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Analysis of characteristics required for gait evaluation of patients with knee osteoarthritis using a wireless accelerometer

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ABSTRACT

Background: Knee osteoarthritis (KOA) is associated with reduced quality of life due to knee pain and gait disturbance. However, the evaluation of KOA is mainly based on images and patient-reported outcome measures (PROMs), which are said to be insufficient for functional evaluation. Recently, gait analysis using an accelerometer has been used for functional evaluation of KOA patients. Nevertheless, evaluation of the entire body motion is insufficient. The aim of this study was to clarify the gait characteristics of KOA patients using the distribution of scalar products and the interval time of heel contact during spontaneous walking and to compare them with healthy subjects.

Methods: Participants wore a three-axis accelerometer sensor on the third lumbar vertebra and walked for 6 min on a flat path at a free walking speed. The sum of a composite vector (CV) scalar product and a histogram for distribution were used for body motion evaluation. The CV consisted of a synthesis of acceleration data from three axes. In addition to the summation of the CV, a histogram can be created to evaluate in detail the magnitude of the waves. The amount of variation was measured in the left–right and front–back directions. Variability was evaluated from the distribution of heel contact duration between both feet measured from the vertical acceleration.

Results: KOA patients showed a smaller sum of CV that converged to small acceleration in the distribution when compared with healthy subjects. In the KOA group, the amount of variation in the forward and backward directions was greater than that in the forward direction. The variability of heel–ground interval time was greater in the KOA group than in healthy subjects.

Conclusion: KOA patients walked with less overall body movement, with limited movable range of the knee joint and pain-avoiding motion. The gait of the KOA group was considered unstable, with long time intervals between peaks. The increase in the amount of forward variation was thought to be due to the effect of trunk forward bending during walking. The clinical relevance of this study is that it was possible to evaluate KOA patients' gait quantitatively and qualitatively.

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1. Introduction

Knee osteoarthritis (KOA) is generally associated with pain and gait disturbance due to joint deformity [1]. Symptoms of KOA are found in 10% of men and 13% of women over the age of 60 years [2]. KOA causes not only pain, but also gait disorders, leading to a decrease in quality of life. Patient-reported outcome measures (PROMs) are routinely used to evaluate the efficacy of KOA treatment [3]. However, PROMs are mainly for evaluation of pain and are insufficient for evaluation of function. Conversely, quantification of patients' daily behavior is useful for assessing prognosis and the effect of rehabilitation [4]. KOA gait patterns, the spatiotemporal parameters of gait, change to replicate redress strategies to decrease joint pain [5,6]. Recently, gait analysis using a three-axis acceleration sensor has become more widely used in the orthopedic and rehabilitation fields. This sensor can use wireless technology and is less expensive than previous large-scale test facilities [5]. Furthermore, research into KOA using accelerometers has focused on comparing the spatiotemporal parameters, such as stride length and speed [6,7]. Many reports of KOA gait analyses using accelerometers have not analyzed body movements, such as the magnitude of acceleration [8,9]. Previous studies have used root mean square (RMS) scalar values to determine the magnitude of body motion acceleration and the amount of fluctuation [8–10]. The RMS value is relatively easy to use and appears to be the most constant parameter [10]. Nevertheless, the RMS value may underestimate the true impulse load factor, because it is not necessarily sensitive to large inherent fluctuations [11]. It may be important to evaluate not only the magnitude of RMS scalar values, but also the distribution of acceleration in order to measure the amount of fluctuation in gait. Therefore, evaluation of the distribution of the RMS scalar values in the overall assessment of KOA patients' gait has not been sufficiently investigated at this time.

The purpose of this study was to clarify the characteristics of the entire gait of KOA patients, including the distribution of scalar magnitude and time variability of heel contact using accelerometers.

2. Materials & methods

2.1. Participants

The participants included 20 patients with KOA aged 52–82 years who required surgery (Table 1). All participants in the KOA group had unilateral KOA. The degree of progression of patients with KOA was confirmed using the Kellgren–Lawrence radiographic grade (KL grade) from simple X-ray images. The KL grade was III or IV in the KOA patients. All participants were diagnosed by experienced orthopedic surgeons at Iwate Medical University Hospital. Exclusion criteria were cerebral infarction, cardiopulmonary disease, neurological diseases such as cervical myelopathy, and gait disorders not related to KOA, such as Parkinson's disease, spinal stenosis, and diabetic neuropathy. Knee OA subjects did not include individuals with impaired gait, such as due to low back pain, hip OA, and other leg abnormalities. However, the areas other than the knee were not confirmed by X-ray examination. For other symptoms, the presence or absence of symptoms was confirmed by medical records and verbally. Knee OA subjects had OA changes in both the tibia and femur, and only medial OA was examined in the present study. However, the period of pain during gait examinations and in daily life was not recorded. In addition, the degree of knee extension of knee OA patients was measured using a goniometer. The healthy volunteer group had no diseases and no gait disorders. Height, weight, and body mass index (BMI) were measured in all participants. The Knee injury and Osteoarthritis Outcome Score (KOOS) was also calculated for each participant as an index of knee joint disease [3,4].

This study was approved by the Ethics Committee of Iwate Medical University School of Medicine (IRB: MH 2020-196). Informed consent was obtained from all subjects.

2.2. Procedures

A three-axis acceleration sensor (Q'z TAG Research: Sumitomo Electric Industries, Osaka, Japan; weight: 15 g, dimensions: $41 \times 41 \times 15$ mm^3) was used to evaluate gait characteristics. All data from the wireless acceleration sensors were recorded in a personal computer (PC). The obtained walking data could be wirelessly sent to a PC via Bluetooth. The sampling rate of

Table 1
Characteristics of subjects in this study.

Subjects	Age (y)	N & Sex (M:F)	Height (cm)	Mass (kg)	BMI (kg/m^2)	KL Grade	Knee Extension
Healthy	63.4 ± 10.4	13 (5:8)	160.7 ± 9.9	65.1 ± 9.8	25.3 ± 4.7	–	1.2 ± 3.2
Knee OA[a]	66.7 ± 8.8	20 (5:15)	157.5 ± 10.2	68.2 ± 15.7	27.3 ± 5.1	iii 8 iv 12	7.2 ± 5.3
Left KOA	65.7 ± 7.5	10 (3:7)	157.7 ± 11.0	64.6 ± 13.6	25.7 ± 3.2	iii 3 iv 7	8.5 ± 5.5
Right KOA	67.6 ± 9.9	10 (2:8)	157.2 ± 9.4	71.7 ± 16.9	28.9 ± 6.1	iii 5 iv 5	6.0 ± 4.8

[a] Including Left and Right Knee OA patients. Mean ± standard deviation (SD) of each indicator is shown. OA: Osteoarthritis, KOA: Osteoarthritis of the knee, N: number of total subjects in each group. M: number of males, F: number of females, BMI: body mass index. KL Gade: Kellgren Lawrence grading.

acceleration data was set to 200 Hz [12]. The sensor was affixed with athletic tape directly to the skin on top of the spinous process of L3, as shown in Figure 1 [10]. The accelerometer was set to ±0 level with the participants in a standing and resting position just before the measurement. According to the method advocated by the Osteoarthritis Research Society International (OARSI), the patient was asked to walk continuously for 6 min [13]. All subjects were instructed to walk along a 25-m horizontal walkway as safely as possible at around walking speed and to return after reaching a cone indicating the end of the course. For the purpose of confirming the walking movement, the gait of each subject was also recorded by a digital video camera in all studies.

2.3. Data analysis

Microsoft Excel 2016 (Microsoft Corp, Redmond, WA, USA) was used for all data analyses. For the acceleration data, data were sampled from 1000 points from 2 min after walking started (Figure 2). All sampled data excluded some parts of the deceleration, acceleration, and gait turning points as identified from the captured video.

$$CV(n) = \sqrt{X(n)^2 + Y(n)^2 + Z(n)^2} \quad n = 1, 2, 3 \cdots 1000. \tag{1}$$

A composite vector scalar product (CV) was created by synthesizing all three directions (see Eq. (1) and Figure 1) [11]. The CV was used to assess the magnitude of body movement during gait. The sum of the CV of each 1000 points was calculated to compare quantitative differences between healthy and KOA subjects (Figure 3). The acceleration data of gait consisted of slow and fast components. Therefore, the histogram of CV scalars (including mean and standard deviation) should identify a qualitative difference between healthy and KOA groups (Figure 4).

$$RMS = \sqrt{\frac{1}{N}\sum_{i}^{N} acc(i)^2} \quad i = 1, 2, 3, \cdots 1000. \tag{2}$$

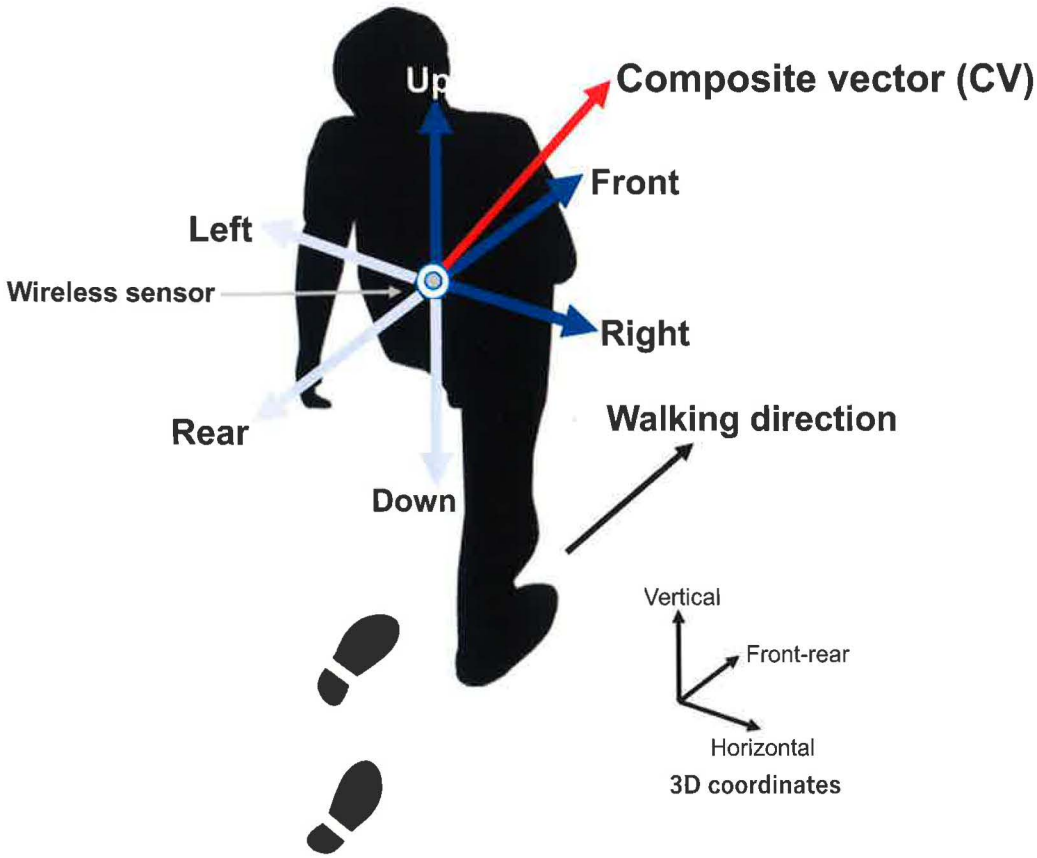

Figure 1. Position of a wireless sensor fixed directly to the skin above the L3 spinous process with athletic tape during walking. The composite vector scalar was obtained from vertical, horizontal, and front–rear acceleration data.

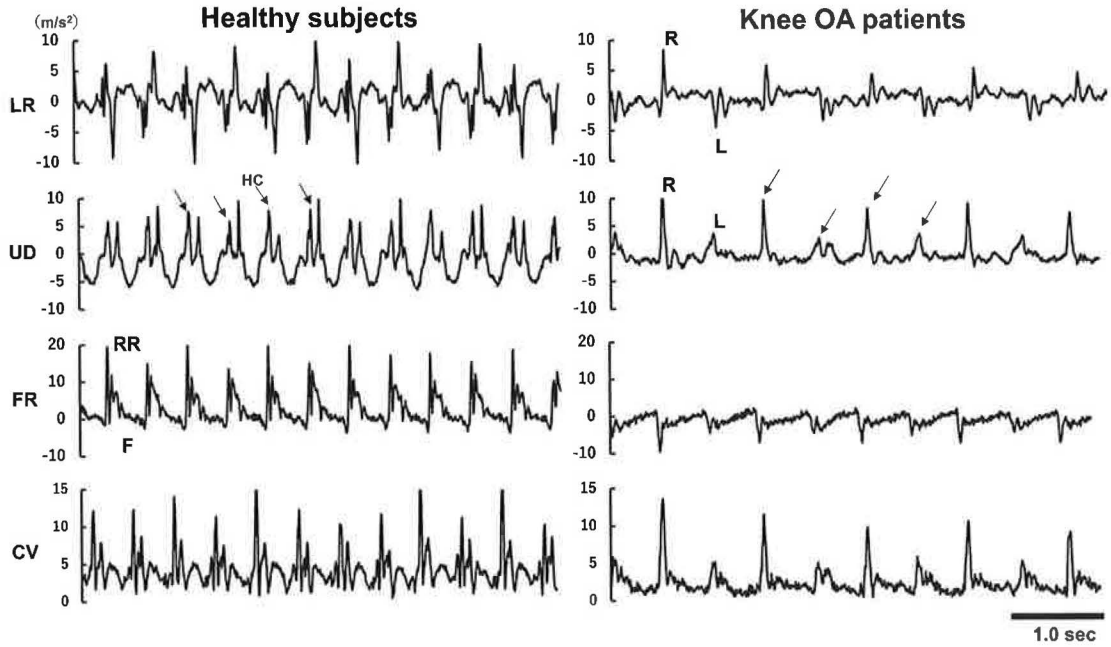

Figure 2. The raw data of the left–right (LR), up–down (UD), front–rear (FR), and composite vector scalar (CV) acceleration of a healthy subject and a knee osteoarthritis (OA) patient are shown. F, front; HC, heel contact; L, left; R, right; RR, rear. Arrow: the heel contact timing is detected from the UD-axis acceleration data.

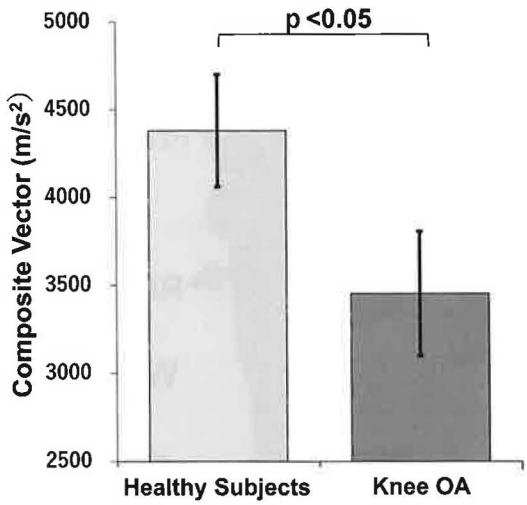

Figure 3. Data comparing mean and standard deviation of composite vectors between healthy subjects and knee osteoarthritis (OA) patients are shown. There was a significant difference between the groups ($P < 0.05$).

The acceleration data in each direction were calculated to scalars using the RMS to compare the left–right and forward–rear differences (see Eq. (2) and Figs. 5 and 6). The results for each direction were summed, and the results for the healthy subjects and the KOA groups were compared.

The mean and standard deviation values of the step interval time were used to compare the healthy and KOA groups. The peaks of heel contact were detected from vertical acceleration data (Figure 1). Furthermore, peak-to-peak intervals (PPIs) were also measured from the peak detection data, and the mean and standard deviation were calculated in each group (Table 2). The variations of heel contact interval times between KOA (L-OA and R-OA) patients and healthy subjects were compared from the Poincare plot in Figure 7 [14]. In the Poincare plot, the x-axis was set to PPI_k, and the y-axis was set to PPI_{k+1}, and the previous and next interval data were plotted as one set.

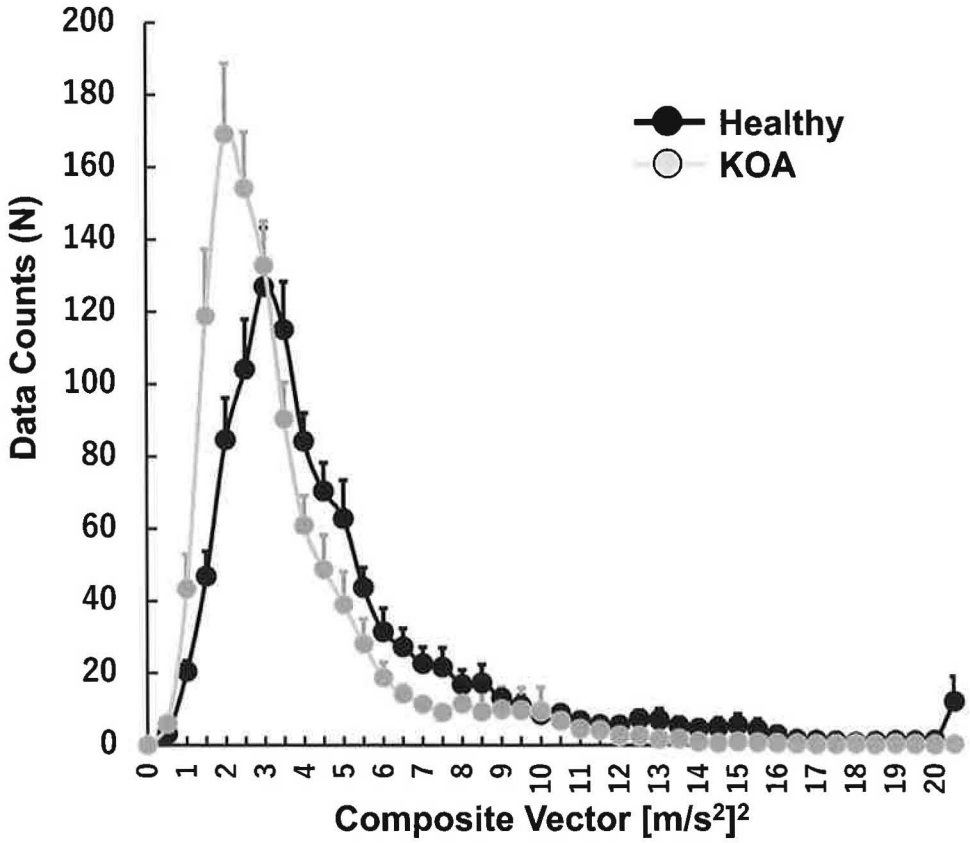

Figure 4. Counts of composite vector values are presented as the distribution of histograms from sampled acceleration data during gait in both healthy and knee osteoarthritis (KOA) subjects. Mean and standard deviation values are shown. There is a significant difference between healthy and KOA distributions (analysis of variance, $P < 0.05$).

2.4. Statistical analysis

Student's *t*-test was used to compare quantitative acceleration between KOA patients and healthy volunteers. A paired *t*-test was used for the time series data. We used a comparison of histogram distributions between KOA and healthy CVs of acceleration data. SPSS (ver. 21.0, IBM Corp., Armonk, NY, USA) was used for statistical analysis, with the level of significance set at $P < 0.05$.

3. Results

The clinical information and measurement results for the KOA patients and healthy volunteers are presented in Table 1. The mean age of the patients with KOA was 66.7 ± 8.8 years, and that of the healthy volunteers was 63.6 ± 10.4 years. The mean BMI values of the patients with KOA and healthy volunteers were 27.3 ± 5.1 kg/m^2 and 25.3 ± 4.7 kg/m^2, respectively. The number of KL grade components in the KOA group is also shown in Table 1. The average loss of extension was 7.2 ± 5.3 degrees in patients with knee OA. Thus, no significant difference was found in either of these factors. Figure 2 shows characteristic raw waveforms from a healthy subject and a KOA patient. In the left–right waveforms, the magnitude of acceleration decreased more in the KOA group than in the healthy group. In the up–down waveforms, the magnitude of acceleration of the KOA group was decreased on the affected side compared with the healthy group. In the anterior–posterior waveforms of the healthy group, the baseline acceleration was generally shifted more posteriorly. In the CV waveform of the KOA group, the magnitude of acceleration was generally smaller and more pronounced on the affected side. The total value of the three-way RMS CV was smaller in the KOA group (Figure 3). There was a significant difference between the two groups ($P < 0.05$). The histograms of the three-way CV are shown in Figure 3. The knee OA patients had more small accelerations than the healthy subjects, and the accelerations converged to 2–3 $(m/s^2)^2$. The comparisons of the differences in the subjects between right and left accelerations are shown in Figure 5. There was no significant right–left difference in the healthy, KOA, L-OA, and R-OA groups. The L-OA groups had a significant difference in the lateral direction of acceleration ($P < 0.05$). In particular, acceleration was larger on the right side than on the left side in L-OA. Comparing the values of right and left accelerations,

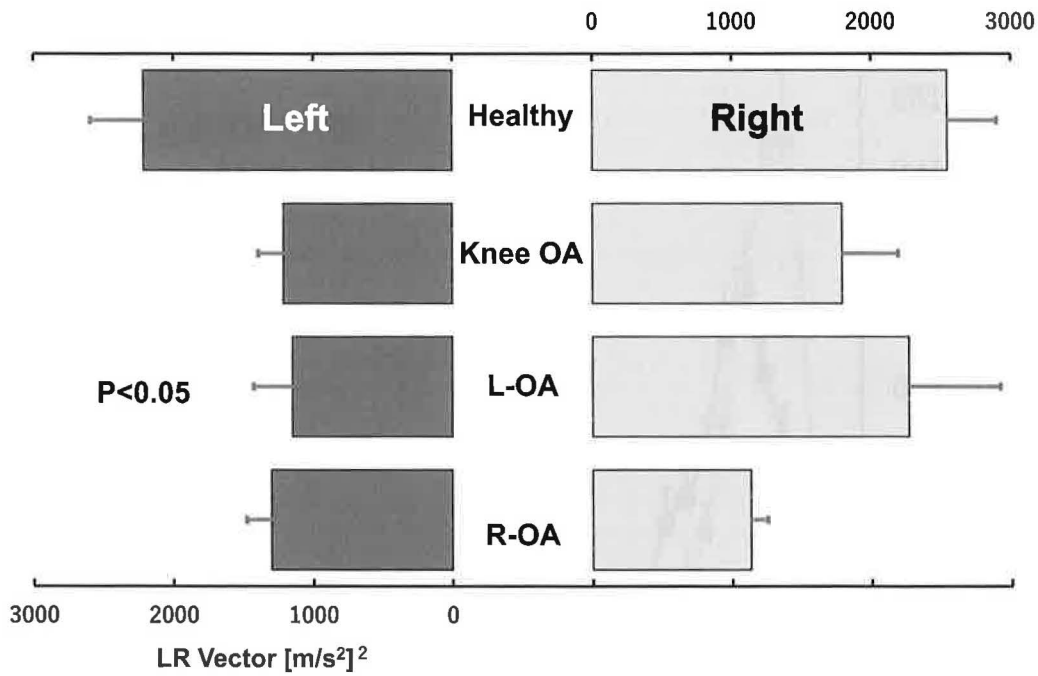

Figure 5. The mean and standard deviation values of left and right variations of four groups (healthy, knee osteoarthritis (OA), left OA (L-OA), and right OA R-OA)) are shown. There were no significant differences in the groups other than left OA ($P < 0.05$). LR: Left and Right.

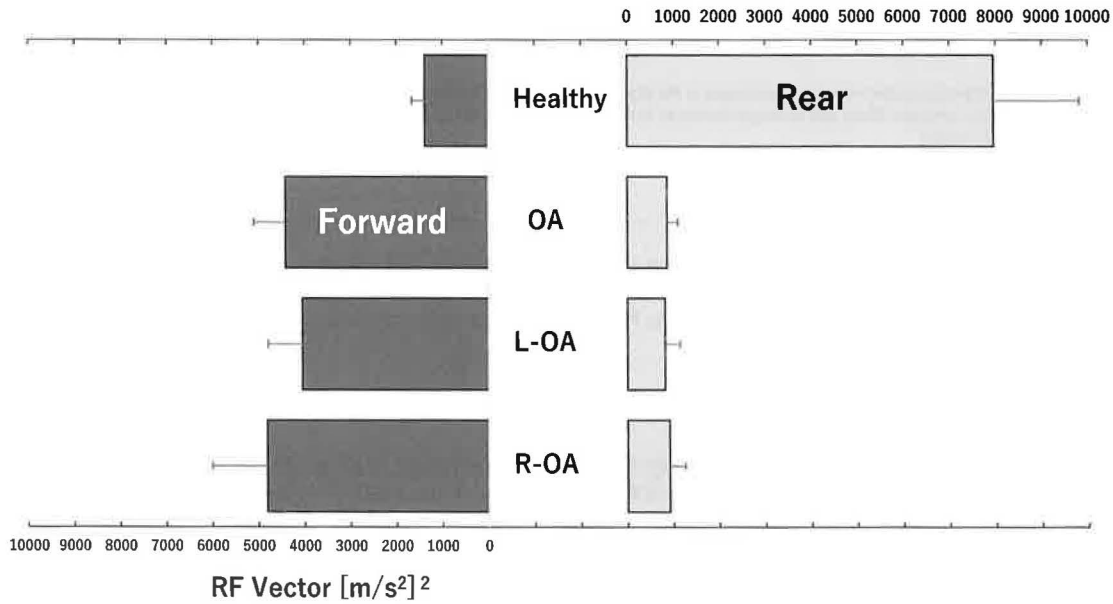

Figure 6. Mean and standard deviations of anterior–posterior variation in the four groups (health, knee OA, left OA, and right OA) are shown. There is a significant difference across all four groups ($P < 0.05$). RF: Rear and Forward.

the healthy group's values tended to be larger than the other groups. Figure 6 shows the comparison of the acceleration variables in the anterior–posterior direction in each group. The acceleration of the healthy group showed a significantly greater value in the posterior direction of acceleration. Table 2 shows that the peak intervals between heel contacts recorded from the vertical direction of the subject's acceleration were measured and averaged. The PPI was significantly longer in the KOA group than in the healthy group ($P < 0.05$). The Poincare plot (PP_k vs. PP_{k+1}) of healthy subjects was distributed near the mean value, but the distribution of KOA patients tended to be widely dispersed (Figure 7). The gray line of this graph means a case

Table 2
Average values of the peak-to-peak interval (PPI) obtained from the heel contact of vertical acceleration.

Subjects	PPI (msec)
Healthy	465.1 ± 43.0
Knee OA[a]	540.7 ± 73.0*
Left KOA	539.4 ± 71.9*
Right KOA	549.8 ± 73.2*

* Vs healthy ($p < 0.05$).
[a] Including Left and Right Knee OA.

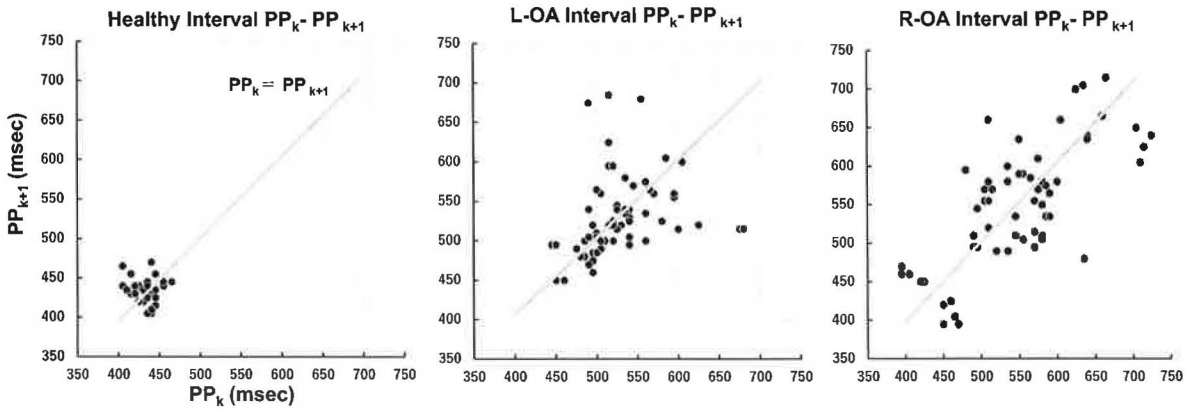

Figure 7. The variations in heel contact interval times between knee osteoarthritis (KOA) (left-osteoarthritis (L-OA) and right osteoarthritis (R-OA)) patients and healthy subjects are compared from the Poincare plot [14]. The gray line of this graph means a case in which the values of both PP_k and PP_{k-1} are equal.

in which the values of both PP_k and PP_{k+1} were equal. The peak interval data plotted near the gray line may have high regularity, as in healthy subjects. Moreover, comparing the PPI distribution of L-KOA and R-KOA, there was clearly a difference in the Poincare plots.

4. Discussion

The purpose of this study was to identify the features of gait in KOA patients using a wireless acceleration sensor. The gait characteristics of the KOA group were analyzed using the acceleration scalar distribution and the interval time of heel contact during spontaneous walking. Recently, there have been some reports of the gait characteristics of KOA patients using accelerometers, but there are few research data that can be applied to preoperative evaluation in rehabilitation and orthopedics [11]. It is necessary to clarify the difference in walking between KOA and healthy subjects for future clinical application. The acceleration is the rate of change in velocity per unit time; we thought that it was necessary to analyze the difference in histogram distributions from the fast component to the slow component in order to consider the change in acceleration during gait. KOA patients showed lower overall acceleration values than healthy subjects (Figs. 2 and 3). From the general clinical findings, KOA patients had a limited range of motion of the knee joint and pain avoidance during walking [15]. In addition, KOA patients have a tendency to reduce lower limb movement due to the limited range of motion of the knee joint [16]. The walking movements of KOA patients may be further restricted with this decreased movement of the lower limbs. In general, humans tend to change their gait to avoid pain from the knee joint and the hip joint [17]. Patients with joint pain store in their brains a walking pattern that involves pain-avoidance behaviors, and as time passes, they unconsciously continue the avoidance behaviors and repeat the behaviors that deviate from normal walking [17]. In this study, restriction of extension was observed in the knee OA group, and it was tempting to speculate that this extension restriction may cause changes in walking movement (Table 1). Figure 4 shows that KOA converges to smaller accelerations, which is thought to be strongly correlated with pain avoidance behavior. It could be suggested that acceleration of the entire gait decreases as walking speed decreases. Although there have been many reports of gait instability, such as frequency analysis, it has been difficult to clinically evaluate the left–right balance of gait movement and body movement variability by frequency alone. The present study suggested that KOA patients may stabilize their gait by reducing the amount of variation in the left–right direction (Figure 5). Previous studies have reported that KOA patients have greater lateral movement in the left and right directions to reduce knee load and pain [12,18]. Conversely, when comparing KOA patients with and without

fear of falling, trunk vibration during walking was decreased in patients with fear of falling [19]. In other words, left and right movements are likely to be inhibited in KOA patients who are experiencing pain and falls or as a behavior to avoid them. The anterior–posterior variability during walking was clearly larger in KOA patients than in normal subjects (Figure 6). It has been suggested that patients with Parkinson's disease show greater acceleration in the forward direction than healthy subjects [20]. In general, patients with Parkinson's disease have a forward leaning posture, and walking with a forward leaning posture is likely to increase forward acceleration. Although the posture of the KOA patients was not measured, it is possible that the patients were leaning forward to maintain gait stability, which may have contributed to the increase in forward acceleration. In the present study, the difference in the distribution of the interval between heel contact for vertical movement between KOA and healthy subjects was investigated. The walking intervals of healthy subjects converged at around 430 ms, but the values of KOA patients did not converge and showed a tendency to have a large variation, as shown in Figure 7. This may be due to the difference in the time between the interval of heel contact from the affected side to the non-affected side and the interval of heel contact from the non-affected side to the affected side. This change may represent motion to avoid loading on the affected side. In the present study, the gait characteristics of KOA patients were as follows: the total acceleration and the left–right acceleration variables were decreased, the anterior acceleration was clearly increased, and the heel–ground interval time was increased compared to healthy subjects.

We will continue to examine whether these findings can be applied to rehabilitation and postoperative evaluation as qualitative characteristics of gait in KOA. In addition, we would like to further investigate the mechanism of left-sided OA, which shows a large difference between the left and right sides.

5. Conclusion

This study showed the characteristics of KOA patients' gait, which is an unstable gait with reduced overall body movement and high variability. The results suggest that the gait characteristics of KOA patients can be easily quantified by measurements using a wireless accelerometer.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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