Digital Object Identifier 10.1109/ACCESS.2020.2990438

ABSTRACT Photoplethysmography (PPG) is a simple method to measure various physiological indices, including heart rate (HR). To prevent motion artifacts, the optimal light wavelength for PPG measurements should be selected. However, this countermeasure has not been examined thoroughly. This study addressed PPG robustness against motion artifacts for different light wavelengths and measuring modes to accurately determine HR. Twelve healthy volunteers underwent motion artifact experiments during PPG measurements, in which they were asked to either remain still or wave their hands horizontally or vertically as fast and rhythmically as possible. Reflectance mode blue (RB), green (RG), red (RR), and near-infrared (RNIR) lights and transmittance mode red (TR) and near-infrared (TNIR) lights were evaluated for PPG signals acquired along with electrocardiogram (for reference HR) and hand acceleration measurements. The analysis revealed that the RB and RG PPG modes increased the signal-to-noise ratio by approximately 8 dB compared to TR PPG, and the HR obtained from both did not exhibit fixed or proportional bias, with a Pearson’s correlation coefficient above 0.986. Furthermore, RNIR PPG was superior to TR PPG by approximately 4 dB, and its calculated HR did not show fixed or proportional bias, with a Pearson’s correlation coefficient of 0.967. The RR, TNIR, and TR PPG modes showed comparable and inferior performance. Therefore, blue and green lights followed by near-infrared light in reflectance mode are the recommended settings to measure HR using PPG. These findings may serve as guidelines for researchers and engineers to improve PPG measurements and devices.

INDEX TERMS Heart rate, motion artifact, peak detection, photoplethysmography sensor, reflection, transmission, visible light.

I. INTRODUCTION Photoplethysmography (PPG) is an easy-to-implement measurement method that allows the determination of various psychophysiological indices [1]. It comprises a light source and a photodetector either in the same plane for reflectance mode measurements or facing each other for transmittance mode measurements. PPG can be used to estimate indices such as heart rate (HR) and blood pressure [2], [3] and to evaluate conditions such as stress and emotional status [4], [5]. PPG technology has been incorporated into commercial devices such as pedometers and smartwatches to continuously monitor HR.

When measuring PPG signals, the effects of motion artifacts should be mitigated to prevent performance degradation [1] and improve reliability [6], [7]. Thus, various signal processing techniques, such as filtering, ensemble averaging, and machine learning, have been explored to remove related noise components from PPG measurements [8], [9]. Despite their effectiveness, all these methods are applied after measurement.

A technique to reduce the effects of motion artifacts during measurement consists of leveraging the optical characteristics of biological tissues to determine the optimal light source for PPG. Previous studies have shown that the extent of motion
artifacts on PPG signals depends on the measurement light wavelength. For instance, a comparison of green and near-infrared light PPG measurements taken from various body parts demonstrated that green light PPG is more robust to motion artifacts [10]. Other studies examining the extent of motion artifacts using blue, green, and red lights revealed that blue and green lights are more robust to motion artifacts than red light in PPG [11], [12]. This effect of wavelength on robustness may be related to the penetration depths of different wavelengths of light into the skin [13], [14]. In fact, blue and green lights reach shallow regions of relatively hard tissues (e.g., dermis), and measurements are made more reliable by the attachment of the sensor to the skin, reducing the susceptibility to motion artifacts. In contrast, red and near-infrared light PPG signals reach deeper areas of softer tissues (e.g., fat and muscle), which are more affected by motion.

In addition to the above findings, further exploration of PPG is required. First, although the robustness of visible light to motion artifacts has been consistently shown, no study has comprehensively examined PPG using all primary light wavelengths (i.e., blue, green, red, and near-infrared) at the same measurement sites. In fact, motion artifacts have been evaluated using green and near-infrared lights [10] or among the primary colors (i.e., red, green, and blue lights) [11], [12] with sensors attached to different body parts [10], [11]. Considering that motion artifacts differ across body parts, multiwavelength evaluation ranging from visible to near-infrared light along with motion measurement should be conducted at the same physical site [15]. Second, transmittance and reflectance modes in PPG have not been simultaneously addressed. Considering that these two modes are common in PPG [1], the lack of studies considering both is somewhat surprising. In fact, in [10]–[12], only the reflectance mode was evaluated. Thus, data regarding the transmittance mode are scarce, and no data are available on the combination of transmittance and reflectance modes.

In this study, a multiwavelength PPG device was developed to enable simultaneous measurements under transmittance and reflectance modes at the same physical site, and experiments with and without motion artifacts were conducted. Thus, the novelty of this study lies in the comprehensive, wide-range, and multimode comparison of PPG signals acquired at one measurement site (Table 1). This study aimed to determine the extent of motion artifacts in PPG signals according to light wavelengths and measurement modes in terms of HR estimation accuracy.

### II. METHODS

#### A. PARTICIPANTS

Twelve university students (5 women and 7 men; Japanese, Sapporo City residents; age, 22.8 ± 1.1 years; body mass index, 20.2 ± 1.6; at least 12 years of education) were recruited via flyers to participate in this study. Given that previous studies on motion artifacts adopted a relatively small sample size (e.g., N = 12 in [11], [12] and N = 11 in [10]) based on the large effect size estimates, a similar sample size was used in this study, and it was a multiple of the balancing order number of six. The criteria for inclusion in the study were the following: age over 20 years, no current cardiovascular disease, and no intake of any prescription medication. No participant declared current or past smoking habits. Participants were asked in advance to refrain from taking any medication 24 h prior to laboratory testing and avoid food and caffeinated drink intake as well as intense physical activity 2 h before laboratory testing. Women were not menstruating during the experimental period. Written informed consent was obtained from the participants after receiving a complete description of the study. This study was approved by the Ethical Committee of the Faculty of Engineering/Faculty of Information Science and Technology from Hokkaido University (H261030 Kaidaizyo_480 and H281019 Kaidaizyo_357) and complied with the Declaration of Helsinki.

#### B. APPARATUS

The device for reflectance mode PPG was fabricated with a blue light-emitting diode (LED) (470 nm; SMC470, Ushio Opto Semiconductors, Tokyo, Japan), a green LED (525 nm; SMC525, Ushio Opto Semiconductors), a red LED (660 nm; MC660N, Ushio Opto Semiconductors), a near-infrared LED (810 nm; SMC810, Ushio Opto Semiconductors), and a photodiode (PD) (BPW34BS, OSRAM Opto Semiconductors, Regensburg, Germany) on the same plane (Fig. 1), thus improving the model from previous studies [11], [16]. A separate PD sensor (OSRAM BPW34BS) for transmittance mode PPG was also integrated into the device by placing the source and sensor facing each other on opposite sides of the fingertip (Figs. 1 and 2). Due to the high absorbance of body tissue, the transmittance could not be measured for blue and green light. Thus, the six PPG modes considered in this study were blue, green, red, and near-infrared light in the reflectance mode (RB, RG, RR, and RNIR, respectively) and red and near-infrared light in the transmittance mode (TR and TNIR, respectively).

The four LEDs and two PDs were connected to a dedicated bioamplifier operated by a microcontroller (Mbed LPC1768, NXP Semiconductors, Eindhoven, Netherlands). One cycle of PPG measurements was set to 4 ms, and each LED was sequentially lit for 0.5 ms within the cycle (Fig. 3). The PD measurements were acquired immediately before turning each LED on and off to remove the effect of environmental

| Wavelength | Mode | Same site |
|------------|------|-----------|
| Red | Green | Blue | NIR | Reflect. | Transmitt. | PPG |
| Maeda et al. [10] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lee et al. [11] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Matsumura et al. [12] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Current study | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

NIR = near-infrared, Reflect. = reflectance mode, Transmitt. = transmittance mode.
light by considering the difference between the readings with the LEDs off and on. Therefore, we calculated the components of RB, RG, RR, RNIR, TR, and TNIR PPG based on the following formula:

\[
PPG = V_{|\text{LED on}} - V_{|\text{LED off}}
\]  

(1)

where \(V_{|\text{LED on}}\) and \(V_{|\text{LED off}}\) represent the readout voltages indicated in Fig. 3 at (H) and (G) for RB, (D) and (C) for RG, (B) and (A) for RR, (F) and (E) for RNIR, (J) and (I) for TR, and (L) and (K) for TNIR, respectively.

Two PD signals through separate but identical amplifier circuits were sampled with a resolution of 12 bits using an analog-to-digital converter (MCP3204, Microchip Technology, Chandler, AZ, USA) connected to the microcontroller. The acquired signals were transformed into six-channel PPG data using (1) at a 250 Hz sampling frequency and transmitted to a computer (MacBook Pro, Apple, Cupertino, CA, USA) via a serial port for storage and processing.

In addition, hand acceleration was measured using a tri-axial accelerometer (ADXL345, Analog Devices, Norwood, MA, USA) at a 250 Hz sampling frequency. This sensor was attached to the transmittance stage and connected to the microcontroller. Electrocardiography (ECG) signals from a dedicated device used in our previous studies [11], [12] were also acquired using the analog-to-digital converter at a 1 kHz sampling frequency.

**C. EXPERIMENTAL PROCEDURE**

The experiment was performed in a quiet 3 × 5 m room at 24–26 °C. Each participant sat in an armchair to support their arms. Disposable electrodes were used for acquiring the ECG signals, and the PPG device was placed on the right index finger (Fig. 2). The LED intensities were adjusted to equalize the dc components of all reflectance mode PPG LEDs (i.e., RB, RG, RR, and RNIR). TR and TNIR PPG signals were measured using the obtained intensity (Fig. 3). After verifying the reliability of the acquired signals, a 3-minute adaptation period was followed by an experimental period of approximately the same length, as detailed in Fig. 4. The procedure primarily followed that of previous studies [11], [12]. During adaptation, the participants sat quietly and were then asked to wave their right hands horizontally or vertically (Fig. 2) as fast and as rhythmically as possible to achieve a shaking frequency above 6 Hz. The horizontal motion (HM) and vertical motion (VM) were selected for their simplicity over compound motions. The shaking frequency of 6 Hz was targeted to easily separate the PPG motion artifact from the HR signal. As the main bandwidth of PPG is below 5 Hz [17], [18], including the HR fundamental signal at approximately 1–2 Hz and its second harmonics at approximately 2–4 Hz, it is easy to discard motion artifacts over 6 Hz. However, low-frequency components remained given the uncertainty of human movements. For the baseline (BL) condition, the participants kept their right hands still at the level they waved their hands, whereas during rest, the participants kept their right hands down and remained still. The order of execution of HM, VM, and BL was varied and balanced across participants (Fig. 4). The sequence of these three conditions was repeated twice in the same order. All 18-second conditions were separated by rest periods of 9 s.

**D. EVALUATED MEASURES**

The signal-to-noise (S/N) ratio was calculated from each PPG signal with a 16.384-second center period in the 18-second
two repetitions to obtain the BL, HM, and VM values. The beat-to-beat HR values derived from the ECG and six PPG signals were averaged for each central 16.384-second period in the 18-second conditions and again averaged across two repetitions to obtain the corresponding values for the motions.

F. STATISTICAL ANALYSIS

To evaluate the experimental results, the frequencies and amplitudes of motion artifacts were compared using paired t-tests between HM and VM. The dc levels of the six PPG signals during BL were compared using one-way repeated-measures analysis of variance (ANOVA). The Greenhouse–Geisser correction was applied to the degrees of freedom where appropriate. For post hoc comparison, Ryan–Einot–Gabriel–Welsch Q (REGWQ) multiple comparisons were used.

The S/N ratios for each PPG type (i.e., RB, RG, RR, RNIR, TR, and TNIR) and condition (i.e., BL, HM, and VM) were evaluated using two-way repeated-measures ANOVA after checking normality by the Shapiro–Wilk test. Again, the Greenhouse–Geisser correction was applied to the degrees of freedom where appropriate, and the REGWQ multiple comparisons were used.

To evaluate the agreement of HR measurements obtained from the six PPG signals and reference ECG HR, geometric mean regression [20] and the Bland–Altman plot [21] were used. For regression, the intercept (fixed bias), slope (proportional bias), and correlation coefficient (Pearson’s r) were calculated. For the Bland–Altman plot, the mean of the differences (fixed bias) and correlation coefficient between averages and differences (proportional bias) were calculated. In each analysis, 36 data points (3 conditions × 12 participants) were considered.

G. ADDITIONAL ARTIFACT ANALYSIS

Although the participants waved their hands as fast and as rhythmically as possible to easily separate the PPG motion artifact from the HR signal, the motion contained lower-frequency components overlapping with the HR frequency band from 1 to 5.5 Hz, given the uncertainty of human movements [17], [18].

To evaluate this influence, we obtained the sum of the signal power from the triaxial acceleration signals during BL and motion including both HM and VM in the frequency bands of 5.5–10 Hz (P_{Accel}|5.5–10 Hz), as intended motion, and 1–5.5 Hz (P_{Accel}|1–5.5 Hz), as unintended motion overlapping with the HR band. Then, we calculated ratio P_{Accel}|1–5.5 Hz/P_{Accel}|5.5–10 Hz.

In addition, to evaluate the effect of P_{Accel}|1–5.5 Hz on the PPG signals, we obtained the HR signal power on PPG in the band of 1–5.5 Hz (P_{Signal}|1–5.5 Hz) and the noise power in the same frequency band (P_{Noise}|1–5.5 Hz) by subtracting P_{Signal}|1–5.5 Hz from the integrated power in 1–5.5 Hz. Then, we calculated the S/N ratio across the three motion conditions with P_{Signal}|1–5.5 Hz and P_{Noise}|1–5.5 Hz representing the signal and noise, respectively, by using (2).
S/N ratios |1–5.5 Hz of the six PPG signals were compared by applying one-way repeated-measures ANOVA to the Greenhouse–Geisser correction after checking normality by the Shapiro–Wilk test. For post hoc comparison, REGWQ multiple comparisons were used.

III. RESULTS

Fig. 6 shows an example of simultaneous acquisition of the six PPG signals, ECG signal, and accelerometer signal for a participant under BL and motion.

A. EXPERIMENTAL CONDITIONS

The characteristics of motion artifacts per condition along with the results of the paired t-tests are summarized in Table 2. The motion frequency during HM was not significantly different from that during VM. In contrast, the horizontal (vertical) amplitude of motion during HM (VM) was significantly larger than that during VM (HM).

The mean dc levels of the six PPG signals during BL along with the results of repeated-measures ANOVA are summarized in Table 3. Post hoc comparisons revealed that the dc values of RB, RG, RR, and RNIR PPG were larger than those of TR and TNIR PPG.

B. S/N RATIOS

The mean S/N ratios for each PPG type (RB, RG, RR, RNIR, TR, and TNIR) and condition (BL, HM, and VM) are summarized in Fig. 7. The Shapiro–Wilks test confirmed the normality of the distributions in all indices (p > 0.098). The two-way repeated-measures ANOVA revealed main effects of type, F(5, 55) = 15.86, p < 0.001, \( \varepsilon = 0.32, \eta_p^2 = 0.59 \), and condition, F(2, 22) = 206.93, p < 0.001, \( \varepsilon = 0.94, \eta_p^2 = 0.95 \), but not of interaction, F(10, 110) = 2.43, p = 0.068.

ϕ = 0.37, \( \eta_p^2 = 0.18 \). Subsequent post hoc REGWQ multiple comparisons revealed that the mean S/N ratios across the three conditions for RB (12.0 dB) and RG (11.9 dB) were...
TABLE 2. Characteristics of types of motions used in experiments and results of statistical tests.

| Characteristic | Condition | Results of statistical test between BL and VM | Results of statistical test between HM and VM |
|---------------|-----------|---------------------------------------------|---------------------------------------------|
| Frequency (Hz) | M (SD)    | M (SD)                                      | M (SD)                                      |
| Accel         | 6.71      | 6.64                                        | 0.58                                        |
| Amplitude (G) | (0.91)    | (0.73)                                      | 0.08                                        |
| Horizontal    | 0.07      | 21.00                                       | 6.92                                        |
| Vertical      | 0.09      | 6.23                                        | 7.47                                        |

BL = baseline, HM = horizontal motion, VM = vertical motion.

TABLE 3. Dc Level of six photoplethysmography (PPG) signals and results of statistical tests.

| PPG      | RB | RG | RR | RNIR | TR | ANOVA | REGWQ multiple comparison |
|----------|----|----|----|------|----|-------|---------------------------|
| M (SD)   | M (SD) | M (SD) | M (SD) | F<sub>ANOVA</sub> | p |
| Dc level (V) | 2.75 | 1.75 | 2.82 | 1.72 | 1.42 | 54.71 | 0.04 < 0.001 RNIR, RR, RB, RG > TNIR, TR |

RB = blue light reflectance mode, RG = green light reflectance mode, RNIR = near-infrared light reflectance mode, RR = red light reflectance mode, TNIR = near-infrared light transmittance mode, TR = red light transmittance mode, ANOVA = analysis of variance, REGWQ = Ryan–Einot–Gabriel–Welsch Q.

higher than those for RNIR (8.5 dB) and RR (6.6 dB), and those of RR were higher than those of TNIR (5.0 dB) and TR (4.2 dB).

C. HR AGREEMENT

Scatter plots of HRs obtained from the six PPG signals against the HR estimated from the ECG signals along with the Bland–Altman plots are shown in Fig. 8. The results of the geometric mean regression and Bland–Altman analysis are summarized in Table 4.

D. ADDITIONAL ARTIFACT ANALYSIS

The mean ± SD values of P<sub>Accel</sub>|1–5.5 Hz and P<sub>Accel</sub>|5.5–10 Hz during BL were 0.005 ± 0.007 and 0.003 ± 0.005 (a.u.), respectively. Those during motion were 112.0 ± 351.0 and 593.9 ± 230.6 (a.u.), respectively. The mean ± SD of P<sub>Accel</sub>|1–5.5 Hz/P<sub>Accel</sub>|5.5–10 Hz during motion was 1/170.1 ± 1/264.7.

The mean S/N ratios |1–5.5 Hz across the three motion conditions for each PPG type (RB, RG, RR, RNIR, TR, and TNIR) are summarized in Table 5. The Shapiro–Wilk test confirmed normality of the distributions in all indices (p > 0.376). The one-way repeated-measures ANOVA revealed main effect of type, F(5,55) = 7.30, p = 0.009, ε = 0.29, n<sup>2</sup> = 0.40. Subsequent post hoc REGWQ multiple comparisons revealed that the mean S/N ratios |1–5.5 Hz of RB were higher than those of TNIR, RR and TR, and those of RNIR were higher than those of RR and TR (Table 5).

IV. DISCUSSION

In this study, the S/N ratio and HR agreement with ECG signals as reference were examined for RB, RG, RR, RNIR, TR, and TNIR PPG using a fabricated PPG device that enables simultaneous measurement of the six PPG signals at the same site under motion artifacts. First, we found that the RB and RG PPG modes show S/N ratios approximately 8 dB higher than TR PPG, that the HR calculated from both modes does not show fixed or proportional bias, and that the Pearson’s correlation is above 0.986. Second, RNIR PPG is superior to TR PPG by approximately 4 dB and comparable to RR PPG.

In addition, the HR calculated from RNIR PPG does not show fixed or proportional bias, reaching a correlation of 0.967, whereas RR PPG shows proportional bias and a correlation of 0.949. Third, the S/N ratios of RR, TNIR, and TR PPGs are comparable, but the fixed and proportional bias are the smallest in TNIR, and the correlation is the largest, reaching 0.959. Finally, the reflectance mode is superior to the transmittance mode by approximately 5 dB overall. Hence, the S/N ratio and HR estimation accuracy during motion decrease in the following order: blue, green, near-infrared, and red light wavelengths and reflectance and transmittance measuring modes.

The mean value of ratio P<sub>Accel</sub>|1–5.5 Hz/P<sub>Accel</sub>|5.5–10 Hz during motion was 1/170.1, which is equivalent to 1/13.04 in amplitude. Therefore, the finger received a lower-frequency motion, whose amplitude corresponds to 1/13.04 times that of 5.5–10 Hz assuming a constant Q value. For example, the amplitude of 1.86 G in VM can be calculated by multiplying 24.21 G (from Table 2) by 1/13.04, which is much larger than that used in a previous study (i.e., below 0.5 G) [12]. Under such conditions, the S/N ratios |1–5.5 Hz of RB were higher than those of TNIR, RR, and TR, and those of RG and TNIR were higher than those of RR and TR. This tendency is consistent with that from the main analysis, which showed a result of over 5.5 Hz. Therefore, our findings cover a wide frequency range, which in turn suggests their applicability to various motions. This is because any form of motion can be represented as a sum of sine waves by Fourier series theory. For example, sudden motion was not used in the study.

However, as it can be decomposed in many sine waves over a period, our findings can also apply to sudden motion. In fact, consistent results were obtained from a previous study considering sudden motion [10]. Therefore, we conclude that our result can be generalized to various types of motions.

Both RB and RG PPG are superior to other PPG modes, which is consistent with the findings from previous studies. However, there are four points worth mentioning. First, the experiment did not address RB, RG, and RR PPG or RG and RNIR PPG alone, but it examined TR and TNIR PPG along with RB, RG, RR, and RNIR PPG simultaneously at the same measurement site, enabling further generalization of the results compared to previous studies. Second, stronger motions were used than those in previous studies. For instance, Matsumura et al. [12] used motions below 0.5 G,
and Lee et al. [11] used approximately 9 G, whereas the participants in the present study performed motions up to 24 G, thus thoroughly testing the robustness of the PPG measurements. Third, unlike previous studies [11], [12], this study evaluated the motion spilled out from over 6 Hz intended motion into HR frequency band and examined its effect on PPG signals. As a result, our findings can be applied to a wide range of frequencies and types of motions if
considering Fourier analysis over a period. Finally, differences in absolute values were determined instead of relative changes considered in a previous study [11]. Although the relative S/N ratio notably decreases due to motion, maintaining high S/N ratios under intense motion is advantageous for accurately and robustly estimating the HR. As this study evaluated PPG signals in terms of absolute values, its results are more robust and may reflect realistic outcomes from performing activities of daily living.

We found that RB PPG is superior to RG PPG in every aspect, unlike previous studies in which RG is regarded as the best approach [11], [12]. This difference can be attributed to the sensors and LEDs used for PPG. The proposed PPG device contained a small but high-brightness blue light LED.
and a PD with enhanced blue sensitivity and a relatively high sampling rate, overcoming the disadvantages of RB PPG to increase performance. However, the absolute difference, as in the other studies, is very small, and any approach is convenient in practice.

The robustness to motion artifacts according to the penetration depth of different light wavelengths implies that red light PPG would exhibit higher performance than near-infrared light PPG. However, this is not reflected in the results, possibly because of the inhomogeneous nature of biological tissue. As the probability distribution of optical PPG paths forms banana- or spindle-like shapes [22], RR PPG might mainly probe the dermis, which contains small arteries and arterioles. In contrast, RNIR PPG probes deeper regions, including the subcutaneous plexus, which contains smaller structures, and thus RR PPG shows a lower S/N ratio. In fact, the ac components of red light PPG are small in general. In addition, the relatively high absorbance of red light may lead to a low signal level, further reducing the S/N ratio. Although the dc levels of all reflectance mode PPG signals were set to be equal in this study, the dc level of transmittance mode PPG was approximately 1.2 times (0.8 dB) higher in TNIR than in TR. This difference agrees with the observed difference between TR PPG (4.2 dB) and TNIR PPG (5.0 dB). Therefore, increasing the intensity of red light in TR PPG may enhance the measurements. Nevertheless, such an intensity increase may also improve TNIR PPG, maintaining the relative difference compared to TR PPG. Overall, disregarding specific tasks such as determining SpO2 levels [23] or heat/cold stress [24], red light PPG offers no advantage regarding motion artifact robustness.

Various limitations of this study remain to be addressed. First, the experiment was conducted on a limited population and under specific situations, and hence further studies with more diverse populations and situations are required. For instance, only periodic motion artifacts above 6 Hz were used. Although such motion actually contains frequency components below 6 Hz, lower-frequency and/or aperiodic motion should be specifically addressed. Second, only one type of device was developed, and different LED and PD arrangements should be evaluated. In addition, separate PPG LEDs and PD were used in the transmittance mode, but using stapler or clothespin integrated devices might improve the S/N ratio. Third, a relatively basic HR detection algorithm was implemented, and more sophisticated methods may yield higher accuracy. Fourth, only HR was examined, as HR is the typical and most frequently used application of PPG, but other estimates such as respiratory rate and pulse volume should be calculated and evaluated. In these cases, the signal power should be calculated not from ECG data but from corresponding references. Finally, only reflectance and transmittance modes were analyzed, but modes such as side scatter remain to be assessed [25]. Specifically, sequential alteration from reflectance to transmittance via side scatter can be addressed. For instance, a previous study revealed that the amplitude of the ac component of PPG is the largest when using an intermediate mode between transmittance and side scatter [16], and this setting is also expected to produce the largest S/N ratio under motion artifacts.

V. CONCLUSION

This paper presents new evidence on PPG robustness against motion artifacts in terms of multiple light wavelengths and two measuring modes for accurate HR estimation. The S/N ratios obtained from RB, RG, and RNIR using a novel integrated PPG device were higher than the S/N ratio of TR PPG by 7.8, 7.7, and 4.3 dB, respectively. In addition, RB, RG, and RNIR showed negligible fixed and proportional bias for HR estimation. These characteristics may be interpreted in terms of the difference in penetration depth of different light wavelengths into the skin. Moreover, these findings suggest that when measuring PPG for HR estimation, blue and green light followed by near-infrared light in the reflectance mode are the recommended settings. Nevertheless, further investigation is required to 1) include more diverse populations, 2) use sensors with different LED and PD arrangements, and 3) evaluate different motion artifacts.

ACKNOWLEDGMENT

The authors would like to give special thanks to Ms. Akiko Doutani for designing and preparing the figures and Dr. Yasuhiro Yamakoshi for his technical assistance. The funding source, JSPS KAKENHI, played no role in the study design, the data collection, analysis and interpretation, and the writing of the report, or the submission decision. K. Matsumura designed the sensors, developed the circuit and program, conceived and designed the study, performed the experiment and the analysis, and wrote the article. S. Toda performed the experiment and analysis. Y. Kato critically reviewed the study and helped to write the manuscript. All the authors approved the submission of the manuscript in its current form.

REFERENCES

[1] J. Allen, “Photoplethysmography and its application in clinical physiological measurement,” Physiol. Meas., vol. 28, no. 3, pp. R1–R39, Mar. 2007, doi: 10.1088/0967-3334/28/3/R01.

[2] K. Matsumura, P. Rolfe, S. Toda, and T. Yamakoshi, “Cuffless blood pressure estimation using only a smartphone,” Sci. Rep., vol. 8, no. 1, Dec. 2018, Art. no. 7298, doi: 10.1038/s41598-018-25681-5.

[3] K. Matsumura, T. Yamakoshi, P. Rolfe, and K.-I. Yamakoshi, “Advanced volume-compensation method for indirect finger arterial pressure determination: Comparison with brachial sphygmomanometry,” IEEE Trans. Biomed. Eng., vol. 64, no. 5, pp. 1131–1137, May 2017, doi: 10.1109/TBME.2016.2591324.

[4] Y. Sawada, G. Tanaka, and K. Yamakoshi, “Normalized pulse volume (NPV) derived photo-plethysmographically as a more valid measure of the finger vascular tone,” Int. J. Psychophysiol., vol. 41, no. 1, pp. 1–10, May 2001, doi: 10.1016/S0167-8760(00)00116-8.

[5] T. W. Smith, B. K. Houston, and R. J. Stucky, “Effects of threat of shock and control over shock on finger pulse volume, pulse rate and systolic blood pressure,” Biol. Psychol., vol. 20, no. 1, pp. 31–38, Feb. 1985, doi: 10.1016/0301-0511(85)90039-0.

[6] H. Han and J. Kim, “Artifacts in wearable photoplethysmographs during daily life motions and their reduction with least mean square based active noise cancellation method,” Comput. Biol. Med., vol. 42, no. 4, pp. 387–393, Apr. 2012, doi: 10.1016/j.compbiomed.2011.12.005.
[7] K. A. Reddy, B. George, and V. J. Kumar, “Use of Fourier series analysis for motion artifact reduction and data compression of photoplethysmographic signals,” IEEE Trans. Instrum. Meas., vol. 58, no. 5, pp. 1706–1711, May 2009, doi: 10.1109/TIM.2008.2009136.

[8] Z. Zhang, “Photoplethysmography-based heart rate monitoring in physical activities via joint sparse spectrum reconstruction,” IEEE Trans. Biomed. Eng., vol. 62, no. 8, pp. 1902–1910, Aug. 2015, doi: 10.1109/TBME.2015.2406332.

[9] Q. Zhang, X. Zeng, W. Hu, and D. Zhou, “A machine learning-empowered system for long-term motion-tolerant wearable monitoring of blood pressure and heart rate with ear-ECG/PPG,” IEEE Access, vol. 5, pp. 10547–10561, 2017, doi: 10.1109/ACCESS.2017.2707472.

[10] Y. Maeda, M. Sekine, and T. Tamura, “Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography,” J. Med. Syst., vol. 35, no. 5, pp. 969–976, Oct. 2011, doi: 10.1007/s10916-010-9505-0.

[11] J. Lee, K. Matsumura, K.-I. Yamakoshi, P. Rolfe, S. Tanaka, and T. Yamakoshi, “Comparison between red, green and blue light reflection photoplethysmography for heart rate monitoring during motion,” in Proc. 35th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC), Jul. 2013, pp. 1724–1727, doi: 10.1109/EMBC.2013.6609852.

[12] K. Matsumura, P. Rolfe, J. Lee, and T. Yamakoshi, “IPhone 4s photoplethysmography: Which light color yields the most accurate heart rate and normalized pulse volume using the iPhysisMeter application in the presence of motion artifact?” PLoS ONE, vol. 9, no. 3, Mar. 2014, Art. no. e91205, doi: 10.1371/journal.pone.0091205.

[13] R. R. Anderson and J. A. Parrish, “The optics of human skin,” J. Invest. Dermatol., vol. 77, no. 1, pp. 13–19, Jul. 1981, doi: 10.1111/1523-1747.ep1247919.

[14] J. Gifford, A. Sira, and P. Helme, “Pulsed multifrequency photoplethysmography,” Med. Biol. Eng. Comput., vol. 22, no. 3, pp. 212–215, May 1984, doi: 10.1007/BF02442745.

[15] J. Spigulis, L. Galilte, A. Lihachev, and R. Eirts, “Simultaneous recording of skin blood pulsations at different vascular depths by multil wavelength photoplethysmography,” Appl. Opt., vol. 46, no. 10, p. 1754, Apr. 2007, doi: 10.1364/AO.46.001754.

[16] K. Matsumura, K. Shimizu, P. Rolfe, M. Kakimoto, and T. Yamakoshi, “Inter-method reliability of pulse volume related measures derived using finger-photoplethysmography: Across sensor positions and light intensities,” J. Psychophysiol., vol. 32, no. 4, pp. 182–190, Oct. 2018, doi: 10.1027/0269-8803/a000197.

[17] M. J. Hayes and P. R. Smith, “A new method for pulse oximetry possessing inherent insensitivity to artifact,” IEEE Trans. Biomed. Eng., vol. 48, no. 4, pp. 452–461, Apr. 2001, doi: 10.1109/10.915711.

[18] A. A. Kamal, J. B. Harness, G. Irving, and A. J. Means, “Skin photoplethysmography—A review,” Comput. Methods Programs. Biomed., vol. 28, no. 4, pp. 257–269, Apr. 1989.

[19] K. Matsumura, P. Rolfe, and T. Yamakoshi, “iPhysisMeter: A smartphone photoplethysmograph for measuring various physiological indices,” Methods Mol. Biol., vol. 1256, pp. 305–326, Mar. 2015, doi: 10.1007/978-1-4939-2172-0_21.

[20] J. Ludbrook, “Comparing methods of measurements,” Clin. Express Pharmacol. Physiol., vol. 24, no. 2, pp. 193–203, Feb. 1997, doi: 10.1111/j.1440-1618.1997.tb01807.x.

[21] J. M. Bland and D. G. Altman, “Statistical methods for assessing agreement between two methods of clinical measurement,” Lancet, vol. 1, pp. 307–310, Feb. 1986, doi: 10.1016/S0140-6736(86)90837-8.

[22] Y. Tsuchiya and T. Urakami, “Quantitation of absorbing substances in tissue using near-infrared spectroscopy,” Opt. Commun., vol. 144, nos. 4–6, pp. 269–280, Dec. 15, 1997, doi: 10.1006/opcom.2000.0496.0.

[23] J. G. Webster, Design of Pulse Oximeters. New York, NY, USA: Taylor & Francis, 1997.

[24] Y. Maeda, M. Sekine, and T. Tamura, “The advantages of wearable green reflected photoplethysmography,” J. Med. Syst., vol. 35, no. 5, pp. 829–834, Oct. 2011, doi: 10.1007/s10916-010-9506-z.

[25] Y. Yamakoshi, K. Matsumura, T. Yamakoshi, J. Lee, P. Rolfe, Y. Kato, K. Shimizu, and K.-I. Yamakoshi, “Side-scattered finger-photoplethysmography: Experimental investigations toward practical noninvasive measurement of blood glucose,” J. Biomed. Opt., vol. 22, no. 6, Jun. 2017, Art. no. 067001, doi: 10.1117/1.JBO.22.6.067001.

K. Matsumura et al.: RGB and Near-Infrared Light Reflectance/Transmittance PPG