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Technical Report

Preliminary evaluation of fatigue level estimation by gait sensor

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Abstract

In an aging society with a declining birthrate, increasing travel opportunities for the elderly will lead to increased revenue in the tourism industry, but simultaneously, consideration must be given to fatigue and injuries caused by unperceived fatigue. Therefore, this paper focuses on walking. Recently, the measurement of gait and analysis of gait data have been widely studied. However, most of the studies that analyze gait are aimed at understanding the health status of walkers, and there are few studies that accurately measure the degree of fatigue of the body. In this study, we developed a device to measure gait data to analyze the degree of body fatigue, and to verify a method to quantify the degree of fatigue. The device was created with a sensor that measures pressure on the sole of the foot and an IMU. The gait data were analyzed using t-SNE and SVM. From the experiment, we could classify the gait data and determine the degree of fatigue. It is expected that this device will be able to detect fatigue during sightseeing.

Keywords

gait sensor, gait analysis, numerical rating scale, fatigue test, physical function assessment

1. Introduction

In an aging society with a declining birthrate, increasing travel opportunities for the elderly are considered to be a profitable business in the tourism industry. However, elderly people have physical problems. If they continue to travel without being aware of their fatigue, they may not be able to fully enjoy sightseeing the next day or later due to fatigue or injuries caused by fatigue. In that case, it may result in a decrease in revenues for tourism operators. Therefore, it is necessary to prevent a situation in which fatigue prevents people from enjoying sightseeing. Hence, we believe that it would be useful to create a device that analyzes the gait, estimates the degree of fatigue, and notifies the user when a certain threshold is exceeded, so that the user can rest before feeling the fatigue.

Research on gait has focused on the physical movement of walking, and methods for measuring the state of walking and analyzing the measured data have been widely studied in research aimed at evaluating the health status of the elderly and the athletic function of athletes. Typical studies include measuring COP (center of pressure) based on plantar pressure and body inclination, and using changes in these values to determine the decline in lower limb function and to consider rehabilitation methods, calculating foot contact time and cadence (walking rate: the number of steps divided by the fixed time) using a floor reaction force meter, and analyzing the data obtained from the measurement of walking. Most of these studies analyzing gait aimed at determining health conditions such as motor function and lower limb function, and few studies have been conducted to accurately measure the current level of fatigue of the body.

In this study, in order to analyze the degree of body fatigue from gait data, we developed a device to measure gait data, examined a method to determine the degree of fatigue from the measurement results, and verified the quantification of the degree of fatigue. If fatigue can be properly determined and the degree of fatigue can be quantified, it is believed that elderly people on a sightseeing tour can be encouraged to take a break before they feel tired, thereby preventing a loss of profit. Additionally, this study is a preliminary evaluation of quantify fatigue from daily walking data for use outside the laboratory.

2. Previous research

2.1 Investigation of the relationship between fatigue and walking

The relationship between gait and fatigue is investigated to see how gait changes with fatigue level. According to Higashi et al.'s research, fatigue causes slower body movements and a decrease in activity. In addition, it has been found that the acceleration applied in the front-back direction and the shift in the center of gravity during walking have a significant effect on the degree of fatigue [Higashi et al., 2001]. Based on this, the following information was considered to be the gait information that changes significantly during fatigue.

- Fatigue causes wobbling of the legs and shortening of the swing phase.
- The gait rhythm becomes unstable because the center of gravity does not coincide with the gait rhythm.
- Walking motion becomes slower due to decreased locomotion.

We developed a device that can measure the abovementioned gait information and constructed an analysis system by using the device.

2.2 Research on gait sensors

Research on the measurement of gait conditions and the analysis of measured data can be divided into three main categories: those using floor reaction force gauges, those using motion sensors, and those using sensors attached to the body [Gafurov and Snekkenes, 2009]. While measurements using floor reaction force gauges and motion sensors can provide precise experimental data, they have the disadvantages of being expensive, require a certain amount of space area for measurement, and are unsuitable for real-time measurement.

To solve these problems, many studies on gait measurement use small and relatively inexpensive devices such as insole-type pressure sensors and IMU (Inertial Measurement Unit) sensors. Lin et al. [2016] developed a gait measurement system using an insole-type sensor consisting of 48 pressure sensors and an IMU. This system can transmit data to a PC or smartphone using Bluetooth communication. In our experiments, we measured walking data in corridors, on stairs, and on slopes, and visualized and classified the data. Additionally, Hu et al. [2018] also used an insole-type pressure sensor for COP measurements. In this study, gait measurement was performed using 12 pressure sensors, which is fewer than in the above study by Lin et al. [2016]. Then, in the study by Higashi et al. [2001], the accelerometer WAA-006 manufactured by Haka Wireless Technology was attached to both ankles, and the participants were asked to walk a straight line of 100 m after exercising for 0 to 2 hours, and the data was used to examine fatigue estimation features. In another study, Baghdadi et al. [2018] also developed a real-time fatigue detection system during physical work, in which participants were asked to work with an IMU attached to their right ankle and were classified as fatigued or non-fatigued individuals. These studies show that it is possible to acquire and measure gait parameters without using large-scale devices such as floor reaction force gauges or motion sensors.

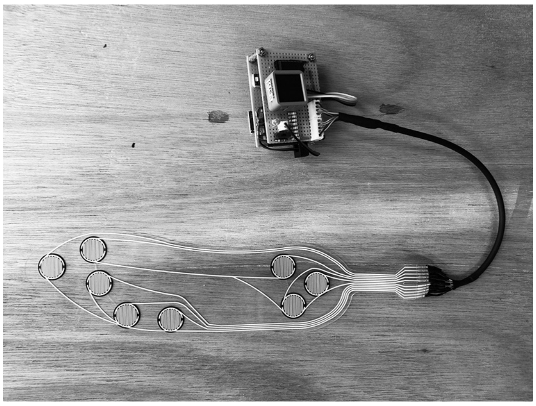
2.3 Research on gait analysis

Many studies have been conducted on gait state analysis using gait data, using machine learning methods such as SVM (Support Vector Machine) and Random Forest. [André et al., 2017; Baghdadi et al., 2018; Sazonov et al., 2018. In these studies, insole-type pressure sensors such as those listed in 2.2 were used, indicating that even simple devices are sufficient for gait analysis.

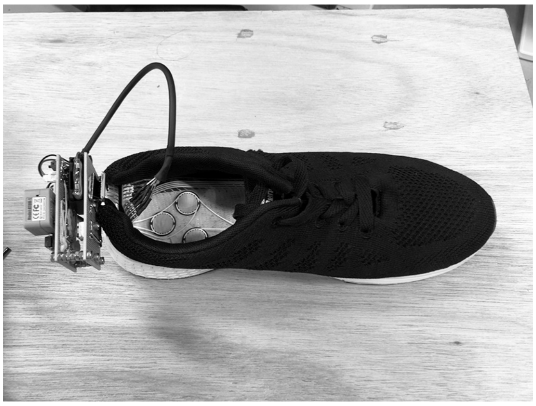
3. Developed devices and analysis systems

In this study, we developed an insole-type pressure sensor. The sensor is expected to measure the natural gait because it can be inserted into the user's favorite shoe without the need for a large-scale experimental device such as a floor reaction force gauge.

Figure 1 shows the developed gait sensor and its installation. In addition, an overview of the created system is shown in Table 1. The constructed analysis system is shown in Figure 2. This system is used to analyze the gait condition and estimate the degree of fatigue. The sampling frequency of the measurement is acquired at 20 Hz. This is because 20 Hz is considered sufficient for action recognition using acceleration in previous research, and we experimented under this condition in this study [Junker et al., 2004].



(a) Gait analysis device



(b) Example of use

Figure 1: Insole-type sensor

Table 1: Device description

Device	Description
Number of pressure sensors	Tiptoe:5, Heel: 3
IMU	LSM9DS1
Microcontroller	M5AtomMatrix
Battery	Lipo
Wireless connection	Bluetooth classic
Sampling frequency	20 MHz

4. Walking experiments to quantify fatigue

4.1 Experimental methods

We conducted a walking experiment to verify the degree that the gait information, which changes significantly with fatigue, actual changes. Three male subjects in their twenties were

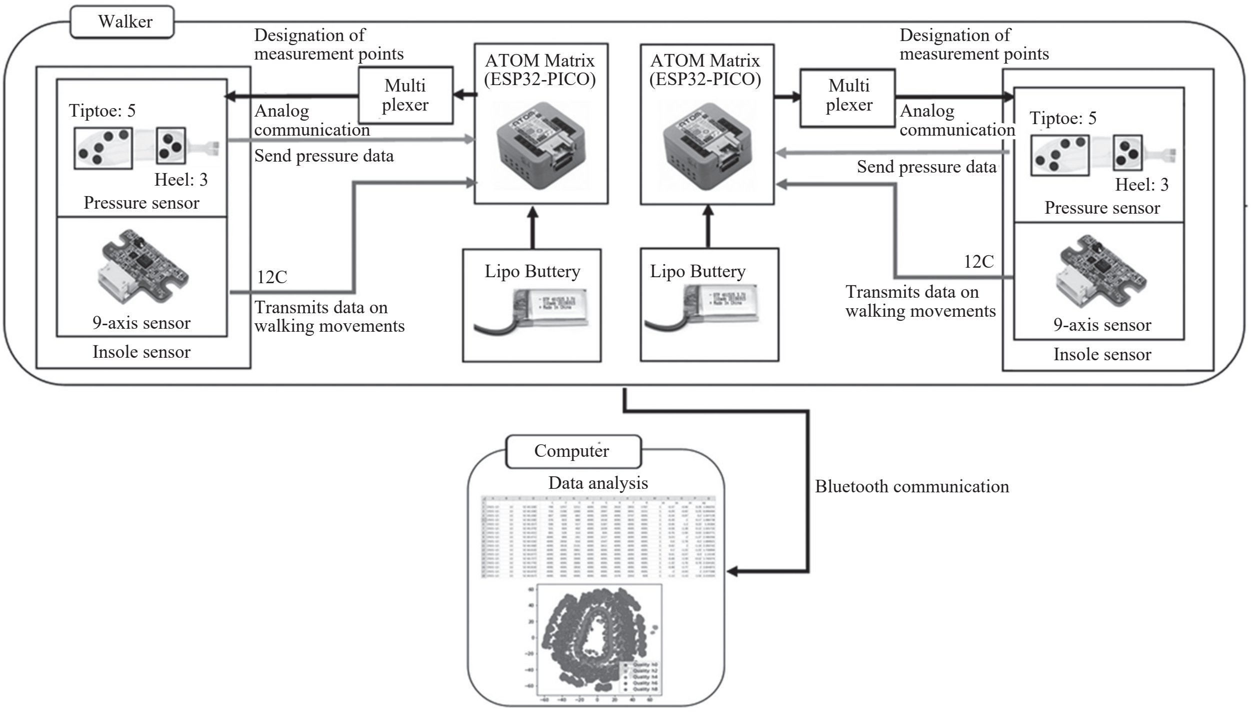


Figure 2: System diagram

chosen as Subject A, Subject B, and Subject C. Gait sensors were attached to their shoes to measure the pressure applied to the plantar area and the movement of their feet. Walking was performed on a treadmill (Well Road 200E, Takei Kiki Kogyo Co., Ltd.) at a constant speed. The experiment is shown in Figure 3.

Subjects subjectively evaluate the degree of fatigue using the NRS (Numerical Rating Scale), which evaluates the degree of pain on a scale of 0 to 10 on an 11-point scale. The Visual Analogue Scale (VAS), which visually indicates the minimum and maximum values of pain at both ends of the scale, is often used as a method of verifying the degree of fatigue. However, in this current study to quantify fatigue, we decided to use the NRS, which is capable of accurate numerical expressions. The NRS and VAS have a strong correlation, and it is expected that the NRS can be used to evaluate the same fatigue level [Japanese Physical Therapy Association, 2011; Japanese Society of Fatigue Science, 2011].

Fatigue level

0	1	2	3	4	5	6	7	8	9	10
Min.										Max.

Figure 4: Numerical rating scale

First, in the experiment, subjects were measured for 5 minutes of normal walking with a fatigue level of 0. The treadmill was set at 4 km/h, the speed of normal walking. The subject then runs at 7 km/h until their fatigue level reaches the specified value. When the fatigue level reaches the specified value, walking is measured at 4 km/h for 5 minutes as in the first stage. The procedure is repeated until the subject measures {0,2,4,6,8} steps at the specified fatigue level.

4.2 Comparison of walking conditions according to fatigue level

The results of the experiment are shown for Subject A in Figure 5, Subject B in Figure 6, and Subject C in Figure 7. These figures are box plots showing the gait data of both legs of each

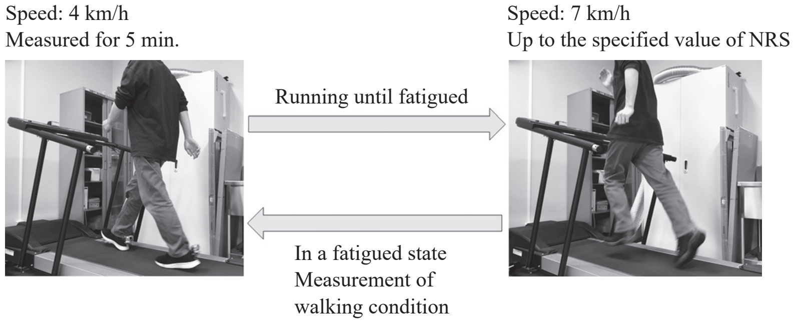


Figure 3: Experiment flow

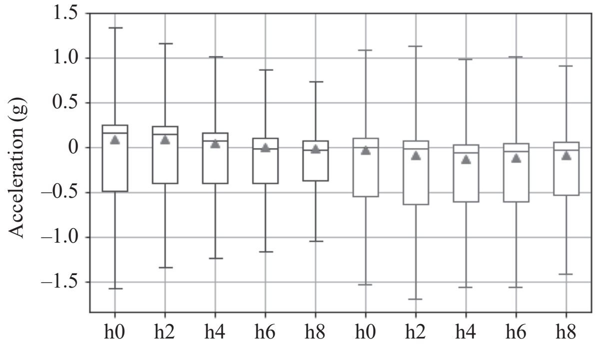
subject, with the NRS h0 to h8 of fatigue on the horizontal axis and the IMU values during walking on the vertical axis. Blue indicates the left leg, and red indicates the right leg. As can be seen in these figures, the maximum value, minimum value, and interquartile range change with increasing fatigue level, indicating that the distribution of IMU values differs between normal and fatigued conditions. Although there are individual differences in the distribution of values for the fatigue of each subject, there is a change in the distribution between normal and fatigued conditions for each of them. This allows us to hypothesize that the developed device may be able to determine whether a subject is walking during fatigue or normal walking on an individual basis.

To confirm the difference between normal and fatigued gait, we used t-SNE (t-distributed Stochastic Neighbor Embedding) to compress the data into two dimensions and compared the similarity of the data. The data handled were all 720-dimensional time-series data measured for 300 seconds by each sensor from the gait sensor, compressed and visualized as a single array. Figure 8 shows the results of t-SNE visualization of the gait data of Subject A, Subject B, and Subject C for each fatigue level. Each color indicates the degree of fatigue. Although there is a difference in distribution among subjects, there is little overlap in each fatigue level in all figures, indicating that the similarity of the data for each fatigue level is low.

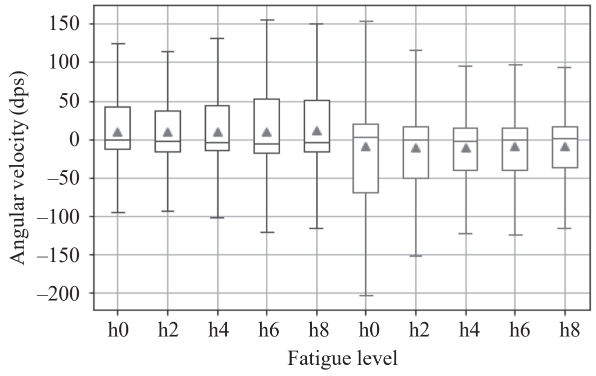
5. Determination of fatigue level by gait data

5.1 Experimental methods

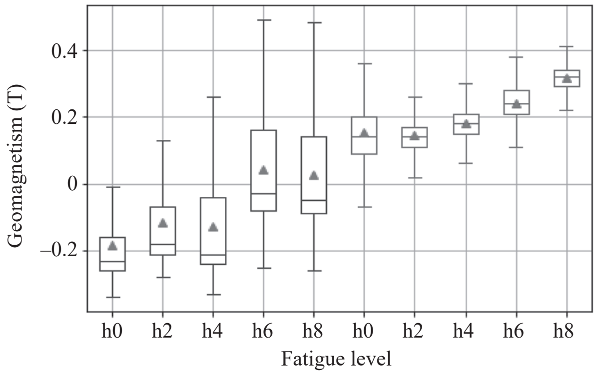
In Section 4, it was confirmed that the gait differs depending on the degree of fatigue. Therefore, we examined whether ma-



(a) Acceleration in front-back direction

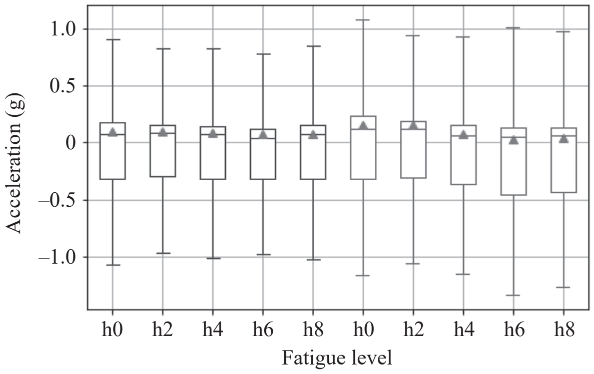


(b) Angular velocity in lateral direction

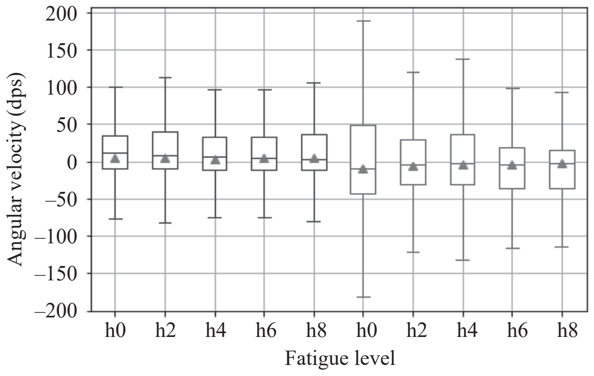


(c) Horizontal tilt

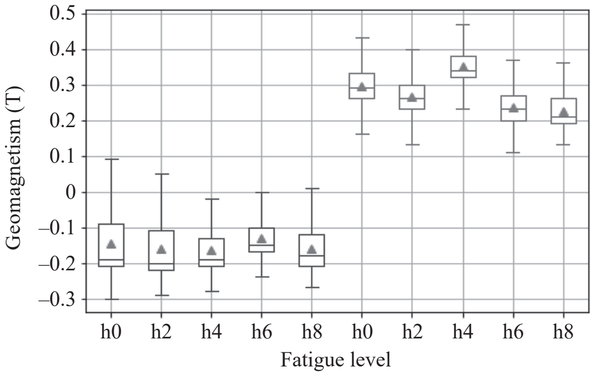
Figure 5: Experimental result of Subject A



(a) Acceleration in front-back direction

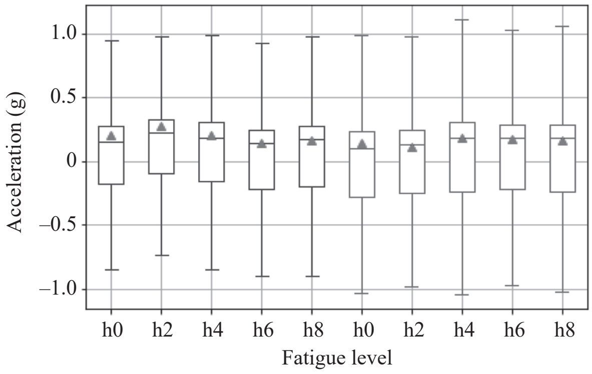


(b) Angular velocity in lateral direction

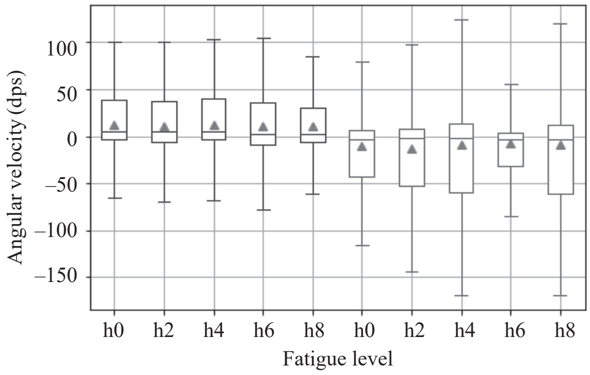


(c) Horizontal tilt

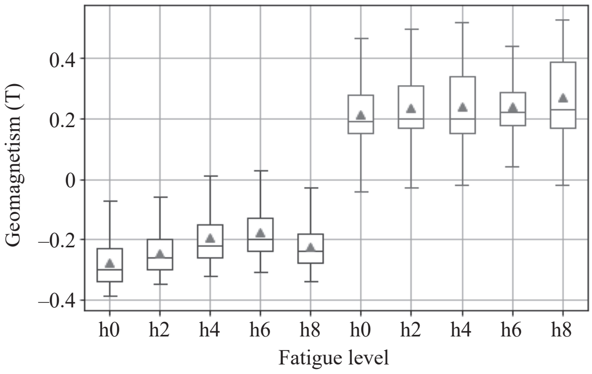
Figure 6: Experimental result of Subject B



(a) Acceleration in front-back direction



(b) Angular velocity in lateral direction



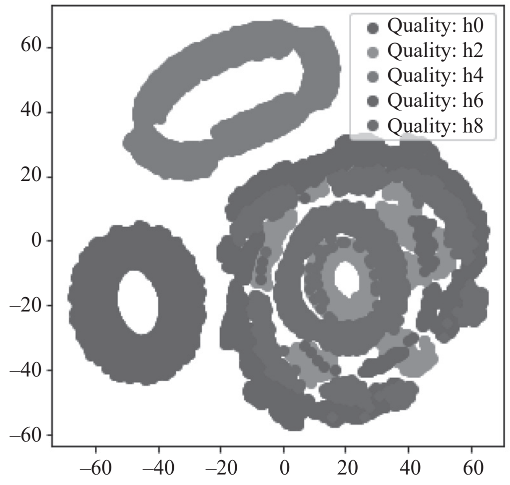
(c) Horizontal tilt

Figure 7: Experimental result of Subject C

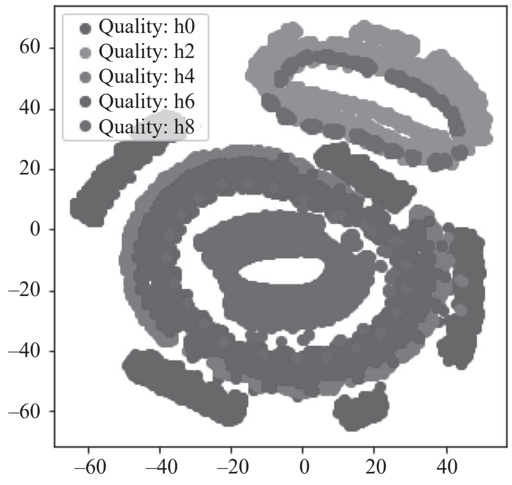
chine learning can be used to evaluate the fatigue level of gait based on the gait information obtained from the measurement experiment.

To evaluate the degree of gait fatigue, we used SVM, which is one of the machine learning methods, to perform classification. This method was chosen because it is expected to achieve high discrimination accuracy even with multidimensional data and it is less prone to overtraining, which occurs in machine learning.

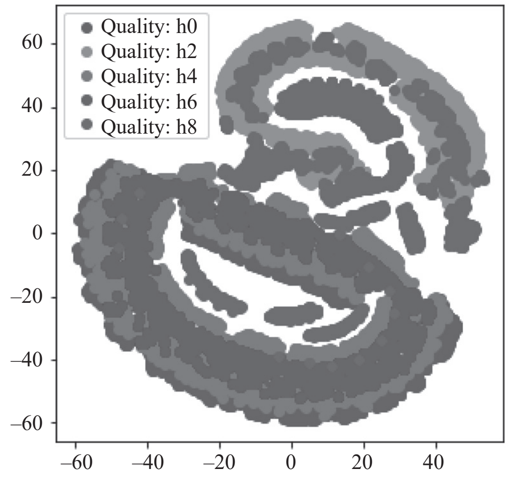
Time-series data from t-SNE are used for training and testing. The measurement results were divided into training and test data at a ratio of 8:2, and the experiment was conducted. Since the form of gait differs greatly from person to person, we verified whether it is possible to discriminate against gait by focusing on the gait of each individual subject, and whether it is possible to discriminate against gait by integrating the gait information of all subjects. Table 2 shows the amount of data in the training and test datasets.



(a) Subject A



(b) Subject B



(c) Subject C

Figure 8: Experiment result using t-SNE

5.2 Experimental results

Table 3 shows the experimental results. From the experimen-

Table 2: Number of data for each test used for fatigue determination

	Subject A	Subject B	Subject C	Total
Fatigue level 0	4173	4957	4989	14119
Fatigue level 2	3298	5100	5128	13526
Fatigue level 4	5056	5058	5042	15156
Fatigue level 6	5013	4786	5014	14813
Fatigue level 8	5083	5131	5076	15290
Total	22623	25032	25249	72904

tal results, it was found that the gait information obtained from the gait sensor can discriminate the state of fatigue. Although the overall correct response rate was lower than the correct response rate for each individual, it was able to discriminate with a high degree of accuracy.

As an additional experiment, the fatigue status of a subject who was not included in the training model was discriminated, and the correct response rate was about 20 %. It can be seen that this method has low discrimination accuracy when the individual gait data is not included in the training.

Table 3: Experimental result

Attendance rate	Subject A	Subject B	Subject C	Total
Fatigue level 0	1.000	0.995	0.956	0.940
Fatigue level 2	1.000	0.950	0.981	0.945
Fatigue level 4	1.000	1.000	0.993	0.967
Fatigue level 6	0.988	0.991	1.000	0.985
Fatigue level 8	0.997	1.000	0.970	0.936
Average	0.996	0.987	0.980	0.955

6. Conclusion

In this study, we developed a device for measuring gait data and examined a method for determining the degree of fatigue by analyzing the gait data, with the aim of appropriately determining fatigue and quantifying the degree of fatigue. The characteristics of gait during fatigue were clarified, and the change in gait condition by the degree of fatigue was confirmed by measuring the gait condition using t-SNE. We also found that the fatigue level can be determined from the gait by classifying the fatigue level using SVM.

In this study, for the purpose of preliminary evaluation, fatigue detection was performed based on the results obtained in the laboratory, however, in the future, we aim to be able to perform routine measurements.

When routine measurements can be performed, our device can be used to estimate the degree of fatigue from the gait and prevent injuries caused by excessive exercise with fatigue. In addition, it can be applied to a system to detect fatigue during sightseeing for the elderly, which is a necessary area of research for the tourism industry.

Acknowledgment

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