Multi-channel pulse oximetry for wearable physiological monitoring

Y. Mendelson, D. K. Dao, K. H. Chon
Department of Biomedical Engineering
Worcester Polytechnic Institute
Worcester, MA 01609
ym@wpi.edu

***Abstract*—Pulse oximetry is a widely accepted clinical method for noninvasive monitoring of arterial oxygen saturation and pulse rate. Significant improvements aimed at curbing motion artifacts and improving reliability in detecting sufficiently strong photoplethysmographic signals are required to reduce errant measurements before the pulse oximeter can be considered for wider mobile applications. The present work describes the development of a wearable multi-channel reflectance pulse oximeter to investigate if a motion artifact-free signal can be obtained in at least one of the multi-channels at any given time. Pilot findings provided a proof of concept to support the hypothesis that photoplethysmograms acquired concurrently from independent channels in a multi-channel pulse oximeter sensor respond differently to motion artifacts, thus laying the foundation for future development of robust active noise cancellation and data fusion based algorithms to mitigate the effects of motion artifacts.**

Keywords—Wearable sensors, pulse oximeter, motion artifacts

I. INTRODUCTION

Steady advances in noninvasive physiological sensing, hardware miniaturization and wireless communication are leading to the development of new wearable technologies that have broad and important implications for civilian and military applications. For example, the emerging development of compact, low-power, small-size, light- weight, and unobtrusive wearable devices may facilitate remote noninvasive monitoring of vital signs from soldiers during training exercises and combat. Telemetry of physiological information via a short-range wirelessly-linked personal area network can also be useful for particular categories of users, such as emergency first-responders, workers in harsh environments, including firemen and rescue patrols, or outdoors sportsmen, including high altitude mountaineers. The primary goals of such a wireless mobile platform would be to keep track of an injured person's vital signs, thus readily allowing the telemetry of physiological information to medical providers, and support emergency responders in making critical and often lifesaving decisions in order to expedite rescue operations. Having wearable physiological monitoring could offer far-forward medics numerous advantages, including the ability to determine a casualty's condition remotely without exposing the first responders to increased risks, quickly identifying the severity of injuries especially when the injured are greatly dispersed over large geographical terrains and often out-of-site, and continuously tracking the injured condition until they arrive safely at a medical care facility.

Several technical challenges must be overcome to address the unmet demand for long-term continuous physiological monitoring in the field. In order to design more compact sensors and improved wearable instrumentation, perhaps the most critical challenges are to develop more power efficient and low-weight devices. To become effective, these technologies must also be robust, comfortable to wear, and cost-effective. Additionally, before wearable devices can be used effectively in the field, they must become unobtrusive and should not hinder a person's mobility. Employing commercial off-the-shelf (COTS) solutions, for example finger pulse oximeters to monitor blood oxygenation and heart rate, or standard adhesive-type disposable electrodes for ECG monitoring, is not practical for many field applications because they limit mobility and can interfere with normal tasks. A potentially attractive approach to aid emergency medical teams in remote triage operations is the use of a wearable pulse oximeter to wirelessly transmit heart rate (HR) and arterial oxygen saturation (SpO_2) to a remote location.

Pulse oximetry is a widely accepted method that is clinically used for noninvasive monitoring of SpO_2 and HR. The method is based on spectrophotometric measurements of changes in the optical absorption properties of deoxyhemoglobin (Hb) and oxyhemoglobin (HbO_2). Noninvasive spectrophotometric measurements of SpO_2 are typically performed in the visible (600-700nm) and near-infrared (NIR) spectral regions between 800-950nm. Pulse oximetry relies on the detection of photoplethysmographic (PPG) signals produced by variations in the quantity of arterial blood that is associated with periodic contractions and relaxations of the heart. Hence, the technique relies on the presence of a stable peripheral arterial pulse.

Pulse oximetry can be performed in either transmission or reflection modes. In transmission pulse oximetry, the sensor is typically attached across a fingertip, foot, or earlobe. In this configuration, the light emitting diodes (LEDs) and photodetector (PD) are mounted on opposite sides of a peripheral pulsating vascular bed. Alternatively, in reflection-mode pulse oximetry, the LEDs and PD are both mounted side-by-side on the same planar substrate to enable readings from multiple body locations where trans-illumination measurements are not feasible. Clinically, reflectance pulse oximetry has long been recognized as a potential alternative method to transmission pulse oximetry in certain medical applications where peripheral perfusion might be compromised. Additionally, reflection-mode is attractive for body sensor networks (BSN) due to the flexibility in choosing various sensor mounting locations over conventional transmission-mode pulse oximetry.

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Several studies have reported that forehead oximeters are at least as accurate as finger mounted oximeters under normal testing conditions, and due to their central placement, are affected less by thermoregulatory vasoconstriction and are able to respond more quickly to desaturation events [1, 2]. Also, during conditions which lead to poor peripheral perfusion, forehead sensors have demonstrated greater accuracy than finger sensors [3, 4]. In addition, pulse oximetry measurements from the forehead offer a potential advantage in tactical settings that require extensive use of the hands that can introduce excessive motion artifacts. While reflectance mode pulse oximetry remains promising, significant improvements aimed at curbing motion artifact and improving reliability in detecting sufficiently strong PPG signals are required to identify and reduce errant measurements before they can be considered for wider and more reliable mobile applications.

II. Motion Artifacts

Although well accepted for use in resting subjects, using pulse oximetry outside of a more controlled hospital setting has been problematic for several reasons. Depending on the measurement site, sensors may be subjected to varying degrees of motion artifacts, resulting in signal corruption and thus inaccurate estimations of HR and SpO_2 [5, 6]. Many clinicians have cited motion artifacts in pulse oximetry as the most common cause of false alarms, loss of signal, and inaccurate readings [7]. While the intelligent design of sensor attachment, form factor and packaging can help to reduce the impact of motion disturbances by making sure that the sensor is securely mounted, it is rarely sufficient for noise removal.

In relation to pulse oximetry obtained from the forehead, it is speculated that the main source of motion artifact is due to changes in the relative position of the sensor with respect to the curved skull rather than the relative movements of the sensor with respect to the skin. Due to the rounded and optically inhomogeneous surface properties of the forehead, alterations in sensor position and orientation will cause changes in the distribution of backscattered light reaching the PD. Therefore, sudden changes in incident light intensity reaching the PD due to cyclical movement of the sensor will result in the corruption of the PPG signals. Some research has also suggested that there may be two other sources of motion artifacts. The first source of motion artifacts can be attributed to the formation of air gaps created between the skin and sensor during physical activity [8], which may cause measurement error. Another source of motion artifact can be attributed to low venous pressure blood "slosh" with back and forth movement which is seen when an individual is physically active. This local perturbation of venous blood adds to the AC component of the PPG signal and can result in low SpO_2 measurements [9].

Combating motion artifacts can be performed via both hardware and computational implementations:

i. Computational Approaches to Combat Motion Artifacts: Various computational algorithms attempt to isolate the effects of undesired motion-induced artifacts by rejecting suspect estimates of signal values [10]. Making matters worse in this case is that the noise can frequently fall within the same in-band frequency as the physiological signal of interest, thus rendering conventional linear signal filtering with fixed cut-off frequencies ineffective. Recently developed pulse oximeters offer potential advantages because they utilize advanced signal-processing methodologies in an attempt to provide continuous and accurate measurements when signals are weak (e.g., low perfusion) or corrupted by motion artifacts. Among the numerous signal processing techniques explored to address the confounding issue of in-band noise is adaptive noise cancellation (ANC). One example of a motion-tolerant algorithm is the Signal Extraction Technology (SET®) developed by Masimo [11].

ii. Hardware Approaches to Combat Motion Artifacts:

Since the introduction of pulse oximetry in the 1980s, improvements have been made to decrease the interference of motion artifacts on continuous, reliable estimation of oxygen saturation. New adhesive materials and mechanical design of the sensor housing placed against the skin have dramatically reduced problems with adherence and almost eliminated skin complications from sensor heat or reaction to adhesive materials. Improvements in sensor technology, particularly those related to minimizing motion artifacts, have progressively improved the accuracy and reliability of the devices during the past 20 years.

As PPG signals are highly susceptible to motion, various strategies have been employed to improve estimates of physiological variables derived from noisy PPG signals. Generally, motion artifacts in the recorded PPG signals are more difficult to remove than instrumental artifact as they do not have a predetermined narrow frequency band and their spectrum often overlaps with the desired signal. Thus, classical linear filtering with fixed cut-off frequencies to minimize the effect of motion artifacts cannot be implemented very effectively. Accelerometers (ACC) combined with ANC have been suggested as a promising approach for active noise cancellation of motion-corrupted biosignals [12, 13]. The most common approach employs an accelerometer sensor based on MEMS technology which offers a low-cost solution [14-16]. For example, Relente et al. [17] used an accelerometer as a motion reference for removing artifacts from a Nellcor pulse oximeter. However, despite these promising results, the effectiveness of an accelerometer-based automatic noise cancellation depends on the type of motion artifacts. For example, the reduction in noise may be limited during less repetitive sporadic movements. Moreover, if the motion frequency shifts rapidly over a wide spectral band, the approach is generally less effective due to a slower adaptation rate.

III. Prototype Sensor Configurations to Study the Effects of Motion Artifacts

Our laboratory has developed several prototype wearable reflectance-type pulse oximeters to investigate the effects of motion artifacts on different sensor configurations.

A. Dual-Wavelength and Single PD Configuration

Fig. 1 depicts a more conventional custom optical sensor configuration comprised of a pair of red (R) and NIR LEDs and a single PD. The wearable sensor contains an optical reflectance module, electronic circuitry and a tri-axial accelerometer. The PPG waveforms are acquired using a small

Fig. 1. Dual-wavelength forehead wearable pulse oximeter.

Silicon photodetector. The built-in accelerometer provides estimates of the wearer's posture and mobility. The sensor is housed in a rigid enclosure that is contoured to an average size adult head. The 30 mm x 70 mm x 15 mm sensor assembly is held in place by a compressive headband. The sensor is powered by a non-rechargeable Lithium-ion battery, providing approximately 100 hours of continuous operation. Data acquired by the wearable sensor are transmitted wirelessly to a USB-based receiver via low-power, peer-to-peer wireless communication over a short-range RF link using the 902-928 MHz ISM band.

Excessive contact pressure between a reflectance sensor and the skin is known to interfere with local blood flow, consequently leading to diminished or loss of the PPG signals. This interference can subsequently affect measurement accuracy. Several studies were conducted to aid in understanding how contact pressure affects pulse oximetry measurements. These studies provide a qualitative description of the effect of contact pressures on the PPG signal and its components [18, 19]. When the contact pressure used to secure the sensor to the body is too low, low amplitude PPG waveforms result in inaccurate measurements. On the contrary, if the contact pressure is too high, blood circulation can be compromised or necrosis could occur, leading to a complete loss of the PPG signal and the ability to obtain SpO_2 and HR measurements if the sensor is worn for extended periods of physical activity.

B. Multi-Channel LED and PD Configurations

Experience has shown that considerable variations in sensor position and tissue heterogeneities could cause large measurement errors. In addition, most of the light emitted from the LEDs is diffused by the underlying subcutaneous tissues predominantly in the forward direction (i.e. perpendicular to the emitting surface of the LEDs). Therefore, only a relatively small fraction of the light is diffused in a lateral direction. This suggests that to capture a larger proportion of the diffused backscattered light, the PD must be able to detect light from an area concentric with respect to the location of the LEDs. To minimize the dependency of backscattered light on local tissue inhomogeneity, a custom sensor has been designed based on a radially-symmetric arrangement of three pairs of identical R and IR LEDs surrounding a spectrally matched PD as depicted in Fig. 2.

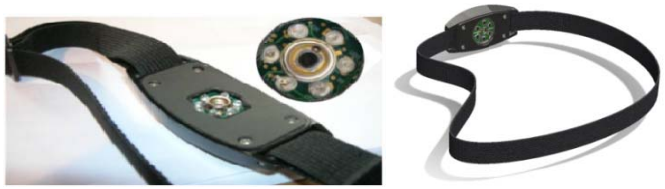

Fig. 2. Multi-channel wearable sensor configuration.

Our goal in designing these sensors was to create a multi-channel pulse oximeter (MCPO) that can be used to investigate how SpO_2 and HR readings may be affected by motion artifacts. The sensor design strategy is analogous to data fusion utilized for example in multi-channel electroencephalographic (EEG) analysis where noise may affect some of the channels but not all channels to the same degree at any given time. The rationale was based on the hypothesis that multiple channels will allow redundancy of data and will likely improve the confidence in making more robust decisions due to the use of complementary information, thus increasing the likelihood of maintaining the accuracy of physiological measurements even during the adverse induction of motion artifacts. Moreover, because of the relative differences in the spatial locations of the LEDs and PDs, we reasoned that local changes in sensor orientation can lead to perturbations in the coupling between the optical components and the skin during movement. These perturbations may have a different effect on the morphological similarities between correlated PPG signals acquired simultaneously by some channels compared to other channels at any given time.

We have developed two different MCPO configurations. The first sensor configuration is based on a single PD and 6 concentrically arranged LEDs. In this embodiment, the PD is used to acquire independently six PPG signals. Digital switching circuits are used to activate each LED in succession and synchronize signal detection using a time-multiplexing approach similar to the operation of a conventional dual-wavelength pulse oximeter, but expanded to include more channels. The second sensor configuration is comprised of six identical PDs arranged symmetrically in a radial configuration surrounding a pair of closely-spaced R and IR LEDs.

IV. EXPERIMENTAL PROTOCOL

To analyze the ability of the MCPO sensor to reject motion artifact, different types of simple physical activities to introduce typical disturbances were tested. All tests were approved by our IRB. Data were first collected in a comfortable laboratory setting from 5 volunteers in an upright sitting position. In this setting, subjects were asked to rest for 5 minutes while PPG data were recorded from the forehead mounted sensor to establish motionless baseline readings. This was followed by a sequence of short activities that included slow left-right (L/R), up-down (U/D) and circular head movements to induce mild motion artifacts. In a second study we recorded PPG signals while the subjects wore the forehead sensor and walked straight, up/down a set of stairs and turned around in a circular pattern to simulate typical daily activities.

V. DATA ANALYSIS

Each digitized PPG signal was separated off-line into time-invariant (DC) and time-variant (AC) components using infinite impulse response (IIR) digital filters. Instantaneous heart rates were determined by computing the time interval between two successive peaks in the AC component of the IR PPG. A 5-point moving average was applied to account for variability in the instantaneous HR readings. SpO_2 were computed from the R/IR ratios using an empirical calibration relationship. Fig. 3 represents two typical examples of PPG signals recorded from different IR channels by the single PD

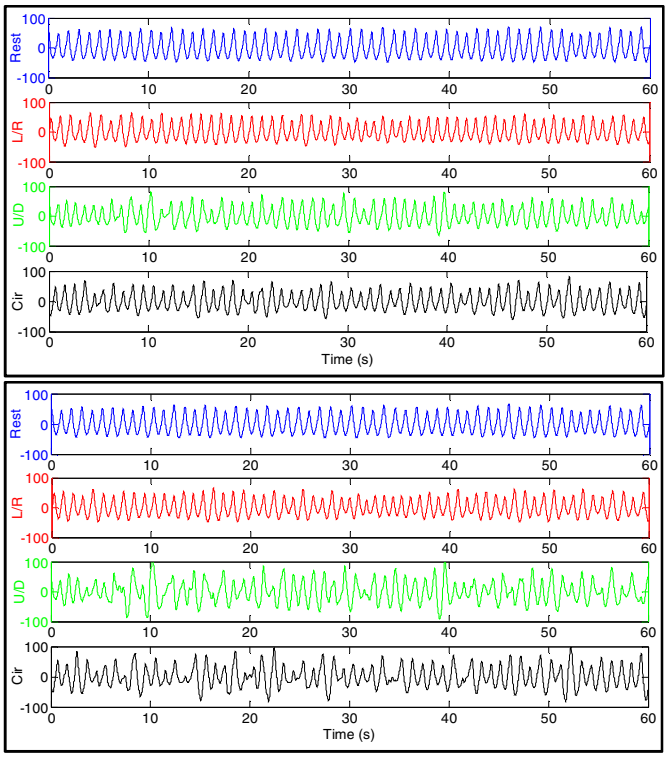

Fig. 3. Typical IR PPG signals recorded simultaneously from two different channels (top and bottom 4 traces) during rest, left-right (L/R), up-down (U/D) and circular head movements.

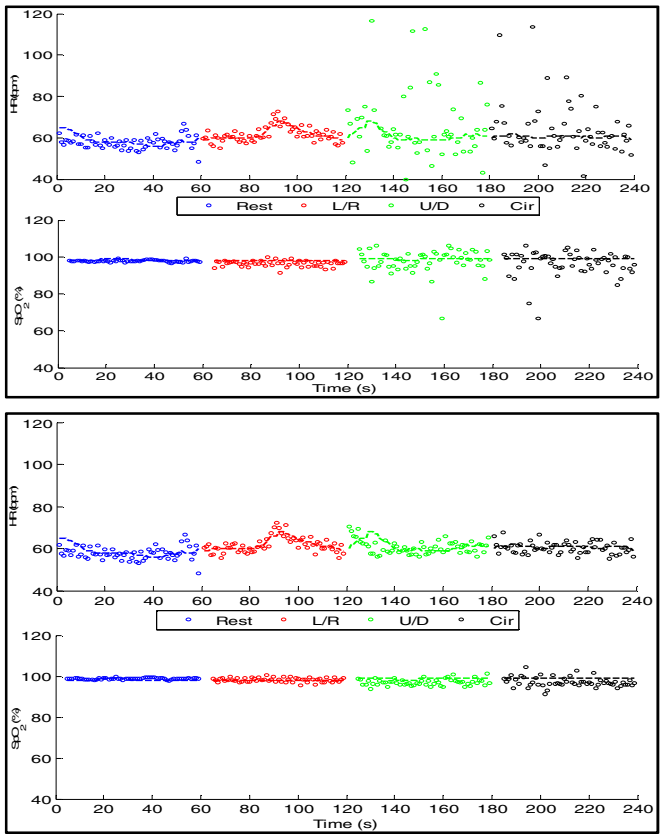

Fig. 4. SpO_2 and HR estimations derived from two different PPG channels recorded simultaneously during rest and motion induced activities. Horizontal traces denote average readings obtained by the reference pulse oximeter.

positioned in the center of the MCPO sensor. Similarly, Fig. 4 shows corresponding SpO_2 and HR estimations derived from two different PPG channels recorded simultaneously during rest and motion induced artifacts. Notice the overall changes in signal amplitude and morphology in the recorded PPG waveforms caused by typical left-right, up-down and circular head movements while the subject remained in a sitting position.

Fig. 5 summarizes the mean and SD corresponding to HR and SpO_2 derived readings obtained from every PPG channel in the MCPO prototype sensor. These data were recorded during rest and voluntary left-right, up-down and circular head movements while the subject remained in a sitting position. Horizontal lines represent mean HR and SpO_2 measurements obtained concurrently by a reference Masimo Radical SET™ pulse oximeter sensor mounted on the subject's finger while the hand was immobilized to limit motion artifacts.

The response of the MCPO to motion artifacts was also evaluated under more representative activities by recording PPG data from the forehead mounted sensor and Masimo finger pulse oximeter while the subject was walking casually, climbing a set of stairs and performing short turning manuvers. Fig. 6 summarizes the mean and SD corresponding to the HR and SpO_2 derived readings obtained during these activities.

Tables I and II compare average HR and SpO_2 measurements derived from different PPG channels in the MCPO sensor during voluntary head movements, while the subject was sitting and performing controlled head movements in the laboratory setting, with measurements obtained during free less restricted body movements outside the laboratory. These data clearly show that calculated HR values derived independently from certain PPG channels are within acceptable errors of ±1 bpm, while other channels produced clinically significant errors.

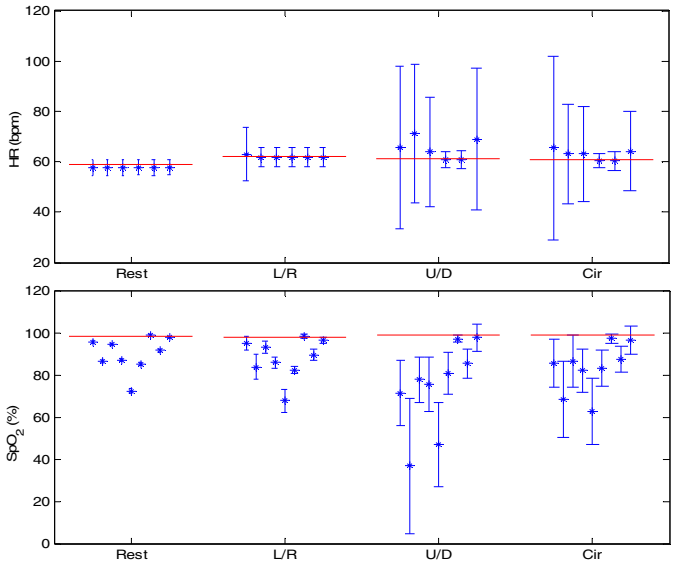

Fig. 5. HR and SpO_2 obtained from 6 independent PPG channels during rest, L/R, U/D and circular head movements. (*Top*) HR derived from each channel. (*Bottom*) corresponding SpO_2 readings derived from 9 R/IR channel pairs. Horizontal lines denote mean measurements obtained concurrently from a finger by the reference pulse oximeter.

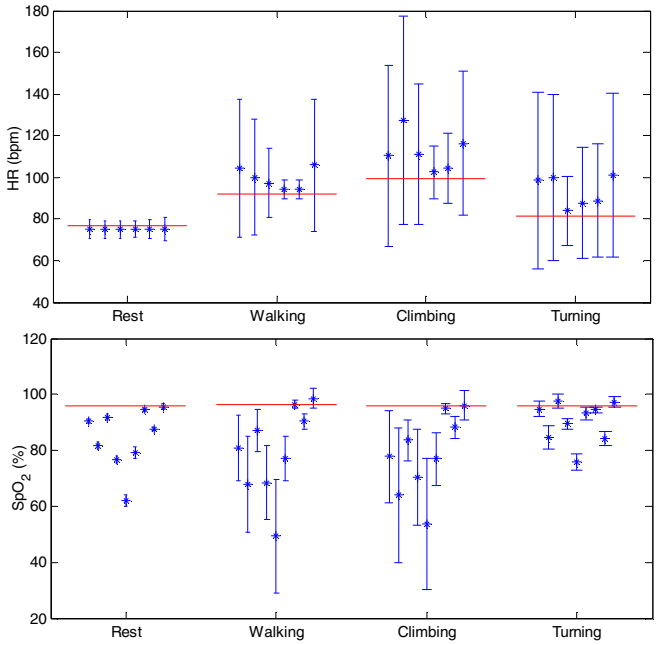

Fig. 6. HR and SpO_2 obtained from 6 independent PPG channels during sitting, walking straight, climbing stairs, and turning to simulate movement artifacts. (*Top*) HR derived from each channel. (*Bottom*) corresponding SpO_2 readings derived from 9 R/IR channel pairs. Horizontal lines represent mean measurements obtained concurrently from a finger by a reference Masimo pulse oximeter.

TABLE I. MEAN HR DIFFERENCES DERIVED FROM DIFFERENT PPG CHANNELS DURING VOLUNTARY HEAD MOVEMENTS (TOP) AND MEASUREMENTS OBTAINED DURING FREE MOVING EXERCISES (BOTTOM).

		LED 1	LED 2	LED 3	LED 4	LED 5	LED 6
Head	***Rest***	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
	L/R	1.0	-0.2	-0.1	-0.2	-0.2	-0.2
	U/D	4.2	9.7	2.5	-0.6	-0.5	7.5
	Circular	4.7	2.3	2.3	-0.4	-0.4	3.4
Body	***Rest***	-1.4	-1.4	-1.4	-1.4	-1.4	-1.3
	Walking	12.4	8.2	5.4	2.2	2.2	13.9
	Climbing	10.9	27.8	11.8	3.0	4.9	17.0
	Turning	16.9	18.2	2.4	6.2	7.1	19.5

TABLE II. MEAN SpO_2 DIFFERENCES DERIVED FROM DIFFERENT COMBINATIONS OF R/IR CHANNEL PAIRS DURING VOLUNTARY HEAD MOVEMENTS (TOP) AND FREE MOVING EXERCISES (BOTTOM).

R/IR pair		1	2	3	4	5	6	7	8	9
Head	***Rest***	-2.5	-11.7	-3.7	-11.1	-25.9	-13.0	0.6	-6.6	-0.4
	L/R	-3.1	-14.3	-5.1	-12.2	-30.3	-15.7	0.2	-8.6	-1.5
	U/D	-27.6	-62.1	-21.1	-23.4	-51.9	-18.2	-1.8	-13.6	-1.2
	Circular	-13.6	-30.7	-12.5	-17.0	-36.5	-15.8	-1.8	-11.6	-2.6
Body	***Rest***	-5.5	-14.2	-4.1	-19.2	-34.1	-16.8	-1.4	-8.3	-0.3
	Walking	-15.3	-28.4	-9.1	-27.9	-46.9	-19.3	0.2	-5.9	2.3
	Climbing	-18.3	-32.1	-12.5	-25.8	-42.4	-19.1	-1.2	-7.8	0.0
	Turning	-1.2	-11.2	1.6	-6.4	-20.0	-2.7	-1.4	-11.8	1.3

VI. CONCLUSIONS

The present work described the development of a MCPO that can be used to investigate how SpO_2 and HR readings may be affected by motion artifacts. These pilot findings showed evidence to support the hypothesis that PPG signals acquired concurrently from independent channels in a wearable reflectance-type MCPO sensor are affected differently by motion artifacts, allowing for automatic adjudication of which signal is likely to be a more accurate reflection of physiological changes, thus helping to reduce measurement errors. Future work will be focused on the development of advanced active noise cancellation algorithms to take advantage of the spatial diversity of different channels and fuse the data measured by the most reliable channels in the MCPO. If proven successful, this strategy will be used to improve real-time measurements of SpO_2 and HR by a wearable reflectance-mode pulse oximeter.

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