Pelvic Kinematics during Gait Following Long-Segment Spinal Fusion Due to Adult Spinal Deformity: An Analysis Using a Smartphone-Based Inertial Measurement Unit

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Abstract:

Introduction: Gait changes could occur after thoracic to pelvic long-segment corrective fusion surgery, a common procedure for adult spinal deformity (ASD), potentially affecting the occurrence and progression of postoperative hip osteoarthritis. We aimed to clarify postoperative pelvic kinematics in patients with ASD by performing gait analysis using a system based on a smartphone-integrated inertial measurement unit (IMU).

Methods: A total of 21 consecutive outpatients (73.6±4.6 years old, 2 men, 19 women) were enrolled. All had undergone long-segment fusion from the thoracic spine to the pelvis for ASD more than 1 year previously and could walk unassisted. A control group comprised 20 healthy volunteers. The IMU was fixed on the sacrum, and data were collected when subjects walked forward on a flat indoor floor. Acceleration in three axial directions and angular velocity around the three axes were recorded simultaneously during gait, and data were cut out for each gait cycle. Of 1043 features obtained, the top 20 features with the smallest *p*-value in a statistical comparison were selected. These features, plus gender and age, were classified using gradient boosting machine learning based on the decision tree algorithm. The classification accuracy and relative importance of the feature items were calculated.

Results: The accuracy rate for gait classification between groups was 96.7% and the F1-score was 0.968. The factor that contributed most to the classification of gait in both groups was "y-angular,_change_quantiles,_f_agg="var",_isabs=True,_qh =0.6,_ql=0.2," which means the variance of the change of the absolute value in the pelvic rotation angular velocity in the horizontal plane in the range of 20%-60% of the gait cycle. Its relative importance was 0.351, which was smaller in the group with fusion.

Conclusions: Patients with ASD following long-segment fusion from the thoracic spine to the pelvis apparently have a gait style characterized by suppressed pelvic rotation in the horizontal plane.

Keywords:

Pelvic kinematics, Smartphone-based inertial measurement unit, Gait analysis, Long-segment spinal fusion surgery, Adult spinal deformity, Pelvic rotation, Hip osteoarthritis

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Introduction

Long-segment corrective fusion surgery from the thoracic spine to the pelvis is often used to restore spinal alignment in patients with adult spinal deformity (ASD), because abnormal postures can lead to difficulty in sustaining standing and walking[1-3]. Long-segment fusion allows good alignment for standing and walking; thus, there is marked improvement of abnormal posture and intermittent back pain[4,5]. However, it does have certain disadvantages; for example, patients can have lumbar stiffness-related disability postoperatively, which can cause difficulty with activities of daily living, such as putting on and taking off their pants, socks, and shoes, performing personal hygiene functions after toileting, and bending forward to pick up small objects off the floor[6-9]. Degenerative changes in the hip joint are reportedly also more likely to develop after spinopelvic fixation[10,11]. Biomechanical and clinical studies have shown that this phe-

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nomenon is also due to stiffness from the spine to the pelvis[12,13]. Therefore, long-segment fusion induces stiffness from the lumbar spine to the pelvis, which may cause compensatory changes in the motion of many body parts. Although patients have a similar posture at rest in the standing position after long-segment fusion to people with a nonfused spine, they may have different gait patterns while walking. Changes in gait style in patients with ASD before and after surgery have recently been studied[14-18]. In one study, gait was analyzed before and after extensive corrective fusion surgery for patients with ASD; there were improvements in postoperative posture, maximum knee extension angle, and step length during gait[14]. However, pelvic kinematics during gait following long-segment fusion from the lumbar spine to the pelvis have not been sufficiently analyzed. The thoracolumbar and lumbosacral junctions reportedly work together to affect the pelvis[15], and pelvic kinematics are affected by lower extremity movements, such as walking speed and step length, during gait in healthy participants[16-18]. Therefore, we hypothesize that the fused pelvis is affected postoperatively during gait in patients with ASD after long-segment fusion.

A gait analysis system using a smartphone-based inertial measurement unit (IMU) has been previously reported[19]. Its advantages include that gait analysis, which typically requires a large measurement environment and expensive equipment[20], can be easily performed at any facility and without special equipment. We performed gait analysis of pelvic kinematics by attaching such a smartphone-based IMU to the sacrum. Differences were successfully classified in lameness patterns based on different factors[19]. This system may facilitate comparison of pelvic kinematics in various differing patients. To our knowledge, there have been no reports of a smartphone-based IMU being used to analyze pelvic kinematics during gait in patients who underwent extensive corrective fusion surgery for ASD. Therefore, we evaluate the characteristics of gait in patients after long-segment corrective fusion for ASD by performing a gait analysis focusing on pelvic kinematics.

Materials and Methods

Methods

This study was approved by our institutional review board before the study began and was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent for publication was obtained from the patients or their family members.

Materials

Consecutive outpatients who visited our institution between April and September 2022 were enrolled in this study. They had all undergone long-segment corrective fusion surgery for ASD at our institution more than 1 year previously and could walk without assistance. The fusion surgery was performed from the lower thoracic spine to the pelvis using bilateral S2 alar-iliac screws. Patients with severe low back pain, with neurological symptoms in the upper and lower extremities, or with symptoms of osteoarthritis in the hip, knee, and ankle joints and those with a history of surgery on the lower extremities were excluded because it was thought that these conditions would skew the results. Finally, 21 patients (73.6±4.6 years old, 2 men, 19 women) were included in this study. Follow-up periods were 3.2±1.8 years. As a control group, we recruited individuals with no reported history of orthopedic or neuromuscular diseases related to gait or balance disorders.

Table 1. Patient Demographics.

	Fusion group (n=21)	Control group (n=20)	*p* value
Age†	72.6±3.6	73.2±5.9	0.744
Sex (male/female) ‡	2/19	9/11	0.015*
BMI† (kg/m^2)	22.9±3.4	22.0±3.1	0.648
Evaluated walking cycles	357	363	

BMI, body mass index; mean±standard deviation, †Mann–Whitney *U* test, ‡Fisher's exact test, *$P<0.05$

The collected demographic characteristics of the patients were sex, age, and body mass index (Table 1) and postoperative sagittal and coronal spinal alignment. For sagittal alignment parameters, we evaluated the spinopelvic parameters of pelvic incidence, lumbar lordosis, pelvic tilt, sacral slope, pelvic incidence-lumbar lordosis mismatch, and sagittal vertical axis and as a coronal alignment parameter, preoperative deviation of the C7 plumb line from the central sacral vertical line (C7-CSVL). All spinopelvic and coronal parameters were measured using a standard standing position radiograph performed at the most recent observation. To evaluate clinical variables at the final observation, we used Oswestry Disability Index, low back and leg pain based on a visual analog scale score, and the short-form 36 health survey questionnaire known as SF-36.

Experimental setting and data collection

Data collection was performed as previously reported[19]. As an inertial measurement unit (IMU), a smartphone with a built-in inertial sensor (Xperia Z5 501SO, Android 6.0.1; Sony Corp., Tokyo, Japan) was fixed to the participant's clothing at the height of the second sacral spinous process using 5-cm-wide adhesive tape. The S2 spinous process was accurately identified using radiographic images or an ultrasound device.

Data was collected while the patient was walking straight ahead on a flat indoor floor. The smartphone was firmly secured in accordance with a previously established method in order not to affect the recording, but so that the tape did not restrict the participant's movement[19]. Tape was fixed at the top and bottom of the smartphone and around the rear pelvic area, following a previously reported method to prevent the smartphone from moving on the clothes[19]. To record in-

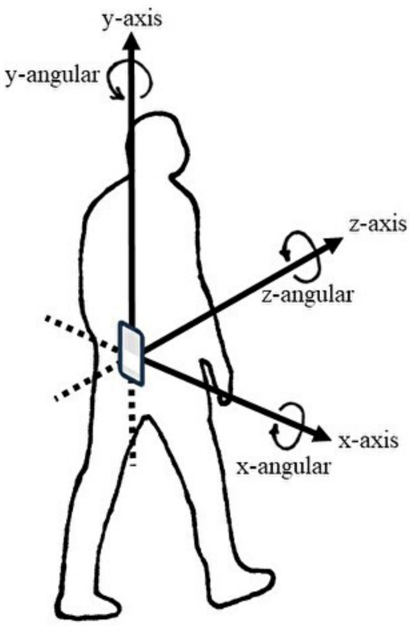

Figure 1. Axis settings in the device and global coordinate systems.

ertial sensor data, a previously used and reported application for the Android platform was installed on the smartphone with built-in inertial sensors[19]. The application was explained to the participants before the gait assessment using voice guidance emitted from the smartphone. With the participant in an upright position, the supervisor initiated the application for data collection. Participants were asked to perform the walking task while listening to a rhythmic sound at 100 beats/min and to stop walking when a beep sounded 6 s after the start sound. Thus, data were recorded for 6 s. The walking task was conducted by walking unaided in a so-called "natural" gait. Participants were instructed to stop walking if they felt that they were in danger of falling, and the walking task was performed with the supervisor beside them to prevent falls. Data were collected by each participant repeating the 6-s walk three times.

During the examination of the gait, acceleration in three axes (vertical, front-to-back, and side-to-side directions) and angular velocities around the three axes were simultaneously recorded (Fig. 1). The axes of the IMU were defined as global y-axis for the walking direction, global x-axis for the left-right direction, and global z-axis for the vertical direction[19]. The time series of acceleration and angular velocity data obtained from the IMU were divided into each gait cycle after noise removal using the previously reported method[19]. This resulted in 363 and 357 walking cycles of data from the control and patient groups, respectively.

Data processing

Data processing was performed in accordance with the previously reported procedure[19]. A comprehensive analysis of multidimensional time series was performed for each gait cycle using Tsfresh (Maximilian Christ, Blue Yonder GmbH, 2016), a Python statistical package to automatically calculate a large number of time series characteristics and features[21]. A total of 1043 feature items were comprehensively extracted for each gait cycle. Among them, the Benjamini-Yekutieli procedure was used to identify the top 20 items with the lowest *p*-values by significant difference between the two groups[22]. These 20 features, plus sex and age, were classified using gradient boosting machine learning based on the decision tree algorithm. As the classifier in this study, we used LightGBM (Microsoft Corp., Redmond, WA, USA), a gradient boosting framework based on the decision tree-based learning algorithm[23], which created a boosting algorithm with fast machine learning efficiency.

Investigated items

Machine learning used k-fold cross-validation (set at k=5 in this study) to evaluate the accuracy of the final five models generated. As before, the final classification accuracy was calculated by averaging the obtained accuracies[19]. Similarly, we assessed the final classification precision, recall, and F1-score. F1-score was calculated using the following formula: F1-score=2×precision×recall/(precision+recall). The F1-score takes values ranging between 0.0 and 1.0; a large value represents both precision and recall being simultaneously high and that the machine learning model is efficient and well-balanced. We also calculated the relative importance of the feature items that contribute to the classification task in machine learning.

Results

Patient characteristics

Table 1 summarizes demographic characteristics, the radiological data, and clinical variables of patients. There proportion of women was significantly higher in the patient group than in the control group. Within the patient group, duration of follow-up after surgery was 3.2±1.8 years, pelvic incidence was 52.2°±10.5°, lumbar lordosis was 43.1°±9.2°, pelvic tilt was 27.5°±9.1°, sacral slope was 24.6°±9.0°, pelvic incidence-lumbar lordosis mismatch was 9.0°±9.1°, sagittal vertical axis was 45.7±40.2 mm, C7-CSVL was 18.7±13.2 mm, Oswestry Disability Index was 18.6±16.0, and visual analog scale score for low back pain, leg pain, and leg numbness were 15.4±25.7, 22.0±29.5, and 30.6±35.1 mm, respectively.

Importance of features

Fig. 2 shows an example of a decision tree algorithm. The results of the fivefold cross-validation showed that the classification accuracy rate for gait classification between the two groups was 96.7% and F1-score was 0.968 (Table 2). The factor that contributed most to the classification of gait in both groups was "y-angular,_change_quantiles,_f_agg ="var",_isabs=True,_qh=0.6,_ql=0.2" (Table 3), which means the variance of the change of the absolute value in the pelvic rotation angular velocity in the horizontal plane in

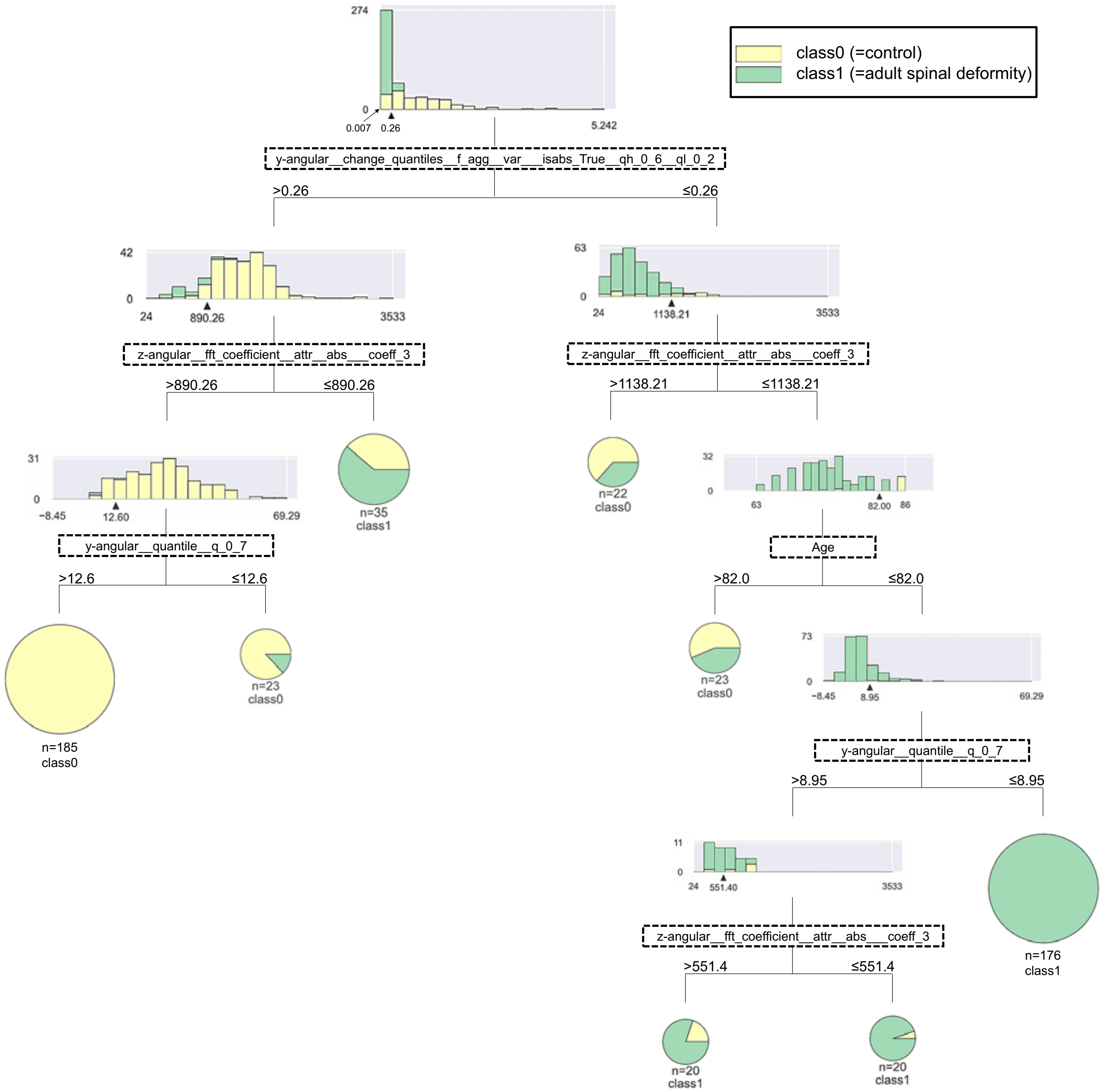

Figure 2. An example of a decision tree algorithm for classification using gradient boosting machine learning. From the top, the feature "y-angular__change_quantiles__f_agg_var__isabs_True__qh_0_6__ql_0_2" shown in the dashed line is first used to classify class 0 (=control) and class 1 (=adult spinal deformity patients), using 0.26 as a threshold, and both are classified. In the algorithm on the left side, the feature "z-angular__fft_coefficient__attr__abs__coeff_3" in the dashed line was then used with a criterion of 890.26 for classification, and the subsequent classification was performed below it. Similar classification to the decision tree algorithm on the right was performed, resulting in the classification of class 0 and class 1, as shown in the pie chart.

the range of 20%-60% of the gait cycle. Because 0% of the gait cycle was set at the moment of total plantar contact after initial contact in this study, the range of 20%-60% of the gait cycle in this study corresponds to the middle of terminal stance to the beginning of mid swing in a typical gait cycle. The relative importance of this factor was 0.351, which was smaller in the patient group than in the control group.

Discussion

We compared patients after long-segment corrective fixation for ASD and control participants by gait analysis focusing on pelvic kinematics, using a gait analysis system with a smartphone-based IMU. The results showed that both groups could be classified with extremely high accuracy and that this study was a highly efficient and balanced machine learning model. The feature item that contributed most to the classification was the variance of the change of the absolute value in the angular velocity of pelvic rotation in the horizontal plane, which was lower in the patient group than in the control group. This may be interpreted as the postoperative patients having a gait characterized by suppressed pelvic rotation in the horizontal plane from terminal stance to mid swing in the gait cycle.

Gait analysis performed on patients after long-segment corrective fixation from the thoracic spine to the pelvis for ASD is not widely reported[14,24-26]. Lower extremity kinematics and spatiotemporal parameters during gait were not significantly improved in one study before and after ASD fusion surgery[24]. Elsewhere, gait posture improved after expansive corrective fusion surgery for patients with ASD[25,26]. Moreover, in a study that investigated gait characteristics after long-range fusion surgery using video camera gait analysis, postoperative walking posture, delayed knee extension during gait, and step length improvement with correction of spinal deformity had significant correlation with postoperative Oswestry Disability Index and postoperative walking speed and step length[14]. However, pelvic kinematics have not previously been adequately described; this study is the first gait analysis after long-segment corrective fixation for patients with ASD to demonstrate that gait is characterized by suppressed pelvic rotational movement in the horizontal plane.

The pelvis was shown in a recent study to move in conjunction with the trunk during gait in heathy people. The anti-rotation of the upper body in relation to the pelvis was mainly secured by the opposition rotational movements of the lumbosacral and thoracolumbar junction in the horizontal plane during gait[15]. Therefore, the lumbosacral and thoracolumbar junctions were fixed in patients after long segmental fusion, which may have strongly influenced the pelvic rotation movement. Rotational movements between the trunk and the pelvis during gait can be suppressed in older patients[16,27]. This study was based on comparisons between groups of people of the same age, so we think there is no concern in this regard.

Table 2. An Accuracy, Precision, Recall, and F1-score Using Fivefold Cross-validation between the Two Groups.

	Mean
Accuracy	0.967
Precision	0.970
Recall	0.970
F1-score	0.968

F1-score is calculated by the following formula; F1-score=2×precision×recall/(precision+recall)

It has been shown that long-segment or lumbar-pelvic fusion affects the hip joint. Osteoarthritis of the hip progresses in 10% of patients after fusion, including the sacroiliac joint for ASD[10]. Furthermore, the longer the range of fusion, the more osteoarthritis of the hip progresses[11]. As basic data to support these clinical studies, the hip flexion-extension and abduction-adduction moments increased after spinopelvic fixation[12]. Finite element analysis has also shown increased load on the hip after long-segment fusion[13]. The suppression of pelvic rotation during gait in patients after long-segment fusion surgery, as demonstrated in this study, may similarly increase the load on the hip joint, and this may be suggested as a contributing factor in the development of hip osteoarthritis. Regarding pelvis lower extremity linkage, women reportedly take longer strides relative to their leg length and walk with a greater pelvic rotation angle of motion than men[28]. Despite the background of significantly more men with low pelvic rotation in the control group, the result of a gait pattern characterized by reduced rotation in the patient group after fixation surgery may reflect the effect of long-segment fusion.

This study has some limitations. First, this was a single-center retrospective study with a relatively small number of subjects, all of whom were of the same ethnicity (Japanese). Future multicenter prospective studies with broader populations are required to confirm our results. Second, the study lacks data on radiological and clinical variables in healthy

Table 3. Average Relative Importance of the Top Features.

Feature names	Relative importance
y-angular,_change_quantiles,_f_agg=”var”,_isabs=True,_qh=0.6,_ql=0.2	0.351
z-angular,_fft_coefficient,_attr=”abs”,_coeff=3	0.268
Age	0.097
z-angular,_absolute_sum_of_changes	0.081
y-angular,_change_quantiles,_f_agg=”var”,_isabs=True,_qh=0.6,_ql=0.4	0.044
y-angular,_fft_coefficient,_attr=”abs”,_coeff=1	0.038
y-angular,_change_quantiles,_f_agg=”var”,_isabs=True,_qh=0.6,_ql=0.0	0.031
y-angular,_quantile,_q=0.7	0.018
Gender	0.015
y-angular,_change_quantiles,_f_agg=”var”,_isabs=True,_qh=0.8,_ql=0.4	0.013

fft; fast fourier transformation, attr; attribute, abs; absolute, coeff; coefficient, f_agg; the aggregator function that is applied to the differences in the bin, var; variance, isabs; the path is absolute (true/false), qh; higher quantile of the corridor, ql; lower quantile of the corridor, q; the quantile to calculate volunteers as a comparison. In addition, it remains unclear whether the changes in pelvic motion were due to ASD itself or due to long-segment corrective fusion surgery, because the controls in this study were not preoperative patients with ASD. Ideally, a comparative study should be performed between pre- and postoperative patients. Therefore, we have collected waveform data during gait in patients with ASD before and after fusion surgery, and this will form the basis of a future analysis in a prospective study. Third, regarding the measurement error of the IMU used in this study, a high degree of similarity between the IMU and an optical motion capture system (CORTEX 5.3.1 by Motion Analysis Inc.) has been demonstrated (unpublished data). Fourth, this study only investigated pelvic kinematics and did not examine the upper and lower limbs or trunk. Therefore, we are currently developing a method of measurement using the smartphone-based IMU by synchronizing multiple IMUs to simultaneously collect data from parts of the limbs and trunk other than the pelvis. However, data on pelvic kinematics after long-segment fusion surgery for ASD have not previously been presented, which is considered to be a strength of the current study. We believe that this study provides a foundation for future investigations on pelvic kinematics during gait in patients after surgery for ASD.

Conclusions

Gait analysis focusing on pelvic kinematics was conducted using a gait analysis system with a smartphone-based IMU. Patients after long-segment corrective fusion for ASD and healthy volunteers could be classified with high accuracy. Patients who have undergone long-segment fusion from the thoracic spine to the pelvis appear to have a distinctive gait characterized by suppressed pelvic rotation in the horizontal plane.

Disclaimer: Yamada and Hashizume are the Editors of Spine Surgery and Related Research and on the journal's Editorial Committee. They were not involved in the editorial evaluation or decision to accept this article for publication at all.

Conflicts of Interest: The authors declare that there are no relevant conflicts of interest.

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Ethical Approval: This study was conducted with the approval of the Research Ethics Committee of Wakayama Medical University (No. 3236).

Informed Consent: Informed consent for publication was obtained from all participants in this study.

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