A Prototype for Presage Detection for Heat Stroke using LPWA Communication and Wearable Devices

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***Abstract*— In recent years, the number of heat stroke cases has been increasing. The manufacturing and construction industries account for 40% of the workplace casualties due to heat stroke. Another problem is the increase in the risk of heat stroke due to the aging of the workforce. Typical symptoms of heat stroke include a rise in core body temperature and delirium. These internal conditions are difficult to obtain from active workers. Therefore, it is common to find signs that appear secondary to these symptoms such as skin body temperature, sweating, and heart rate. In this study, we developed a sensor device that detects signs of heat stroke and a gateway that can temporarily store data. Using these devices, it is possible to implement a system that notifies the supervisor of the signs of heat stroke of workers through LPWA communication, and a system that manages the biometric data of workers in a database and visualizes them in graphs and maps. In order to develop such a system, in this study, we verified whether our device can acquire changes in the biometric data of the user.**

***Index Terms*—Heat stroke, LPWA communication, Wearable device, Construction industry, Manufacturing industry.**

I. Introduction

SINCE 2010, the number of heat stroke cases has been on the rise in Japan; 2018 was the hottest year on record, with 1178 heat stroke deaths and injuries, the highest number over the past 10 years, followed by 829 in 2019. From 2015 to 2019, the manufacturing and construction industries accounted for about 40% of the heat stroke casualties by industry each year [1]. Furthermore, the construction industry has experienced a significant aging of its workforce [2]. In general, the amount of water as a portion of body weight decreases with age, and thus the elderly are more likely to suffer from heat stroke than younger workers. Therefore, measures to prevent heat stroke among workers in the manufacturing and construction industries are urgently needed.

In this study, sensor devices that acquire biometric data and environmental data are attached to the helmets of construction workers. We propose a system to detect presages of heat stroke and visualize the biometric data acquired by the devices. If workers in the construction and manufacturing industries are to wear sensor devices, the following should be considered:

- Indicators that can be obtained even from active workers should be adopted.
- Sensors that are inexpensive and available in large quantities should be implemented.
- Reliable wireless communication should be used to collect data at any location, including those sites where mobile communication networks are not available.

In this paper, we introduce our research on heat stroke and methods to prevent heat stroke in Section 2, and we describe our proposed system in Section 3. Section 4 discusses the experiments conducted to investigate the effectiveness of the sensor used, and Section 5 presents our conclusions.

II. Related Works

A. Symptoms and Signs of Heat Stroke

Studies on the symptoms of heat stroke and the detection of signs of heat stroke have already been widely conducted. The study of Glazer et al. [3] analyzed the risk of heat stroke in people's living environments. According to this study, it is important for individuals to wear appropriate clothing, stay well hydrated, and avoid exposure to heat in order to prevent heat stroke. In their experiment, government and medical personnel provided early warning of danger to facilitate evacuation to a heat shelter in a hot and humid area. As a result, the number of deaths due to heat stroke decreased. However, it is burdensome for the government to provide individual warnings to citizens. In addition, the risk reduction is limited due to individual differences in tolerance to hot environments [4]. Therefore, it is necessary to detect the signs of heat stroke using biometric information based on individual models.

Hifumi et al. [5] and Kondo et al. [6] compared the symptoms of heat stroke patients and non-heat stroke patients using the JAAM [7] and Bouchama [8] criteria. According to these studies, sweating was the most common symptom observed in heat stroke patients. Furthermore, significant differences between heat stroke patients and healthy subjects were found

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in age, heart rate, and other factors. A study by Yuda et al. [9] confirmed that spiky bursts appear in the high frequency (HF) component of heart rate variability about two hours before the onset of heat stroke. It has been surmised that these bursts are a biological response to the release of heat produced in the body. Various methods have been proposed to model and simulate such heat transfer in the body. A typical example is Gagge’s two-node model [10], which assumes that the human body is a sphere with two layers: a skin layer and a core layer. This model can simulate the flow of metabolic heat between the two nodes until it is released from the body through blood flow, respiration, perspiration, and direct conduction. A 25-node model [11] that divides the human body into limbs, torso, and head and a 65-division thermoregulatory model [15] have also been proposed. These models provide more detailed simulations, but they are more computationally intensive. It is inefficient to perform such calculations on end devices. In our study, we create a biothermal model of an individual on a database server using the collected data. By sending only the sensor value thresholds calculated from the model to the device, the end process can be simplified.

B. Detecting the Presages of Heat Stroke

Currently, wireless sensor devices are widely used for monitoring heart rate and other parameters. One of the inherent drawbacks of using wireless devices is their low computational resources. Additionally, the ECG signal may be noisy due to the user’ s body movements during activity. In this situation, it is necessary to determine whether the acquired ECG signal is sufficiently reliable. Tanatorn et al. [12] [13] [14] have made it possible to detect QRS waves and RR intervals from ECG signals with a small amount of computation. They also implemented an automatic signal quality evaluation system and an automatic classifier for arrhythmia, and succeeded in reducing the probability of false alarms. Against this background, a number of devices have been developed in recent years to detect heat stroke using heart rate and perspiration rate. Kosuda et al. [16] and Matsumoto et al.[17] developed wearable devices that detect the signs of heat stroke using the sweat rate. In a study by Uchiyama et al. [18], the deep body temperature was estimated from the body surface temperature obtained with a smartwatch designed to detect the signs of heat stroke. In a study by Palma Oscar Antonio et al. [19], a wearable device was developed to detect heat stroke using heart rate and temperature sensors. In these studies, the sensor data were collected using Wi-Fi or a mobile communication network. However, in the construction industry, such devices are not usable in places where there are no routers or no radio signals, such as mountains, underground, and tunnels.

In Shih-Sung Lin et al.’s study [20], heart rate, humidity, body temperature, and air temperature were collected using LoRa communication. LoRa (Long Range) communication is one of the LPWA (Low Power Wide Area) communication standards. In LPWA communication, nodes communicate via gateways. The gateway must be within the range of direct communication with the devices. Therefore, it is impossible to centrally manage the database server because the device, the

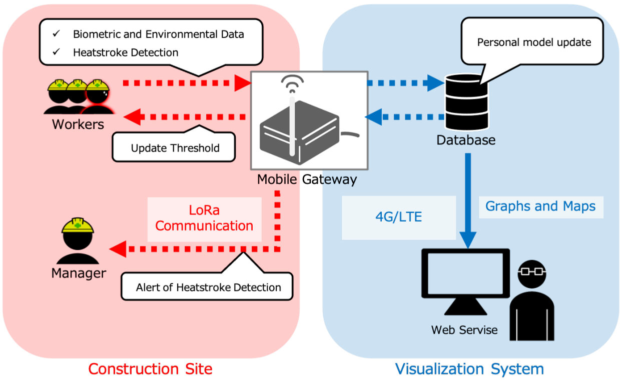

Fig. 1. System Overview

gateway, and the database server all need to exist in one place. In this study, we develop a gateway that allows both LoRa communication and mobile communication. This enables us to manage database servers and web servers anywhere.

III. Proposed System

This section describes the system proposed in this research (Fig. 1). This system consists of two subsystems:

- At a construction site, an extended sensor device attached to each worker’s helmet detects presages of heat stroke and notifies the supervisor. The supervisor can then take appropriate action to prevent a serious labor accident.
- The biometric data of each worker are displayed as a map and a graph on a web application to visualize the risk of heat stroke.

In this study, we develop a portable gateway to integrate the two systems. The portable gateway is capable of both LoRa communication and mobile communication. In addition, it can be used at a site without power supply because it is battery-powered. The portable gateway collects the data of each worker at the work site by LoRa communication. When the portable gateway receives signs of heat stroke from a sensor device, it sends a notification to the supervisor’s sensor device. It sends the collected data to a distant database server via a mobile network. In this way, the network can be deployed at any location, and data can be sent to and received from a distant database.

In the next sections, we describe the details of the heat stroke detection as well as the notification and visualization systems.

A. Detecting signs of heat stroke

In this study, we develop wearable devices that combine two devices. The ”Head Unit” and ”Back Unit” are fixed on the front & inside of the helmet and on the back & outside of the helmet, respectively. The functions of the Head Unit, the Back Unit, and the portable gateway are illustrated in Figure 2.

1) Figure 3 shows that the Head Unit is fixed to the inside of the helmet. The Head Unit is equipped with blood oxygen concentration and heart rate sensors along with

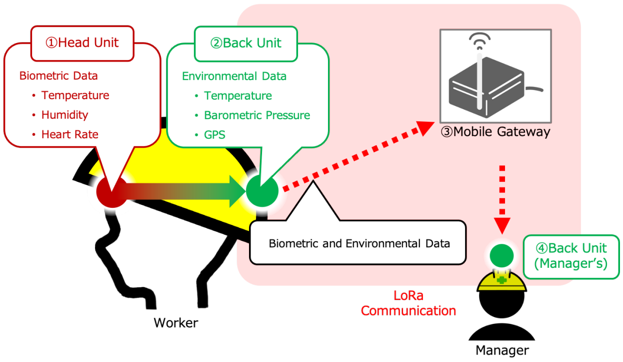

Fig. 2. The Proposed System at a Construction Site

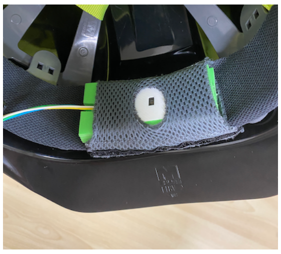

Fig. 3. Head Unit fixed to the interior of the helmet

temperature and humidity sensors in order to detect signs of heat stroke in workers. The following factors should be considered regarding these biological data:

- In general, a blood oxygen level of 100% to 95% is normal, and a level below 90% indicates respiratory failure. However, it is difficult to obtain an accurate blood oxygen concentration within a few percent from the forehead of an active worker.
- Temperature and humidity are easily influenced by external factors such as climate. It is necessary to determine whether changes in values are due to biological reactions or to the environment.

Since various factors are involved in heat stroke, a variety of sensors can be additionally implemented to increase accuracy.

2) Figure 4 shows the Back Unit fixed to the exterior of the helmet, which is connected to the Head Unit by a wire. The Back Unit is equipped with a GPS module, a barometric pressure sensor, a temperature sensor, and a LoRa communication module. It is possible to establish an independent network even in areas where mobile communication networks are not available, since LoRa communication permits bidirectional communication between devices. The GPS module obtains the time and the earth coordinates of the worker, and the barometric sensor obtains the height from the ground. Since air pressure always fluctuates even at the same spot, it is necessary to acquire the air pressure at the reference point. The Back Unit receives biological data from the Head Unit. Biometric and environmental data are transmitted to the portable gateway via LoRa communication when heat stroke is detected and at certain time intervals.

Fig. 4. Back Unit fixed to the exterior of the helmet

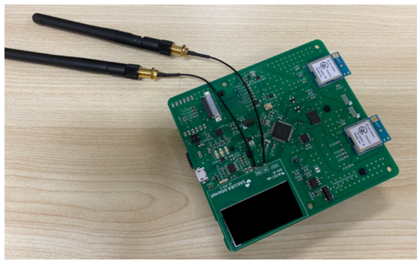

Fig. 5. portable gateway

3) Figure 5 shows the portable gateway. In this study, the portable gateway is always placed on the ground at the construction site. It was equipped with the same barometric pressure sensor as the Back Unit to serve as a reference standard for barometric pressure measurement. In addition, the portable gateway is capable of 4G mobile communication. The data of each worker is stored in the server via 4G mobile communication, and it is visualized by a web application. In order to store the data from several days to several weeks even when there is no base station for mobile communication, a large-capacity flash memory is installed. When the gateway detects that mobile communication is possible, it can be set to transmit the data to prevent data loss.
4) When the gateway receives detection of a worker's heat stroke from the Back Unit, it sends an alert to the supervisor's Back Unit. At that time, the supervisor can take appropriate action to the worker to prevent serious industrial accidents. The reason for not notifying the workers directly is to prevent them from feeling that they are being monitored, and also because they may not feel comfortable voluntarily requesting a work suspension.

B. *Visualization System*

The visualization system displays the biometric data of workers stored in a database on a web application. The data can be displayed in the form of maps or graphs as shown in Figures 6 and 7. The data of heat stroke cases are distinguished by red icons, indicating where and at what time of the day the heat stroke occurred. In addition, by setting the period of time for the data to be displayed, the transition of areas where heat stroke is likely to occur can be visualized. By considering such data, it is possible to take measures to ensure that employees who work in such areas take frequent breaks.

Fig. 6. Example of Map in Visualization System

Fig. 7. Example of Graph in Visualization System

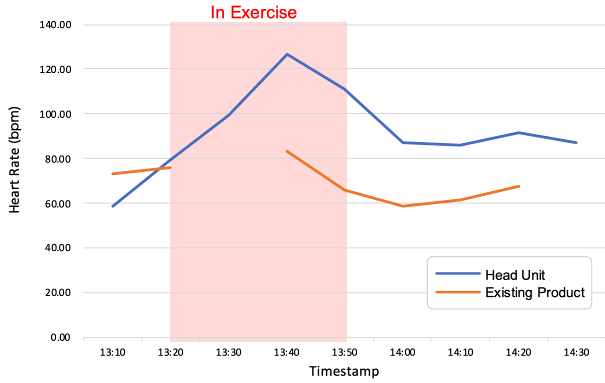

Fig. 8. Heart Rate Comparison Between Head Unit and Existing Devices

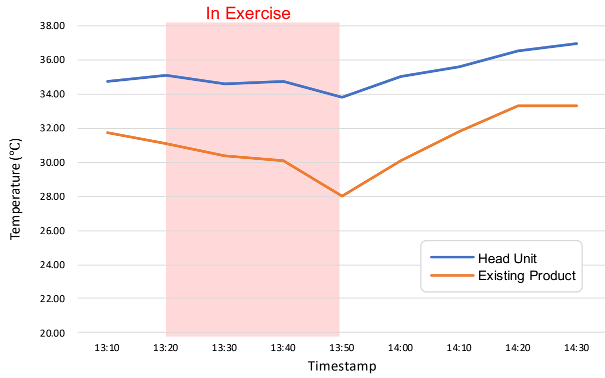

Fig. 9. Temperature Comparison Between Head Unit and Existing Devices

IV. EXPERIMENTS

Considering the conditions of application to workers in the construction and manufacturing industries, the lower the cost of the device worn by each worker, the better. In other words, it is not practical to install expensive sensors or microcontrollers capable of complex calculations.

Therefore, it is necessary to analyze the functions of the sensors and the computing power required to detect heat stroke from an economic perspective. In this study, we conducted the following two experiments:

- To confirm whether the quality of the biometric data acquired by the Head Unit is sufficient, we compared it with existing products.
- As mentioned above, the heart rate, temperature, and humidity sensors are easily affected by the climate. We analyzed the data from each sensor in the Head Unit and the Back Unit to investigate whether it is possible to eliminate these effects. Specifically, we checked the fluctuations of the sensor values depending on the position where the device is installed.

A. Comparison with Existing Products

We compared the efficiency of the Head Unit's sensor with that of the external sensor for helmets used by an existing heat stroke detection service. The sensors used in the Head Unit are a temperature and humidity sensor "SHT31-DIS-B2.5KS" made by Sensirion, and a heart rate sensor "MAX30102" made by Maxim Integrated. The temperature and humidity sensors cost about $3 to $6 and the heart rate sensor costs about $8 to $10, respectively, and can be purchased by anyone. For the comparison experiment, we used the sensor devices used in the "Worker Safety Monitoring System," a service provided by Murata Manufacturing Co., Ltd [21]. The experiment was conducted on a male in his twenties who had no exercise habits. Figures 8 and 9 show the results of the heart rate and temperature data of the devices during exercise and at rest. The exercise consisted of climbing stairs and jogging for a certain period of time.

In Figure 8, the data of the Head Unit showed that the heart rate rises to about 120 bpm during exercise, while that of the existing products was as low as 83 bpm during exercise. Moreover, there were other cases where the existing products could not acquire data correctly. In Figure 9, although the changes in the graphs were similar, the data obtained by the Head Unit were closer to the skin temperature of a human. In addition, the heart rate fluctuated immediately after the start of exercise, while the temperature fluctuates slightly after the start of exercise. Since blood can circulate around the body in approximately 50 seconds, and more quickly during exercise, the heart rate fluctuation is expected to appear immediately. In contrast, there was a delay in the change of temperature because it takes time for the heat generated by the muscles to be carried to the body surface. Therefore, the data acquired by the Head Unit was more accurate than that of existing devices,

Fig. 10. Equipment for the Experiment

even during exercise. In addition, the faster and more accurate calculation of the heart rate should help in detecting signs of heat stroke earlier than usual.

B. Influence of External Factors

Next, we examined the influence of external factors on sensor values. External factors refer to factors other than biological reactions that may affect sensor values. Quantitative evaluation of the influence of such factors is necessary to prevent false positives of predictive signs. This requires a comparison of sensor values inside and outside the helmet to calculate the differences. The Head Unit and Back Unit each have their own temperature sensors. Therefore, in this experiment, temperatures inside and outside the helmet obtained from each unit were compared under several environmental conditions. In the experiment, the Back Unit and the Head Unit were fixed at about 160 cm from the ground surface, assuming the height of an actual worker, as shown in Figure 10. The temperature was measured in the sun and shade outdoors and indoors using the sensors of the Head Unit and the Back Unit, respectively. The Head Unit was fixed inside the helmet, and the Back Unit was fixed outside the helmet, unless otherwise noted.

This experiment tested the effect of the following factors on the temperature sensor of each unit:

- Radiant heat from sunlight
- Difference in efficiency of sensors in each unit
- Temperature change due to outdoor wind

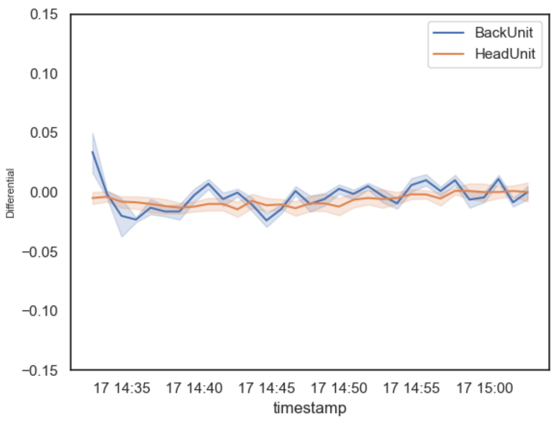

Fig. 11. Difference in Temperature Values for Outdoor Shade

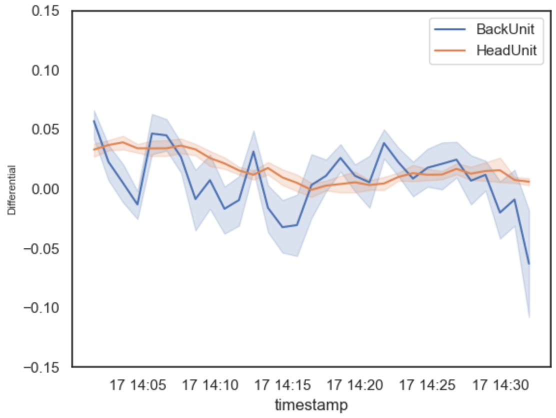

Fig. 12. Difference in Temperature Values in the Sun Outdoors

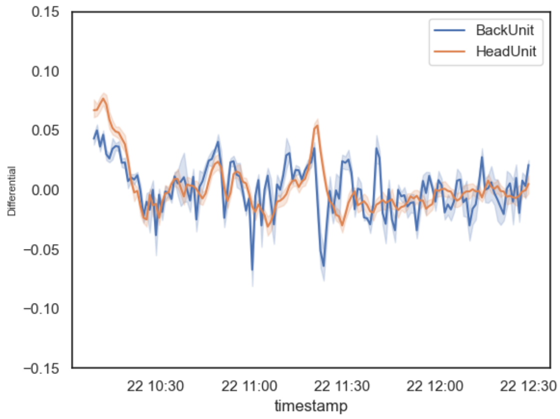

Fig. 13. Difference in temperature between Head Unit and Back Unit fixed at the same position

The continuously measured temperature data were divided into windows of 1 minute in length, and the median value was used as the input data for analysis. The graphs plot the difference between the median value and the value obtained one minute earlier. The shaded area shows the 95% confidence interval of the temperature. First, the graphs in Figures 11 and 12 show that the temperature variance is larger outside the helmet than inside the helmet when the helmet is placed in the sun.

Next, we conducted an experiment to examine whether the efficiency of the sensor was the cause of the temperature variance. In advance, both the Head Unit and the Back Unit were fixed to the exterior of the helmet, and the accuracies of the sensors were compared through the temperature values acquired in the sun.

The graph in Figure 13 plots the difference in the median temperature, as in Figures 11 and 12. Figure 13 shows that the data acquired by the Head Unit and the Back Unit, which are fixed in the sun outdoors, show the same variance. The temperature changes were also similar.

Next, the helmets were repositioned to compare indoor and outdoor temperature changes. Compared to the data shown

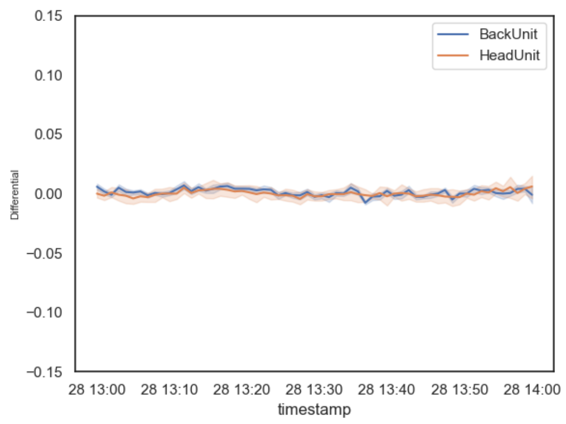

Fig. 14. Difference in temperature indoors

in Figure 14 and in Figure 11, there was no change in the variance. The temperature changes were also similar. The above results indicate that the variance of the temperature outside the helmet increases as the helmet is heated by the radiant heat from sunlight. The difference in the efficiency of the temperature sensors in the Back Unit and the Head Unit, and the outdoor wind did not significantly affect the temperature change and variance inside and outside the helmet. Accordingly, it is possible to evaluate the effect of sunshine by considering the variance of the difference in the values cyclically acquired by the temperature sensor of the Back Unit.

V. CONCLUSION

In this paper, we have created the following devices.

- The Head Unit that acquires biometric data from the user.
- The Back Unit that transmits data from the Head Unit and environmental data to a gateway via LoRa communication.
- The portable gateway capable of LoRa communication and mobile communication.

Using these devices, we proposed a system to detect and notify the signs of heat stroke and a system to visualize workers' data on a web page. In the experiments, we compared the existing wearable devices and our system, and we found that the biometric data could be obtained with sufficient accuracy. The results also showed that external factors can be detected by the sensor device. However, this is only a qualitative verification. To verify this quantitatively, it is necessary to obtain a large amount of vital data from workers in a hot environment and make comparisons. Therefore, we plan to conduct large-scale data collection experiments by having actual workers wear our devices. This allows for a more quantitative evaluation of the relationship between changes in an individual's vital data and external factors. Using these data, we aim to implement an algorithm for detecting signs of heat stroke using an unsupervised learning algorithm, and to demonstrate the effectiveness of the system. Moreover, heat stroke is a problem not only in the construction and manufacturing industries but also in the security industry, livestock industry, and athletics. Therefore, we will study the future application of LPWA communication, which can be deployed at any location, in such worker environments.

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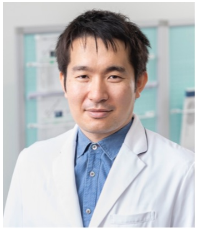

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