Statistical Estimation of Body Temperature from Skin Temperature for Smart Band

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Abstract— As wearable devices have been activated, smart band functions are becoming more diverse. They have many functions that measure a person's physical activity, and body temperature is one of them among these functions. Therefore, this paper proposes a statistical evaluation method based on actual body temperature measurement values for smart band's body temperature measurement. The proposed method estimate skin temperature to body temperature by obtaining two approximate Gaussian functions and mapping these Gaussian functions to each other. This is the application of the central limit theorem of statistics. The proposed method will verifies the accuracy and validity of the body temperature assessment through our experiments.

Keywords— smart band, central limit theorem, Gaussian function

I. INTRODUCTION

As we are more interested in health, we are increasingly developing IT devices to health. One of these devices will be a smart watch or a smart band. Smart watches or smart bands provide activities or health information about a person's exercise. However, in many of these information, they do not provide information about body temperature, and its accuracy is unreliable. This is because the body temperature measured on the skin is affected by the external environment. Therefore, this paper proposes a method to evaluate skin temperature to actual body temperature using statistical methods with human body temperature data measured in various environments.

Skin temperature is affected by external conditions such as ambient temperature and wind. However, a person's body temperature is not affected by these external conditions. Therefore, evaluating skin temperature to body temperature is a very complex problem. We will use the central limit theorem of statistics as a way of solving these problems. The theorem is that arbitrary distributions are normally distributed as the number of data increases. Using this theorem, we obtain normal distribution of skin temperature and body temperature and map each normal distribution to each other.

We use infrared sensors to measure skin temperature. Then a hardware module was built to transmit the measured temperature to a computer or a smart phone. Here, the purpose of this study is to evaluate body temperature, so the description of the hardware module will not be detailed.

A total of 900 measurement data were built for this paper. The modeling data are related to skin temperature, body temperature and sensor device temperature, and were measured on four people indoors and outdoors for four months. First, we draw the histograms of the skin temperature and body temperature, and based on these histograms, we can get the approximate Gaussian functions. Then, by mapping the Gauss function of skin temperature to the Gauss function of body temperature, we can evaluate skin temperature to body temperature. Experiments show that estimated body temperatures are within the margin of error tolerance with the actual body thermometer, so we could obtain reliable results.

This paper is composed of the following. Chapter 2 examines infrared sensors that measure skin temperature, and explains the relationship between skin temperature and body temperature. Chapter 3 describes our statistical estimation, and Chapter 4 analyzes the results of the experiment and we concludes in Chapter 5.

II. RELATED WORK

A. Temperature Sensor and Hardware Module

Hardware modules that measure skin temperature using sensors and apply them have developed into various forms. In order to monitor health, Kim, Dong-Sun, et al designed, fabricated and characterized about the wearable type smart band module to measure the physiological signals from human body [1]. Enamamu proposed a novel body temperature authentication system, BTAuthen, to authenticate the user by using the body temperature information extracted via a smart watch for continuous and nonintrusive user authentication [2]. Suarez presented a computationally efficient, quasi three-dimensional TEG model and used this model to explore the design criteria for current state-of-the-art rigid TEG modules as well as prospective flexible modules for body wearable applications [3].

B. Skin Temperature and Body Temperature

For this study, it is essential to identify the relationship between skin temperature and body temperature. Therefore, we looked at the relationship between different types of skin temperature and body temperature in related studies. Huizenga collected skin temperatures, core temperature, thermal sensation, and comfort responses for 19 local body parts and for the whole body [4]. They found that core temperature increased in response to skin cooling and decreased in response to skin heating. In addition, they showed that hand and finger temperatures fluctuated significantly when the body was near a neutral thermal state. Sim assessed the feasibility of wrist skin temperature monitoring for estimating subjective thermal sensation and invented a wrist band that simultaneously monitors skin temperatures from the wrist and the fingertip [5]. MacRae insisted that setup variables and conditions of use could influence the measured temperature from contact skin temperature sensors and thus key setup variables need to be appropriately considered and consistently reported [6]. Lenhardt concluded that estimation of mean-body temperature (MBT= 0.64. TCore + 0.36. TSkin.) from mean skin and core temperatures is generally accurate and precise [7].

III. METHODOLOGY

We proceed with the following procedures to change skin temperature to body temperature.

A. Hardware Module

We used an infrared sensor MLX90614ESF to measure skin temperatures. The sensor can measure from -40℃ to +125 ℃ and provides sufficient accuracy for medical applications. Basically, the sensor can monitor the two kinds of temperatures. The first temperature is the one at which an object is measured by infrared light. We will call it a skin temperature because we are going to gauge our skin temperature. The second measurement is the temperature of the sensor device itself. That is to say, the temperature generated by the sensor, we would call it a sensor device temperature. The sensor device temperature could be affected by the current air temperature because the sensor's surface is contacted with the outside. We will use the sensor device temperature to determine whether the sensor has come into contact with the skin or not.

The sensor has been added with a Bluetooth module to implement the hardware module shown in Fig. 1. This is a test-bed module that can apply to smart bands for scanning body temperature. In addition, the hardware module can communicate with a smart phone and periodically read a skin temperature and a sensor device temperature from the application we have made as shown in Fig. 2.

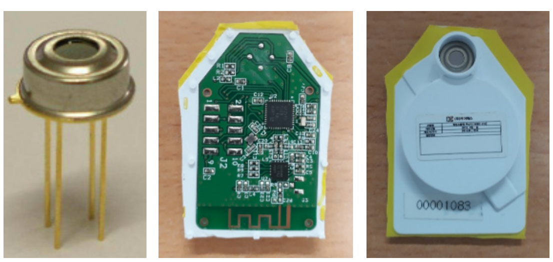

Fig. 1. Hardware Module

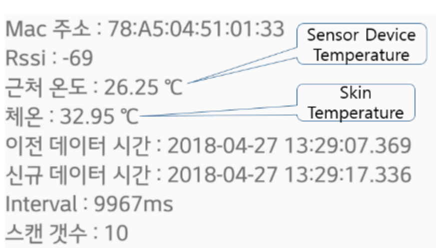

Fig. 2. Reading Temperatures through Application

B. Collecting Data for Statistical Model

We collect modeling data according to the following procedures. First, we put the sensor on the person's wrist as shown in Fig. 3 and connect it to the mobile phone's application after a while. The human body temperature are measured through the ear using a normal thermometer. The hardware module, including the sensor, can periodically measure a person's skin temperature and the sensor device temperature. The two temperatures are saved in a log file. Therefore, we can create the data such as Table 1 by opening log files and reading the skin temperature and the sensor device temperature closest to the time we measured the body temperature of the ear. This will be used for the statistical model.

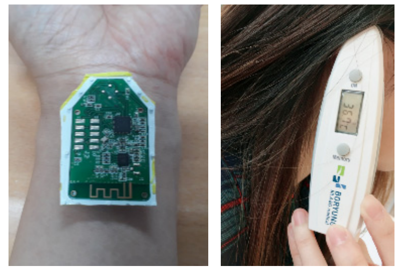

Fig. 3. Measurment of Skin Temperature and Ear Body Temperature

TABLE I. MODELING DATA

Skin Temperature (ST)	**Skin Device Temperature (SDT)**	**Ear Body Temperature (BT)**
33.95	30.39	35.90

To make our model data, four students (two men and two women) obtained a total of 894 observations indoors and outdoors from May to August 2018. The observations were measured less than 10 times a day to prevent bias in observations. Of the measured data, 804 data are used for modeling and 90 data are used as test data to evaluate generalized performance.

C. Statistical Model

To build our statistical model, we carry out the following steps.

① Draw a boxplot. There may be some errors that we measured. Therefore, we will draw a boxplot and exclude outliers from the model data based on body temperature.

② Draw a histogram of skin temperature and body temperature respectively. Next, we will find fitting Gaussian functions based on the histograms. This may be the case with the central limit theorem of statistics. That is, based on the most frequently measured values, arbitrary distributions constitute a normal distribution. Therefore, we can obtain Gaussian function (1) for skin temperature and Gaussian function (2) for body temperature. Here x is the random variable for skin temperature and y is the random variable for body temperature. In addition a1 and b1 are the amplitudes, a2 and b2 are the centroids, and a3 and b3 represent the peak widths. Fig. 4 shows an example of a histogram and a Gaussian function.

$$\text{skin\_gauss}(x) = a_1 * \exp[-((x-a_2)/a_3)^2] \quad (1)$$

$$\text{body\_gauss}(y) = b_1 * \exp[-((y-b_2)/b_3)^2] \quad (2)$$

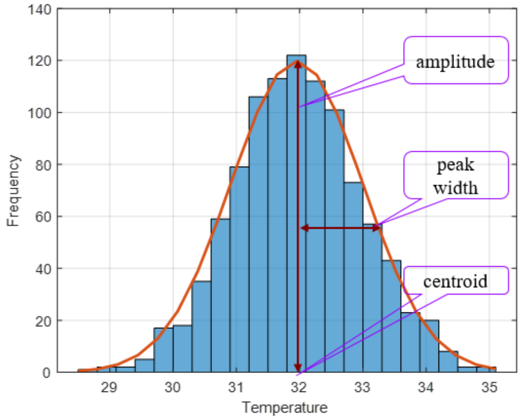

Fig. 4. Example of a histogram and a Gaussian function

③ Map the Gaussian function of skin temperature to the Gaussian function of body temperature. First, the Gaussian function of skin temperature is mapped to a standard normal distribution. Let us map the standard normal distribution to the Gaussian function of body temperature. Figure 5 shows the relevant mapping and (3) is the corresponding formula.

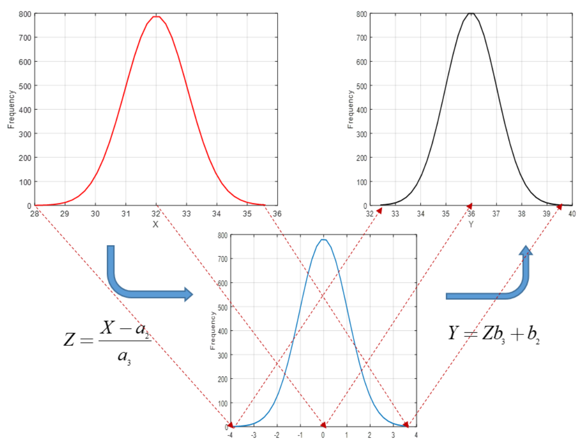

Fig. 5. Mapping Skin's Gaussian function to Body's Gaussian Function

$$Y = b_3\left(\frac{X - a_2}{a_3}\right) + b_2 \quad (3)$$

④ The last step is to check that the sensor is properly in contact with the skin. At this time, we use the sensor device temperature. If the difference between skin temperature and sensor device temperature is less than the contact criterion of (4), we can judge that it is not adequately contacted and it could measure the ambient temperature. However, if the difference is above the criterion value, it can be normal contact and we will evaluate the skin temperature to the body temperature.

$$\text{contact criterion} = \{\text{skin's Mean} - \text{skin's STD}\} - \{\text{SDT's Mean} + \text{SDT's STD}\} \quad (4)$$

$$\text{if (ST-SDT)} \geq \text{(contact criterion) then Good Contact else Failed Contact} \quad (5)$$

IV. Experiments and Results

We used the Matlab Statistics and Machine Learning Toolbox to implement the statistical models. The experiment was conducted at each stage of our statistical model.

A. Boxplot

Fig. 6 shows a boxplot of model data. Here, based on body temperature, not less than 36 and not more than 37.3 body temperatures correspond to outliers and are expressed as '+'. These outliers were incorrectly measured and were excluded from the model data. The total number of outliers was 64 and, 8.56%.

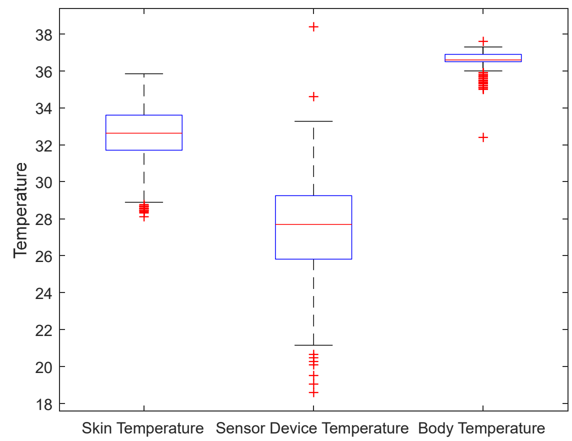

Fig. 6. Boxplot of Model Data

B. Histogram and Fitting Gaussian Function

Fig. 7 shows a histogram and an approximate Gaussian function for skin temperature. The bin of the histogram was determined by the automatic binning algorithm and the number was 16. This means that the distribution of skin temperature is slightly wider. Equation (6) is the approximate Gaussian function in which the coefficient is determined.

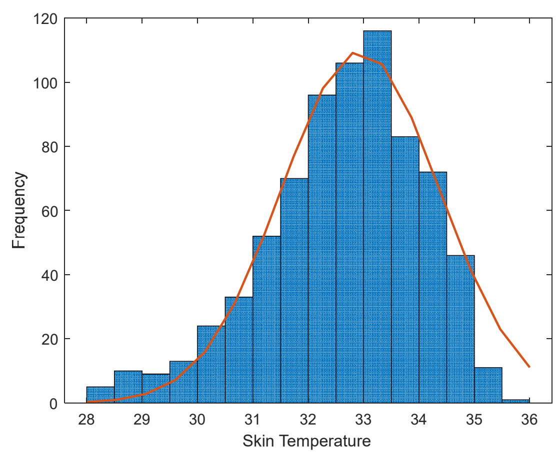

Fig. 7. Histogram and Gaussian Function of Skin Temperature

$$\text{skin\_gauss}(x) = 109.7 * \exp[-((x-32.94)/2.02)^2] \quad (6)$$

Fig. 8 shows a histogram and an approximate Gaussian function for body temperature. We also used an automatic binning algorithm. Here, the number of bins in the histogram is 13 and smaller than the number of bins in the histogram for skin temperature. This means that the body temperature distribution is smaller than the skin temperature distribution. This is also consistent with the fact that a person's body temperature is constant. Equation (7) is the approximate Gaussian function in which the coefficient is determined about body temperature.

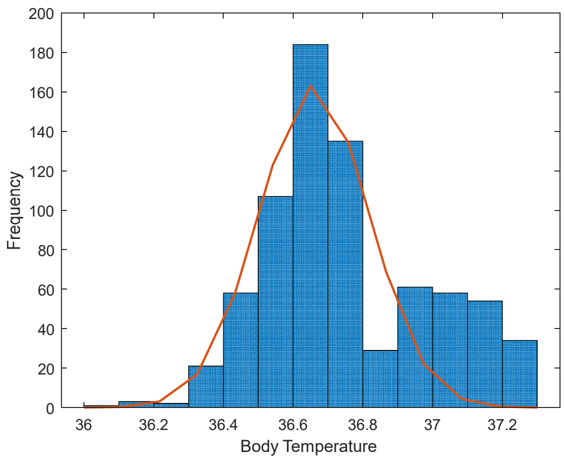

Fig. 8. Histogram and Gaussian Function of Body Temperature

$$\text{body\_gauss}(y) = 163.2 * \exp[-((y - 36.66)/0.22)^2] \quad (7)$$

C. Mapping Skin Temperature to Body Temperature

By using the coefficients obtained in (6) and (7), we can find the mapping formulas such as (3). The results are in (8) and (9). The amplitude did not comment here, because the amplitude is the frequency of the measured temperature and depends on the number of modelling data.

$$Y = 0.22\left(\frac{X - 32.94}{2.02}\right) + 36.66 \quad (8)$$

$$Y = 0.109X + 33.07 \quad (9)$$

D. Checking Sensor Contact with Skin

We used the sensor device temperature to check if the sensor was properly contact with the skin. The contact criteria as defined in (4) were used to obtain the contact criteria as shown in (10). As a result of applying the contact criteria to the model data, there were 6 data in poor contact, which was 0.8% of the total data.

$$\begin{aligned}\text{contact criterion} &= \{32.65 - 1.42\} - \{27.67 + 2.49\} \\ &= 1.07\end{aligned} \quad (10)$$

E. Estimating Modeling Data

Fig. 9 shows the results of an evaluation to skin temperature for the modelling data. As a result, the skin temperature was properly converted to body temperature. The MAE (Mean Absolute Error) was 0.2195. Here, the 'Mean Absolute Error' is the average of the absolute value to the error between the actual body temperature and the estimated body temperature. Because the error range of the thermometer we used in measuring the ear body temperature is ±0.2℃, the error of our experimental results was within the allowable range.

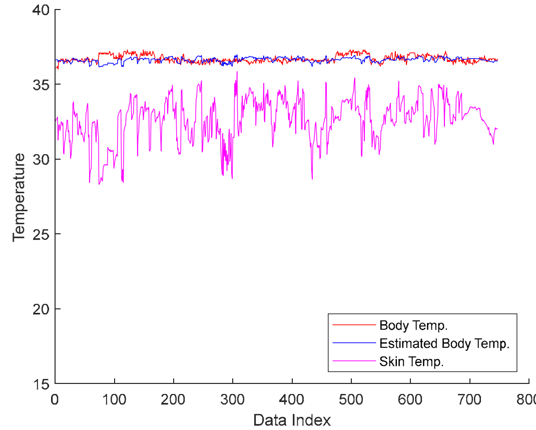

Fig. 9. Estimated Temperature of Modeling Data

F. Estimating Testing Data

Fig. 10 shows the results of an evaluation to skin temperature for the testing data. In this result, the skin temperature was also properly converted to body temperature. The MAE was 0.1918 and was within the allowable range of the thermometer error. Any failed contact beyond the contact criteria in (10) did not occur in the test data.

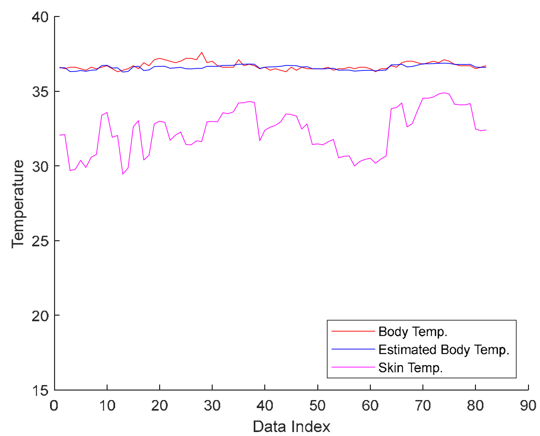

Fig. 10. Estimated Temperature of Testing Data

V. CONCLUSION

Many people are using various smart bands in these days. These smart bands offer a number of functions, including body temperature. However, they do not provide accurate body temperature. Therefore, this paper proposed a method of directly measuring skin temperature and body temperature and evaluating skin temperature to body temperature by statistical method. First, we draw the histograms of the skin temperature and body temperature, and based on these histograms, we can get the approximate Gaussian functions. Then, by mapping the Gauss function of skin temperature to the Gauss function of body temperature, we can evaluate skin temperature to body temperature. We also provide the contact criteria for assessing whether the sensor is properly in contact with the skin. Through our experiments, we achieved good accuracy within the error tolerance about the modeling data and the testing data. The proposed method has been tested on a specific sensor, and if the same method is applied to various sensors that users want to use, effective results can be expected.

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