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ORIGINAL ARTICLE

Quantification of Changes in Gait Characteristics Associated With Intermittent Claudication in Patients With Lumbar Spinal Stenosis

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Study Design: Cross-sectional observational study.

Objective: To quantify changes in gait characteristics associated with claudication after continuous walking, and to investigate the relationship between walking capacity and gait characteristics in patients with lumbar spinal stenosis (LSS).

Summary of Background Data: Walking difficulty due to pain or neurological symptoms accompanied by continuous walking may have negative effects on gait characteristics in patients with LSS. However, there are few detailed reports on the association of these changes with intermittent claudication and their relationship with walking capacity.

Methods: For this study, 11 LSS patients with intermittent claudication were recruited. The subjects continued walking until they expressed a difficulty in continuing further. Postural sway, autocorrelation peak (AC), stride frequency (SF), and coefficient of variance (CV) were analyzed using accelerometers. To detect changes in gait parameters, we compared acceleration at the start and at the end of the walking task.

Results: Walking difficulty during the test increased from 4 (interquartile range, 1–5) to 9 (interquartile range, 7–10). The postural sway significantly increased after the onset of maximum walking difficulty. AC, SF, or CV did not show significant change. Maximum walking distance significantly correlated with postural sway at the cervical sensor ($r = -0.64$), and CV ($\rho = -0.66$), an index of gait variability, at the beginning of the walking task.

Conclusions: The change in gait parameters associated with claudication during continuous walking is detectable using accelerometers. Postural sway increases after the provocation of walking difficulty due to pain or neurological symptoms. In addition, walking capacity correlated with postural sway of the upper trunk and gait variability during walking initiation. This methodology warrants further studies to confirm its usefulness as an assessment tool for patients with LSS.

Key Words: gait, intermittent claudication, lumbar spinal stenosis, accelerometer, walking capacity, walking difficulty, postural sway, gait variability

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Many people with lumbar spinal stenosis (LSS) have limited walking abilities due to pain or neurological symptoms associated with neurogenic claudication.[1] Limitations in walking ability, together with pain and related symptoms, restrict physical activity[2] and diminish health-related quality of life in patients with LSS.[3–5] Clinicians and researchers often measure walking ability when assessing functional status, treatment outcomes, and natural progression of LSS.[6] Thus, it is important to objectively and accurately quantify walking ability.

In general, walking capacity, for instance walking distance, is often assessed to quantify walking ability in people with LSS. Clinical tests, such as self-walking on a walkway or treadmill[6,7] and self-reported questionnaires[8–11] are often used to evaluate walking distance. Similarly, walking difficulty due to pain or neurological symptom accompanied by continued walking may have negative effects on gait characteristics in patients with LSS. However, there are few detailed reports on the changes in gait characteristics due to intermittent claudication. Quantification of changes in these characteristics resulting from intermittent claudication will enhance our understanding of LSS, and this information will enable us to create a new objective outcome to assess walking ability.

Recently, wireless, triaxial accelerometers are widely used for gait analyses, because they are simple and inexpensive and do not require a laboratory environment. It is

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possible to quantify gait characteristics, such as variability, stability, and regularity, by analyzing raw acceleration data collected during walking.[12] Gait analysis using an accelerometer enables us to clarify the relationship between gait characteristics and walking capacity in a setting similar to normal life. This information can also help us predict the walking capacity of LSS patients from their gait characteristics.

The aims of this study were as follows: (1) to quantify the changes in gait characteristics associated with claudication after continuous walking, and (2) to investigate the relationship between gait characteristics and walking capacity in patients with LSS using accelerometers.

MATERIALS AND METHODS

Participants

This was a cross-sectional observational study. The participants of this study were selected from among LSS patients with intermittent claudication. Eleven outpatients (8 males, 3 females; mean age = 72.8 ± 5.5 y; mean height = 162.2 ± 7.5 cm; mean body mass = 68.0 ± 12.9 kg; body mass index = 25.7 ± 3.3 kg/m^2) were recruited for this study (Table 1). The inclusion criteria was a clinical diagnosis of LSS by orthopedic surgeons. Diagnosis made was based on the review of patient history, physical examination, and confirmation of lumbar spinal canal stenosis on magnetic resonance imaging. All participants were required to have documented symptoms of neurogenic claudication (eg, pain, numbness, weakness, or tingling in the lower extremities brought on by lumbar extension, standing, or walking). Patients were excluded if they previously had a stroke, Parkinson disease, cervical spondylotic myelopathy, severe cardiovascular disease, chronic obstructive pulmonary disease, or sever osteoarthritis of the hip or knee. Subjects with arteriosclerosis obliterans were also excluded after assessment using the ankle brachial index. Of the 11 participants, 4 had cauda equina type neuropathy, 1 had nerve root type neuropathy, and 6 had combined type neuropathy. Each participant gave informed consent indicating their agreement with the study protocol. This research was approved by the Ethical Review Board of Kyoto University Graduate School of Medicine, Kyoto, Japan.

TABLE 1. Subject Demographics, Clinical Presentation (n = 11)

Variables	Mean (SD)
Age, y	72.8 (5.5)
Sex, % male	72.7
Height, cm	162.2 (7.5)
Weight, kg	68.0 (12.9)
Body mass index, kg/m^2	25.7 (3.3)
Duration of symptoms, y	2 (2–5)*
Self-reported walking distance, m	489 (393)
Walking difficulty, mm	53 (21)
JOA score	16 (13–18)*
ODI, %	34 (22–40)*

*Median (IQR).
IQR indicates interquartile range; JOA, Japanese Orthopaedic Association; ODI, Oswestry Disability Index.

Testing Procedures and Protocol

Study participants were instructed to walk 50 m on a horizontal walkway, and to return after reaching a cone indicating the end of the course. The participant walked repeatedly until they expressed difficulty in continuing. Collection of acceleration data, oral questionnaire pertaining to walking difficulty, and measurement of walking distance were performed at the beginning of the walking task and after every minute. Acceleration signals were recorded for 15 seconds for each recording and data from the first 10 seconds were used for analysis. The participants were asked the following question every minute to quantify walking difficulty: "How is your walking difficulty now?" with 0 denoting no difficulty and 10 denoting maximum difficulty. Walking distance was recorded by measuring the distance travelled along the walkway every minute to estimate walking speed and the maximum distance walked. To detect changes in gait parameters associated with neurological symptoms, we compared the acceleration features at the beginning and at the last walking measurement.

Apparatus

We used 2 triaxial accelerometers (model WAA-066, 17 g, 38 × 38 × 10 mm, 200 Hz sampling frequency; ATR-Promotions Co., Japan) to evaluate gait characteristics. One terminal was attached over the L3 region close to the patients' center of mass during quiet standing,[13] and the other was attached over the C7 region on the skin with surgical tape (Fig. 1) to assess upper trunk movement. The testing reliability of trunk accelerometry during walking has been confirmed previously.[14] The measurements that signified change in direction at both ends of the walkway were excluded.

Data Processing

We selected the following gait parameters to analyze, based on previous studies: root mean square (RMS),[13] autocorrelation peak (AC),[15] stride frequency (SF),[15] and coefficient of variance (CV) of accelerometer peak interval.[16]

The RMS value indicates postural sway during walking; thus, a higher RMS value represents postural instability. In this study, we used RMS data only in the mediolateral direction to eliminate gravitational artifacts due to postural changes and anterior tilting of the upper trunk associated with intermittent claudication. The AC value indicates interstride trunk acceleration variability. The AC function estimates how a time series is correlated with itself over different time period. The SF value indicates the frequency of gait cycle. Our analysis program uses a fast Fourier transformation to convert the acceleration signal to the fundamental frequency of periodic movement: step frequency. By definition, a complete

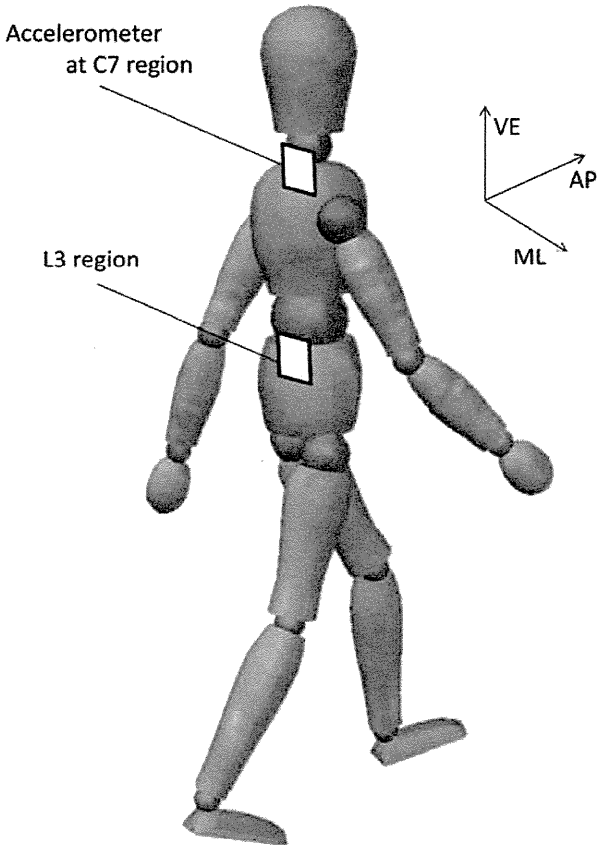

FIGURE 1. Instrument placement and acceleration sign convention. AP indicates anterior-posterior direction; ML, mediolateral direction conversion; VE, vertical direction.

stride includes 2 steps; thus, SF was calculated as half the fundamental frequency and is expressed in Hz. The CV value indicates the gait variability (ie, the variability in elapsed time between the contact of 2 consecutive footfalls). To calculate gait parameters except for RMS, we used the absolute values from the triaxial acceleration data.

The RMS of acceleration data $a_{t_1:t_n}$ was calculated as follows:

$$\mathrm{RMS}=\left(\frac{\int_{t_1}^{t_n} a(t)^2 dt}{t_n-t_1}\right)^{1/2}$$

Here, t_1 and t_n, respectively, denote the start time and the stop time of our gait analysis measurement. To eliminate the walking speed effect, the RMS was normalized by dividing by the square of the walking speed.[17]

The AC was calculated as follows:

$$\mathrm{AC}=\frac{1}{N-|m|}\sum_{i=1}^{N-|m|} X_{t_i}+X_{t_{i+m}}$$

Here, N denotes the number of acceleration data samples, and m indicates increasing time lag. X_t denotes normalized acceleration data, which was calculated by both the mean (a_{mean}) and SD (a_{SD}) of the acceleration data $a_{t_1:t_n}$:

$$X_{(t)}=\frac{a(t)-a_{\mathrm{mean}}}{a_{\mathrm{SD}}}$$

The CV was calculated from the means (t_{mean}) and SD (t_{SD}) of the time intervals as follows:

$$\mathrm{CV}=\frac{t_{\mathrm{SD}}}{t_{\mathrm{mean}}}\times 100$$

Clinical Measurement

The Japanese Orthopedic Association's (JOA) evaluation system for lower back pain syndrome (JOA score, full mark: 29 points) was used as an overall assessment, including subjective symptoms (lower back and leg pain) and clinical signs (sensory and motor disturbance)[18] (Table 2). The Oswestry disability index was also used to assess subjective clinical symptoms and function.[19] A 100 mm visual analog scale for walking difficulty adapted from Yamashita et al[20] was included. Subjects were asked to mark the 100 mm line in response to the statement, "indicate how much difficulty in walking you have had during the past week, with 0 denoting no difficulty and 100 denoting maximum difficulty." Furthermore, the subjects were asked to assess walking capacity as follows,[6] "If you were to go for a walk today, how far would you be able to walk at your own pace, on level ground, before being forced to stop due to symptoms of LSS?"

Statistics

The Kolmogorov-Smirnov test was used to test the normality of distributions. To determine the gait change after the onset of claudication, a paired t test was used for continuous variables with normal distribution, and Wilcoxon rank-sum test was used for non-normally distributed variables. To estimate effect size, Cohen d was used for the t test, and r was used for Wilcoxon rank-sum test.

The relationship between the maximum walking distance and gait characteristics at the beginning of the walking task was analyzed using Pearson correlation coefficient or Spearman rank correlation coefficient. SPSS (Windows version 19.0; SPSS Inc., Chicago, IL) software was used for data analyses, and statistical significance was set at $P < 0.05$.

RESULTS

Maximum walking distance was 548 ± 470 m, and walking difficulty during the test increased from 4 (interquartile range, 1–5) to 9 (interquartile range, 7–10) ($P < 0.01$, $r = 0.89$). Although the walking speed tended to decrease at the end of the walking task, the difference was not statistically significant ($P = 0.21$, $d = 0.23$) (Table 3).

The RMS at the cervical and lumbar sensors increased significantly after the onset of maximum walking difficulty (cervical sensor: $P < 0.01$, $d = 0.75$; lumbar sensor: $P < 0.05$, $d = 0.60$) (Table 3). Acceleration waveforms in the mediolateral direction at the cervical

TABLE 2. The JOA Evaluations System for Lower Back Pain Syndrome (JOA Score)

Symptoms and Signs	Evaluation	Score
Subjective symptoms		
Lower back pain		
	None	3
	Occasional mild pain	2
	Occasional severe pain	1
	Continuous severe pain	0
Leg pain and/or tingling		
	None	3
	Occasional slight symptoms	2
	Occasional severe symptoms	1
	Continuous severe symptoms	0
Gait		
	Normal	3
	Able to walk farther than 500 m although it results in symptoms	2
	Unable to walk farther than 500 m	1
	Unable to walk farther than 100 m	0
Clinical signs		
Straight leg raising test		
	Normal	2
	30–70 degrees	1
	< 30 degrees	0
Sensory disturbance		
	None	2
	Slight disturbance (not subjective)	1
	Marked disturbance	0
Motor disturbance		
	Normal	2
	Slight weakness (MMT 4)	1
	Marked weakness (MMT 3–0)	0

	Severe	Moderate	None
Restriction of ADL			
Turn over while lying	0	1	2
Standing	0	1	2
Washing	0	1	2
Leaning forward	0	1	2
Sitting (about 1 h)	0	1	2
Lifting or holding heavy objects	0	1	2
Walking	0	1	2
Urinary bladder function			
Normal		0	
Mild dysuria		−3	
Severe dysuria		−6	

ADL indicates activity of daily living; JOA, Japanese Orthopaedic Association; MMT, manual muscle testing.

sensor in 1 representative patient are shown in Figure 2. AC, SF, or CV did not change significantly ($P \geq 0.05$) (Table 3).

Correlation coefficients between maximum walking distance and gait characteristics at the beginning of the walking task are shown in Table 4. The maximum walking distance was significantly correlated with RMS at the cervical sensor ($r = -0.64$), and CV ($\rho = -0.66$).

DISCUSSION

The present study investigated changes in gait characteristics associated with intermittent claudication in patients with LSS. To our knowledge, this is the first study to quantify these changes during a walking task in LSS patients. The main findings of this study are as shown below: the changes in gait parameters are detectable using accelerometers and postural sway during walking increased after the onset of walking difficulty. Finally, walking capacity correlated with postural sway in the upper trunk and gait variability at the beginning of the walking task.

Walking ability in LSS patients has previously been quantified using self-walking distance tests or walking distance questionnaires. Although these measurements can quantitatively assess walking capacity, they cannot evaluate changes in gait characteristics. For this purpose, gait analysis using force plates has been performed in LSS patients.[21] However, this aforementioned study included a simple comparison of gait characteristics between LSS patients and healthy controls and could not demonstrate changes associated with the onset of claudication during actual walking tasks. The present study demonstrated that gait analysis using accelerometers enables quantification of changes in gait characteristics in LSS patients during continuous walking. The RMS, which increased in

TABLE 3. Changes in Gait Parameters Before and After the Appearance of Augmentation of Walking Difficulty (n = 11)

Variables	Sensor Position	Before	After	*P*	Effect Size
Walking feature					
Walking speed, m/s	—	1.01 (0.17)	0.96 (0.17)	0.21	0.23
Walking difficulty during test	—	4 (IQR, 1–5)	9 (IQR, 7–10)	< 0.01	0.89
Maximum walking distance, m	—	—	548 (470)	—	—
Accelerometer feature					
RMS, g	Neck	0.16 (0.07)	0.23 (0.11)	< 0.01	0.75
	Lumbar	0.16 (0.06)	0.20 (0.10)	0.04	0.60
Autocorrelation coefficient	Neck	0.77 (0.13)	0.74 (0.12)	0.53	0.25
	Lumbar	0.68 (0.14)	0.66 (0.15)	0.64	0.14
Stride frequency, Hz	Lumbar	1.00 (0.04)	0.99 (0.06)	0.22	0.38
Coefficient of variance	Lumbar	6.1 (IQR, 3.6–7.5)	7.1 (IQR, 3.2–16.5)	0.16	0.16

Mean (SD) or median (IQR).
Effect size: Cohen *d* was used for *t* test, and *r* was used for Wilcoxon rank-sum test.
IQR indicates interquartile range; RMS, root mean square (which indicates postural sway).

the present study, represents stability during walking. The postural sway during walking increases in older adults[22] and diabetic patients.[23] The provocation of postural sway in the present study indicates that walking stability deteriorates with the onset of neural symptoms in LSS patients. Menz et al[24] demonstrated a correlation between walking stability and sensorimotor function, including proprioception and lower limb strength. We deem that the neurological symptoms associated with intermittent claudication likely decreased sensorimotor function in the lower limbs of LSS patients and increased postural sway. Senden et al[25] demonstrated that postural sway in older adults with greater fall risk was higher than in older adults without the same fall risk. In addition, Kim et al[26] reported an increase in fall risks in LSS patients. Although we cannot conclude a definitive relationship between falling and increased postural sway, walking with neural symptoms may increase the risk of falling in LSS patients. Hence, further studies should focus on detailed evaluation of gait changes after continuous walking in patients with LSS, especially in relation to their walking capacity and risk of falling.

Before the current study, we hypothesized that gait characteristics, such as AC, SF, and CV would change at the pain onset or other neurological symptoms. However, there were no significant changes in these parameters. This result may indicate that LSS patients can keep the walking cycle or rhythm even with increased neurological symptoms. The small sample size used in this study, however, carries a risk of statistical type II error and thus requires a cautious interpretation.

Walking capacity was significantly correlated with postural sway at the cervical and CV. Intermediate grade correlation ($r = -0.55$) was also implied for postural sway at the lumbar with borderline significance ($P = 0.08$). Suda et al[21] reported that postural sway

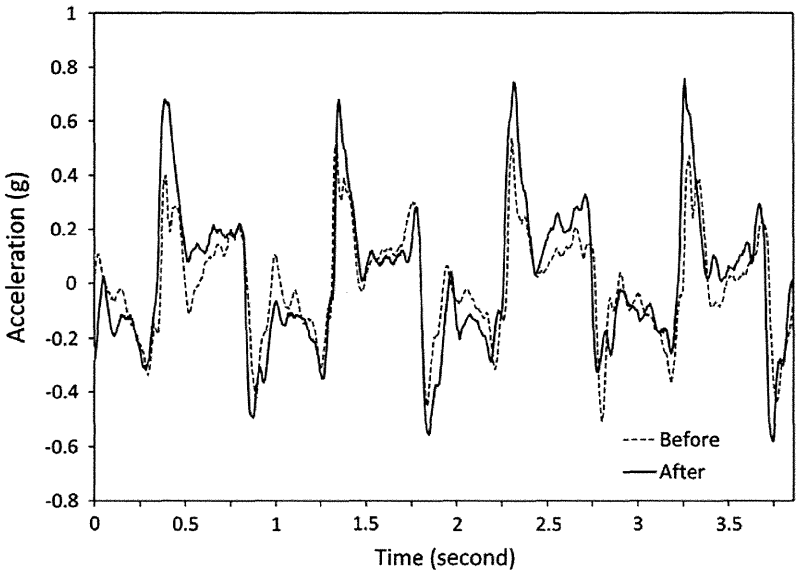

FIGURE 2. Acceleration waveforms in the mediolateral direction at the cervical sensor in 1 representative patient before and after the provocation of walking difficulty.

TABLE 4. Correlation Coefficient Between Maximum Walking Distance and Gait Characteristic at the Beginning of the Walking Task (n = 11)

Variables	Sensor Position	Correlation Coefficient	*P*
RMS	Neck	−0.64*	0.03
	Lumbar	−0.55*	0.08
Autocorrelation coefficient	Neck	0.37*	0.26
	Lumbar	0.53*	0.10
Stride frequency	Lumbar	0.43*	0.19
Coefficient of variance	Lumbar	−0.66†	0.03

*Pearson correlation coefficient.
†Spearman rank correlation coefficient.
RMS indicates root mean square (which indicates postural sway).

assessed using force plates during walking was greater in LSS patients than in healthy people and another study demonstrated that gait variability increased in LSS patients.[27] Postural sway and gait variability may increase according to LSS progression and disease condition. In this study, postural sway and gait variability possibly reflected the severity of the disease and thus correlated with walking capacity. To our knowledge, few studies have reported the relationship between walking capacity and gait characteristics. The present results propose the usability of accelerometer as an assessment tool in a clinical setting. Multivariable analysis with larger sample size should establish the predictive role of gait characteristics assessed with accelerometers for walking capacity. Depending on positive results, this method can replace the standard assessment of maximum walking distance which is often difficult for LSS patients.

A potential weakness of this study is a lack of kinematic data. There is the possibility that trunk posture or lower limb movement changed during the walking test according to the onset of claudication; we could not quantify these parameters by accelerometers. However, the acceleration parameters are not greatly affected by kinematic change; therefore, the present results remain reliable to some extent as an assessment of gait changes in patients with LSS. Further studies are needed to obtain a detailed understanding of gait parameters including kinematics in LSS patients. Gait characteristics according to neuropathy types, for example, cauda equina type, nerve root type, or combined type, is another important issue to be addressed in future studies.

In clinical site, older patients with symptomatic stenosis often have several comorbidities (eg, other orthopedic diseases, visual disturbance, balance disorder). Causes of gait disturbance in LSS are also various; for example, leg pain, sensory disturbance, muscle weakness, and psychological factors. Therefore, to adopt the present result to all patients with LSS should be cautious at this moment. In addition, our findings do not indicate the usefulness of measurement technique for prediction of stenosis symptom, or for assessment of surgical treatment.

In conclusion, we demonstrated that change in gait parameters associated with intermittent claudication during continuous walking is detectable using accelerometers, and postural sway increases after the provocation of walking difficulty due to pain or neurological symptoms. In addition, walking capacity correlated with postural sway in the upper trunk and gait variability at the beginning of the walking task. This method warrants further studies to confirm its usefulness as an assessment tool for LSS patients.

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