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Relationship between Lower Limb Pain Intensity and Dynamic Lumbopelvic-Hip Alignment in Patients with Degenerative Lumbar Spinal Canal Stenosis: A Cross-Sectional Study

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Study Design: This cross-sectional study was conducted in a single hospital.

Purpose: To clarify the relationship between lower limb pain intensity and dynamic lumbopelvic-hip alignment in patients with lumbar spinal canal stenosis (LSS), using a three-dimensional (3D) motion analysis system.

Overview of Literature: Although it is well known that leg symptoms have a close relationship with posture in patients with LSS, the relationship under dynamic conditions, such as gait, remain unclear.

Methods: Thirty patients with LSS scheduled for spine surgery participated in this study. Lower limb pain was assessed using the Visual Analog Scale (VAS), and the patients were divided into two groups based on the mean scores (patients with scores above and below the mean were classified as the high-VAS and low-VAS groups, respectively). The kinematics of the spine, pelvis, and hip joints during gait were then measured using a 3D motion analysis system. Student paired *t*-tests were used to compare the angles of the spine, pelvis, and hip during gait between the two groups.

Results: Compared to those in the low-VAS group, the spine was significantly extended and bent toward the more painful lower limb side, and the pelvis was significantly anteriorly tilted among individuals in the high-VAS group.

Conclusions: Patients with LSS experiencing severe pain in their lower limb tend to keep the spine in a more extended position, bend laterally toward the painful side, and have an anteriorly tilted pelvic posture. The dynamic spinal and pelvic alignment was closely related to the intensity of the lower limb pain.

Keywords: Lumbar spinal stenosis; Lower limb pain; Three-dimensional motion analysis; Dynamic spinal alignment; Dynamic pelvic alignment

Introduction

Lumbar spinal canal stenosis (LSS), defined as narrowing of the spinal canal with compression of the spinal nerve root and/or cauda equina in one or multiple segments [1], is the most common prevalent degenerative disease of

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the spine in older adults. A nationwide population-based study in Japan estimated that 3,650,000 people (5.7%) aged 40–79 years have LSS [2]. One of the characteristics of LSS is lower limb pain at rest and during gait [3,4]. This lower limb pain, which is reported by 80%–90% of patients with LSS [5,6], reduces the patient's activities of daily living and/or quality of life (QOL) [7-9]. As the main goal of treatment is typically to improve the QOL, it is important to appropriately evaluate the lower limb pain and its effect on the QOL.

It is well known that leg symptoms have a close relationship with posture in patients with LSS. Trunk extension usually induces and aggravates leg symptoms. In contrast, flexing the trunk or guiding the pelvis backward can reduce and improve symptoms. Although this phenomenon suggests that trunk and pelvic alignment could be associated with lower limb pain in patients with LSS, most previous studies on the spinal alignment of patients with LSS have been performed only in a static environment [10-13]. Few studies describe its relevance in dynamic conditions, such as gait. In our previous study [14], a significant correlation was found between the degree of lower limb pain and the maximum spinal extension angle during gait (r=0.688, p=0.038). Similarly, Kuwahara et al. [15] reported that patients with LSS who experienced more severe lower limb pain had a smaller trunk flexion angle during gait (r=−0.828, p=0.003). However, it is not clear how the differences in lower limb pain intensity are related to their lumbopelvic-hip alignment during gait.

The goal of this study was to clarify the relationship between the intensity of lower limb pain and dynamic lumbopelvic-hip alignment in patients with LSS using three-dimensional (3D) motion analysis. Our hypothesis was that increases in lower limb pain severity increase the lumbopelvic-hip malalignment.

Materials and Methods

1. Study design

This cross-sectional study was performed at a single hospital. All study participants provided written consent prior to data collection. This study was conducted with the approval of the institutional review board of Fukushima Medical University (approval no., general 29263). STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines were followed.

2. Participants

The particiants of this study were elective surgical candidates who presented to the Departments of Rehabilitation & Orthopaedic and Spinal Surgery, Aizu Medical Center, Fukushima Medical University (Aizuwakamatsu, Japan) between December 2016 and April 2021. The inclusion criteria were patients complaining of lower limb pain and/or numbness with neurogenic intermittent claudication, who had been diagnosed with LSS by a board-certified attending orthopedic spinal surgeon approved by the Japanese Society for Spine and Related Research. Those with sagittal malalignment, such as adult spinal deformity, a history of cerebrovascular and/or cardiovascular disease, dementia, and severe knee, and/or hip osteoarthritis, which made it difficult for the patient to carry out the experimental task, were excluded from the study.

3. Assessment of low back and lower limb pain

The Visual Analog Scale (VAS) was used to evaluate lower back and lower limb pain, with pain rated on a 100-mm line; 0 mm was equivalent to no pain and 100 mm indicated the maximum unbearable pain [16]. Participants were asked to subjectively rate the degree of pain experienced in their lower extremities during gait. The mean value of the ratings of all 30 participants was calculated; those with ratings higher than this mean value were assigned to the high-VAS group, whereas those with lower ratings were assigned to the low-VAS group.

4. Dynamic alignment measurement

A 3D motion analysis system, VICON MX (Vicon Motion System, Oxford, UK), was used to measure the dynamic lumbopelvic-hip alignment. Eight infrared cameras were also used. The sampling frequency was 200 Hz, and 35 reflection markers 14 mm in diameter were bilaterally attached to the landmarks on the body surface according to the Plug-In Gait Full-Body model (Fig. 1).

The experimental task and measurement were performed as follows: first, a 1.5×5.0 m walkway was prepared, and eight cameras were mounted on the ceiling, focusing on the walkway. Two force plates (AMTI, Watertown, MA, USA) were longitudinally placed on the walkway in the gait direction. The sampling frequency of each force plate was 1,000 Hz. Then, the participants were

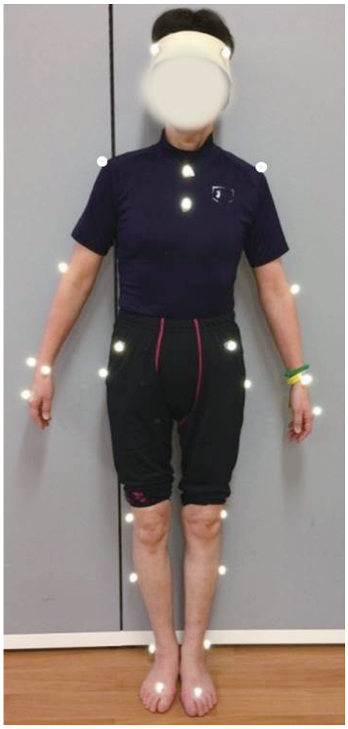

Fig. 1. The markers attached to a subject. Written informed consent for publication of this image was obtained from the patient.

asked to walk on the walkway at their normal pace. They were instructed to step on each of the force plates using the foot on the side with the more severe lower limb pain. One full gait cycle was recorded during each walk trial, and the task was repeated until data from three gait cycles were obtained.

5. Data processing

Vicon Nexus software (Vicon Motion System) was used to analyze the gait data. The following three segments were used for the analysis: (1) the thorax segment defined by four markers on the manubrium sterni, xiphisternum, spinous process of the seventh cervical vertebra, and spinous process of the tenth thoracic vertebra; (2) the pelvic segment defined by four markers on the left and right anterior superior iliac spine and posterior superior iliac spine; and (3) the thigh segment defined by two markers on the lateral thigh and lateral knee epicondyle. The angles of the thorax and pelvis were calculated in a global coordinate system. The angle of the spine was calculated as the mo-

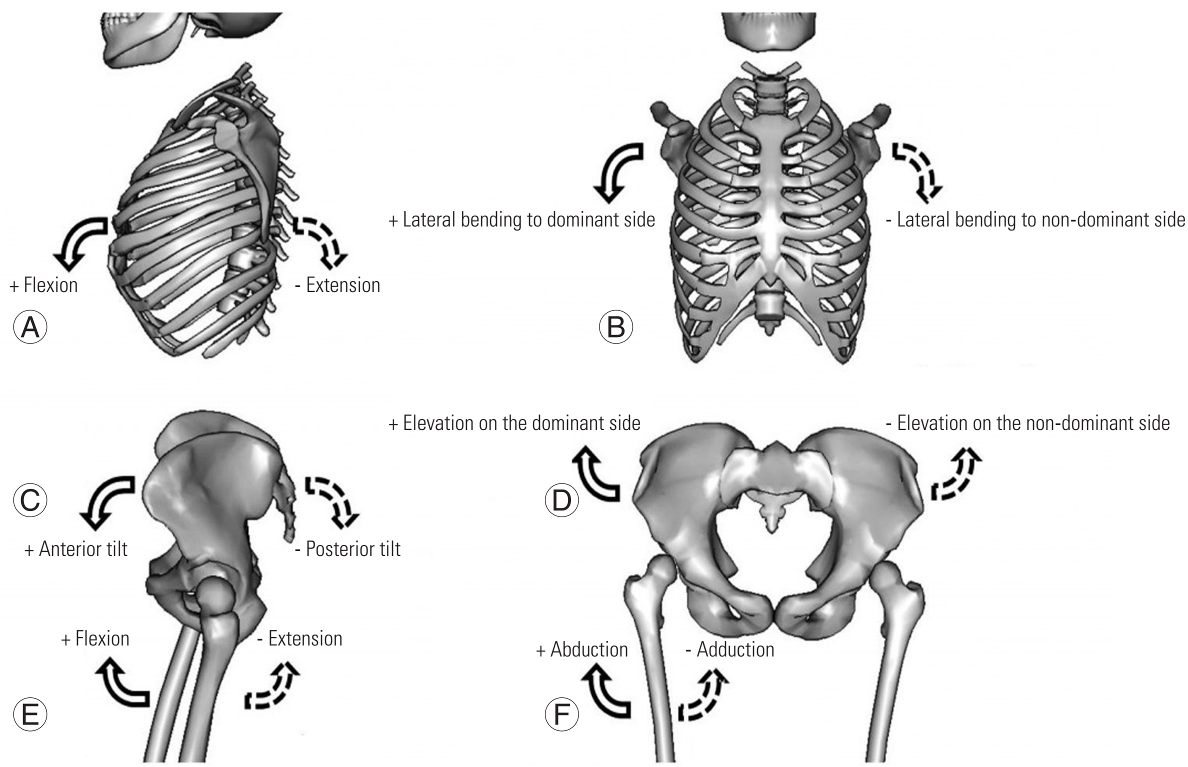

Fig. 2. The definition of positive (solid arrow) and negative (dotted arrow) values in each kinematic data. The spine angle in (A) the sagittal plane (positive: flexion, negative: extension) and (B) the frontal plane (positive, lateral bending toward the dominant side; negative, lateral bending toward the non-dominant side). The pelvic angle in (C) the sagittal plane (positive, anterior tilt; negative, posterior tilt) and (D) the frontal plane (positive, elevation on the dominant side; negative, elevation on the non-dominant side). The hip angle in (E) the sagittal plane (positive, flexion; negative, extension), and (F) the frontal plane (positive, abduction; negative, adduction). The dominant side means the side with the more severe lower limb pain.

tion of the thorax segment relative to the pelvic segment. In addition, the hip angle was calculated as the motion of the thigh segment relative to the pelvic segment.

The angle of each segment during gait was measured in two motion planes, the sagittal and frontal planes. The side with the more severe lower limb pain was defined as the dominant side. The definitions of positive and negative values in each set of kinematic data are shown in Fig. 2.

Data analysis was performed throughout a gait cycle, which was normalized to 100%. Segment data and one gait cycle were synchronized using the gait analysis software Polygon (Vicon Motion System) to obtain marker coordinate data. Those data and analog data from the two force plates were filtered (Butterworth 4th order-low pass filter; 6 Hz). After processing, the three trials were averaged to a single data set (101 data points) that was used for the statistical analyses.

6. Statistical analyses

The Oswestry Disability Index (ODI) and EuroQol-5 dimension (EQ-5D) system were used as patient-reported outcome measures related to QOL. In addition, the sagittal alignments of the spine (lumbar lordosis and thoracic kyphosis angle) and pelvis (sacral inclination angle) were measured on the body surface using a SpinalMouse (Index Ltd., Tokyo, Japan). In addition to QOL and sagittal alignment, age, height, weight, VAS of low back pain, VAS of lower limb pain, gait speed, cadence, and stride length in both groups were used for demographic analyses, and the angles of the spine, pelvis, and hip in both the sagittal and frontal planes were analyzed. Using Student paired *t*-tests, demographic and angle data were compared between the two groups. These angle data were compared every 10 points. IBM SPSS software ver. 26.0 (IBM Corp., Armonk, NY, USA) was used for statistical processing, and the statistical significance was set at $p<0.05$.

Results

Thirty patients with LSS (13 females) participated in this study. The mean age, height, and weight of the participants were 68.8±8.4 years, 159.4±10.5 cm, and 63.4±10.7 kg, respectively. The participant characteristics are shown in Table 1. There was a significant difference in the lower limb pain in the high-VAS group (n=16, 80.7±7.9 mm) and low-VAS group (n=14, 36.7±20.1 mm) ($p<0.01$), as well as in the ODI ($p=0.004$) and EQ-5D ($p<0.001$). However, there was no significant difference in age, height, weight, sagittal alignment of the spine and pelvis measured from the body surface, VAS of low back pain, walking speed, cadence, and stride length between the two groups (Table 1).

Table 1. Characteristics of the high-VAS and low-VAS groups

Characteristic	LSS patients (n=30)		*p*-value
	High-VAS (n=16)	Low-VAS (n=14)	
Age (yr)	69.1±6.6	67.5±9.9	0.57
Height (cm)	159.4±9.6	159.3±11.6	0.90
Weight (kg)	62.8±10.0	64.0±11.8	0.92
Sagittal alignment (°)			
Thoracic kyphosis	32.1±9.5	33.6±6.3	0.63
Lumbar lordosis	14.2±7.8	10.1±6.8	0.11
Sacral inclination	4.1±4.8	5.5±3.4	0.37
VAS			
Low back pain (mm)	52.0±25.4	30.0±26.0	0.07
Lower limb pain (mm)	80.7±7.9	36.7±20.1[a]	<0.01
Gait speed (m/sec)	0.82±0.14	0.77±0.15	0.27
Cadence (steps/m)	108.1±6.2	107.3±8.8	0.61
Stride length (m)	0.91±0.14	0.85±0.14	0.34
Oswestry Disability Index	43.2±11.7	29.3±12.2[a]	0.004
EuroQol-5 dimension	0.46±0.15	0.70±0.09[a]	<0.001

Values are presented as mean±standard deviation.
VAS, Visual Analog Scale; LSS, lumbar spinal canal stenosis.
[a]Significant difference between the two groups.

1. Relationship between lower limb pain intensity and spine angle

The sagittal spine angle of the high-VAS group was significantly extended compared to that in the low-VAS group during the entire gait cycle (Fig. 3A, Table 2). In the frontal plane, the high-VAS group significantly bent their spine to the dominant side between the initial contact (IC) and mid-stance phase (0%–30%), and between the terminal swing phase and IC (80%–100%) (Fig. 3B, Table 3).

2. Relationships between lower limb pain intensity and each pelvic and hip angles

The sagittal pelvic angle of the high-VAS group was significantly tilted forward compared to that of the low-VAS

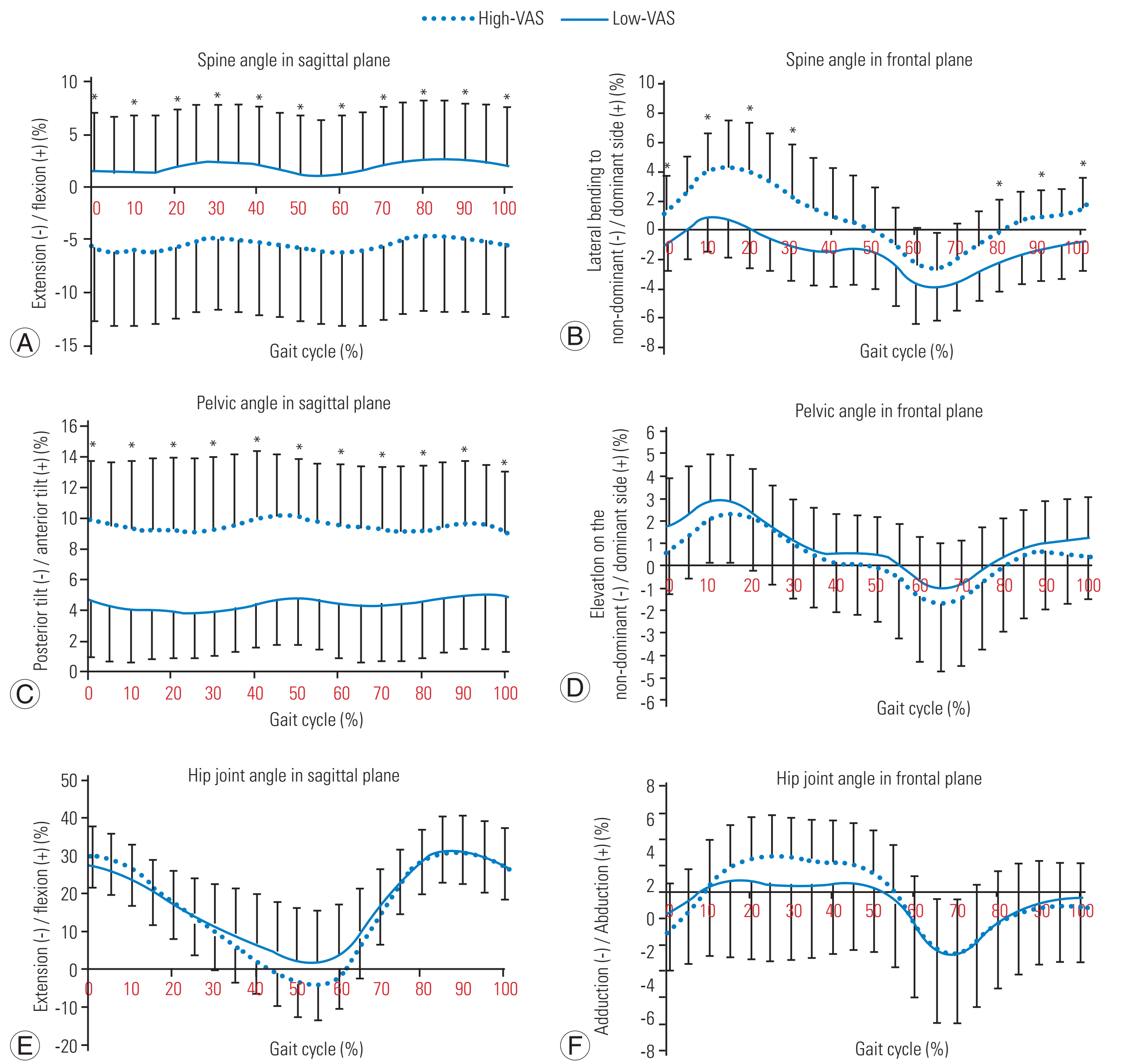

Fig. 3. Kinematic data of the spine **(A, B)**, pelvis **(C, D)**, and hip joint **(E, F)** during one gait cycle in a time series. The dotted lines represent the high-Visual Analog Scale (VAS) group, and the solid line represents the low-VAS group. The error bar represents ±standard deviation at each time point. Significant difference between the two groups (*p<0.05).

group during the entire gait cycle (Fig. 3C, Table 4). No significant difference was found in the frontal pelvic angle (Fig. 3D). There were no significant differences in the sagittal and frontal hip joint angles between the high- and low-VAS groups (Fig. 3E, F).

Discussion

This study is the first to characterize the alignment of the spine, pelvis, and hip during gait in terms of the intensity of lower limb pain in patients with LSS. We demonstrated that dynamic spinal and pelvic alignment was closely related to the intensity of lower limb pain. When walking, the spinal posture of patients with severe lower limb pain was more extended and more bent to the painful side, and their pelvic posture was tilted more anteriorly than those of patients with mild lower limb pain.

Crawford et al. [17] reported that poor alignment in the sagittal plane was associated with lower limb pain, based only on the X-P. In the kinematic analysis, Goto et

Table 2. The sagittal spine angle of the high-VAS and low-VAS groups in one gait cycle

Gait cycle (%)	High-VAS (n=16)	Low-VAS (n=14)	*p*-value	Effect size (95% CI)
0	-6.0±5.5	1.3±7.7	0.009[a)]	-1.116 (-1.939 to -0.274)
10	-6.3±5.3	1.2±7.6	0.007[a)]	-1.164 (-1.911 to -0.316)
20	-5.9±5.4	1.7±7.4	0.006[a)]	-1.185 (-2.015 to -0.335)
30	-5.1±5.4	2.2±7.5	0.009[a)]	-1.124 (-1.948 to -0.281)
40	-5.4±5.4	1.9±7.7	0.010[a)]	-1.109 (-1.930 to -0.267)
50	-5.9±5.5	1.1±7.8	0.012[a)]	-1.064 (-1.882 to -0.227)
60	-6.4±5.3	1.2±7.7	0.007[a)]	-1.172 (-2.00 to -0.323)
70	-6.0±5.3	1.8±7.6	0.005[a)]	-1.218 (-2.051 to -0.363)
80	-5.0±5.4	2.4±7.6	0.007[a)]	-1.150 (-1.976 to -0.304)
90	-5.2±5.2	2.4±7.6	0.006[a)]	-1.182 (-2.012 to -0.332)
100	-5.8±5.4	1.8±7.4	0.006[a)]	-1.186 (-2.016 to -0.335)

Values are presented as mean±standard deviation or effect size (95% CI), unless otherwise stated.
VAS, Visual Analog Scale; CI, confidence interval.
[a)]Significant difference between the two groups.

Table 3. The frontal spine angle of the high-VAS and low-VAS groups in one gait cycle

Gait cycle (%)	High-VAS (n=16)	Low-VAS (n=14)	*p*-value	Effect size (95% CI)
0	1.4±2.3	-0.9±1.9	0.011[a)]	1.082 (0.244 to 1.902)
10	4.0±2.6	0.9±2.4	0.004[a)]	1.261 (0.401 to 2.099)
20	3.9±3.4	0.03±2.5	0.004[a)]	1.264 (0.404 to 2.102)
30	2.2±3.6	-1.1±2.3	0.011[a)]	1.081 (0.243 to 1.901)
40	0.9±3.3	-1.4±2.4	0.062	0.771 (-0.038 to 1.564)
50	-0.04±2.9	-1.5±2.6	0.184	0.538 (-0.253 to 1.318)
60	-2.3±2.4	-3.6±2.6	0.211	0.506 (-0.283 to 1.285)
70	-2.0±2.4	-3.6±2.6	0.075	0.731 (-0.074 to 1.522)
80	-0.09±2.2	-2.2±2.1	0.022[a)]	0.964 (-0.138 to 1.773)
90	0.84±1.8	-1.4±2.1	0.007[a)]	1.155 (0.308 to 1.981)
100	1.6±2.0	-0.8±2.1	0.006[a)]	1.193 (0.342 to 2.024)

Values are presented as mean±standard deviation or effect size (95% CI), unless otherwise stated.
VAS, Visual Analog Scale; CI, confidence interval.
[a)]Significant difference between the two groups.

al. [18] found that the flexion angle of the thoracic spine increased, the pelvis tilted anteriorly, and the hip joint flexed significantly after gait compared to before gait in patients with LSS. Our results differed from these studies, suggesting that patients with LSS usually walk with a less extended spine angle, as the spinal canal becomes wider in a flexed position than in an extended position. The previous studies did not consider the effect of lower limb pain intensity, which may explain the divergent results. By dividing the participants into groups based on pain intensity, the differences in spine and pelvic alignment during gait between those with and without severe lower limb pain may have been elucidated.

Few studies have provided objective and quantitative data on the relationship between pain intensity and 3D kinematics during gait in patients with LSS. In our previous study, we reported a significant correlation between the degree of lower limb pain and the maximum spinal extension angle during gait in patients with LSS [14]. Kuwahara et al. [15] reported that the trunk flexion angle during gait was significantly smaller in patients with LSS than that in healthy elderly people, and that the small

Table 4. The sagittal pelvic angle of the high-VAS and low-VAS groups in one gait cycle

Gait cycle (%)	High-VAS (n=16)	Low-VAS (n=14)	*p*-value	Effect size (95% CI)
0	9.9±3.7	4.7±3.7	0.002[a)]	1.373 (0.499 to 2.224)
10	9.3±4.4	4.0±3.5	0.003[a)]	1.305 (0.440 to 2.148)
20	9.3±4.8	3.9±2.9	0.003[a)]	1.326 (0.458 to 2.171)
30	9.3±4.7	3.9±2.8	0.002[a)]	1.363 (0.490 to 2.213)
40	10.0±4.2	4.5±2.9	0.001[a)]	1.521 (0.627 to 2.391)
50	10.0±3.8	4.9±3.1	0.001[a)]	1.488 (0.599 to 2.354)
60	9.5±3.9	4.5±3.7	0.003[a)]	1.304 (0.439 to 2.146)
70	9.3±4.2	4.5±3.7	0.005[a)]	1.224 (0.368 to 2.057)
80	9.2±4.2	4.6±3.6	0.007[a)]	1.166 (0.318 to 1.993)
90	9.7±4.0	5.0±3.5	0.004[a)]	1.236 (0.379 to 2.071)
100	9.1±3.9	4.9±3.6	0.008[a)]	1.136 (0.291 to 1.960)

Values are presented as mean±standard deviation or effect size (95% CI), unless otherwise stated.
VAS, Visual Analog Scale; CI, confidence interval.
[a)]Significant difference between the two groups.

flexion angle of the thorax and lumbar spine was correlated with lower limb pain intensity in patients with LSS. They also pointed out that the trunk in patients with LSS with severe lower limb pain was more extended than in those with mild lower limb pain during gait. The results of this study are similar to those of the two previous studies on the relationship between the sagittal plane alignment of the spine and lower limb pain. In addition, this study newly revealed that not only the sagittal plane but also the frontal plane alignment of the spine was associated with lower limb pain.

The reported gait patterns of patients with LSS differ in the literature: a flexed lumbar spine during gait [18] versus an increased lumbar spine extension during gait [14]. Patients with LSS might have different types of kinematic patterns during gait. Igawa et al. [19] reported that these patients pick one of two different strategies during gait; either they walk with a flexed trunk, with simultaneously increased stride and hip extension angle, or they walk while extending the trunk and reducing both the stride and the hip extension angle. The results of this study supported the second strategy. The dynamic alignment of the hip joint was not significantly different between the VAS groups. Even in the low-VAS group, the hip extension angle was not wide. This may be because of the presence of lower limb pain and may be a compensatory gait adaptation when the spine is in the extended position. The results of this study may be more useful in the field of rehabilitation when applied to clinical practice. For example, for patients with LSS in conservative therapy, dynamic spinal alignment in a more extended position or dynamic pelvic alignment in a more anterior tilt may be associated with severe lower extremity pain. In such cases, physical therapists may be able to reduce the exacerbation of lower extremity pain by correcting the dynamic spinal and pelvic alignment during gait. In particular, it may be important to provide posture guidance during the walking phase, where significant differences were observed between the groups. However, it should be noted that this was a cross-sectional study, and therefore, causality cannot be mentioned.

This study has several strengths. First, the gait of patients with LSS was analyzed via a 3D motion analysis system. Until now, gait analysis in clinical practice has generally been based on physical therapists' visual or subjective perceptions. In contrast, the 3D motion analysis system has been used in many musculoskeletal fields and is widely recognized as a reliable and valid tool for joint kinematic and/or kinetic measurements. Second, the participants were divided into groups according to the degree of lower limb pain. Previous studies on the gait of patients with LSS have not considered the degree of symptoms or examined the effects of pain and functional impairment on gait in detail [15,18,19]. In contrast, this study focused on lower extremity pain, which clearly showed the difference in gait dynamics between patients with different degrees of symptoms. Third, this study recorded time-series data. The use of time-series data makes it possible to visualize the differences between patients with LSS with severe limb pain and those with relatively mild limb pain in any phase of gait, which may help clinicians better understand the results of this study.

Yet, these results must be considered in the context of the following study limitations. First, the sample size was too small to obtain reliable results. However, when the effect size was calculated for all comparisons as an index independent of sample size, the lowest effect size was 0.96, which was higher than 0.8, which is considered to be a large effect size. A post-test was performed with G*Power (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany; http://www.gpower.hhu.de/) using the effect sizes shown in Tables 2–4. As a result, the lowest power was 0.72. As this value is below 0.8, which is generally set as the desired test power, a type II error was likely [20]. This suggests that an increase in sample size may lead to the detection of additional differences between the two groups in our study. Second, there might be a selection bias. As all participants in this study were patients with LSS scheduled for surgery, they had relatively severe dysfunction. Therefore, different results may be obtained from patients with less severe impairment, such as those receiving conservative therapy. Third, no control group was prepared in this study. If healthy older adults were included as a control group, the results obtained would be more instructive to all healthcare professionals who treat patients with LSS.

Conclusions

Patients with LSS with severe pain in their lower extremities tend to have a spinal posture that is more extended and bent more laterally toward the painful side, and to have an anteriorly tilted pelvic posture. The results of this study can provide useful information for therapists who teach posture to patients with LSS.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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