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Low-Cost Wearable Device for Sleepiness Detection Based on Heart Rate Monitoring

Marvin Yonathan Hadiyanto[1*], Ananda Keshava[1], Budi Harsono[1], Shoaib Aslam[2,3]

[1]Faculty of Engineering and Computer Science, Krida Wacana Christian University, Jl. Tanjung Duren Raya No. 4 Jakarta Barat 11470, DKI Jakarta, Indonesia

[2]Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

[3]Department of Mechatronics and Control Engineering, University of Engineering and Technology Lahore, Khurianwala Bypass, Khurrian Wala, Faisalabad, Punjab, Pakistan

[*]marvin.yonathan@ukrida.ac.id

Abstract. Driver sleepiness is one of the most contributing factors in car accidents. Preventions to this problem have been made with various types of driver's sleepiness detection system, such as systems based on face detection and electrocardiography approaches. However, these approaches require sophisticated systems and impractical design that are not suitable for the low-cost wearable device for daily use. Photoplethysmography based sensor is very favorable to be implemented in the low-cost wearable device to monitor the driver's heart rate due to its reliability in measurement and simplicity in design. In this study we propose a photoplethysmography based wearable device that is low-cost, wearable, simple to build, and good reliability. We have shown that our wearable device exhibits less than 3.12 BPM in average absolute error heart rate with the standard instruments, moreover, our low-cost wearable device is successfully detecting sleepiness based on heart rate reduction of the subjects, which in sleepy condition the heart rate decreases typically ~30 % from the normal condition. Here, we design a sleepiness detection device with 3 levels of sleepiness alarm based on heart rate reduction that is very promising to be implemented as a wearable device in daily use for car drivers to prevent accidents due to sleepiness factor. In the future, this concept can be further improved as a smart driver monitoring system that can monitor physical conditions, mental conditions, and driver's behavior particularly for the upcoming era of semi-autonomous and autonomous car.

Keywords: sleepiness detection system, driver alert system, wearable technology, heart rate monitoring, PPG sensor

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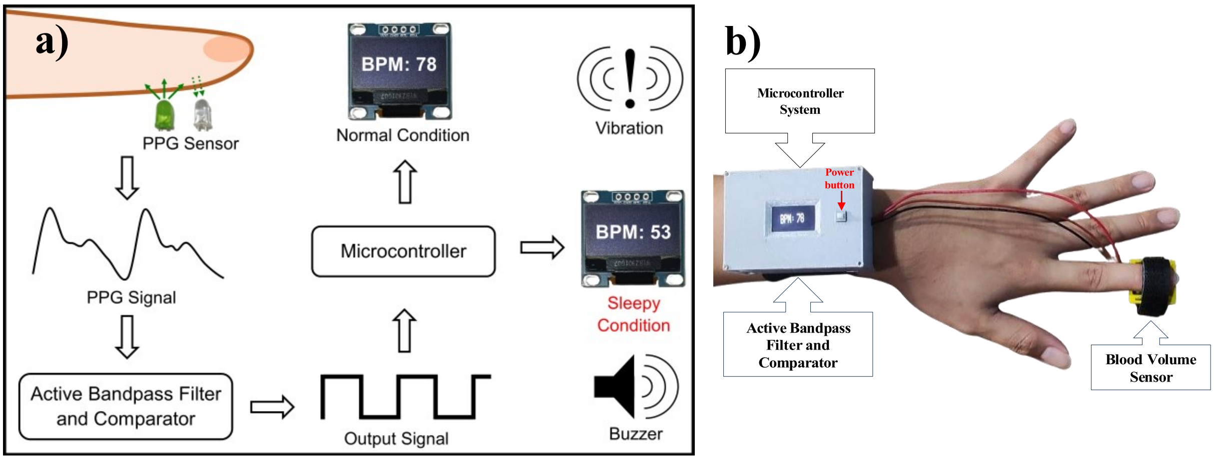

Figure 1 (a) Graphical abstract of the wearable device. **(b)** The overview of the proposed wearable device for sleep detection.

1. Introduction

Human error is one of the most contributing factor in car accidents [1]. Up to 30% fatal crashes are caused by driver sleepiness [2]. Car-safety systems such as monitoring system of the driver state is critical to improve the prevention method to reduce the number of car accidents. The most commonly approaches to monitor the driver's sleepiness are typically based on facial features detection and driving performance [3]. These methods will be problematic in the current era of semi-autonomous and autonomous car due to computer-assisted driving feature that can take control the car meanwhile the driver's eyesight can be in the inappropriate direction for driving [4], [5]. Additional data that contains real-time physiological indicators of sleepiness are beneficial to monitor the driver's state regardless of the activation of autonomous mode while driving the car.

Heart rate (HR) is the number of heart beats per minute (BPM), HR increases when a person exercises as well as HR decreases when a person is in resting condition. The correlation between HR with resting condition can be a good indicator to monitor the driver's sleepiness. With the current sensor technologies available in the commercial market today, low-cost, high reliability, and wearable HR sensing devices can be easily built. Wearable HR sensing devices are very potential to be used as the instrument to measure real-time driver's HR to monitor the driver's sleepiness while driving. Previous studies have been conducted to develop the sleepiness monitoring system for the driver, namely Chellappa et. al. that have proposed sleepiness detection using camera by observing the eye of the driver [6], Safarov et. al. have proposed similar approach that is based face detection with the aid of deep learning to detect the driver's sleepiness [7]. These studies have successfully demonstrated the driver's sleepiness monitoring system by utilizing face detection approach, however these approaches suffer from impracticalities due to the use of camera and the need major face detection method adjustments to be implemented in autonomous cars. Alternatively, several groups have studied the effectiveness of electrocardiography (ECG) signal, Fujiwara et. al. and Fouad have proposed ECG based method to detect the driver drowsiness [8], [9]. However, this method requires attaching the electrodes to the driver body for the purpose of ECG signal measurements that is very impractical to be a daily used wearable device.

Photoplethysmography-based HR estimation is very promising to be used in wearable devices due to the feasibility to measure the signal at the peripheral position such as fingertip [10]. Photoplethysmography (PPG) needs to use sensor that consists of a light source and a detector to measure the change of intensity of the light that is transmitted or reflected through the skin of a fingertip [11]–[13]. The electrical signal that is converted by the photodiode from either the reflected or transmitted light can describe the cardiac rhythm to estimate HR, between the reflection and transmission approach, the former have been shown to have a higher absorptivity for both oxyhemoglobin and deoxyhemoglobin particularly for green light [14], [15]. In this paper we proposed a sleepiness detection system based on light reflection-PPG method by designing a wearable device that

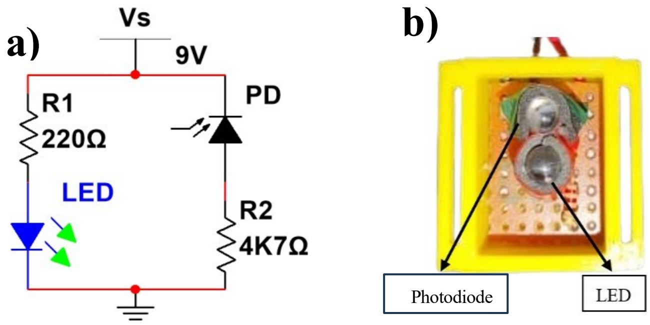

Figure 2 Blood volume sensor **(a)** schematic and **(b)** device.

can monitor HR in real time and activate 3 levels of alarm to alert the driver when sleepiness is detected. As demonstrated by Hanggara et. al. the importance of emerging portable and low-cost physiological sensing device, we propose a wearable that is simple to build and assembled from commercially available electronic components and electronic modules that are low cost [16]. Our proposed wearable device is superior in simplicity for daily use in comparison with ECG based devices that only need to be wrapped on the wrist to attain HR signal from the fingertip. Moreover, the PPG based device offers a significantly simpler approach to monitor the driver's state contrasted with the facial detection that needs a high computational complexity. Our proposed device is very promising to be implemented as a wearable device in daily use for car drivers to prevent accidents due to sleepiness factor.

2. Methods

The proposed wearable device consists of three main parts, namely blood volume sensor, active bandpass filter and comparator, as well as microcontroller system. The system is programmed in C++ language and packaged with fully 3D printed case as the overview of our system is shown in **Figure 1**, it shows that the signal is obtained from the fingertip, filtered, and processed in the microcontroller to display real-time HR data while monitoring the sleepiness state.

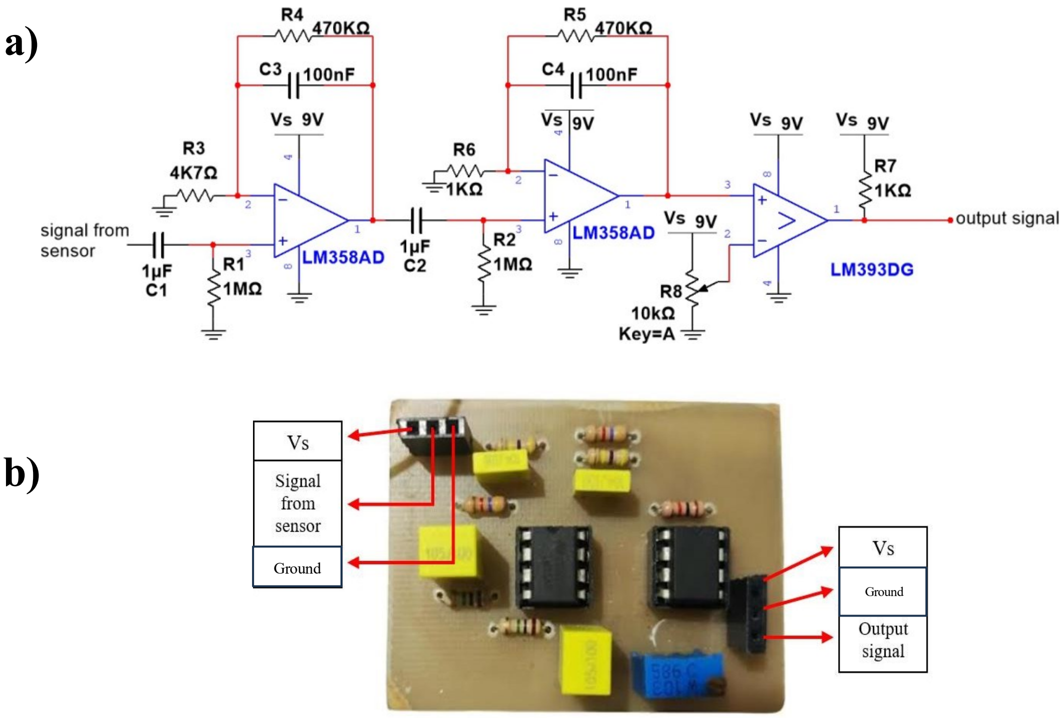

Figure 3 Active bandpass filter **(a)** schematic and **(b)** device.

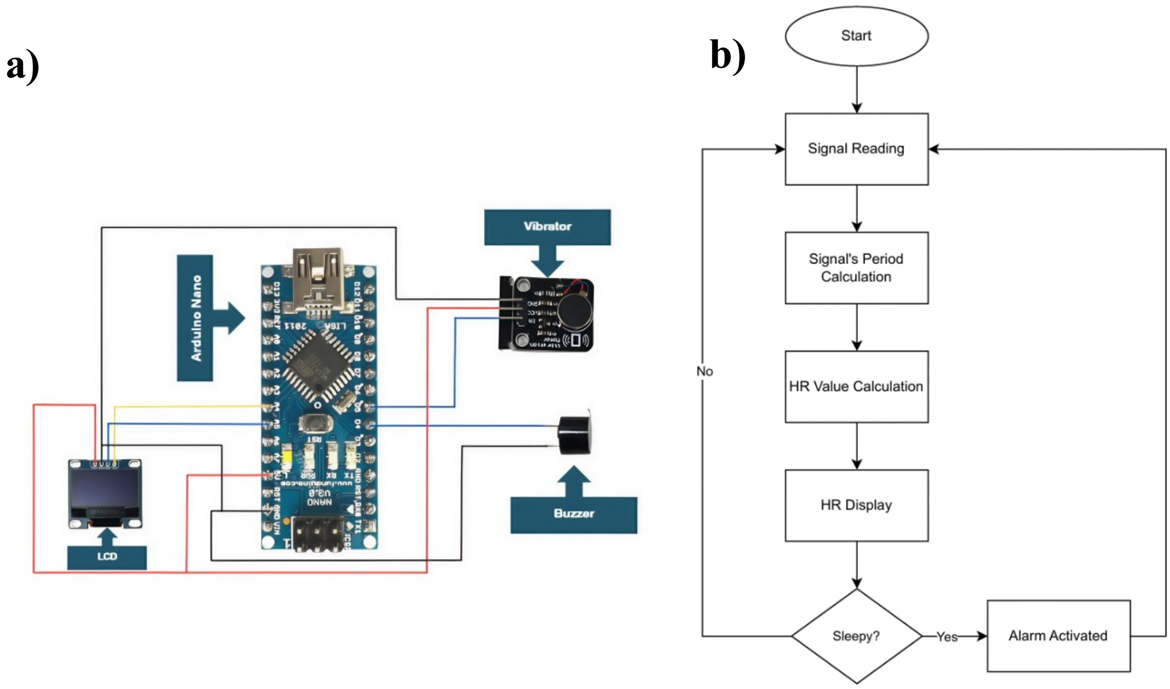

Figure 4 (a) Schematic of microcontroller system. **(b)** Flowchart of microcontroller system procedure.

2.1. Blood Volume Sensor

We design our blood volume sensor that is based on light reflection-photoplethysmography method which measures the light intensity that is reflected from the finger as the blood volume changes. As shown in **Figure 2**, Green LED in the circuit is the source of the light that illuminates the blood through a fingertip. Blood volume changes due to the artery pulse will affect the light that is reflected to the photodiode and the absorbed light is converted to the electric signal that is a function of the blood volume change in real-time.

2.2. Active Bandpass Filter and Comparator

As shown in **Figure 3**, the electric signal from the photodiode in the blood volume sensor is forwarded to the active bandpass filter circuit to filter signals with frequency that is outside the filter's bandwidth frequency. Here, we use an active bandpass filter that has been demonstrated by Harsono et. al. with the bandwidth frequency from 0.159 Hz to 3.386 kHz [17]. Output signal from the active bandpass filter is then forwarded to the comparator circuit that converts the signal from analog to digital, which one cycle the digital signal that consists of single HIGH and LOW pulse represents a HR of human subject.

2.3. Microcontroller System

The microcontroller system consists of an Arduino Nano, liquid crystal display (LCD), buzzer, and vibrator as shown in **Figure 4 (a)**. The microcontroller system procedure can be seen in **Figure 4 (b)**, when the button power in the wearable device is pressed, the microcontroller starts, then it will read the signal and record the period value of a heartbeat, this value will then be used for real-time HR value that is displayed in the LCD, when HR value is lower than the sleepy HR threshold the buzzer and vibrator will be activated to alert the driver.

$$absolute\ error_i\ (\%) = |x - y_i| \quad \textbf{(1)}$$

$$heart\ rate\ reduction\ (\%) = \frac{sleepy\ BPM - normal\ BPM}{normal\ BPM} \times 100\% \quad \textbf{(2)}$$

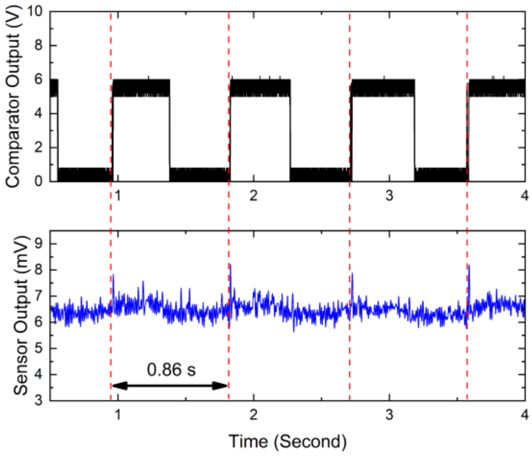

Figure 5 The output signal from the blood volume sensor and active bandpass filter-comparator.

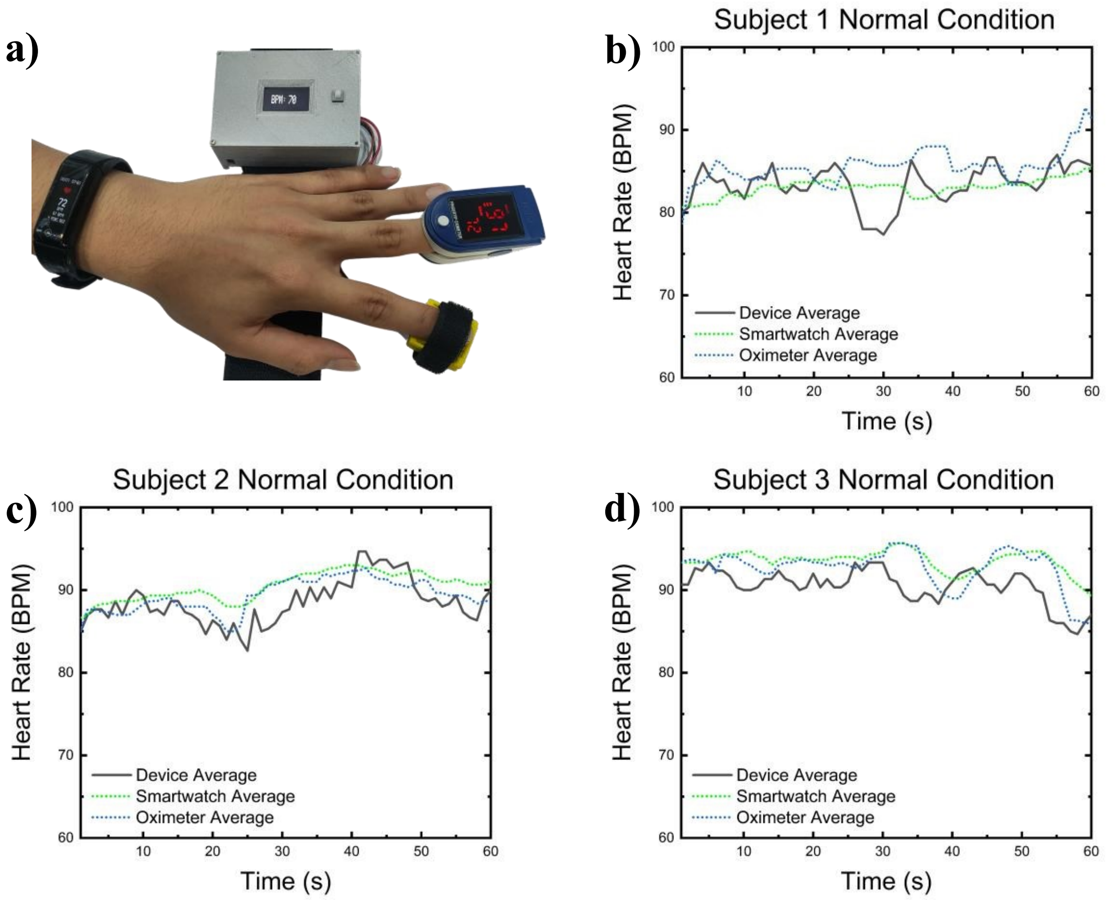

Figure 6 **(a)** HR measurement using our proposed device, smartwatch, and oximeter from **(b)** subject 1, **(c)** subject 2, and **(d)** subject 3 in normal condition.

2.4. HR Measurement

Measurement of the subject's HR is taken from the fingertip of a human subject, HR value of a human subject is shown on a display in real time. In this paper we measure human subjects in normal conditions and sleepy conditions, normal condition measurement is taken for one minute from sitting position and rest condition, while sleepy condition is taken for one minute from sleeping position and nearly sleep condition. For normal conditions, we compare the HR result from our proposed device with Xiaomi Smartband 2 and oximeter to observe the absolute error of HR, the absolute error is defined with **Equation 1** to measure the accuracy of our wearable device to the standard HR measurement instruments, where x is HR data from our wearable device, y is HR data from the other two instruments. In sleepy conditions we calculate HR reduction for each human subject with respect to their normal condition, the calculation is defined with **Equation 2**. The reduction of HR when the subject is sleepy will be used as the threshold for determining the threshold of 3 levels of sleepiness alarm.

3. Results and Discussion

3.1. Output Signal

Output signal from the blood volume sensor and active bandpass filter-comparator are presented in **Figure 5**, we can see the blue colored signal is the output signal of the blood volume sensor is less than 10 mV at the highest pulse and a period of a heartbeat is approximately 0.86 seconds that equivalent with ~70 BPM. After the signal is processed by active bandpass filter-comparator, the resulting signal is displayed in black colored, the output of HIGH signal is 5 V following the rate of the Arduino nano with a very similar period to the signal from blood volume sensor output (blue colored signal). The resulting signal of 5 V is more readable by the commonly used microcontroller, as well as its digital form is very beneficial to perform pulse's period calculation in the microcontroller.

3.2. Normal and Sleepy Conditions HR Measurement

Normal condition average heart rate is taken in one minute for three measurements from the fingertip of three human subjects from sitting position and rest condition, for comparison we use a Xiaomi Smartband 2 and an oximeter in the measurement to observe the absolute error of HR value between our wearable device and the other two instruments as displayed in **Figure 6 (a)**. We define the parameter absolute error with **Equation 1** to measure the accuracy of our wearable device to the standard HR measurement instruments, where x is HR data from our wearable device, y is HR data from the other two instruments. We can see from **Figure 6 (b)**, subject 1 shows HR in the range from 80-90 BPM, data from our wearable device show a very similar value in comparison to HR data from the other two standard instruments, we can see that the average absolute errors are 1.75 BPM and 2.80 BPM from Xiaomi Smartband 2 and oximeter respectively. From **Figure 6 (c)**, subject 2 shows HR that is typically around 85-90 BPM, the average absolute errors are 2.35 BPM and 1.77 BPM from Xiaomi Smartband 2 and oximeter respectively. While from **Figure 6 (d)**, subject 3 shows HR in the range from 85-95 BPM, the average absolute errors are 3.12 BPM and 2.53 BPM from Xiaomi Smartband 2 and oximeter respectively. For comparison, several studies have shown a similar average absolute error of heart rate, Zhang et. al. reported 2.34 BPM and Sun et. al. reported 2.13 BPM of average absolute errors [18], [19]. This data indicates that our wearable device shows comparable accuracy in comparison to the standard instruments that are widely used in recent days as well as to several studies that have been reported.

Sleepy condition average heart rate is taken in one minute for three measurements from the fingertip of three human subjects from sleeping position and nearly sleep condition. We can see from **Figure 7 (a)**, subject 1 shows average sleepy HR in the range from 50-60 BPM with the average HR reduction of 36.15% from its normal condition, this HR reduction is calculated with **Equation 2**. in **Figure 7 (b)**, subject 2 shows average sleepy HR that is typically around 55 BPM with the average HR reduction of 32.27% from its normal condition, while subject 3 shows average sleepy HR around 63 BPM with the average HR reduction of 30.28% from its normal condition as can be seen in **Figure 7 (c)**. Based on this data, we can infer that the HR reduction between normal and sleepy conditions can be used as the parameter to determine the sleepiness state of a subject. Here in our wearable device, we define three levels of alarm to alert the subject when the HR indicates reduction more than 20% from the normal condition, those alarm are consisted of short pulse of vibration and buzzer for level 1 (20% HR reduction), long pulse of vibration and buzzer for level 2 (25% HR reduction), as well as continuous vibration and buzzer for level 3 (30% HR reduction). The HR reduction in sleepy state in this study

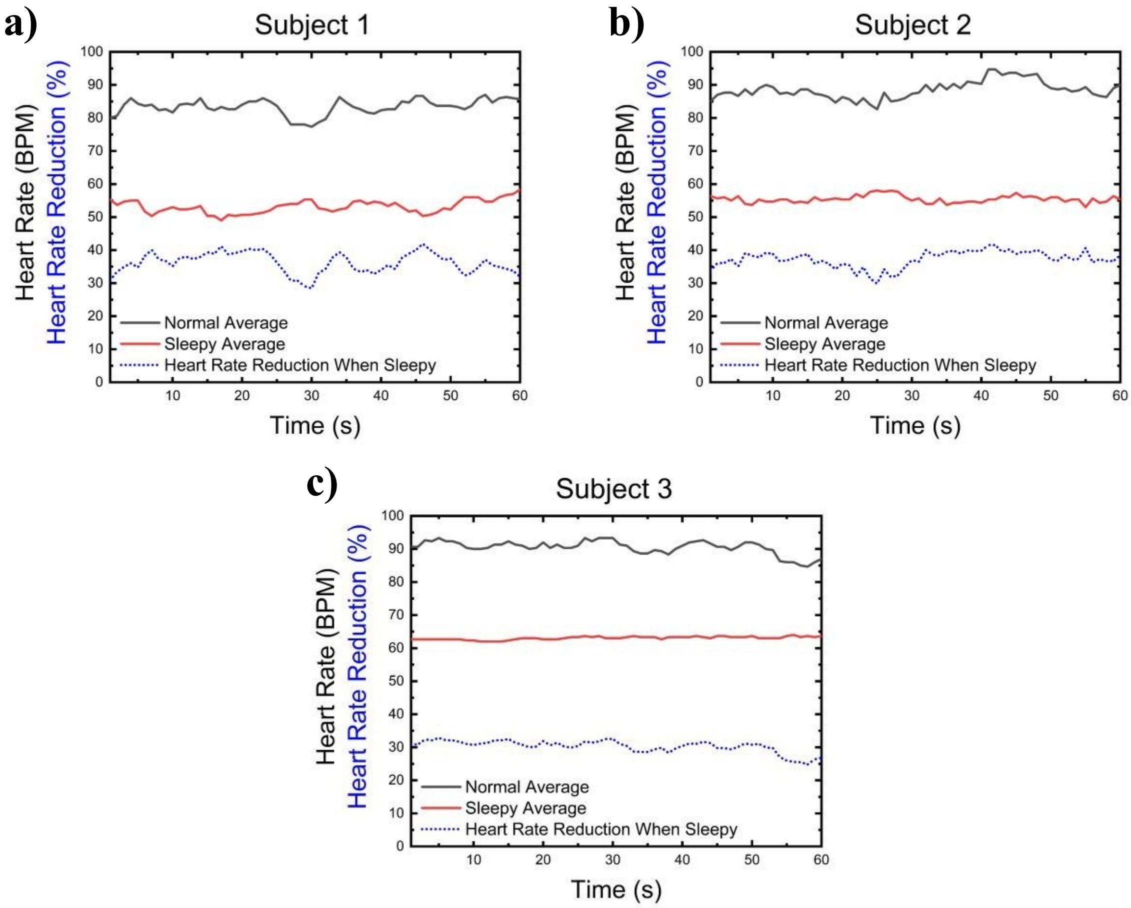

Figure 7 Average HR comparison between normal, sleepy condition and its respective heart rate reduction using our proposed device, smartwatch, and oximeter from **(a)** subject 1, **(b)** subject 2, and **(c)** subject 3 in sleepy condition.

show a similar trend of reduction with several studies that have been previously reported, however the HR reduction in the sleepy state varies among the studies [20]–[22]. There are some limitations in this research, the subjects that are measured are the human subjects with a healthy condition and small number of volunteers. Despite the limitations our study shows a very promising method to be implemented to monitor the driver's state through HR reduction.

4. Conclusion

In summary, we have demonstrated the low-cost wearable sleepiness detection device with a very good accuracy that is typically less than 3.12 BPM in average absolute error with the widely used standard instruments. We have shown that with our wearable device we can detect sleepiness by monitoring the HR reduction from the normal condition, it has been shown that the HR reduction is more than 30% when the subject is in a sleepy condition. Based on the HR reduction we design 3 levels of alarm to alert the subject when HR reduction is reaching the sleepy threshold, those are short pulse of vibration and buzzer when HR reduction reaches 20% or level 1, long pulse of vibration and buzzer when HR reduction at 25% or level 2, as well as continuous vibration and buzzer when HR reduction more than 30% or level 3. To be more effective and accurate in determining sleepy state over the variety of driver physical and mental conditions, larger clinical data and measurements will be needed to support our findings. The low-cost and practical design of our wearable device that has been proposed here is very promising to be implemented in daily use for car drivers to prevent accidents due to sleepiness factor. In the future, this concept can be further improved as a smart driver monitoring system that can monitor physical conditions, mental conditions, and driver’s behavior particularly for the upcoming era of semi-autonomous and autonomous car.

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