A Wearable Fatigue Monitoring System
- Application of Human-Computer Interaction Evaluation -

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Abstract

We developed a wearable fatigue monitoring system with a high-sensitivity 2-axis accelerometer and an on-board signal processing microcontroller. The proposed system measures faint motion of the user's head while the user is trying to stand still for 30 seconds. The two axes of the accelerometer were settled parallel to the ground. As one of the candidates for diagnostic parameters, we adopted a time-integral of acceleration trace pattern length, which was defined as the length between the adjacent two acceleration X-Y plots. As artificially introduced physical stress such as running as well as some physically or mentally exhausted situations made consistent changes in the acceleration trace length, the proposed system was shown to have a capability of evaluating the degree of tiredness. Then we applied the proposed system to evaluation of human-computer interaction. We performed experiments on a computer entertainment using immersive display devices such as head-mounted displays and wide-angle plasma displays. As a result, the measured values of the acceleration trace length showed some inconsistency with user-interviews consist of subjective questionnaires about the user's fatigue.

Keywords: accelerometer, wearable computer, fatigue, human-computer interaction, immersive display

1 Introduction

It is very hard to keep the position of one's head even in the case of just standing straight. Faint as well as random motion is always observed. On the other hand, we can feel a little bit larger swing of motion while standing still when we feel tired by some reasons such as a lack of sleeping time, catching a cold, and so on. If we would like to numerate the degree of tiredness or fatigue in these cases, some subjective methods using a set of questionnaires such as "Do you feel tired? <very : moderate : a little bit : no : not at all>" are widely used instead of using objective physiological methods, because the questionnaire-based methods are simple and can be performed anytime anywhere. For example, the heart rate and the blood pressure can give information on the subject's physical and mental conditions. However, it is hard to extract the information on the subject's fatigue alone from the measured data because the heart rate and the blood pressure are determined by a complex mechanism of our autonomic nerve system. Some other physiological methods such as electroencephalograph and tests on body fluid (Soma, Sato, Shimizu and Fukumoto 2003) are reported to determine the degree of the subject's fatigue. Nonetheless the physiological methods are not easy to apply anytime anywhere.

In our previous paper (Matsushita, Oba, Otsuki, Toji, Otsuki and Ogawa 2003) we reported a possibility of a wearable computing system to evaluate the user's physical or mental conditions by using a 2-axis (front-to-back and left-to-right) accelerometer attached on the top of the user's head. 30-second measurements on faint acceleration signals (typically 10 to 30 milli-G, where G shows the acceleration due to gravity: $\sim 9.8 \text{m/s}^2$) were performed while the user was standing still. Although it is very hard to separate the measured acceleration values into the portion of the true motion and the pseudo signal due to the changes in tilt angle to the ground, we found that the acceleration trace length, which is defined as a 30-second integration of the 2-dimentional distance between the adjacent plots of acceleration values, could tell us some useful information on the user's physical and mental conditions. A similar evaluation method, which is based on measurements on the position of the center of gravity (COG) by using a force plate on which the user is standing still, seems to be able to perform almost the same task (Shimba 1984, Benda, Riley and Krebs 1994). However, the force plate diagnosis method, which is called stabilometry and is the authorized procedure by Japanese National Health Insurance System, can not easily be applied to a wide range of situation due to its environmental requirements such as quite a flat surface parallel to the ground and so on. On the other hand, our proposed device is wearable and can be applied to a wide variety of situation not only because of its principle of measurement but also due to a light social weight (Toney, Mulley, Thomas and Piekarski 2002). The device looks like a typical headset (or headphone) and is not a strange device even if the user is wearing it all the time.

In this paper, first we will introduce our headset device. Then we try to make it clear if the headset device can tell us the degree of tiredness or fatigue. Finally we will show the results from the evaluation of a human-computer interaction application using immersive display devices as one of the most exhaustive interaction for the user.

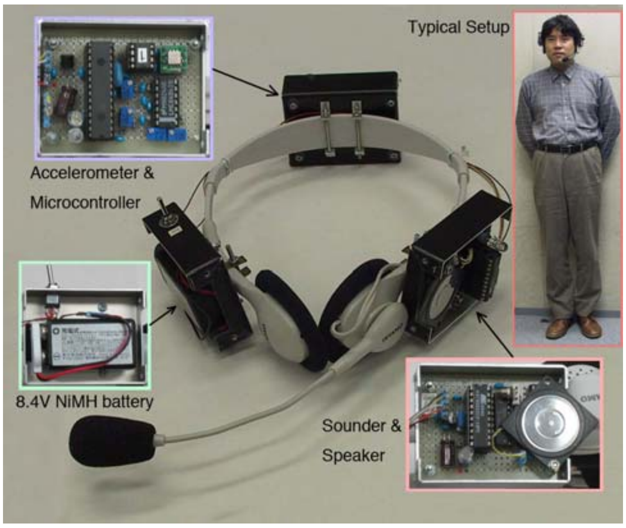

Figure 1: Wearable sense of balance monitoring device using a high-sensitivity accelerometer

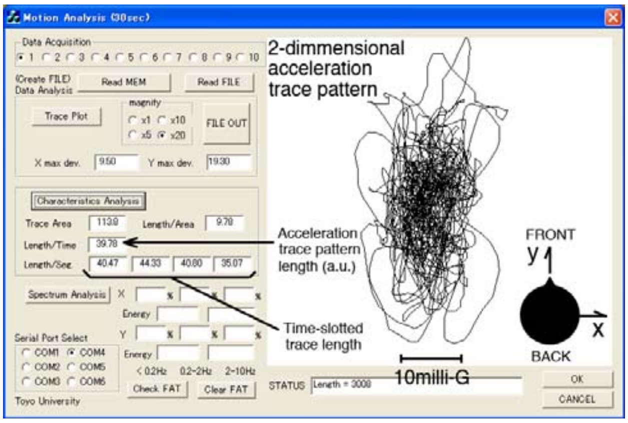

Figure 2: Screenshot of the analysis software

2 A Wearable Fatigue Monitoring Device

Figure 1 shows the photograph of the fatigue monitoring headset device. At the top of the user's head, there are a 2-axis accelerometer (ADXL202E 2005), analog signal conditioning circuits, an 8-bit microcontroller and a 1-Mbit flash memory chip to memorize up to 10 acceleration pattern records (30 seconds each). The 2-axis accelerometer was settled so as to the measurement axes made a plane parallel to the ground. The x-axis was defined as the left-to-right direction. The y-axis corresponded to the front-to-back direction. The characteristics of the measurement system are as follows:

(a) resolution of acceleration: 2.9 milli-G

(b) band width : 10Hz (50Hz 6dB/oct LPF and software)

(c) sampling period : 100 samples per second

(d) noise floor: 1.3~2.7 milli-G RMS, 8.8milli-G peak

The user was wearing the headset device and was asked to be standing still for 30 seconds while the user's eyes open or closed. According to our previous research, user's eyes open and closed cases showed almost the same acceleration measurement results for healthy subjects. We chose 'eyes-closed' condition for measurements because it seemed to be more robust against some disturbance the user might see while the measurement. After the measurements, the microcontroller performed a calculation of diagnostic parameters. On the other hand, the 1-Mbit flash memory chip was able to be read by a notebook PC based analysis system. Figure 2 shows the screen shots of the analysis software. The software calculates the acceleration trace pattern length as defined in our previous paper (Matsushita, Oba, Otsuki, Toji, Otsuki and Ogawa 2003) as well as some other parameters. In this study, we took the acceleration trace pattern length as a primary diagnostic parameter. In Fig.2, there are 5 boxes indicating the acceleration trace pattern length. The one labeled "Length/Time" shows the 30-second integral of the trace length. The four boxes show the normalized 5-second integral of the trace length (from the left, 2-to-7 sec., 9-to-14 sec., 16-21 sec., and 23-to-28 sec.). They were used to determine how the acceleration trace pattern length was stable during the measurement. In more than 90 percent of measurement cases with healthy subjects, we had not seen the cases in which the data needed to be thrown away.

3 Artificially Introduced Fatigue Response

From our previous research (Matsushita, Oba, Otsuki, Toji, Otsuki and Ogawa 2003), we found that the acceleration trace length had a relationship with the user's physical and mental conditions in terms of fatigue. To numerate the degree of fatigue, there is an established stamina evaluation method in Japan. The subject performs a periodical up-and-down exercise with a low-height stool for a few minutes, then the heart rate is counted. The heart rate decreases after the exercise more rapidly when the subject is in a good physical condition. Then we considered an experiment in which both the heart rate and the acceleration trace length were measured periodically after some physical exercise. The time schedule of the experiment was as follows:

(1) Before the exercise, the acceleration measurements were performed for 3 times while the user was resting.

(2) The user was asked to run for 5 minutes with a constant speed as far as possible.

(3) Just after the exercise, the user was asked to count his/her heart rate for 30 seconds.

(4) 1 minute after the exercise, the acceleration measurement was performed.

(5) The heart rate counting and acceleration measurement were alternatively performed. While the experiment, the user did not sit down not to make sudden changes in blood pressure because it might affect the acceleration measurement due to extraordinary blood flow.

The experiments were performed both in the morning and in the evening in order to observe differences due to the initial conditions of the subject. In this experiment, the subject was a healthy 41-year-old male. It should be noticed that the acceleration trace length tends to be smaller as the time passed after wake-up as we reported in the previous paper (Matsushita, Oba, Otsuki, Toji, Otsuki and Ogawa 2003).

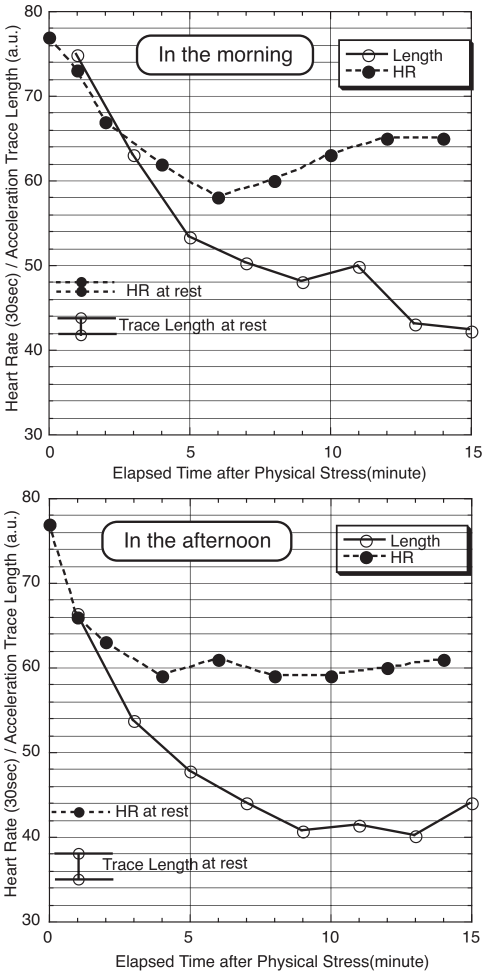

Figure 3: Acceleration trace length and heart rate measurements after the 5-min physical exercise

Figure 3 shows the changes in the heart rate and the acceleration trace length after the exercise in the morning and afternoon. As it can be seen that the continuous decrease in the trace length was observed for each situation. On the other hand, it is interesting that the continuous decrease in the trace length continued after the decrease in the heart rate ended or even increased again. It would suggest that the artifacts due to the user's breathing motion did not affect the acceleration measurements very much. Moreover, the trace length returned to the initial value in the morning, but it did not return in the afternoon. As we observed almost the same curves in other physical stress experiments, it can be concluded that the acceleration trace pattern length measurement gives us some quantitative information on the subject's physical conditions.

As the number of the users involved in the experiments at this point was quite limited, we planned to perform population tests in the next stage of our research.

		subject 1	subject 2	subject 3	subject 4	subject 5	subject 6
Trace Length	Min.	31.3	27.8	40.7	40.4	36.1	31.2
	Average	38.9	34.5	43.8	41.1	43.0	37.0
	Max.	49.6	43.4	51.0	42.5	49.9	40.7

Table I : Summary of the results from acceleration trace length measurements for 6 healthy subjects

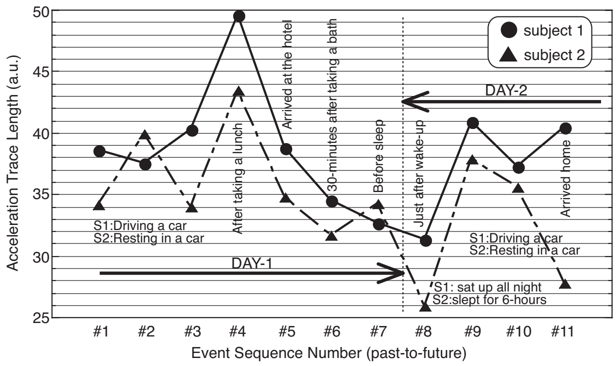

Figure 4: Daily changes in acceleration trace pattern length for two healthy subjects

4 Population Tests

Table I shows the measured values for 5 healthy subjects (ages 21-23, male) and a subject (39, male) observed in daily life. The experiments had been performed for at least more than 3 days. All measurements were done in 30 seconds while the subject's eyes closed. In the experiment, we noticed that there were some failed measurements which were suggested by large (typically 10.0 or more) differences among the 5-second-slots as mentioned in Section 2. The reasons we guessed from interviews with the subjects are as follows:

(1) Response to the surrounding sounds: Some subjects reported that sounds such as talks around them made some motion unwillingly.

(2) Headset device fits the subject or not: When the headset device was not fit, a feeling that the device moves easily affected the user's mental conditions.

(3) 30 seconds while standing still is rather long time to endure: Some subjects complained that the 30-second measurements were too long. Especially in the case of being tired and having some ache in their foot, a sudden change in the position of the subject's head was observed.

As for the problem with surrounding sounds, we tried to sound a music from the ear pads of the headset. From the experiments, it was shown that a music with large sound sufficiently erases the noises from outside is effective to overcome the problem. The second problem concerning the fit of the headset seems to be solved by the design. On the other hand, the last problem seems to be quite a hard to solve because we feel rather a lack of measurement time to obtain a sufficient accuracy. If the noise from the accelerometer, which currently affects the accuracy, can be much reduced, the development of effective diagnosis method which requires less measurement time would become to be crucial. Figure 4 shows the acceleration trace length measurement results for two subjects appeared in Table I for 2 days. From the results, we considered that the proposed device might show some numerated figure concerning the subjects' conditions because a similar pattern of the changes in acceleration trace pattern length was observed while the two subject were in almost the same situations. As the proposed device can be used freely anytime anywhere, it can be used as a health monitoring device just like a clinical thermometer. Although the numerical value itself is different among the users, the tendency of changes might show some information on the user's conditions.

5 Objective Evaluation of Immersive Displays

Although there still remains a number of issues which should be considered to clarify what the headset device measures, we tried to find some practical applications. As it is suggested that the measurement of the acceleration trace length shows the degree of the user's fatigue, we performed an evaluation of visual display device. Three healthy subjects were asked to play 3-dimensional simulation game software packages by using a head-mounted display (viewing angle = 25 deg. stereo) and a wide-angle (32") plasma display (viewing angle = 70 deg) for 60 minutes. Typical game packages used in the experiments were a 3-D airplane simulator (Ace Combat 4 on Playstation 2 from Sony Computer Entertainment) and a 3-D action arcade game (Halo on X-Box from Microsoft Corp.). The head-mounted display was not a see-through type and therefore the subject could not see outside during the experiment. Figure 5 shows the results from the experiment. In the middle of Fig.5, the daily change ranges of the acceleration trace length for each subject are shown. The subjects were the same as in Table I. From the results, it can be said that the wide-angle plasma display made rather significant effects on the user's conditions. Although the subject 1 reported a heavy tiredness only after using the head-mounted display, the acceleration measurements showed a discrepancy, that is, the acceleration trace length decreased after using the head-mounted display. The subject 2 complained a slight tiredness for both cases. However, the acceleration trace length decreased in the case of using the head-mounted display. As a result, we observed that the acceleration trace length does not seem to be connected with the user's subjective feeling of tiredness. Nevertheless, it is very interesting to have yet another objective evaluation method which can be used anytime anywhere.

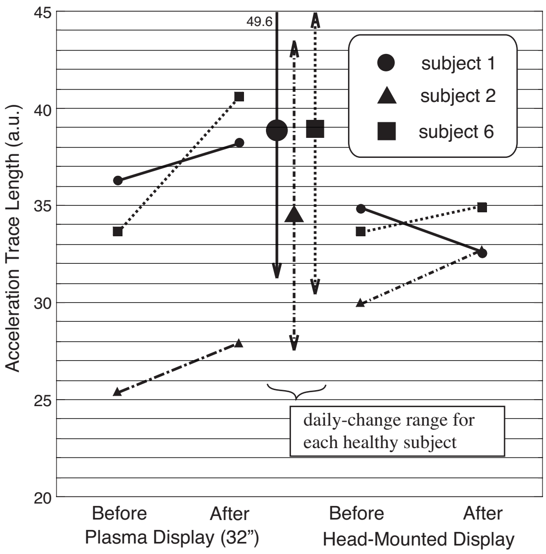

Figure 5: Evaluation of different type of immersive graphical display devices

6 Conclusions

In this study, we obtained the following conclusions:

(1) Artificially introduced physical stress made the consistent changes in the acceleration trace length as the diagnostic parameter of the user's condition. Therefore, the headset device was shown to have a capability of evaluating the degree of physical tiredness.

(2) Population tests showed a similar tendency in the acceleration trace length values among the healthy subjects. Although the mechanism has not yet been fully clear, the proposed wearable device showed a possibility to evaluate the user's conditions with objective scores.

(3) As for an example of objective evaluation method for the changes in the user's conditions, we performed a comparison between a head-mounted display and a wide-viewing-angle flat display. As a result we found that there was some discrepancy between the user's subjective opinion on their tiredness and the measurements with the proposed wearable fatigue monitoring device system.

As the proposed system is portable and usable almost anytime anywhere, we think that our system would be useful for an objective evaluation method of human-computer interactions.

7 Acknowledgements

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