



# Analysis of pelvic compensation for dynamic sagittal imbalance using motion analysis

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## Abstract

**Purpose** To analyze pelvic compensation during walking in patients with severe sagittal plane deformity by using motion analysis.

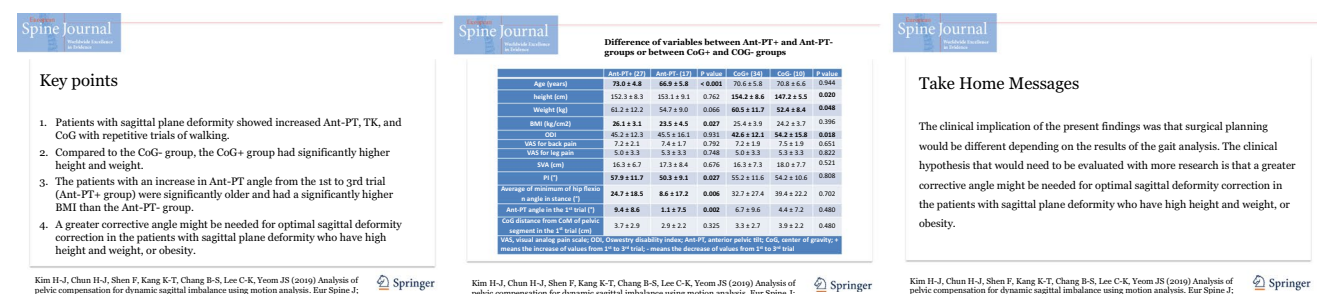
**Methods** A total of 44 patients with sagittal plane deformity who were scheduled to undergo surgery were included. Motion analysis was performed 3 consecutive times during walking to estimate the anterior pelvic tilt (Ant-PT) angle, trunk kyphosis (TK) angle, and distance of the center of gravity (CoG) from the center of mass (CoM) of the pelvic segment, and hip and knee joint angles during gait. The patients were classified into Ant-PT+/Ant-PT-, TK+/TK-, and CoG+/CoG- groups according to the changes in Ant-PT angle, TK angle, and distance of the CoG from the CoM of the pelvic segment. Increases and decreases in the values of the variables from the first trial to the third trial were indicated with “+” and “-” signs, respectively.

**Results** The mean Ant-PT angle, TK angle, and distance of the CoG from the CoM of the pelvic segment increased progressively, and the differences in the values of these variables from the first to the third trials were statistically significant ( $P=0.046$ ,  $P=0.004$ , and  $P=0.007$  for the Ant-PT angle, TK angle, and distance of the CoG from the CoM of pelvic segment, respectively). Among the 44 patients, 27 and 34 were classified into the Ant-PT+ and CoG+ groups, respectively. Older age and higher body mass index (BMI) were significantly associated with the Ant-PT+ group. The CoG+ group demonstrated a significantly higher height and weight than the CoG- group.

**Conclusions** Higher BMI, height, and weight are risk factors for progressive worsening of dynamic sagittal imbalance.

## Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.



Ho-Joong Kim and Heung-Jae Chun have equally contributed to this work.

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Extended author information available on the last page of the article

**Keywords** Dynamic sagittal imbalance · Motion analysis · Pelvic compensation · Center of gravity · Anterior pelvic tilt angle

## Introduction

In patients with sagittal plane deformity, pelvic compensation occurs first, indicating retroversion of the pelvis over the femoral head to restore sagittal balance in the standing position, resulting in increased pelvic tilt [1–3].

In patients with sagittal imbalance, walking could be more challenging than standing. A recent study reported that 10 min of walking can reveal hidden decompensation of sagittal imbalance in compensated deformities [4]. Therefore, the evaluation of dynamic sagittal imbalance during walking can be more important than that in the standing position. Thus far, assessments of sagittal balance and compensatory movement in patients with sagittal plane deformity have been performed using static radiographic standing images [1, 5, 6]. A main limitation of radiological assessment of sagittal plane deformity is the widely recognized discordance between the natural standing posture and the posture during standing radiography (hands on the clavicle or hands on the mandible/fist on the clavicle) [7, 8] because the standing position used to capture a lateral whole-spine radiograph significantly affects sagittal spinal alignment and balance [9].

Compared with static standing radiography, motion analysis can demonstrate natural dynamic sagittal balance and patterns in patients with adult spinal deformity (ASD) during gait [9]. Therefore, the purpose of this study was, first, to analyze pelvic compensation for dynamic sagittal balance in patients with ASD by using motion analysis and, second, to identify characteristics that indicate failure of pelvic compensation.

## Materials and method

### Study design and participants

The hospital institutional review board approved this study. All data were obtained from preoperative radiographs, medical records, and motion analyses, which were collected as part of the routine health checkup of patients before surgery. Data were retrospectively reviewed, and personal information was redacted.

The study included patients with severe sagittal plane deformity. All patients were scheduled to undergo spine surgery for ASD. The inclusion criteria were as follows: (1) age 65–85 years and (2) a diagnosis of ASD with positive sagittal balance and planned corrective surgery for ASD,

defined as a sagittal vertical axis (SVA) of  $> 5$  cm, pelvic tilt (PT) of  $> 20^\circ$ , or pelvic incidence (PI) – lumbar lordosis (LL) of  $> 20$  on lateral radiographs in the standing position [10, 11]. The exclusion criteria were as follows: (1) presence of any other spinal disease such as herniated intervertebral disease, spinal stenosis, and cervical myelopathy; (2) severe hip, knee, or ankle joint pain impeding walking; (3) peripheral vascular disease; (4) inappropriate radiograph; (5) any syndromic or neuromuscular disease; (6) any serious uncontrolled medical comorbidity such as sepsis or malignancy that can cause disability or worsen general health; and (7) inability to complete questionnaires on health-related quality of life and disability.

A total of 44 patients with ASD diagnosed as having severe sagittal plane deformity were included in this study at a single tertiary hospital between September 2016 and August 2018.

### Clinical outcome measures

Medical records were used to obtain data on sex, height, weight, body mass index (BMI), medical history, and clinical outcomes, including visual analog scale (VAS) scores for back and leg pains, Oswestry Disability Index (ODI) scores, and EuroQol (EQ-5D) scores [12, 13]. The ODI is a self-administered questionnaire that measures back-specific functions on a 10-item scale with 6 response categories each [13]. Each item is scored from 0 to 5, and the summation of the scores for each item is converted into a percent scale. The final score does not have a unit, and no value has been established for a specific health status or change in health status. The EQ-5D is a five-dimensional health state classification. The 5 dimensions are mobility, self-care, usual activities, pain/discomfort, and anxiety/depression [12, 14]. An EQ-5D “health state” is defined by selecting one level from each dimension. The EQ-5D preference-based measure can be regarded as a continuous outcome scored on a scale from 0 to 1.00, with 1.00 indicating “full health” and 0 indicating death.

### Measurement of hand grip strength

Hand grip strength (HGS), a measure of voluntary muscle function, has often been used as an indicator of generalized muscle strength. Many studies have demonstrated the high predictive value of HGS for sarcopenia [15, 16]. HGS was measured on both hands using a hand dynamometer (GRIP-D5101, Takei, Niigata, Japan) for evaluating generalized muscle weakness [16, 17]. The patients were asked

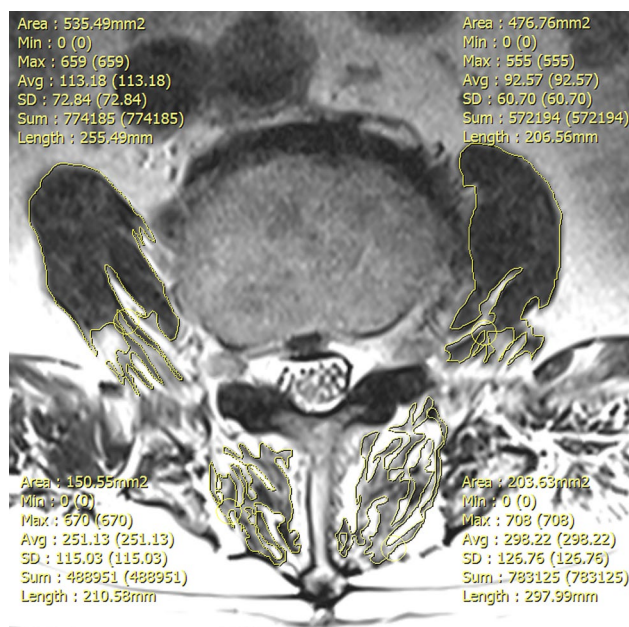
to hold the dynamometer between their fingers and palm, at the base of the thumb, with the elbow extended to the side and squeeze it with maximum strength. After a brief rest, the measurement was repeated twice for both the right and left hands. The best performance of these efforts was recorded in kilograms and used for analysis.

### Measurement of the cross-sectional area of the paraspinal muscles

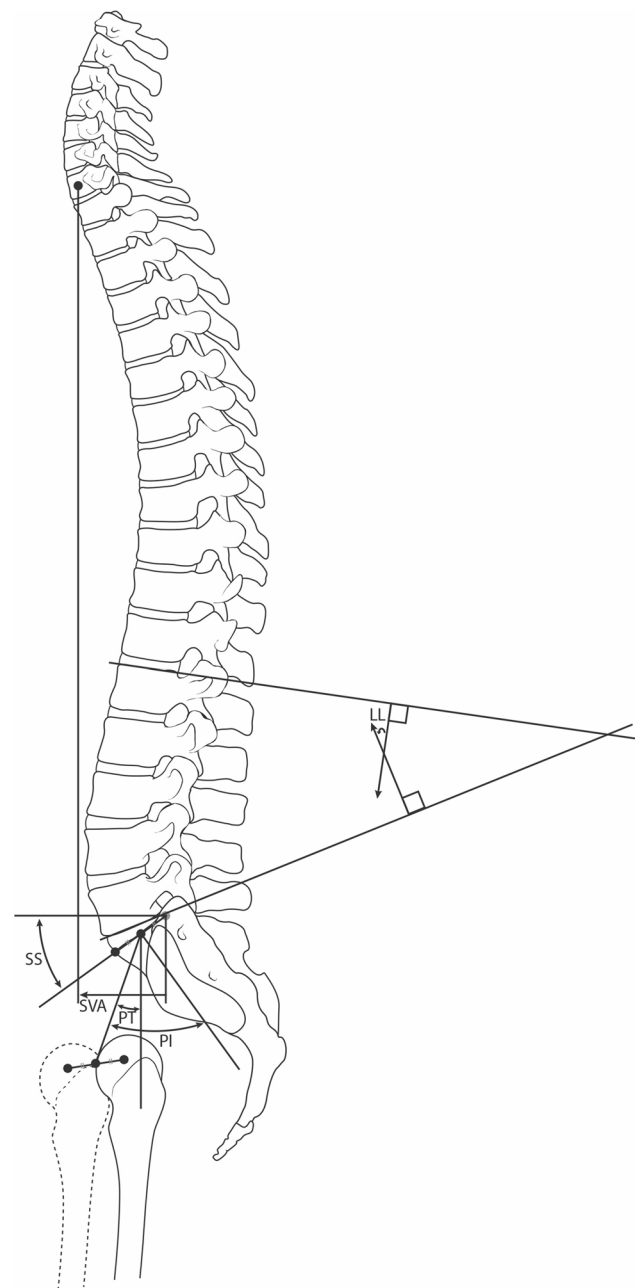
Preoperative lumbar spine magnetic resonance imaging examinations were performed for all the patients using a 1.5-T magnetic resonance scanner (Gyrosan Intera Achieva, Philips Healthcare) with a Synergy Spine Coil (Philips Healthcare) at our hospital. Quantitative measurements of the paraspinal muscles, including the psoas (PS) and multifidus (MF) muscles, were obtained from T2-weighted axial images using the PACS software (Infinitt, Bracknell, Berkshire, UK). The bilateral cross-sectional area (CSA) of the PS and MF muscles was measured at the inferior end plate of the L3 lumbar vertebra, subtracting the white area considered as fat infiltration (Fig. 1). Measurements were performed 2 times by 2 investigators, and the average value was recorded.

### Radiographic assessment

Sagittal spinopelvic parameters, including SVA, LL, PT, sacral slope, and PI, were measured on whole-spine lateral radiographs (Fig. 2). PI – LL was also calculated.



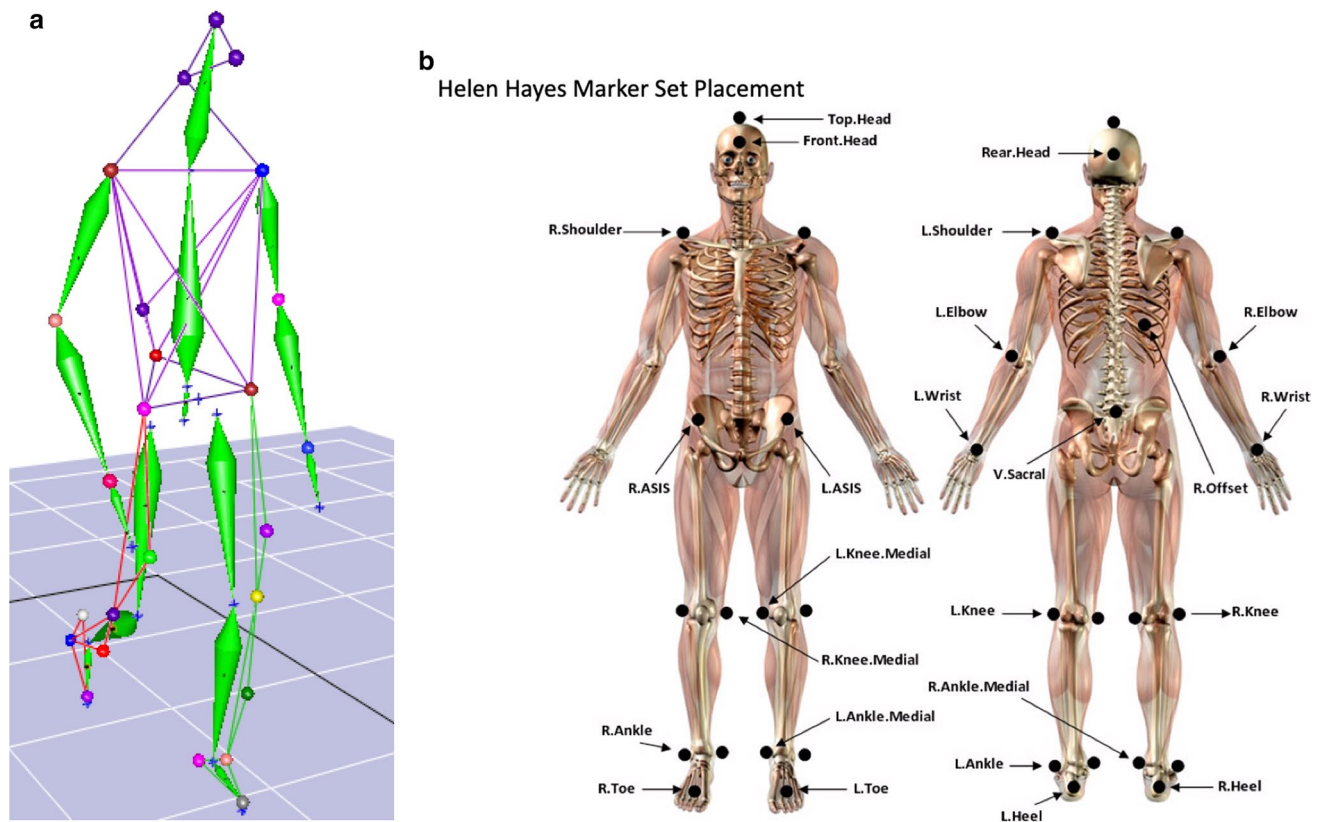
**Fig. 1** Measurement of cross-sectional area (CSA) of bilateral psoas (PS) and multifidus (MF) muscles in a T2-weighted axial MR image



**Fig. 2** Sagittal spinopelvic parameters: sagittal vertical axis (SVA), lumbar lordosis (LL), pelvic tilt (PT), sacral slope (SS), and pelvic incidence (PI)

### Motion analysis during gait

Three-dimensional gait analysis was performed a few days before surgery by using a motion analysis system (Motion Analysis Corporation, CA, USA) equipped with 10 cameras and 2 different force plates (60 cm × 50 cm) for each foot (Fig. 3a). Optical markers were placed by 2 operators in accordance with the Helen Hayes marker set (Fig. 3b). Marker locations were verified by palpation. The patients



**Fig. 3** Gait analysis of patients with sagittal plane deformity. **a** Walking balance and global alignment on the force platform, reconstructed using optical markers. **b** Optical markers were attached according to the Helen Hayes marker set

walked barefoot on a 9-m walkway 3 times consecutively, and kinematic data and temporal parameter values were recorded.

The center of gravity (CoG) was calculated using the segmental method [18]. As a surrogate of sagittal balance during walking, the sagittal distance from the CoG to the center of mass (CoM) of the pelvic segment was measured during walking in all the trials (Fig. 4a). The trunk kyphosis (TK) angle was measured as the difference in angles between the pelvic and trunk segments (Fig. 4b). The minimum hip and knee flexion angles in the stance phase were estimated from the position of the representative optical markers, which represented lower limb compensation for positive sagittal imbalance (Fig. 4c). No significant difference in angle was found between the right and left sides, and statistical results were the same between the 2 sides. Therefore, only the values on the left side were described. The anterior PT (Ant-PT) angle was estimated as the difference in posterior/anterior superior iliac spine angle relative to the floor as a horizontal reference line in the sagittal plane.

The data from the 3 trials were analyzed separately and averaged to obtain the trend of the changes in the index variable values. The patients were classified into Ant-PT+/Ant-PT-, TK+/TK-, and CoG+/CoG- groups according

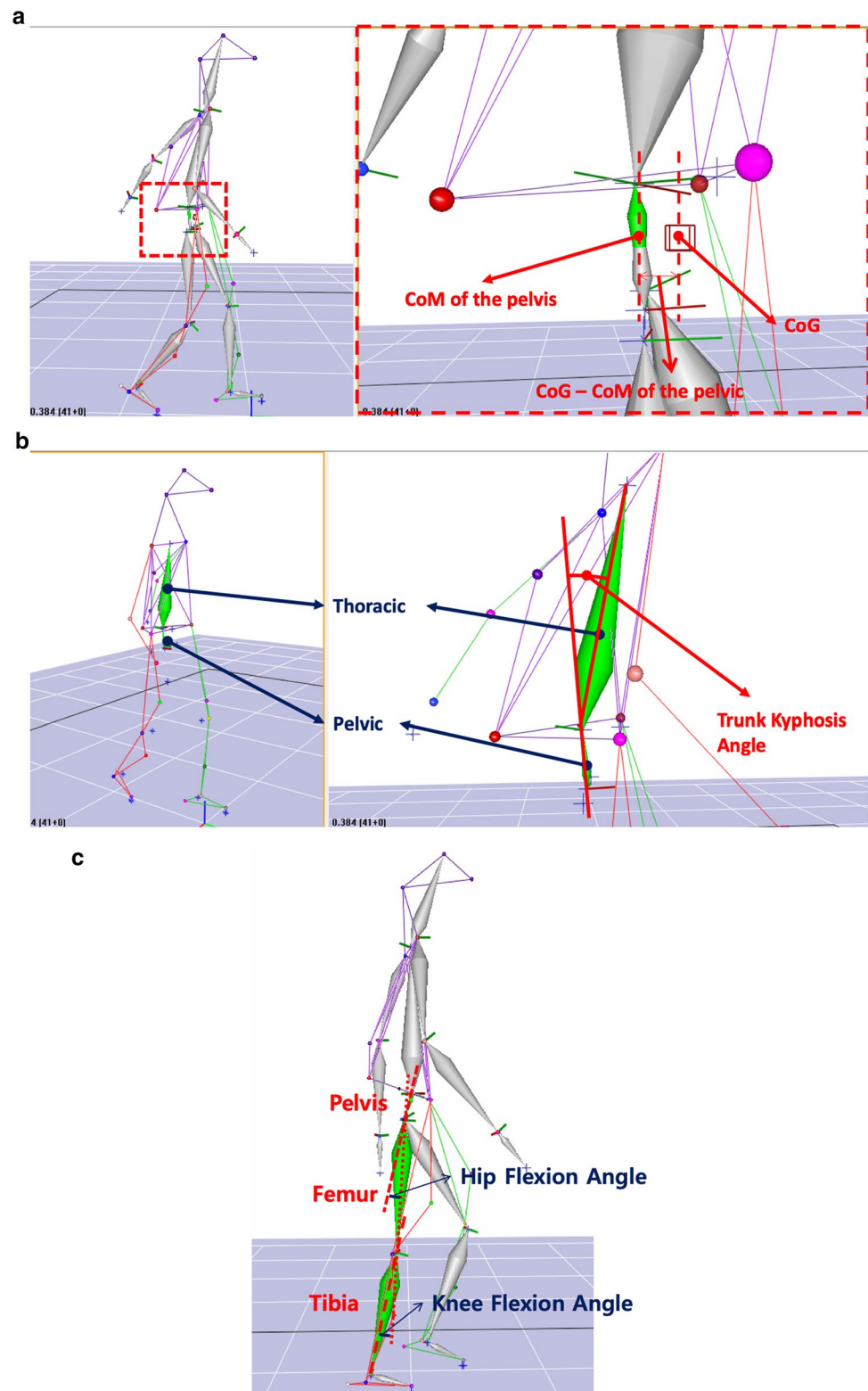
to changes in the Ant-PT angle, TK angle, and distance of the CoG from the CoM of the pelvic segment. Increases and decreases in the values of the variables from the first to the third trial were indicated with “+” and “-” signs, respectively.

### Statistical analyses

All the values are described as mean  $\pm$  standard deviation (SD). One-way repeated-measures analysis of variance was performed to examine the changes in the gait parameters across the repeated tests with time. For comparison of the variables between the Ant-PT+ and Ant-PT- groups, between the CoG+ and CoG- groups, and between the TK+ and TK- groups, the Mann–Whitney test was used. Given the mean differences in the statistically significant variables between the + and - groups, post hoc power analysis was performed with an alpha value of 0.05 using G\*power 3.1 (University of Dusseldorf, Dusseldorf, Germany). The  $\alpha$ -level for significance was set at 0.05. All statistical analyses were performed using the SPSS version 20.0.0 software (SPSS, Inc., Chicago, IL, USA).



**Fig. 4** **a** Estimation of the distance of the center of gravity (CoG) from the center of mass (CoM) of the pelvic segment. **b** Estimation of trunk kyphosis (TK) angle between the trunk and pelvic segments. **c** Minimum hip and knee flexion angle during gait



**Table 1** Descriptive analysis for clinical, radiological, and motion analysis variables in the present cohort

	ASD with sagittal plane deformity (44)
Age (years)	70.7 ± 5.9
BMI (kg/cm <sup>2</sup> )	25.1 ± 3.9
Male/female ( <i>n</i> )	4:40
VAS for back pain	7.3 ± 1.9
VAS for leg pain	5.1 ± 3.3
ODI (%)	45.3 ± 13.8
EQ-5D	0.365 ± 0.305
HGS (kg)	18.0 ± 6.8
CSA of PS (mm <sup>2</sup> )	953.9 ± 373.1
CSA of MF (mm <sup>2</sup> )	285.6 ± 129.4
SVA (cm)	16.7 ± 7.3
SS (°)	16.5 ± 9.5
PT (°)	38.6 ± 12.5
PI (°)	55.0 ± 11.3
LL (°)	− 3.9 ± 13.5
PI − LL (°)	58.9 ± 16.5
Average of minimum of knee flexion angle in stance (°)	20.1 ± 6.0
Average of minimum of hip flexion angle in stance (°)	18.5 ± 19.5
Average of Ant-PT angle (°)	6.5 ± 9.4
Mean CoG distance from CoM of pelvic segment (cm)	3.6 ± 2.7
Mean TK angle (°)	5.3 ± 11.9

Values are mean ± SD

*SD* standard deviation, *ASD* adult spinal deformity, *BMI* body mass index, *VAS* visual analog pain scale, *ODI* Oswestry disability index, *EQ-5D* EuroQol, *SVA* sagittal vertical axis, *SS* sacral slope, *PT* pelvic tilt, *PI* pelvic incidence, *LL* lumbar lordosis, *Ant-PT* anterior pelvic tilt, *CoG* center of gravity, *CoM* center of mass, *TK* trunk kyphosis, *HGS* handgrip strength, *PS* psoas, *MF* multifidus, *CSA* cross-sectional area

## Results

### Demographics and baseline data

Table 1 shows baseline patient data. The mean (± SD) age was 70.7 ± 5.9 years. Of the patients, 4 were male and 40 were female. The mean (± SD) ODI and EQ-5D score were 45.3 ± 13.8 and 0.365 ± 0.305, respectively. The mean (± SD) PT and PT − LL were 38.6° ± 12.5° and 58.9° ± 16.5°, respectively (Table 1). The mean (± SD) HGS was 18.0 ± 6.8 kg. In the motion analysis, the mean (± SD) Ant-PT angle, distance of the CoG from the CoM of the pelvic segment, and TK angle were 6.5° ± 9.4°, 3.6 ± 2.7 cm, and 5.3° ± 11.9°, respectively (Table 1). In addition, the minimum knee and hip joint flexion angles were 18.5° ± 19.5° and 20.1° ± 6.0°, respectively. Therefore, our clinical assessment is that these findings mean the included patients walked with kyphotic posture, anteriorly shifted CoG, and compensatory hip and knee joint flexion (Table 1).

**Table 2** Changes of gait parameters from first to third trials of gait analysis

	First trial	Second trial	Third trial	<i>P</i> value*
Ant-PT angle (°)	6.2 ± 9.1	6.7 ± 9.6	6.8 ± 9.6	<b>0.046</b>
TK angle (°)	4.9 ± 11.7	5.4 ± 11.8	5.8 ± 12.1	<b>0.004</b>
CoG distance from CoM of pelvic segment (cm)	3.4 ± 2.6	3.6 ± 2.7	3.7 ± 2.7	<b>0.007</b>

Bold values indicate statistical significance

Values are mean ± SD

*Ant-PT* anterior pelvic tilt, *CoG* center of gravity, *CoM* center of mass, *TK* trunk kyphosis

\*means the effect of trial on the change of variable

### Motion analysis during gait

Table 2 shows the separate motion analysis of the data from each trial. The mean Ant-PT angle, TK angle, and distance of the CoG from the CoM of the pelvic segment increased progressively, and the differences in the values of these

**Table 3** Difference of variables between Ant-PT+ and Ant-PT– groups or between CoG+ and CoG– groups

	Ant-PT+ (27)	Ant-PT– (17)	<i>P</i> value	CoG+ (34)	CoG– (10)	<i>P</i> value
Age (years)	73.0 ± 4.8	66.9 ± 5.8	<b>&lt; 0.001</b>	70.6 ± 5.8	70.8 ± 6.6	0.944
height (cm)	152.3 ± 8.3	153.1 ± 9.1	0.762	154.2 ± 8.6	147.2 ± 5.5	<b>0.020</b>
Weight (kg)	61.2 ± 12.2	54.7 ± 9.0	0.066	60.5 ± 11.7	52.4 ± 8.4	<b>0.048</b>
BMI (kg/cm <sup>2</sup> )	26.1 ± 3.1	23.5 ± 4.5	<b>0.027</b>	25.4 ± 3.9	24.2 ± 3.7	0.396
ODI	45.2 ± 12.3	45.5 ± 16.1	0.931	42.6 ± 12.1	54.2 ± 15.8	<b>0.018</b>
VAS for back pain	7.2 ± 2.1	7.4 ± 1.7	0.792	7.2 ± 1.9	7.5 ± 1.9	0.651
VAS for leg pain	5.0 ± 3.3	5.3 ± 3.3	0.748	5.0 ± 3.3	5.3 ± 3.3	0.822
HGS (kg)	18.4 ± 6.4	17.4 ± 7.5	0.650	19.1 ± 6.9	14.6 ± 5.1	<b>0.064</b>
CSA of PS (mm <sup>2</sup> )	1002.0 ± 385.6	877.6 ± 349.8	0.287	991.1 ± 391.6	827.7 ± 282.4	0.228
CSA of MF (mm <sup>2</sup> )	289.1 ± 131.2	280.0 ± 130.3	0.824	298.3 ± 132.5	242.4 ± 113.9	0.235
SVA (cm)	16.3 ± 6.7	17.3 ± 8.4	0.676	16.3 ± 7.3	18.0 ± 7.7	0.521
PI (°)	57.9 ± 11.7	50.3 ± 9.1	<b>0.027</b>	55.2 ± 11.6	54.2 ± 10.6	0.808
Average of minimum of hip flexion angle in stance (°)	24.7 ± 18.5	8.6 ± 17.2	<b>0.006</b>	32.7 ± 27.4	39.4 ± 22.2	0.702
Ant-PT angle in the first trial (°)	9.4 ± 8.6	1.1 ± 7.5	<b>0.002</b>	6.7 ± 9.6	4.4 ± 7.2	0.480
CoG distance from CoM of pelvic segment in the first trial (cm)	3.7 ± 2.9	2.9 ± 2.2	0.325	3.3 ± 2.7	3.9 ± 2.2	0.480

Bold values indicate statistical significance

VAS visual analog pain scale, ODI Oswestry disability index, Ant-PT anterior pelvic tilt, CoG center of gravity, + means the increase in values from first to third trial, – means the decrease in values from first to third trial, HGS handgrip strength, PS psoas, MF multifidus, CSA cross-sectional area

variables between the first trial and third trial were statistically significant ( $P = 0.046$ ,  $P = 0.004$ , and  $P = 0.007$  for Ant-PT angle, TK angle, and the distance of the CoG from the CoM of the pelvic segment, respectively; Table 2).

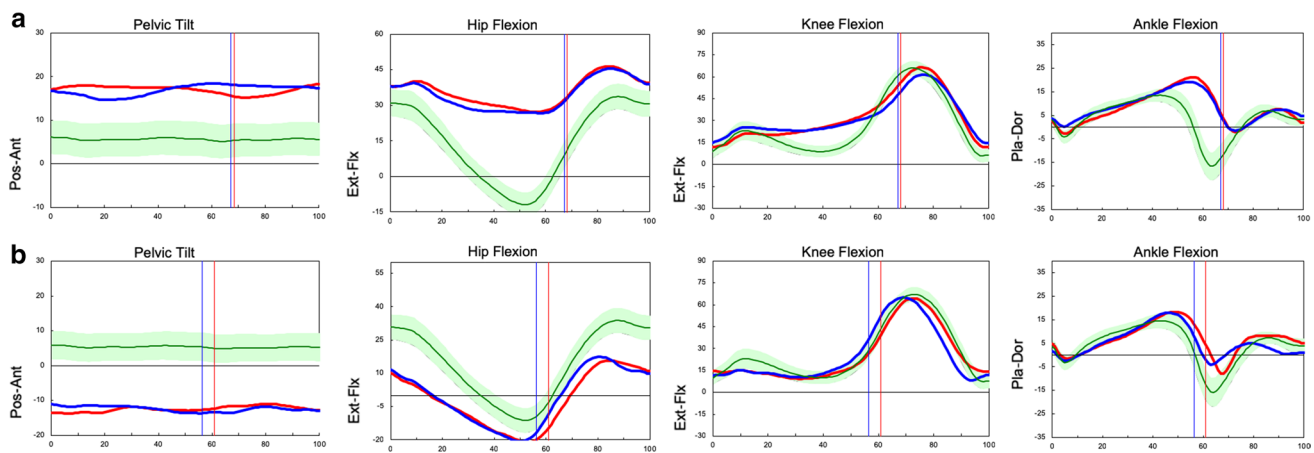
### Analysis of the variables between the Ant-PT+ and Ant-PT– groups or between the CoG+ and CoG– groups

Among the 44 patients, 27, 34, and 31 were classified into the Ant-PT+, CoG+, and TK+ groups, respectively, from the first to the third trials (Table 3). The values of all the variables were not significantly different between the TK+ and TK– groups.

Older age and higher BMI were significantly associated with the Ant-PT+ group (Table 3). Post hoc power analysis confirmed the differences in mean and standard deviation in the age and BMI between the Ant-PT+ and Ant-PT– groups, with an alpha value of 0.05 for both and statistical powers of 89.9% and 73.3%, respectively. The Ant-PT+ group had a significantly higher PI, mean minimum hip flexion angle in stance, and Ant-PT angle in the first trial than the Ant-PT– group (Table 3). Post hoc power analysis confirmed the differences in the mean and standard deviation in the PI and Ant-PT angle in the first trial between the 2 groups, with an alpha value of 0.05 for both and statistical powers of 73.0% and 92.6%,

respectively. However, no significant differences in clinical outcomes, including VAS scores for back and leg pain, ODI, and EQ-5D scores, were found between the Ant-PT+ and Ant-PT– groups. Furthermore, the HGS and CSA of the PS and MF muscles were not significantly different between the Ant-PT+ and Ant-PT– groups. Figure 5 demonstrates the variations in the Ant-PT angle and knee and hip flexion angles during the gait cycle. In the Ant-PT+ group, positive values of anterior pelvic tilt angle were demonstrated in all gait cycles, with higher compensatory hip flexion angles, which indicates failure of pelvic compensation (Fig. 5a). By contrast, in the Ant-PT– group, negative values of anterior pelvic tilt angle were demonstrated in all gait cycles (Fig. 5b).

The CoG+ group demonstrated significantly higher height and weight than the CoG– group (Table 3). Post hoc power analysis confirmed the differences in mean and standard deviation in the height and weight between the 2 groups, with an alpha value of 0.05 for both and statistical powers of 92.1% and 72.4%, respectively. However, the values of all the gait parameters and radiological variables were not significantly different between the 2 groups. Only ODI was significantly higher in the CoG– group than in the CoG+ group. Post hoc power analysis confirmed the difference in mean and standard deviation in ODI between the 2 groups with an alpha value of 0.05 and a statistical power of 71.9%. In addition, no significant differences in the CSAs of the PS and MF muscles were found between



**Fig. 5** Variation of Ant-PT, hip, and knee joint angles during gait (blue and red lines represent right and left lower extremity, respectively. Green line and color represent normal gait patterns in healthy

population. The vertical lines represent toe-off which discriminate swing phase with stance phase.). **a** A case of Ant-PT+ group. **b** A case of Ant-PT– group

the CoG+ and CoG– groups. A higher HGS was observed in the CoG+ group, with a trend toward statistical significance ( $P = 0.064$ ; Table 3).

## Discussion

This study demonstrates that patients with sagittal plane deformity showed increased Ant-PT angle, TK angle, and CoG in repetitive trials of walking. Failure of pelvic compensation occurred in some patients with sagittal plane deformity. However, no significant differences in the HGS and CSA of the PS and MF muscles were found between the Ant-PT+ and Ant-PT– groups. In addition, clinical outcomes were not dependent on pelvic compensation in the patients with severe sagittal plane deformity.

The mean value of the anteriorly shifted CoG from the CoM of the pelvic segment increased in the consecutive trials. This suggests that continuous walking worsened the sagittal plane deformity. A recent study that used motion analysis showed similar results; some patients with severe positive sagittal imbalance demonstrated paradoxical anterior (forward) pelvic tilt during walking [11]. The underlying mechanism of failure of pelvic compensation after continuous walking could be fatigue of the paraspinal and hip extensor muscles and uncompensated severe positive sagittal imbalance, which induces increased forward-lever arm on the pelvis through the sacroiliac joints, resulting in anterior pelvic tilt during walking [11]. Coactivation and interaction among the paraspinal, psoas, hip extensor, and hip abductor muscles play critical roles in maintaining both sagittal balance and pelvic compensation during walking [19–21]. Significant increases in Ant-PT and TK angles were observed in the trials of motion analysis. These findings

were also related to the same mechanisms of muscle fatigue and increased forward-lever arm by uncompensated positive sagittal imbalance during continuous walking.

We also intended to investigate the characteristics of the group with failure of pelvic compensation from the first to the third trial. Compared with the patients in the CoG– group, those in the CoG+ group had significantly higher height and weight. This indicates that increased body weight and height can be risk factors for progressive worsening of sagittal imbalance with walking. This could be explained by the increased moment arm of the CoG from the ground. Relatively tall and heavy patients with positive sagittal imbalance can have an increased moment arm for anterior shifting of the CoG during walking. Likewise, the patients in the Ant-PT+ group were significantly older and had a significantly higher BMI than those in the Ant-PT– group. Older age and higher BMI in the Ant-PT+ group might be associated with frailty of the paraspinal/hip muscles and higher moment of anterior pelvic tilt, respectively. Furthermore, the Ant-PT+ group showed a significantly increased mean minimum hip and knee flexion angles in stance compared with the Ant-PT– group (Fig. 5), which indicates lower limb compensation in case of failure of pelvic compensation (increased Ant-PT angle) during walking. This finding is in agreement with that of a recent study by Jalai et al. who showed that obese patients have lower extremity compensatory mechanisms because of the limited pelvic retroversion [22]. The Ant-PT+ group was also associated with significantly higher Ant-PT angle in the first trial. The mean Ant-PT angle was  $9.4^\circ$  in the Ant-PT+ group, whereas the mean Ant-PT angle in the Ant-PT– group was nearly horizontal ( $1.1^\circ$ ). This suggests that failure of pelvic compensation in the first walking trial progressively worsens in the succeeding walking trials and vice versa.



An intriguing result is that no significant differences in the HGS and CSA of the paraspinal muscles were found between the CoG+ and CoG− groups or between the Ant-PT+ and Ant-PT− groups. These results and a generally held opinion appear to be opposed, with the previous opinion emphasizing that progressive worsening of dynamic sagittal imbalance is associated with muscle weakness [4, 21]. Various reasons could explain these results. First, the patients with severe sagittal imbalance in the CoG (Ant-PT)+ and − groups who were included in this study already had severe weakness of the back muscles and generalized muscle weakness. Second, the key method for pelvic compensation is posterior pelvic tilt by the hip extensors (hyperextension) [22], which was not measured in this study.

It is interesting that the CoG− group showed a significantly higher ODI than the CoG+ group. This result might be due to the difference in HGS between the 2 groups. The CoG+ group demonstrated higher HGS, with a trend toward statistical significance ( $P=0.064$ ), than the CoG− group. According to previous studies [16, 17, 23, 24], HGS is associated with physical functioning, disability, and health-related quality of life. In addition, this result does not seem to indicate that CoG+ is more favorable than CoG− because both groups showed extremely high ODI.

The clinical implication of the present findings is that surgical planning would be different depending on the gait analysis results. A greater corrective angle may be necessary in case of the Ant-PT+ or CoG+ group to obtain natural balance during walking because progressive anterior shifting of the CoG and failure of pelvic compensation occur in these groups. This is in line with a previous study by Lee et al. [21], who reported that corrective surgery for sagittal imbalance was ineffective, resulting in postoperative persistent stooping in patients who had anterior pelvic tilt during gait.

The present study has several limitations. First, this study included patients with severe positive sagittal imbalance who have a mean SVA of 16.7 cm and mean PI–LL of 58.9°. This should be considered when interpreting the present results. The present findings might not be applicable to patients with mild sagittal imbalance. Second, a relatively small number of patients with sagittal plane deformity were included in the gait analysis. However, we attempted to maintain homogeneity of the enrolled patients. All the patients in this study only had sagittal plane deformity, without other degenerative spinal diseases such as severe coronal plane deformity, spinal stenosis, and herniated lumbar disk.

In conclusion, the present study elucidated the risk factors for progressive worsening of sagittal balance by the failure of pelvic compensation in patients with severe sagittal plane deformity. Therefore, a greater corrective angle might be needed for optimal sagittal deformity correction in patients with sagittal plane deformity who have high height and weight or obesity.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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