Table 1. It is indicated that the wet bulb globe temperature

The heatstroke risk is classified into five levels, as shown in Table 1. It is indicated that the wet bulb globe temperature

1. Introduction

In recent years, management of health conditions and behavior using wearable devices has become important. Wearable devices that detect risk conditions, such as heatstroke, and present the risk information will thrive in the future. Critical information about danger due to heatstroke needs to be presented reliably and intuitively to the user. However, in existing display devices and speakers, there is a possibility that sufficient information cannot be presented to the user, depending on the surrounding environment.

To solve this problem, a wristwatch-type device is being developed to judge heatstroke risk and to present the risk information via the wrist skin. Various studies on tactile sensation have been conducted wherein information is presented through the skin [1]–[3]. Lee [4] and Sawada [5] succeeded in recognizing patterns and letters for absolute value information. However, with these methods, it took time to present the information, and the user needs to concentrate on recognizing it. Tchakoute [6] showed that by generating a plurality of stimulation patterns from vibrating elements mounted on shoes and presenting them to the user, it was possible to recognize the risk level of four stages with an accuracy of 95%. In such a case, the relationship between stimulation and risk was not intuitive, and the user needs to concentrate on recognizing the risk level can be recognized from heatstroke, which is an indicator of the physical condition. We examined the waveform conditions for recognizing the difference between five stages of heatstroke risk by pulse-like stimulation. In the state of being concentrated on the stimulation, it was possible for the subject to recognize the five stages with over 80% accuracy when the ratio of the stimulation period in two adjacent stages was set to 1.6 or more. However, in the state of doing other work, the subject’s recognition rate decreased to 40% at the worst recognition in all stages when changing only the stimulation period. In contrast, it was found that when the current intensity and period of the stimulation were changed, especially such that the number of period steps per current intensity step is 3 or less, the difference in stages could be recognized with accuracy of 80% or more even in the state of doing other work.

Therefore in the present study, a new intuitive method is proposed to present risk information by imparting a pulse-like stimulation, which can be learned easily. An image of the proposed skin stimulation device is shown in Fig. 1. Environmental and vital signal sensors for detecting heatstroke risk along with actuators for stimulation are mounted on a wristwatch-type device. The device evaluates heatstroke risk from the sensor data and presents pulse-like stimulations to the wrist, according to the risk level. The pulse is an important indicator of the body’s condition, and it is proposed that by imparting stimulation with a pseudo changed pulse, it is possible to intuitively present the danger by perceiving the change in the body condition, as shown in Fig. 2. The difference in the risk level can be recognized by the difference in the period and current intensity of stimulation from the usual pulse. Since the actual pulse does not change, there is no danger to the user’s body due to stimulation. The pulse that a person can take is around 50 bpm (WBGT) is an environmental index [7], and if it is high, such an environment is likely to cause heatstroke. Core body temperature is a physical index, and if it is high, this indicates that the user is already experiencing a heatstroke [8]. To prevent heatstroke, it is necessary to indicate how dangerous the user is in the environment and whether the user has suffered from heatstroke. For that purpose, a presentation method that clearly distinguishes the five stages shown in Table 1 is required. Further, when presenting a dangerous state such as heatstroke, a method for presenting the degree of risk more intuitively is necessary.

Table 1 Risk level of heatstroke.

| Risk level | WBGT | Core body temperature |
|------------|------|-----------------------|
| 0          | -25 °C | -                     |
| 1          | 25 °C - 28 °C | -                     |
| 2          | 28 °C - 31 °C | -                     |
| 3          | 31 °C< | -                     |
| 4          | 31 °C< | 37.5 °C<              |
| 5          | -     | 38.5 °C<              |

Key Words: human interfaces, human-machine systems, ubiquitous healthcare.
to 200 bpm [9], [10], and most people have ever checked their pulse status in their life. By presenting a pulse-like stimulation, it is easy to recognize how fast the stimulation is compared to one’s normal pulse. Therefore, it is considered that it is possible to recognize the difference in the stimulus with almost no prior learning required in the conventional research.

To reduce the risk of heatstroke, it is necessary to reliably alert the user at the stage when core body temperature begins to rise, which is the most dangerous stage. Therefore, in the present study, the aim is to recognize 100% of the most dangerous stages and recognize the other stages with at least 80% accuracy. This must be achieved even in situations where it is difficult to continuously focus on the stimuli that are given to the arm in everyday life, for example, when performing other tasks. To validate the feasibility of the device, the conditions of the stimulation waveform have been examined that can recognize the stage of risk with high accuracy. This satisfies the above conditions even in situations when it is not possible to concentrate on the stimulation.

### 2. Stimulation Waveform Design

There are several types of skin stimulation methods, such as mechanical stimulation, electrical stimulation, thermal stimulation, etc. Mechanical and electrical stimulations have been widely studied from the viewpoint of responsiveness and controllability of stimulation [11]–[13]. In the present study, electrical stimulation has been used because it is easy to miniaturize the device, and it is possible to obtain stimulation strength in a wide and dynamic range, even for small devices.

Current-controlled stimulation with a square waveform has been used for pulse-like stimulation. To find the appropriate waveform parameters that lead to a wide range of perceived intensity without pain being felt, the effects of pulse width and current intensity on the perceived intensity have been investigated.

The experimental method is as follows. First, a pulse serving as a reference for perceptual intensity was set. The current value of the target pulse was recorded when its current value was changed and the perceived intensity of the reference pulse and the target pulse became equal. The pulse width of the reference pulse was fixed at 1 ms, and the current value was set in seven steps from 2 mA to 4.5 mA in 0.5 mA increments. The device configuration is such that a pulse is generated using an electrical stimulator, input to the isolator, and then output from the isolator to the electrode.

The result is shown in Fig. 3. In the figure, the current intensity at each point represents a ratio from 2 mA as a reference. Specifically, the current intensity A is a distribution of a reference pulse of 2 mA, and the current intensity F is a distribution of a reference pulse of 4.5 mA. It has been found that perceptual intensity can be changed greatly by changing the current intensity when the pulse width is 1 ms or less. However, if the pulse width becomes too small, the required current increases. Therefore, in this study, the experiment was conducted with the pulse width fixed at 1 ms.

### 3. Stage Recognition Experiment during Concentration

#### 3.1 Outline of the Experiment

As a preliminary experiment, the accuracy for recognizing multiple stages in a state of being concentrated on stimulation was confirmed. Additionally, in order to confirm the relationship between the number of stages and the recognition accuracy, not only five stages but also three and four stages were evaluated. An experiment was conducted to impart multiple stimulations to the subject’s wrist with different periods corresponding to several stages.

#### 3.2 Experimental Method

The experimental setup is shown in Fig. 4. The current-controlled stimulation with a square waveform (a pulse width of 1 ms and a current value of 0 mA to 4 mA) was generated by controlling the DC voltage of 60 V using a current regulation circuit and a microcomputer. Experiments were carried out in four patterns: presentation in three, four, and five stages (two patterns). The specific stimulation waveforms and their stage settings for each pattern are shown in Fig. 5. The stimulation was randomly delivered, and subjects answered as to
which stage the stimulation corresponded to. The stimulation was delivered 20 times at each stage, for a total of 60 times for three stages, 80 times for four stages, and 100 times for five stages. Each stimulation was continuously delivered until the subject answered, and the stimulation was stopped promptly after the subject responded. The interval of each stimulation was set to about 10 s. During the experiment, the subjects rested the arm on which the electrodes were placed on a desk. Each experiment consisted of a learning session where stimulation at all stages was delivered first, and specific stages were also presented according to the request of the subject. The subjects were three men in the age range of 20 years to 50 years.

3.3 Experimental Result

In this experiment, we used a correct answer rate and detection sensitivity as evaluation indices. The correct answer rate is a hit rate in the signal detection theory [14] and is a rate of correctly answering the presented stage. The detection sensitivity is obtained by subtracting the false alarm rate from the hit rate in the signal detection theory. In this study, the hit rate and false alarm rate were calculated using one of the stages as a signal trial and the others as a noise trial. This was calculated for each of the five stages. The results of the experiments are shown in Fig. 6. It was possible to recognize the difference with 100% accuracy in three stages. Accuracy was reduced when the stimulation was set to have five stages and only the stimulation period was changed as shown in Test No. (c). The accuracy decreased with each increase in stages 2, 3, and 4. On the other hand, from the result of Test No. (d), which employed a different current intensity, the difference could be recognized with 100% accuracy in stage 5 and more than 80% accuracy in all stages, even though there are five stages.

3.4 Discussion

3.4.1 Stimulation period

The ratio of stages 1–2 was fixed at 2 for all experiments, and the correct answer rate was 100% for all the experiments in stage 1. The ratio of stages 2–3 was also 2 in Test No. (a), and the correct answer rate was 100% as well. From these results, it can be observed that if the ratio of the stimulation period in two adjacent stages is at least 2, the difference in the stages can be recognized clearly.

The relationship between the ratio of the stimulation periods in two adjacent stages and the recognition accuracy in a five-stage test for the same subjects has been determined. As a verification method, several patterns of five stages of stimulation with different ratios of adjacent stimulation periods were prepared and presented to the subjects. The ratios of the stimulation period in the adjacent stages were set to 1.2, 1.4, 1.6, and 2. The stimulation was randomly delivered to the subject, and the subject answered as to which stage it was. The period of stage 1 was set to 1200 ms for all the experiments, and after stage 1, the period was set shorter according to each ratio. The number of stimulations at each stage was set to 10. The current intensity was adjusted to a value that allowed subjects to clearly distinguish the stages and was painless. The other conditions were the same as in the previous experiment. The results are shown in Figs. 7 and 8. As shown in the figures, it was confirmed that both correct answer rate and detection sensitivity were over 90% in all stages at ratios 1.6 and 2. Therefore, the information from five stages can be accurately identified when the ratio of the stimulation period in two adjacent stages is 1.6 or higher.

3.4.2 Regarding combination of stimulation intensity and period

The stimulation periods in each stage were the same in Test Nos. (b) and (d), except stage 5 in Test No. (d), as shown in Fig. 5. Since the percentages of the recognition accuracy were almost equal, it indicates that it is possible to independently recognize the difference in current intensity and period. Furthermore, both correct answer rate and detection sensitivity of stage 5 in Test No. (d) are 100%. Therefore, setting the more
dangerous state to a high current intensity stage makes it possible to reliably present the danger to the user. As shown in Table 1, in this study, stages 4 and 5 are set to the stage where the physical condition has changed. It is considered that the risk of heatstroke can be more intuitively recognized by introducing the high current intensity to stages 4 and 5. In this case, it is necessary to recognize the difference between two or three periods for each current intensity. About this, the accuracy in the presentation of only three stages was 100% as shown in Fig. 6 (a). Therefore, if the number of stages changing stimulation periods is three or less, it is considered that recognition can be performed with high accuracy even in the presentation of five stages including two current intensity.

In order to confirm this, the recognition accuracy in five stages was confirmed through the settings shown in Table 2. The low current intensity $\alpha$ was adjusted to a value that allowed subjects to clearly distinguish the stages and was painless. The high current intensity was set to a value increased by 0.5 mA from the lower one. It was confirmed that the subject did not have any pain even at a high current intensity. Other conditions were set as in the previous experiment. As shown in Fig. 9, over 90% accuracy was obtained for all subjects. Therefore, it was confirmed that the combination of stimulation intensity and period can be recognized with high accuracy.

4. Stage Recognition Experiment during Other Work

4.1 Outline of the Experiment

In the previous section, it has been found that high accuracy could be obtained with two stimulation waveform designs for five stages of recognition when the subject was concentrating in stimulation. Based on this result, when the subject was actually performing a different task, the subject’s ability to recognize the five stages with these waveforms was tested. In this experiment, $N$-back test was set as another task [15]. In the $N$-back test, visual information on the screen was presented one after another, and the subject reacted when the presented visual information was the same as that during the $N$th time. Since most things are multitasking in real life, we chose $N$-back test. During this $N$-back test, skin stimulation was performed simultaneously, and the recognition accuracy was investigated.

4.2 Experimental Method

The experimental setup is shown in Fig. 10 (a) and a specific test screen is shown in Fig. 10 (b). The number $N$ was then set to 3. A blue mark repeatedly appeared and disappeared at random positions on the $3 \times 3$ squares on the screen. When this mark appeared at the same position as before thrice, the subject was to press the button in hand. The conditions for the $N$-back test were standard [16]. Specifically, the mark presentation time was observed to be 0.5 s, the period from the disappearance of the mark to the next mark presentation was 2.5 s, and this repeated 29 times constituted one set.

The skin stimulation conditions are the two conditions shown in Table 3. Each stimulation was continuously applied until the subject responded, and then the presentation was stopped immediately. The interval between each stimulation was about 10 s. The low current intensity $\alpha$ was adjusted to a value that allowed subjects to clearly distinguish the stages and was painless. The high current intensity was set to a value increased by 0.5 mA from the lower one. It was confirmed that the subject did not have any pain even at a high current intensity.

First, only the skin stimulation was randomly presented 50 times without performing the $N$-back test, and the correct answer rate was confirmed. Then, an experiment in which the $N$-back test and skin irritation were performed simultaneously was performed. The process flow of this experiment is as follows. First, the operation method of the $N$-back test was explained to the subject, and the subject performed one set without skin
stimulation. Next, the skin stimulations of all stages were applied, and the specific stage was applied several times according to the subject’s request. Thereafter, the N-back test was commenced, and skin stimulations were introduced at an appropriate time. Since the N-back test was completed 29 times per set, the skin stimulation was completed at the end of the N-back test, and a 2 min break was taken. This was carried out for 10 cycles.

Throughout the experiment, the subject placed the electrode on the right arm, operated the answer button for the N-back test with the left hand, and operated the answer button for stimulation with the right hand. The subjects were ten men, including the previous three. They ranged in age from 23 to 50, and the average age was 34.

4.3 Experimental Result

Figure 11 shows the recognition accuracy when only skin stimulation was performed without performing the N-back test. Both conditions (a) and (b) showed high accuracy of over 80%.

The results of recognition accuracy when N-back test and skin stimulation were performed simultaneously are shown in Fig. 12. In condition (a), the accuracy of answers was considerably reduced in stages 2, 3, and 4. In addition to this, it can be seen that in stages 3, 4, and 5, the variation in data is large. On the other hand, in condition (b), the correct answer rate was over 80% and the detection sensitivity was also over 80% except for stage 2 of 78%. Moreover, stages 4 and 5 were over 99% even in the detection sensitivity.

Figure 13 shows the comparison results of detection sensitivity when only stimulation was performed and when N-back test and stimulation were simultaneously performed. In this figure, (a) is a condition in which five stages are set by changing only the stimulation period, and (b) is a condition in which five stages are set by combining the stimulation period and the current intensity. Error bars indicate standard deviation.
are set by combining the stimulation period and the current intensity. The asterisks * and ** in the figure are groups with significant differences at $p$ values of 0.05 or less and 0.01 or less in Welch’s $T$ test [17]. As shown in the figure, under the condition that only the stimulation period was changed, a significant difference was observed with/without the $N$-back test except for stage 5. On the other hand, no significant difference was observed at all stages under the condition combining the stimulation period and the current intensity.

4.4 Discussion

The reason for the recognition rate deteriorating when only the stimulation period was changed is that there is no room for attention to be paid to skin stimulation when another task is being performed. Hence, the subject answered without sufficient verification performed in the brain. It is also possible that the subject was not able to remember the particular stimulation stage well due to being distracted by the $N$-back test. In particular, all five stages differed only in terms of the stimulation period, and if subjects can pay enough attention only to the skin stimulation, they can discriminate between the stages. However, in order for the subjects to identify the five stages while performing some other task, it appears that the difference needs to be large enough for the subject to discern the stage.

On the other hand, when the current intensity and period of the stimulation are changed, the number of steps per current intensity is 3 or less, and the stimulation itself is easier to discern, which reduces the need for attention to the stimulation. From the above, in order for a subject to recognize five stages while performing some other task, it is necessary to set the number of parameters of the period per stage of intensity to 3 or less.

However, a characteristic of electrical stimulation is that the administered intensity depends on the state of the electrode-skin interface. Control of the current intensity requires real-time feedback.

5. Conclusion

In this study, a multi-level risk determination procedure using pulse-like stimulation has been proposed. Moreover, the waveform conditions for recognizing the difference between five stages conveying five levels of heatstroke risk by pulse-like stimulation have been examined. Electrical stimulation has been used, and current-controlled stimulation with a square waveform has been designed according to the perception characteristics of electrical stimulation. Experiments have been conducted to induce multiple stimulations to the subject’s wrist with different periods and current intensities corresponding to several stages.

During the state of being focused on the stimulation, it is possible for the subject to recognize the five stages with over 80% accuracy when the ratio of the stimulation period in adjacent stages is set to 1.6 or more. Moreover, the recognition accuracy is also greater than 90% when the current intensity and period of stimulation are altered.

When the subject is performing a different task, the recognition rate decreases to 40% at the worst recognition in all stages when changing only the stimulation period. In contrast, when both current intensity and period of stimulation are changed, especially when the number of period steps per current intensity step is 3 or less, the difference in stages can be recognized with an accuracy of 80% or more even while the subject is distracted by some other activity.

From the above, the possibility of intuitive identification of five stages of information has been demonstrated by using proposed pulse-like stimulation.

Acknowledgments

This paper is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

References

[1] L.M. Brown, S.A. Brewster, and H.C. Purchase: A first investigation into the effectiveness of tactons, First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 167–176, 2005.
[2] H. Shirado, M. Konyo, and T. Maeno: Modeling of tactile texture recognition mechanism, Transactions of the Japan Society of Mechanical Engineers C, Vol. 73, No. 733, pp. 2514–2522, 2011.
[3] H. Kajimoto, N. Kawakami, and S. Tachi: Psychophysical evaluation of receptor selectivity in electro-tactile display, 13th International Symposium on Measurement and Control in Robotics, pp. 3–6, 2003.
[4] J. Lee, J. Han, and G. Lee: Investigating the information transfer efficiency of a 3x3 watch-back tactile display, Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI ’15), pp. 1229–1232, 2015.
[5] Y. Mizukami and H. Sawada: Tactile information transmission by apparent movement phenomenon using shape-memory alloy device, International Journal on Disability and Human Development, Vol. 5, No. 3, pp. 277–284, 2006.
[6] L.D. Chapwone Tchakouté, D. Gagnon, and B.A.I. Méndez: Use of tactons to communicate a risk level through an enactive shoe, Journal on Multimodal User Interfaces, Vol. 12, No. 1, pp. 41–53, 2018.
[7] D.S. Moran, A. Laor, Y. Epstein, and Y. Shapiro: A modified discomfort index (MdI) as a substitute for the wet bulb globe temperature (Wbgt), Medicine & Science in Sports & Exercise, Vol. 30, Supplement, p. 284, 1998.
[8] L.R. Leon and A. Bouchama: Heat stroke, Comprehensive Physiology, Vol. 5, No. 2, pp. 611–647, 2015.
[9] P.O. Astrand and B. Stalinit: Maximal oxygen uptake and heart various types of muscular activity, Journal of Applied Physiology, Vol. 16, No. 6, pp. 977–981, 1961.
[10] K. Umetani, D.H. Singer, R. McCraty, and M. Atkinson: Twenty-four hour time domain heart rate variability and heart rate: Relations to age and gender over nine decades, Journal of the American College of Cardiology, Vol. 31, No. 3, pp. 593–601, 1998.
[11] K. Kato, H. Ishizuka, H. Kajimoto, and H. Miyashita: Double-sided printed tactile display with electro stimuli and electrostatic forces and its assessment, Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI ’18), pp. 1–12, 2018.
[12] D.G. Seo and Y.H. Cho: Resonating tactile stimulators based on piezoelectric polymer films, Journal of Mechanical Science and Technology, Vol. 32, No. 2, pp. 631–636, 2018.
[13] V. Yem, R. Okazaki, and H. Kajimoto: FinGAR: Combination of electrical and mechanical stimulation for high-fidelity tactile presentation, ACM SIGGRAPH 2016 Emerging Technologies (SIGGRAPH ’16), pp. 2006–2007, 2016.
[14] H. Stanislaw and N. Todorov: Calculation of signal detection theory measures, Behavior Research Methods, Instruments, & Computers, Vol. 31, No. 1, pp. 137–149, 1999.
R. Groner, and K. Gutbrod: Does excessive memory load attenuate activation in the prefrontal cortex? Load-dependent processing in single and dual tasks: Functional magnetic resonance imaging study, *Neuroimage*, Vol. 19, No. 2, pp. 210–225, 2003.

[16] S.M. Jaeggi, M. Buschkuehl, J. Jonides, and W.J. Perrig: Improving fluid intelligence with training on working memory, *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 105, No. 19, pp. 6829–6833, 2008.

[17] B.L. Welch: The generalization of ‘Student’s’ problem when several different population variances are involved, *Biometrika*, Vol. 34, No. 1, pp. 28–35, 1947.

---

**Yoshiyuki Kaiho**

He received the B.E. degree in engineering and M.E. degree in biomedical engineering from Tohoku University, Miyagi, Japan, in 2008 and 2010, respectively. He joined Seiko Instruments Inc., Chiba, Japan, in 2010, and joined the Graduate School of Frontier Sciences, the University of Tokyo, Chiba, Japan, in 2016. His research interests are in wearable device integrated sensors and actuators as well as MEMS devices.

**Toshihiro Itoh**

He received the B.E., M.E., and Ph.D. degrees in precision engineering from the University of Tokyo, Japan, in 1988, 1990 and 1994, respectively. He had joined the faculty of the University of Tokyo in 1995 and was an associate professor at the Research Center for Advanced Science and Technology (RCAST) and the Department of Precision Engineering from 1999 to 2007. Since 2007, he has been a research manager of MEMS-related laboratory in National Institute of Advanced Industrial Science and Technology (AIST), Japan. Now, he is a professor at the Department of Human and Engineered Environmental Studies, the University of Tokyo, Japan. His research interests are in MEMS and wireless sensor nodes for sensor networks as well as large area MEMS.