Physiological Sensing on the Upper Arm with a Wireless Multi-Modal Wearable

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ABSTRACT

In this research, we examine the potential of measuring physiological variables, including heart rate (HR) and respiration rate (RR) on the upper arm using a wireless multimodal sensing system consisting of an accelerometer, a gyroscope, a three-wavelength photoplethysmography (PPG), single-sided electrocardiography (SS-ECG), and bioimpedance (BioZ). The study included collecting HR data when the subject was at rest and typing, and RR data when the subject was at rest. The data from three wavelengths of PPG and BioZ were collected and compared to the SS-ECG as the standard. The accelerometer and gyro signals were used to exclude data with excessive noise due to motion. The results showed that when the subject remained sedentary, the mean absolute error (MAE) for the HR calculation for all three wavelengths of the PPG modality was less than two bpm, while the BioZ was 3.5 bpm compared with SS-ECG HR. The MAE for typing increased for both modalities and was less than three bpm for all three wavelengths of the PPG but increased to 7.5 bpm for the BioZ. Regarding RR, both modalities resulted in RR within one breath per minute of the SS-ECG modality for the one breathing rate. Overall, all modalities on this upper arm wearable worked well when the subject was sedentary. Still, the SS-ECG and PPG showed less variability for the HR signal in the presence of motion during micro-motions such as typing.

Keywords: photoplethysmography, bioimpedance, single-sided electrocardiography, multi-wavelength, heart rate, respiration rate, wireless wearable, upper arm

1. INTRODUCTION

Vitals such as heart rate (HR) and respiration rate (RR) are important signals to understand the health status of a patient [1]. In clinical settings, these vitals are typically acquired from pulse oximeters, electrocardiograms (ECGs), and impedance pneumograms. In ambulatory settings, wearable technology offers the opportunity to monitor these vitals. However, activities of daily living (ADL) can lead to motion artifacts and other types of noise in the measured wearable signals. As an example, Holter monitors for ECG generally use long cables and gel electrodes, making this device unsuitable for long-term use, especially during physical activity. To combat this issue, wearable chest straps and patch-based ECG systems have become commercially available. These designs remove the need for cables and, in some cases, gel electrodes, but can be uncomfortable to wear continuously and can lead to allergic reactions (e.g., adhesives are needed to keep the devices in place). An alternative measurement technique that has gained popularity in consumer devices (e.g., health and fitness trackers) is photoplethysmography (PPG). PPG is an optically based signal that measures changes in blood volume as a function of the cardiac cycle within an area of tissue. PPG devices are advantageous because they can be worn on the wrist, but they are particularly sensitive to motion artifacts, both macro-motions (e.g., walking and running) and micro-motions (e.g., typing on a computer or tapping one's fingers [2]).

To address the above limitations of commercially available devices, we propose a wearable design that combines several modalities into a device that can be worn on the upper arm. Our proposed device contains three complementary sensing modalities: (1) a multi-wavelength PPG sensor (green, red, and IR), (2) a single-sided (SS) ECG, and (3) bioimpedance (BioZ), as well as linear and angular inertial measurements (i.e., accelerometer, gyroscope). While PPG, SS-ECG, and

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BioZ can capture HR and RR [4, 5], they have radically different modes of operation. SS-ECG is passive and measures low-voltage electrical signals as they traverse away from the heart through the body, whereas BioZ injects an oscillating injection current using two electrodes and measures the tissue impedance change with two voltage-sensing electrodes. As such, the combination of PPG, SS-ECG, and BioZ can provide a high degree of fault tolerance and robustness to motion artifacts. To our knowledge, this is the first device to combine PPG, SS-ECG, BioZ, and inertial measurements into a single wearable for the upper arm.

In the present study, we analyze the signal characteristics from the device from a subject under sedentary and micro-motion activities. In particular, we analyze the robustness of PPG and BioZ-based HR during typing moments and their ability to capture R-R time series in sedentary moments compared to the SS-ECG signal. We also show that the accelerometer/gyroscope signals can be used to identify moments of motion that could introduce artifacts in the physiological signals.

2. MATERIALS AND METHODS

2.1 Wearable Sensor Design for the Upper Arm

As noted earlier, our wireless/wearable device includes five sensors: PPG, BioZ, SS-ECG, accelerometer, and gyroscope. PPG, BioZ, and SS-ECG were used to measure HR and RR, while the accelerometer and gyroscope were used to identify segments with high motion artifacts. All sensor signals were sampled at 100 Hz, and the data was stored on an internal SD card accessible with a USB-C port and a PC. Printed circuit boards (PCBs) were designed containing the PPG analog-front-end (AFE) (MAX30101), SS-ECG AFE (AD8232), accelerometer/gyroscope (ISM330DHCX), BioZ circuit, the P-NUCLEO-WB55 microcontroller, and other peripherals. To measure SS-ECG and BioZ, gel electrode leads were integrated within the wearable so gel Ag/AgCl electrodes could interface with the device and the subject. The PPG sensor and BioZ electrodes were placed along the left arm's brachial artery. Three SS-ECG electrodes were positioned at the top of the arm and spread around the circumference of the arm (Figure 1).

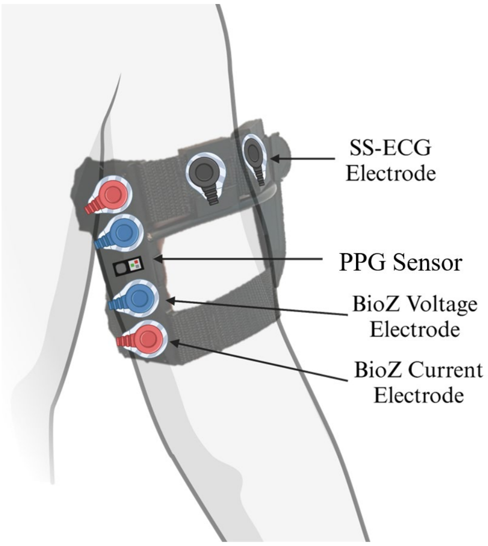

Figure 1. Relative locations of the SS-ECG electrodes (one on the back of the arm), BioZ electrodes, and PPG sensor within the wearable device, placed on the left arm and aligned with the brachial artery.

The three most common wavelengths for acquiring PPG signals are green, red, and infrared. To measure HR, most wearables utilize green light; however, melanin absorbs green more, creating a discrepancy for subjects with darker skin tones [3]. The PPG AFE included three wavelengths: green (537 nm), red (660 nm), and infrared (880 nm). The ECG AFE was set up in a three-electrode configuration to acquire SS-ECG signals. Lastly, the BioZ system was set up in a four-electrode configuration where the two outer electrodes injected a sinusoidal current at 17 kHz with an amplitude of 900 µA, and the two inner electrodes measured a differential voltage using an instrumentation amplifier. The BioZ circuit was designed and tailored for the upper arm using an improved Howland current pump for current injection and a demodulator (AD630) for the BioZ signal extraction from the voltage measurements. A 16-bit analog-to-digital-convertor (ADS7066) was used to sample the BioZ signal.

2.2 Study Protocol

The human subject study was approved by the Texas A&M University institutional review board (IRB2022-0227D) and included written consent from the subject. To assess the ability for the device to measure HR in different motion circumstances, a subject was asked to sit sedentary for 2 min and then type for another 2 min. This sequence of events was repeated three times. Typing allowed for the assessment of micro-motions that could possibly perturb the signal, and therefore reducing the accuracy of RR measurements. In this case, SS-ECG from the left upper arm was treated as ground-truth for HR.

To measure RR, the subject was asked to follow an audiovisual pacing signal from a mobile app (Breathing Zone) at six breaths/minute for 2-min increments for three trials, with a 2-min break to breathe normally between each trial. This breathing rate was chosen as it is known to be a resonance of the cardiorespiratory system that maximizes heart rate variability. All RR trials were performed when the subject was sedentary.

2.3 Signal Processing for Heart Rate and Respiration Rate Calculations

The SS-ECG, PPG, and BioZ signals were digitally filtered (MATLAB 2023a) to isolate fiducial points for HR calculations. Preprocessing of all signals was conducted and then time and frequency domain features were isolated for HR and RR. For each 2-min trial, 15 seconds at the start and the end of each protocol were removed as there was noticeable motion within the accelerometer and/or gyroscope (fluctuations from baseline measurement of > ± 500 m/s^2 and > ±200 m/rad, respectively. To process the signals, a bandpass filter of 0.25-5 Hz was applied to the PPG and BioZ signals to isolate the AC component of the signals to calculate the HR. The quasi-DC component of these signals, which was isolated with an envelope filter using the envelope function in MATLAB, was used to calculate the RR. A bandpass filter with cutoff frequencies of 5 and 20 Hz was applied to the SS-ECG signal to extract the HR and RR.

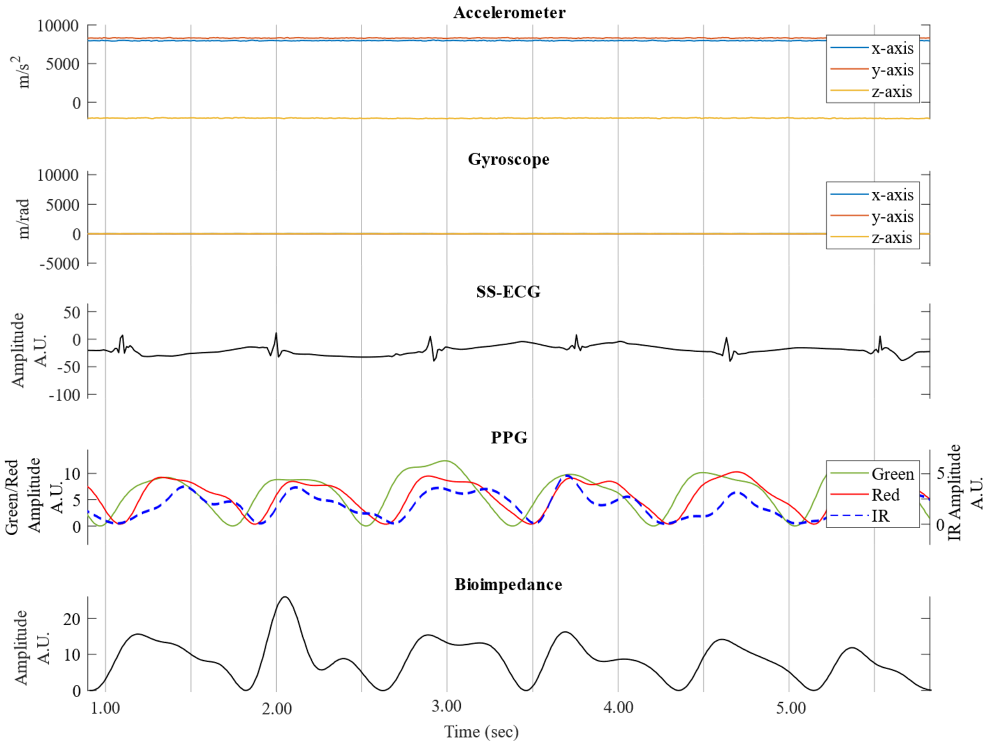

Figure 2. An example of the captured signal during a sedentary period including 3-axis accelerometer/gyroscope, a SS-ECG signal, and the AC components of the PPG (green, red, and IR) and BioZ signals acquired from the upper arm wearable after digital signal preprocessing.

To analyze HR, fiducial points were isolated from the AC component of the signals: R peaks from the SS-ECG signal and systolic peaks from PPG and BioZ (MATLAB function findpeaks). A window of 12 seconds with an overlap of 4 seconds was used to estimate the average HR for the whole trial. The HRs calculated for all the windows were averaged for a single trial's HR measurement.

The RR was calculated from the quasi-DC component of the PPG and BioZ signals. A FFT of the quasi-DC components were acquired, and the signal's fundamental frequency was isolated which corresponded to the RR. SS-ECG based RR was obtained from applying a 0.05-0.5 Hz bandpass filter to remove artifacts that were not related to respiration [6].

2.4 Performance Evaluation Metrics

Mean absolute error (MAE) was used to assess HR and RR performance for multiwavelength PPG and BioZ relative to SS-ECG (ground truth). Following prior work [7], HR was considered to be in agreement with ground truth if within 5 beats/minute (MAE), and RR if within 1 breath/min (MAE).

3. RESULTS AND DISCUSSION

3.1 Heart Rate Estimation

HR estimations were determined for three trials of sedentary and typing. Within each 1.5-minute trial, 12-second windows with a 4 second overlap were used to determine the overall average HR per trial. The average and standard deviation of the HR across all three trials was calculated to determine the spread of the HR measurements for the sedentary and typing trials. MAE across all trials was calculated by comparing the modalities under investigation, multiwavelength PPG and BioZ, with the reference signal, SS-ECG (Table 1).

Table 1. Average, standard deviation (STD), and mean absolute error (MAE) HR for all three sedentary and typing trials. The calculated HR from the SS-ECG modality was considered the true value when computing MAE.

	Sedentary			**Typing**		
Modality	Average *(bpm)*	STD *(bpm)*	MAE *(bpm)*	Average *(bpm)*	STD *(bpm)*	MAE *(bpm)*
PPG - Red	78.8	1.50	1.00	76.3	2.00	3.00
PPG - IR	77.0	0.50	1.83	77.0	2.10	3.00
PPG - Green	78.8	1.50	1.00	78.8	0.60	2.17
BioZ	75.3	1.90	3.50	75.3	3.00	7.50
SS-ECG	78.8	2.00	NA	79.3	0.80	NA

During the sedentary trials, all three PPG wavelengths under investigation agreed with the reference calculated HR to an MAE within 1-2 bpm, while the BioZ MAE was higher at 3.5 bpm, which was within the distinguished accuracy cutoff. In terms of typing, the MAE increased for all modalities; the MAE for the three PPG wavelengths was < 3 bpm, but the MAE for BioZ (7.5 bpm) was larger than the accuracy cutoff. The larger MAE of the BioZ measurements suggests that the modality is affected by micro-motions more than PPG.

3.2 Respiration Rate Estimation

An estimated RR was determined for each of the three 1.5-minute trials of paced breathing. The average and standard deviation across all trials were calculated, and the MAE was calculated by comparing the RR calculated from the modalities under investigation and the reference modality, SS-ECG (Table 2). As before, modalities were considered accurate in determining RR if the calculated MAE was within 1 breath/min. Overall, the calculated MAE was equal to or less than 1 breath/min for all modalities except IR PPG.

Table 2. Average, standard deviation (STD), and mean absolute error (MAE) RR calculations for all three paced-breathing trials. The calculated RR from the SS-ECG modality was considered the true value when computing MAE.

	6 breaths/min		
Modality	Average	STD	MAE
PPG - Red	6.00	1.22	1.02
PPG - IR	5.00	0.71	1.44
PPG - Green	6.50	0.71	0.52
BioZ	6.00	1.22	1.02
SS-ECG	6.44	0.26	NA

4. CONCLUSION

The multi-modal wireless upper arm band was able to be used for measuring HR and RR from multi-wavelength PPG and BioZ during moments when the subject was sedentary. During typing, the BioZ modality had a larger MAE relative to PPG suggesting the modality is more affected by noise. A larger study with a diverse population would need to be conducted to conclude the accuracy of HR and RR calculations during different activities.

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