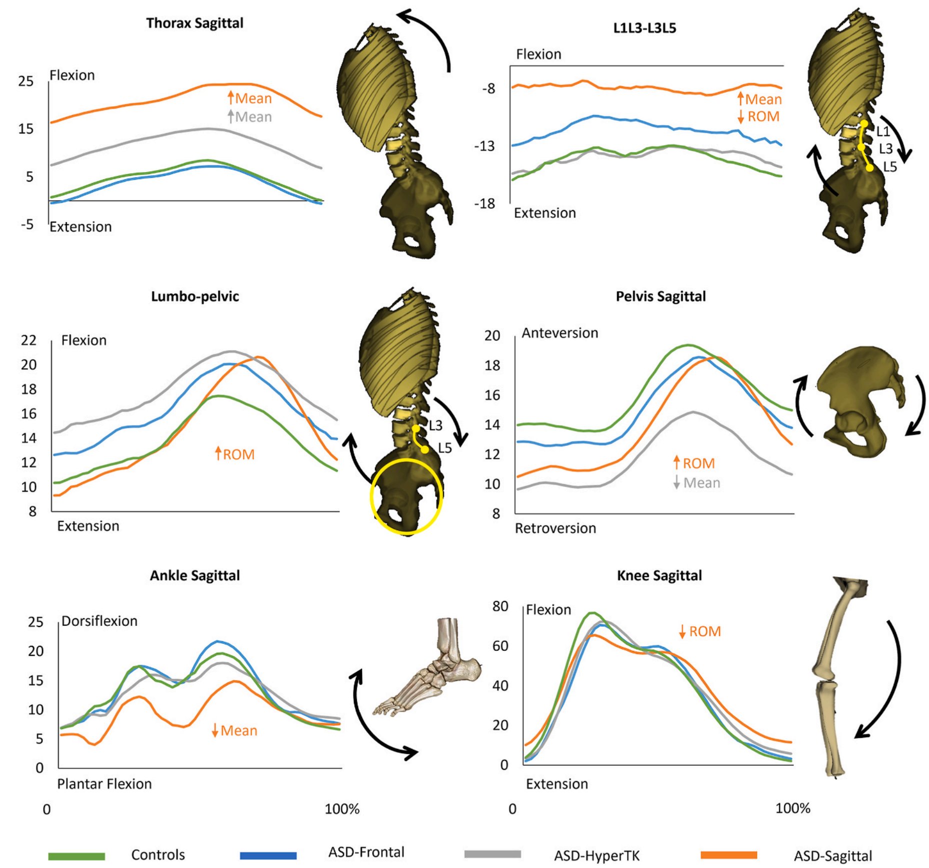

Fig. 4. Average kinematic waveforms for the four groups during the ascending stair movement, normalized between 0 and 100 %. Statistical differences for mean or ROM are marked on the graph according to the group's color code.

Table 1
Comparison of health-related quality of life (HRQoL) scores between controls and the four groups of ASD.

	Mean ± SD				*p-value*	Controls vs ASD-Front	Controls vs ASD-HyperTK	Controls vs ASD-Sagittal	ASD-Front vs ASD-HyperTK	ASD-Front vs AS-Sagittal	ASD-HyperTK vs ASD-Sagittal
	Controls	ASD-Front	ASD-HyperTK	ASD-Sagittal							
Short Form-36 (SF-36) Physical Component Summary (PCS)	49.6 ± 8.3	44.5 ± 9.7	40.7 ± 7.6	36.2 ± 7.8	**<0.001**		*	*		*	
Short Form-36 (SF-36) Mental Component Summary (MCS)	55.1 ± 6.7	48.3 ± 6.8	50.5 ± 10	51.2 ± 9.3	**0.016**	*					
Oswestry Disability Index (ODI)	3.9 ± 5.7	21.0 ± 20.6	27.5 ± 17.7	36.5 ± 17.6	**<0.001**	*	*	*		*	
Visual Analog Scale (VAS)	1.6 ± 1.2	4.2 ± 2.6	6.0 ± 2.7	6.7 ± 2.5	**<0.001**	*	*	*	*	*	
Beck's Depression Inventory (BDI)	2.5 ± 3.8	8.7 ± 6.4	10.9 ± 8.1	11.3 ± 9.7	**0.001**	*	*	*			

(−18.3° vs −8°, $p < 0.001$) and increased flexion of C7T2-T2T10 (36.2° vs 25.4°, $p < 0.001$) when compared to controls.

Spine and lower limbs kinematics in the ASD-Front group were comparable to controls (Supplement 2).

3.6. Correlation analysis

The highest significant correlations between spine kinematics and HRQoL scores were found between the mean thorax flexion/extension and PCS and ODI ($r = -0.45$ and $r = 0.43$, respectively). Moreover, a significant correlation was found between the pelvic tilt ROM and ODI score ($r = 0.46$). The increased ROM of pelvis-L3L5 flexion/extension was correlated with the decreased PCS and increased ODI ($r = -0.30$ and $r = 0.37$ respectively). In addition, kinematic parameters also showed a strong correlation with radiographic parameters: mean thorax flexion/extension correlated with the SVA ($r = 0.70$); both pelvic tilt ROM and pelvis-L3L5 ROM correlated with the radiographic pelvic tilt ($r = 0.45$ and 0.41, respectively; Fig. 5).

4. Discussion

Over the past decade, studies have reported that ASD population

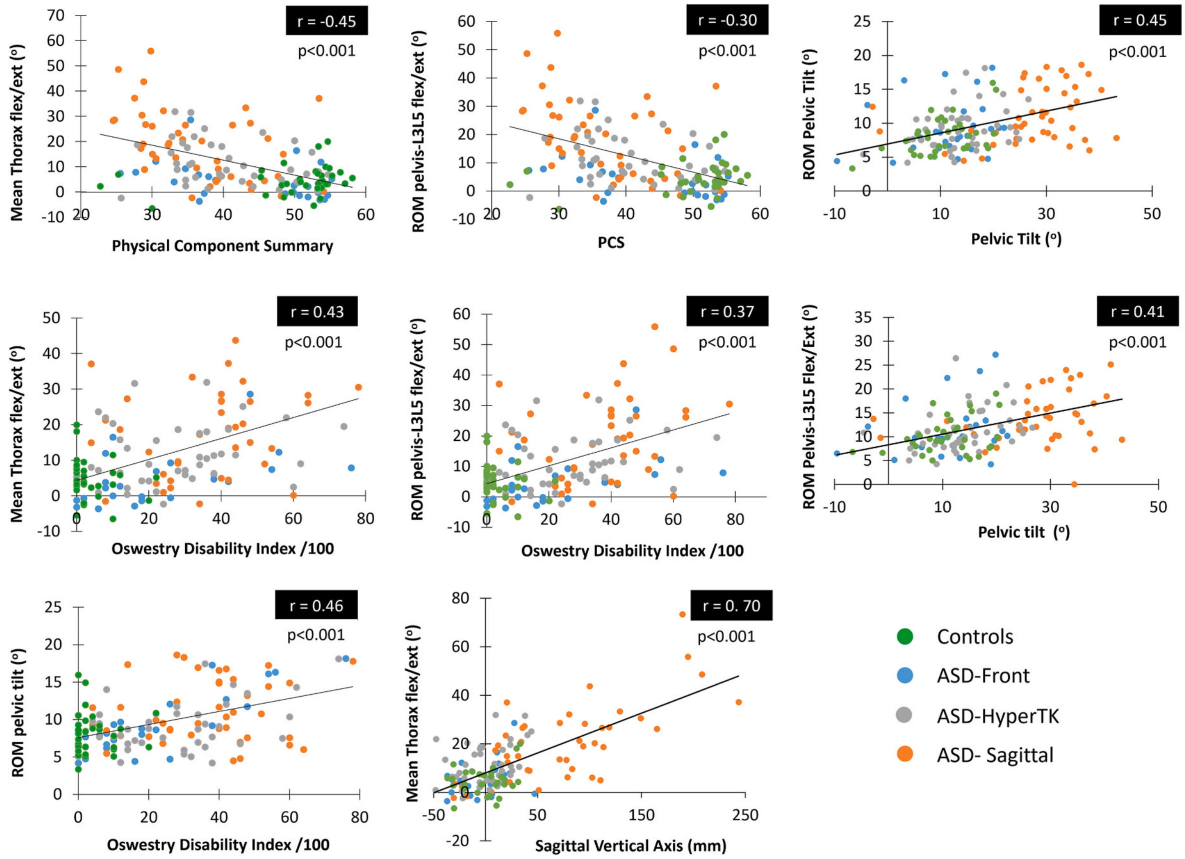

Fig. 5. Correlation between kinematic parameters with radiographic parameters and HRQoL scores while ascending and descending a stair step.

suffers from functional limitations during daily activities such as walking, sitting and standing (Kawkabani et al., 2021; Semaan et al., 2022; Saad et al., 2022). The aim of this study was to investigate the spine and lower limb kinematics during the ascent and the descent of a stair step in ASD patients, classified according to the type of spinal deformity. This study showed that patients with sagittal malalignment had a forward shift of the thorax during ascent and descent of the stair step as well as a limited knees ROM. Patients presenting with an isolated hyperkyphosis showed similar lower limb kinematics compared to those presenting a sagittal malalignment but to a lesser extent; they forwarded their thorax during both ascending and descending the stair step. Spine and lower limbs kinematics in ASD patients with only a coronal deformity were comparable to controls.

The stair step ascending is initiated by hip and knee flexion of one side, while the subject maintains a single limb standing on the contralateral side. Once the swinging foot reaches the step, the subject demonstrates a reduced lumbar lordosis inducing flexion of the trunk to project the center of gravity forward and thus to facilitate propulsion. A vertical push of the body occurs until an extension of the hip and the knee are achieved and consequently a bipodal support on the stair step attained. Stair step descent shows mostly inverse sequence of events. The same patterns were found in our control group when compared to the literature (Novak and Brouwer, 2011).

On the standing X-rays, ASD-Sagittal group had a decreased lumbar lordosis. This resulted in a forward shift of the trunk, increasing the risk of falling forward. This group showed higher pelvic retroversion and increased knee flexion to maintain sagittal balance. Thereafter, during both stair ascent and descent, they showed a significant thorax flexion in ascent but especially in descent and projected their head in extension in order to maintain a horizontal gaze, which is a usual compensation in ASD patients (Diebo et al., 2016). The increased head extension might be related to the increased prevalence of neck pain and discomfort reported by ASD patients during physical examination. Moreover, the increased thorax flexion during stair ascent and descent in these patients highlights the importance of evaluating trunk kinematics and adjacent segments after surgical intervention to restore spinal alignment. It is important to note that a combination of spinal deformity criteria (those defined by ISSG) and some physiological changes with age (such as increased SVA) were present in this ASD cohort.

While controls tend to slightly flex the L1L3-L3L5 lumbar segment during ascending the stair step, the ASD-Sagittal group showed a reduced ROM of this segment since they primarily present a decreased lumbar lordosis and a spine rigidity (Daniels et al., 2015). This kinematic limitation was compensated by an increased mobility of the lumbo-pelvic segment as noticed in the L3L5-pelvis ROM. Although they had a normal hip and knee mean flexion/extension when compared to other groups, subjects in ASD-Sagittal group showed a lack of ankle dorsiflexion while ascending the stair step. This might be related to a reduced mobility of the ankle toward dorsiflexion that is frequently encountered in elderly population (Soucie et al., 2011), which increases the risk of tripping when using the stairs.

Moreover, a reduced knee ROM was observed, most probably related to the increased radiographic knee flexion on standing radiographs, a known compensatory mechanism in the presence of sagittal spinal deformity.

As expected, ASD-HyperTK group presented an increased thoracic kyphosis in static imaging, which was compensated at the lumbar spine level by an increased lordosis in standing position. This indicates that this group shows a flexible spine. During movement, they presented with a flexed thorax, compared to controls, but to a lesser extent than the ASD-Sag group. However, given the difficulty in maintaining an increased lumbar lordosis during ascending a stair step, they showed an increased retroversion of the pelvis to avoid falling forward.

Patients forming the ASD-Front group presented only with a coronal

Cobb angle and showed almost similar kinematics in ascending and descending compared to control subjects indicating non-affected kinematics while performing the stair ascent and descent movement.

The kinematic limitations observed in ASD were correlated to the radiographic alterations: the increase of SVA was correlated to a severe thoracic flexion, the increase of radiographic pelvic tilt was correlated to an increased ROM of pelvic retroversion and lumbo-pelvic joint. Moreover, ODI and PCS estimated from SF36 were correlated to the increased thorax flexion, that seems to be the major kinematic limitation in ASD when using stairs.

The major limitation of this study remains in the use of one stair step that might not be representative of the daily activity when using multiple stairs. However, it can give a quite precise idea of this functional task. Furthermore, the use of standard stairs where the subjects will take consecutive steps, might be affected by the muscle weakness or fatigue frequently encountered in ASD patients (Ferrero et al., 2021). Future studies will investigate the impact of lower limbs and trunk muscle strength on functional abilities in ASD patients.

5. Conclusion

In conclusion, while coronal spine deformity does not affect kinematics during stairstep ascent and descent, sagittal malalignment seems to be the main driver of kinematic limitations. ASD patients with sagittal malalignment had an increased thorax flexion compensated by an extended head. This was coupled with an increased pelvic retroversion and lumbo-pelvic flexion to reduce the anterior projection of the center of mass and therefore to ensure balance. Patients with isolated hyper kyphosis had the same kinematic limitations as patients with sagittal malalignment but to a lesser extent. This study will serve as a baseline to evaluate the effect of conservative treatment or surgical intervention for these patients on their ability to perform daily life activities, such as stair ascent and descent, and its implication on their quality of life.

Conflict of interest

None.

Acknowledgment

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bas.2024.104153.

References

Abi Karam, K., El Rachkidi, R., Semaan, K., et al., 2024. Kinematic adaptations from self-selected to fast speed walking in patients with adult spinal deformity. Spine Deform 12, 423–431. https://doi.org/10.1007/s43390-023-00799-3.

Bess, S., Line, B., Fu, K.-M., et al., 2016. The health impact of symptomatic adult spinal deformity: comparison of deformity types to United States population norms and chronic diseases. Spine 41, 224–233. https://doi.org/10.1097/BRS.0000000000001202.

Chaibi, Y., Cresson, T., Aubert, B., et al., 2012. Fast 3D reconstruction of the lower limb using a parametric model and statistical inferences and clinical measurements calculation from biplanar X-rays. Comput. Methods Biomech. Biomed. Eng. 15, 457–466. https://doi.org/10.1080/10255842.2010.540758.

Daniels, A.H., Smith, J.S., Hiratzka, J., et al., 2015. Functional Limitations Due to Lumbar Stiffness in Adults with and without Spinal Deformity, vol. 40, pp. 1599–1604. https://doi.org/10.1097/BRS.0000000000001090.

Davis, R.B., Ounpuu, S., Tyburski, D., Gage, J.R., 1991. A gait analysis data collection and reduction technique. Hum. Mov. Sci. 10, 575–585. https://doi.org/10.1016/0167-9457(91)90046-Z.

Diebo, B.G., Challier, V., Henry, J.K., et al., 2016. Predicting cervical alignment required to maintain horizontal gaze based on global spinal alignment. Spine 41, 1795. https://doi.org/10.1097/BRS.0000000000001698.

Ferrero, E., Skalli, W., Khalifé, M., et al., 2021. Volume of spinopelvic muscles: comparison between adult spinal deformity patients and asymptomatic subjects. Spine Deformity 9, 1617–1624. https://doi.org/10.1007/s43390-021-00357-9.

Glassman, S., Bridwell, K., Berven, S., et al., 2005. The impact of positive sagittal balance in adult spinal deformity. Spine J. 4, S113–S114. https://doi.org/10.1016/j.spinee.2004.05.231.

Kawkabani, G., Saliby, R.M., Mekhael, M., et al., 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.

Kim, H.Y., Cha, Y.H., Chun, Y.S., Shin, H.S., 2017. Correlation of the torsion values measured by rotational profile, kinematics, and CT study in CP patients. Gait Posture 57, 241–245. https://doi.org/10.1016/j.gaitpost.2017.06.014.

Lafage, R., Schwab, F., Challier, V., et al., 2016. Defining spino-pelvic alignment thresholds. Spine 41, 62–68. https://doi.org/10.1097/BRS.0000000000001171.

Le Huec, J.C., Thompson, W., Mohsinaly, Y., et al., 2019. Sagittal balance of the spine. Eur. Spine J. 1–17. https://doi.org/10.1007/s00586-019-06083-1.

Leardini, A., Biagi, F., Merlo, A., et al., 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.

Mekhael, E., El Rachkidi, R., Saliby, R.M., et al., 2023. Functional assessment using 3D movement analysis can better predict health-related quality of life outcomes in patients with adult spinal deformity: a machine learning approach. Frontiers in surgery 10. https://doi.org/10.3389/FSURG.2023.1166734.

Novak, A.C., Brouwer, B., 2011. Sagittal and frontal lower limb joint moments during stair ascent and descent in young and older adults. Gait Posture 33, 54–60. https://doi.org/10.1016/j.gaitpost.2010.09.024.

Pellisé, F., Vila-Casademunt, A., Ferrer, M., et al., 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.

Protopapadaki, A., Drechsler, W.I., Cramp, M.C., et al., 2007. Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. Clin. BioMech. 22, 203–210. https://doi.org/10.1016/j.clinbiomech.2006.09.010.

Saad, E., Semaan, K., Kawkabani, G., et al., 2022. Alteration of the sitting and standing movement in adult spinal deformity. Front. Bioeng. Biotechnol. 9, 751193. https://doi.org/10.3389/fbioe.2021.751193.

Schwab, F., Dubey, A., Pagala, M., et al., 2003. Adult scoliosis: a health assessment analysis by SF-36. Spine 28, 602–606. https://doi.org/10.1097/01.BRS.0000049924.94414.BB.

Schwab, F., Ungar, B., Blondel, B., et al., 2012a. Scoliosis Research Society-Schwab adult spinal deformity classification: a validation study. Spine 37, 1077–1082. https://doi.org/10.1097/BRS.0b013e31823e15e2.

Schwab, F., Ungar, B., Blondel, B., et al., 2012b. Scoliosis research society—schwab adult spinal deformity classification. Spine 37, 1077–1082. https://doi.org/10.1097/BRS.0b013e31823e15e2.

Semaan, K., Rachkidi, R., Saad, E., et al., 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.

Soucie, J.M., Wang, C., Forsyth, A., et al., 2011. Range of motion measurements: reference values and a database for comparison studies. Haemophilia : the official journal of the World Federation of Hemophilia 17, 500–507. https://doi.org/10.1111/J.1365-2516.2010.02399.X.

United Nations, Department of Economic and Social Affairs PD, 2017. World Population Ageing 2017 - Highlights (ST/ESA/SER.A/397).