disp2ppg: Pulse Wave Generation to PPG Sensor using Display

ABSTRACT

Research on wearable devices has been actively conducted, and devices of various shapes and wearing areas have been proposed. Wearable devices are often used to record the user's biometric information, and methods to detect physical abnormalities from the acquired data have been proposed. Among biometric data, pulse data has been used in methods such as emotion estimation. The most common type of pulse sensor is the PPG (Photoplethysmogram), which irradiates a green LED on the skin and measures pulse data from the changes in the light reflected through the blood vessels. PPG sensors have been introduced into commercially available wearable devices such as smartwatches. The PPG sensor requires blood flow for data acquisition due to the characteristics of the mechanism. When a smartwatch is worn on an artificial body such as a prosthetic hand or a wearable robot arm, correct data cannot be acquired because there is no blood flow. In this study, we propose a method to make the PPG sensor measure arbitrary pulse data using a display. If this method is realized, it will be possible to input pulse data measured at the junction of the live body and the prosthetic hand to the display, and have the smartwatch attached to the prosthetic hand read same pulse data. In this paper, we focus on the heart rate, and describe the results of an experiment in which the target heart rate was input and the display was controlled, and whether the target heart rate could be obtained by a smartwatch worn on the display. We implemented a display drawing program and a smartwatch application, and conducted an evaluation experiment using a smartwatch and three displays.

KEYWORDS

ppg sensor, display, pulse wave, heart rate, smartwatch

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1 INTRODUCTION

With the growing awareness of health management, wearable devices that record biometric information have become widely used. The biometric information to be recorded includes a variety of information such as activity, respiratory rate, body temperature, cardiac potential, blood pressure, gaze, etc. The pulse wave and the heart rate are among them. The pulse sensor used to acquire the pulse waves and the heart rate irradiates the skin with LEDs that emit infrared, red light, or light with a green wavelength around 550 nm. The oxidized hemoglobin in the blood of arteries has the property of absorbing these lights. The pulse sensor utilizes the fact that the amount of reflected light decreases as the arterial blood flow increases with the timing of the heartbeat, and uses a phototransistor to acquire changes in the amount of reflected light and measure the pulse wave. The pulse wave data is numerical data of the change of the reflected light, and the heart rate is measured by detecting the peak appearing in the pulse wave data. This types of pulse wave measurement method is called PPG (Photoplethysmogram). Many commercially available wearable devices, such as smartwatches, are equipped with PPG sensor as a pulse sensor.

We consider the possibility of measuring an arbitrary pulse wave by giving a change of light to the PPG sensor and in this paper we propose disp2PPG, a method to let the PPG sensor to acquire pulse data using a display. The proposed method makes a smartwatch to measure an arbitrary heart rate. We assume two objectives for disp2PPG: PPG transfer and fake PPG.

As an application of PPG transfer, artificial bodies, such as prosthetic hands, wearable robot arms, and telepresence robot do not have blood flow. Therefore, it is not possible to measure the biometric data even if a smartwatch is worn on the wrist. Smartwatch functions such as calling, messaging, clocking, and payment, as well as sensors such as accelerometers and GPS, can be used in artificial bodies as in the living body, but pulse data cannot be measured. When a smartwatch is forcibly attached to other body parts where blood flow exists, such as the ankle, in order to measure pulse data, the usability of other functions, such as the messaging, is reduced. With the proposed method, even when a smartwatch is attached to an artificial body, the smartwatch can read the person's pulse data by changing the light of the display under the PPG sensor of the smartwatch according to the pulse data measured at the junction of the living body and the prosthetic hand. It is possible to use the functions provided by a smartwatch since the smartwatch is not modified and only the display is mounted on the artificial body. Users can compare various items such as design, function, and weight of commercial smartwatches and use the model of his/her choice. When applied to a remote robot avatar, the operator's biometric data can be measured on the avatar's body.

As an application of fake PPG, it is possible to let the PPG sensor to measure an arbitrary heart rate by the proposed method and a malicious user could falsify the heart rate and pretend to exercise or continue resting. If a device that realizes the proposed method becomes widely feasible and has a significant social impact, it will be necessary to discuss the use of the current PPG sensor from the viewpoint of the vulnerability of the PPG sensor.

2 RELATED WORK

2.1 Studies using Smartwatch

Smartwatches have been commercially available for a long time and many researches using a smartwatch have been conducted.

Sen et al.[10] proposed a method to record eating behavior, such as whether the user ate with hands, chopsticks, or a spoon, using data obtained from the accelerometer and gyroscope of a smartwatch. Johnston et al.[6] proposed a method for biometric authentication based on gait using data obtained from the accelerometer and gyroscope of the smartwatch. Iakovakis et al.[4] conducted a study that predicts the blood pressure drop caused by postural changes using a smart watch. Mauldin et al.[9] proposed an Android application "SmartFall" that detects falls using acceleration data obtained from a commercially available smartwatch. These methods using inertia sensors such as accelerometers are applicable even with artificial body, however, methods using pulse data are unavailable.

2.2 Studies using Pulse Data

There have been proposed several methods and applications using pulse data. Havriushenko et al.[3] proposed a method for estimating respiratory rate from pulse wave data using neural networks. Han et al.[2] proposed a method for detecting premature atrial contraction (PAC) and premature ventricular contraction (PVC) using PPG data acquired from a smartwatch. Goshvarpour et al.[1] have proposed a method for classifying emotional responses by means of a simple dynamic signal processing technique and fusion frameworks. The authors recorded the electrocardiogram and finger pulse activity of 35 participants during rest condition and when subjects were listening to music intended to stimulate certain emotions. After using poincare plots, the SVM was used to classify them into four emotions: happiness, sadness, peacefulness, and fear. Kajiwara et al.[7] focus on the fact that many logistics companies adopt a manual order picking system, and that emotions and engagement affect work efficiency and human errors, and proposed a method for predicting emotions and engagement during work with high exercise intensity based on behavior and pulse waves acquired by wearable devices. Pulse wave, eye movements, and movements are input to deep neural networks to estimate emotion and engagement. The results of verification experiments showed that emotion and engagement during order picking can be predicted from the behavior of the worker with an accuracy of error rate of 0.12 or less. Lee et al.[8] have conducted research on improving the speed of emotion recognition using PPG signal. A two-dimensional emotion model based on valence and arousal is adopted, and one-dimensional convolutional neural network (1D CNN) is used to recognize emotion from 1.1 second PPG signal. They tested the 1D CNN as a binary classification (high or low valence and arousal) using the dataset for emotion analysis using physiological (DEAP) signals, and achieved recognition accuracy of 75.3% for valence and 76.2% for arousal.

Pulse data is one of the most important biological information, as it can detect abnormalities in the body and estimate emotions. Most of the pulse sensors in commercially available wearable devices use photoplethysmogram. Therefore, when a wearable device is worn on an artificial body where blood flow does not exist, pulse data cannot be acquired. We focus on pulse data and propose a method to let a wearable device to measure pulse data similar to that of a living body even on an artificial body.

3 PROPOSED METHOD

This section explains the details of the proposed method.

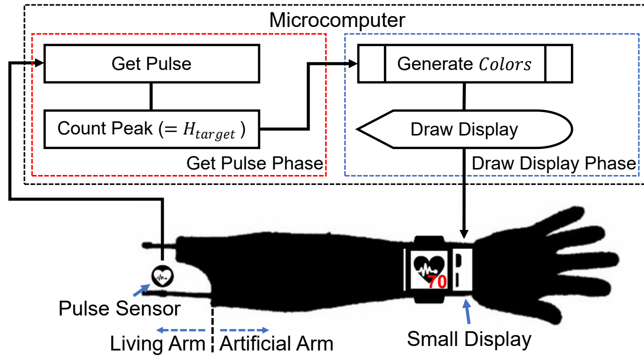

Figure 1: Process flow of the proposed method.

3.1 Overview

The flow of the proposed method is shown in **Figure 1**. First, the real and target heart rate of the user is obtained with PPG sensor which is different to the smartwatch. The proposed method changes the brightness of the display connected to a computer according to the target heart rate. Then, the smartwatch worn over the display measures the heart rate which is the same value as the target heart rate.

3.2 Target Heart Rate Setting

The target heart rate that the proposed method lets the smartwatch to measure is the wearer's heart rate obtained using another PPG sensor, and that value can be specified in real time. Let H_{target} be the target heart rate. H_{target} can also be given manually if the user want the smartwatch to measure specific heart rate.

3.3 Display Control

The brightness of the display is controlled so that the heart rate measured by the smartwatch becomes H_{target}. An array *Colors* which is light changes in the display that would let the smartwatch to detect a single pulse is prepared in advance. *Colors* is grayscale data. Grayscale is a type of computer color representation that uses 256 levels (0-255) to represent shades of color from black to white. *Colors* is generated in the following flow.

1. $Colors[i] = \sin\left(\frac{2\pi i}{L}\right) \ (i = 0, \ldots, L)$
2. $Colors[i] = Colors[i] + 1$
3. $Colors[i] = 1 \ (\text{if } Colors[i] > 1)$
4. $Colors[i] = Colors[i] * SCALE + BASE$

Colors when L is set to 19, $SCALE$ to 30, and $BASE$ to 225 is plotted in **Figure 2**.

PPG sensors irradiates infrared, red or green LEDs onto the skin and measures pulse data from the changes in light reflected through the blood vessels. Because blood flow increases with the timing of the pulse, more light is absorbed by the blood vessels, and the reflected light is dimmer. The decreasing values in **Figure 2** represent the timing when the reflected light becomes dark. The smaller the grayscale, the closer it is to black. Since black absorbs more light than white, the more the display is rendered black, the darker the light emitted from the smartwatch worn on the display and reflected through the display.

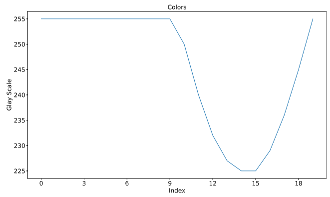

Figure 2: Time-series brightness of the display that makes a smartwatch detect a single pulse.

The drawing interval T[s] for each value of $Colors$ is set as follows, so that $Colors$ is played H_{target} times in one minute.

$$T = 60/(len(Colors) * H_{target}) \tag{1}$$

$len(Colors)$ is the data length of $Colors$. The proposed method draws the values of $Colors$ on the display T[s] one by one for each .

3.4 Pulse Data Measurement

In the proposed method, a smartwatch is worn over a blinking display and pulse data is measured. Pulse data measured from a PPG sensor equipped on a smartwatch can be used in various applications. However, the performance of the PPG sensor and the algorithm for measuring the pulse data vary depending on the model of the smartwatch equipped with it, and are not disclosed to the public. Therefore, the target heart rate is set manually in the evaluation experiment. We observe the error between the target heart rate and the heart rate measured by the smartwatch, and discuss the effects of the smartwatch model and display.

4 EVALUATION

This section describes the experiments conducted to evaluate the effectiveness of the proposed method. We measured the heart rate acquired by the smartwatch when an arbitrary target heart rate was given.

4.1 Display Control Software

A program to change the brightness and darkness of the display was implemented using Python and Processing. Processing[1] is a programming language based on Java that excels in visual expression, and is used to create electronic art and visual design. The process flow of the implemented program is shown below. First, Python receives the target heart rate H_{target} from the standard input. In the color data creation part, we use Numpy[2] to create $Colors$. Then, T[s] is calculated using equation (1). The system sends the created $Colors$ one by one to Processing using Python's `socket` library and waits for the drawing to complete. When Processing receives the data, it uses `background` method to draw the grayscale as the background color of the window on the display. When drawing is complete, Python is notified. When Python receives the notification, it obtains the current time and compares it with T_{send} obtained just before sending the data, and sends the next color data when T[s] has passed. The system repeats this flow, and when all the data in $Colors$ has been sent, it retrieves the data from the first of $Colors$ again in the same way and processes it.

[1]https://processing.org
[2]https://numpy.org

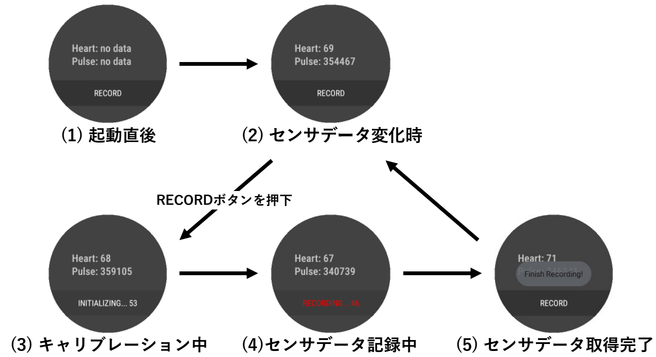

Figure 3: Details of the implemented application.

4.2 Smartwatch Application

4.2.1 Wear OS by Google. In the evaluation experiment, a smartwatch is used to measure the heart rate. However, the application initially installed on the smartwatch stops sensing and turns off the screen after a certain period of time, and the heart rate cannot be saved as a numerical value, so we implemented a smartwatch application that logs the heart rate.

For this evaluation experiment, we used a smartwatch equipped with Wear OS by Google[3] which is an operating system designed for smartwatches based on Google's Android. For this reason, we implemented the application using Android Studio[4]. The implemented application is shown in **Figure 3**. When we start the application, the screen shown in (1) will be displayed. The acquisition of the sensor value starts automatically, and when there is a change in the value, the sensor value is displayed as shown in (2). "Heart" indicates the value of the heart rate sensor, and "Pulse" indicates the value of the PPG sensor. If we want to record the data, we press the "RECORD" button. Then, the 60-second calibration will start as shown in (3). This calibration waits for the value variation to stabilize. We will adjust the wearing position of the smartwatch during this time. When the 60-second calibration is completed, the sensor data is acquired for 60 seconds as shown in (4) and stored in a variable. At the end of the sensor data acquisition time, the data stored in the variable will be saved in the smartwatch storage in csv format, and a message indicating the completion of data acquisition will be displayed as shown in (5). **Table 1** shows the details of the sensors used in the implementation. The sensor number for acquiring PPG data varies from device to device. In this table, we show the sensor number of TicWatch Pro WF12106 (Mobvoi) and PUMA Smartwatch (PUMA) used in the evaluation experiment. The rate of events "SENSOR_DELAY_UI" is a sampling rate suitable for the implementation of the user interface.[5]

4.2.2 watchOS. Apple Watch comes standard with an application that measures heart rate.[6] The collected heart rate data can be

[3]https://wearos.google.com
[4]https://developer.android.com/studio
[5]https://developer.android.com/reference/android/hardware/SensorManager
[6]https://support.apple.com/en-us/HT204666

Table 1: Details of the sensor used for implementation.

Device	Target data	Sensor No.	Rate of events
TicWatch Pro	Heart rate	21	SENSOR_DELAY_UI
PUMA Smartwatch	PPG data	65572	

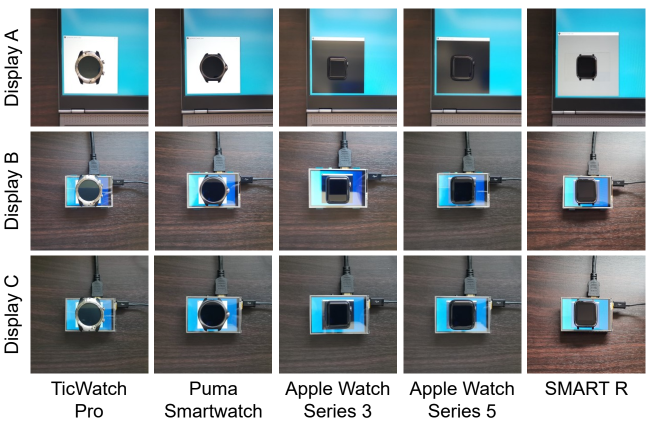

Figure 4: Heart rate acquisition in the evaluation experiment.

output as numerical data in XML format using "Health" application of iPhone paired with AppleWatch.[7]

4.2.3 Original OS. SMART R F-18 used in the evaluation experiments is equipped with a proprietary operating system developed by the manufacturer. By using "WearHealth" application developed for Android and iPhone, heart rate data collected by this smartwatch can be viewed on the application.[8][9]

4.3 Evaluation Environment

TicWatch Pro WF12106 (Mobvoi), PUMA Smartwatch (PUMA), Apple Watch Series 3 and Series 5 (Apple), and SMART R F-18 were used for the evaluation experiments. For the display, we used the built-in display of Legion 7 15IMH05 (Lenovo), a notebook PC used to run the program (hereinafter referred to as Display A), and two small 3.5-inch displays (OSOYOO, KeDei) designed for Raspberry Pi, a microcomputer (hereinafter referred to as Display B, C) were used. Although Display B was equipped with a function to adjust the brightness, all experiments were conducted with the brightness set to maximum. HDMI was used to connect Display B or C to the notebook PC run the program. To obtain the correct heart rate, a 2mm acrylic plate was placed on top of the display in some conditions, and a smartwatch was worn on top of it to obtain the heart rate.

4.3.1 Wear OS Smartwatch. The display drawing program implemented in Section 4.1 and the smartwatch application implemented in Section 4.2 are used to collect the data. The data acquisition was done in the following flow. First, we launch the smartwatch application we implemented. Next, we run the display drawing program and start drawing the display at an appropriate heart rate. In this state, we place the smartwatch on the display and make sure that the heart rate is updated near the set value. After the placement is completed, we enter the target heart rate into the standard input of the display drawing program. Then, we press the "RECORD" button of the smartwatch application. We acquired data while increasing the target heart rate in increments of 5 from 60 to 100 beats per minute, the average heart rate for adults[5]. This process is performed for three sets. The above process was used to acquire data using three displays.

4.3.2 Apple Watch. To collect the data, we used the display drawing program implemented in Section 4.1 and the heart rate acquisition application that comes standard with Apple Watch. The data acquisition was done in the following flow. First, we place the smartwatch on the display. Next, we run the display drawing program and start drawing the display with the target heart rate of 60, and launch the Apple Watch heart rate acquisition application. The acquisition of the heart rate starts automatically. When the data acquisition is finished, Apple Watch screen turns off. Then, we run the display drawing program and start drawing the display with the target heart rate of 65, and tap the screen of Apple Watch. The acquisition of the heart rate starts automatically. We acquired data while increasing the target heart rate in increments of 5 from 60 to 100 beats per minute, the average heart rate for adults[5]. This process is performed for three sets. The above process was used to acquire data using three displays.

4.3.3 Original OS Smartwatch. To collect the data, we used the display drawing program implemented in Section 4.1 and "WearHealth" application. The data acquisition was done in the following flow. First, we place the smartwatch on the display. Next, we run the display drawing program and start drawing the display with the target heart rate of 60, and start acquiring the heart rate data using "WearHealth" application. After 30 seconds of data acquisition from the smartwatch, the final heart rate value acquired is displayed on the application. We acquired data while increasing the target heart rate in increments of 5 from 60 to 100 beats per minute, the average heart rate for adults[5]. This process is performed for three sets. The above process was used to acquire data using four displays.

4.4 Results and Discussion

4.4.1 Wear OS Smartwatch. We calculated the error between the set target heart rate and the heart rate. This result is the average of three sets. 0 means that the heart rate is consistent with the target heart rate, and minus means that the heart rate is insufficient. Also, "Average" is the average of the errors for each display. The sampling rate for heart rate data acquisition is approximately 1 Hz. The conditions under which the data was acquired are shown in **Table 2** and **Table 3**. The results of the evaluation experiment using TicWatch Pro and PumaSmartwatch are shown in **Table 4** and **Table 5**. The results showed that when the target heart rate was between 60 and 100 beats per minute which is the average heart rate of adults, the heart rate could be input into the smartwatch within an error of less than -3 beats per minute. In both smartwatch results, the average error is smaller for Display A, B, and C in that

[7] https://support.apple.com/guide/iphone/share-health-and-fitness-data-iph27f6325b2/ios

[8] https://play.google.com/store/apps/details?id=com.zjw.wearhealth

[9] https://apps.apple.com/jp/app/wearhealth/id1265052549

Table 2: Conditions when acquiring heart rate with TicWatch Pro.

Conditions	Display A	Display B	Display C
L	20	20	20
SCALE	30	30	30
BASE	225	225	225
Acrylic plate	×	○	○

Table 3: Conditions when acquiring heart rate with PumaSmartwatch.

Conditions	Display A	Display B	Display C
L	20	20	20
SCALE	30	30	30
BASE	225	225	225
Acrylic plate	×	×	×

Table 4: Error between the set target heart rate and the heart rate obtained by TicWatch Pro.

H_{target}	Display A	Display B	Display C
60	-1.7	-1.4	-1.4
65	-1.8	-1.4	-1.3
70	-1.8	-2.1	-1.2
75	-2.2	-1.6	-1.5
80	-2.0	-1.5	-1.1
85	-1.8	-1.5	-1.6
90	-2.0	-1.7	-1.0
95	-2.0	-1.2	-1.1
100	-1.9	-1.5	-1.4
Average	-1.9	-1.5	-1.3

Table 5: Error between the set target heart rate and the heart rate obtained by PumaSmartwatch.

H_{target}	Display A	Display B	Display C
60	-1.1	-1.8	-0.8
65	-1.3	-1.6	-0.5
70	-1.9	-1.9	-0.5
75	-3.0	-1.6	-0.6
80	-2.4	-1.5	-1.6
85	-2.4	-1.7	-1.7
90	-2.5	-1.7	-1.8
95	-2.7	-1.4	-2.0
100	-2.7	-2.1	-2.0
Average	-2.2	-1.7	-1.3

order. This suggests that differences in performance, such as display brightness and refresh rate, may affect the generated heart rate. In the future, we need to conduct evaluation experiments using more displays to find displays with smaller errors.

4.4.2 Apple Watch. In the experiment using Apple Watch, the heart rate data was acquired using the application provided by the manufacturer, so the data acquisition time and calibration time could not be set. However, the data is time-stamped. Observing the acquired data, it was found that the data was acquired for approximately 160 seconds at maximum, considering the time when the first sample was acquired as 0. However, it may include data acquisition in the background while the display is off. 30 seconds from the time when the first sample was obtained was used as calibration time, and the data obtained during that time was not used. The time 30 seconds after the first sample was obtained was let to 0, and only the data obtained during the next 60 seconds was used for evaluation. If there were no data acquired after the calibration time, only the last data acquired was used.

Table 6: Conditions when acquiring heart rate with Apple Watch Series 3.

Conditions	Display A	Display B	Display C
L	10	10	10
SCALE	20	40	40
BASE	0	0	0
Acrylic plate	×	×	×

Table 7: Conditions when acquiring heart rate with Apple Watch Series 5.

Conditions	Display A	Display B	Display C
L	10	10	10
SCALE	20	50	40
BASE	0	50	20
Acrylic plate	×	○	×

We calculated the error between the set target heart rate and the heart rate. 0 means that the heart rate is consistent with the target heart rate, and minus means that the heart rate is insufficient. Also, "Average" is the average of the errors for each display. The sampling rate for heart rate acquisition with Apple Watch varied with each acquisition. "MAX" is the maximum number of data obtained in that acquisition cycle, and "MIN" is the minimum number. This number of data does not include the data obtained during calibration. The conditions under which the data was acquired are shown in **Table 6** and **Table 7**. The results of the evaluation experiment using Apple Watch Series 3 are shown in **Table 8**, **Table 9**, and **Table 10**. The results of the evaluation experiment using Apple Watch Series 5 are shown in **Table 11**, **Table 12**, and **Table 13**. Using Display C, when the target heart rate was between 60 and 100 beats per minute which is the average heart rate of adults, the heart rate could be input into the Apple Watch within an error of 0.2 to -1.3 beats per minute. On the other hand, when using Display A and B, it was not possible to obtain the correct heart rate under some conditions. In particular, when the target heart rate was set to 60 with the combination of Apple Watch Series 5 and Display A, the correct heart rate was not obtained even once. However, there are many cases where the heart rate is obtained correctly. In the future, it is necessary to clarify the conditions under which the heart rate cannot be obtained correctly.

Table 8: [1st] Error between the set target heart rate and the heart rate obtained by Apple Watch Series 3.

H_{target}	Display A	Display B	Display C
60	0.0	0.8	-0.3
65	1.2	0.7	-0.3
70	0.0	1.0	-0.2
75	0.0	1.4	-0.8
80	-0.7	0.7	-0.6
85	-0.4	-0.6	-0.9
90	0.0	-1.5	-1.0
95	-1.4	-0.3	-1.0
100	-1.0	-1.2	-0.8
Average	-0.2	0.1	-0.7
MIN	2	6	11
MAX	9	13	12

Table 9: [2nd] Error between the set target heart rate and the heart rate obtained by Apple Watch Series 3.

H_{target}	Display A	Display B	Display C
60	0.8	1.1	-0.3
65	0.0	-0.4	-0.2
70	0.0	2.2	-0.1
75	0.0	3.6	-0.6
80	-0.5	1.2	-0.3
85	-0.7	-0.9	-0.3
90	-1.0	-1.2	-0.3
95	-1.2	-0.8	-1.0
100	-1.2	-1.3	-0.5
Average	-0.4	0.4	-0.4
MIN	2	9	11
MAX	10	13	13

Table 10: [3rd] Error between the set target heart rate and the heart rate obtained by Apple Watch Series 3.

H_{target}	Display A	Display B	Display C
60	0.5	1.2	-0.2
65	0.7	0.0	0.2
70	0.3	2.6	0.2
75	0.0	3.4	-0.3
80	-0.3	1.2	-0.5
85	-15.0	-0.5	-0.6
90	-0.8	-1.1	-0.5
95	-2.0	-0.2	-0.9
100	0.0	-0.8	-0.7
Average	-1.9	0.6	-0.4
MIN	1	8	12
MAX	13	13	13

Table 11: [1st] Error between the set target heart rate and the heart rate obtained by Apple Watch Series 5.

H_{target}	Display A	Display B	Display C
60	58.1	0.0	0.1
65	4.3	0.0	0.1
70	3.4	5.0	0.0
75	0.0	0.0	-0.3
80	1.1	1.0	-0.3
85	-0.9	-1.0	-0.9
90	2.6	-1.7	-0.8
95	0.7	-0.5	-1.2
100	-0.5	-21.0	-1.3
Average	7.6	-2.0	-0.5
MIN	6	1	12
MAX	13	5	13

Table 12: [2nd] Error between the set target heart rate and the heart rate obtained by Apple Watch Series 5.

H_{target}	Display A	Display B	Display C
60	58.7	0.4	-0.2
65	43.4	-0.3	0.0
70	0.5	1.0	0.2
75	2.2	0.2	-0.3
80	2.2	0.7	-0.2
85	-0.5	-1.0	-0.9
90	11.0	-1.3	-1.0
95	-0.4	-0.5	-1.1
100	1.1	-1.0	-0.2
Average	13.1	-0.2	-0.4
MIN	5	2	12
MAX	13	7	13

Table 13: [3rd] Error between the set target heart rate and the heart rate obtained by Apple Watch Series 5.

H_{target}	Display A	Display B	Display C
60	57.8	0.0	-0.2
65	0.6	-1.0	0.1
70	0.8	1.2	0.1
75	0.1	0.0	-0.1
80	0.3	1.0	-0.7
85	-0.4	-1.0	-0.8
90	-0.8	0.0	-1.0
95	-0.5	0.0	-1.1
100	-1.3	0.0	-0.9
Average	6.3	0.0	-0.5
MIN	5	1	12
MAX	13	5	13

4.4.3 Original OS Smartwatch. We calculated the error between the set target heart rate and the heart rate. This result is the average of three sets. 0 means that the heart rate is consistent with the target heart rate, and minus means that the heart rate is insufficient. Also, "Average" is the average of the errors for each display. The conditions under which the data was acquired are shown in

Table 14: Conditions when acquiring heart rate with SMART R.

Conditions	Display A	Display B	Display C
L	20	20	20
SCALE	100	100	100
BASE	0	0	0
Acrylic plate	◯	×	×

Table 15: Error between the set target heart rate and the heart rate obtained by SMART R.

H_{target}	Display A	Display B	Display C
60	-1.7	-1.7	-1.0
65	-1.3	-1.7	-1.7
70	-1.0	-1.3	-1.0
75	-2.0	-2.0	-1.7
80	-1.0	-2.0	-2.0
85	-1.7	-1.7	-2.0
90	-2.3	-2.0	-2.3
95	-1.7	-1.3	-2.3
100	-3.0	-3.0	-2.7
Average	-1.7	-1.9	-1.9

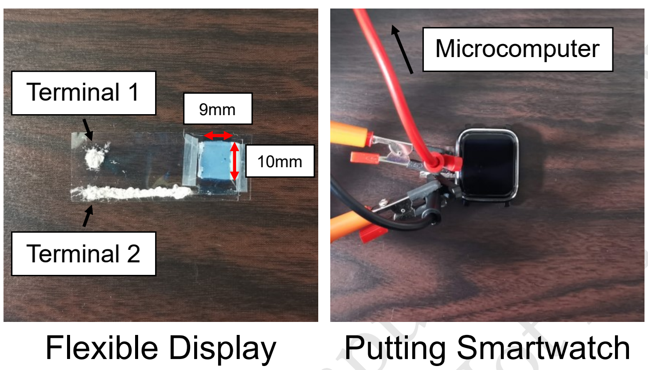

Figure 5: Appearance of the flexible display.

Table 14. The results of the evaluation experiment using SMART R are shown in **Table 15**. The results showed that when the target heart rate was between 60 and 100 beats per minute which is the average heart rate of adults, the heart rate could be input into the smartwatch within an error of less than -3 beats per minute.

4.5 Flexible Display

The evaluation was conducted using a lightweight and flexible display designed to be worn on the body. The size of the lighted part of the flexible display is 1cm square. The appearance of the flexible display is shown in the left side of **Figure 5**.

The flexible display blinks by switching the potential direction applied to the terminals. We implemented a system to realize the proposed method described in Section 3 using a microcomputer, Arduino Uno R3. This microcontroller can control the output voltage by PWM (Pulse Width Modulation). We connected the PWM

Table 16: Error between the set target heart rate and the heart rate obtained by SMART R.

H_{target}	Flexible Display
60	1.0
65	-1.7
70	-1.0
75	-0.3
80	0.0
85	-0.3
90	-1.0
95	0.0
100	0.0
Average	-1.1

output terminals of the Arduino to Terminals 1 and 2 of the Flexible Display. The Arduino receives the target heart rate from Python running on a computer connected to it, and changes the voltage value according to the value. The color of the display becomes darker when voltage is applied to Terminal 1, and lighter when voltage is applied to Terminal 2. *Colors* described in Section 3.3 are set as follows.

$$Colors = \begin{pmatrix} Terminal_1 = [5, 0](V) \\ Terminal_2 = [0, 5](V) \end{pmatrix}$$

This is a sequence of numerical values of the voltage change given to the terminals. The system simultaneously switches the voltage applied to Terminal 1 and 2 according to the above sequence. The interval between switching voltages follows $T[s]$, which is calculated from equation (1). Here, $len(Colors)$ is 2.

Since the SMART R was the only smartwatch in which the size of the PPG sensor did not exceed the size of the light-emitting part, we conducted the evaluation using only this smartwatch. Data acquisition was performed in the same flow as in Section 4.3.3. In cases where obviously incorrect values were obtained, the data was obtained again.

We calculated the error between the set target heart rate and the heart rate. This result is the average of three sets. 0 means that the heart rate is consistent with the target heart rate, and minus means that the heart rate is insufficient. Also, "Average" is the average of the errors for each display. The results of the evaluation experiment using SMART R are shown in **Table 16**. The results showed that when the target heart rate was between 60 and 100 beats per minute which is the average heart rate of adults, the heart rate could be input into the smartwatch within an error of less than -2 beats per minute.

5 CONCLUSION

In this paper, we proposed a method to let the PPG sensor measure an arbitrary heart rate using a display. We implemented a display drawing program and a smartwatch application, and conducted an evaluation experiment using a smartwatch and three displays to confirm the effectiveness of the proposed method. As a result, the overall error between the target heart rate entered and the heart rate acquired by the smartwatch was within -3 beats per minute.

In the evaluation experiment, we were able to make the smartwatch measure the target heart rate with an error of less than -3 beats per minute using the display. However, there are restrictions on the display, and there is a possibility that the acquired values may vary severely depending on the position of the wearer.

In the future, we will improve the reproducibility of PPG data for use in a real environment, and implement a mechanism that allows the wearable device worn on the display to measure the same PPG data by inputting PPG data obtained from a live body part. To achieve this, the system needs to continue to automatically determine the colors to be drawn on the display. Therefore, we will build a generative model that can output the color to be drawn on the display by inputting PPG data. In addition, we will miniaturize the device to be worn on the body part, and conduct experiments using more wearable devices.

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