Contact pressure as influencing parameters for PPG sensors during physical activities

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Abstract *–Photoplethysmographic (PPG) sensors are catching on in field of wearable sensors for the measurements of the heart rate, combining the advantages in costs, weight and size. Despite their potential, the accuracy of heart rate evaluation is affected by several influencing parameters, including the contact pressure between the skin and the sensor.*
Thus, a PPG sensor was tested in a cohort of 25 subjects at different speed of physical activity (i.e. 3, 6 and 8 km/h) and for different contact pressures (i.e. 20, 60 and 75 mmHg), with the aim of determining the optimal CP to produce a reliable signal during physical activity. Results show that the CP of 75 mmHg provides unreliable results at all speeds. The mean absolute percentage error presented its lower value at 3 km/h with a contact pressure of 20 mmHg while presented a value of 9.6% for a contact pressure of 60 mmHg and a speed of 6 km/h. Authors found that changes in the CP have a significant effect on PPG-HR signal quality. Although future studies on a larger cohort of subjects and for different wavelengths are still needed, this study could contribute a profitable indication to enhance accuracy of PPG-based wearable devices.

1. INTRODUCTION

The improvement of clinical treatments and pharmacology has allowed globally an increase in life expectancy. Indeed, life expectancy has increased by more than 6 years between 2000 and 2019 as reported by the World Health Organization (WHO) [1]. This has led to an increasing number of both elderly and frail people requiring health care, and people saved from acute pathologies but not from the consequent chronic degenerative pathologies [2]. Thus, nowadays, health providers operate under unsustainable conditions, which lead to offer an inadequate health care system. Chronic diseases and cognitive impairments pose a crucial burden that requires a change in the healthcare paradigm, which is expected to put in place new low-cost, high-efficacy interventions and technologies to achieve a new preventive treatment, which is preventing rather than curing. A significant percentage of this population could potentially avoid hospitalizations or the worsening of the physiological conditions if monitored continuously during normal daily life with wearable sensors.
In the last decade, more and more wrist-worn wearable device, like smartwatches and smartband, are integrating different sensors (e.g. photoplethysmographic (PPG)), to provide the user with some important vital parameters, Indeed, PPG-based devices, represent a promising technology capable in detecting several physiological parameters [3] (e.g. heart rate (HR), blood oxygenation, breathing rate and blood pressure) via extremely small sized and low cost device.
The principal components of a PPG sensor are: i) a light source, which usually is between 525 and 780 nm, and ii) a photodetector (PD). Those components can be arranged in two different configurations: transmission mode, which is having the measuring site in between the LED and the PD, and reflective mode, which is having the LED and the PD on the same plane with the measuring site underneath. This last configuration, which is capable to provide a good signal [4] is suitable to be integrated in wearable devices such as smartwatches.
These devices are used by athletes that want to monitor their health status during physical activities and to improve the training and, more in general, by people that want to monitor their health status during normal daily activities.
Despite their huge potential, PPG-based devices are barely used to support clinical decision-making process and are not used for clinical purposed due to the sensitivity of the PPG sensor to several influencing parameters [5, 6] which prevents the sensor in providing accurate HR measures. Among several influencing sources (e.g. motion artefacts [7], skin colour [8],) the contact pressure (CP) between the sensor and the skin seems to play an important role [9].

Indeed, if the pressure is to low, the signal's quality is harmed by the external light and by a non-optimal contact of the sensor to the skin and it's also more prone to relative motion between the sensor and the skin. Conversely, an excessive contact pressure can modify the vessels' bed underneath the sensor, modifying the input quantity.
Therefore, it is essential to improve the performance of wearable technologies and on the other hand to direct more effort to obtain reproducible results in a daily life context.
Based on these considerations, as the future of medicine lies in an uniformity and reliability of testing procedures and on the metrological quality of the measurements, it is essential to improve the quality of PPG sensors through a better understanding of the principal influencing parameters, such as the CP. Assessing the optimal contact pressure, which anyway may depend by each individual, [10, 11] is still challenging but may have significant benefits in improving the overall accuracy and usability of PPG sensors.
The aim of this study is to assess the accuracy of PPG at different CPs and for different intensities of physical activities. Twenty-five healthy subjects were enrolled for the study and performed nine different session of physical activity wearing both a PPG-based device and a ECG-based device used as reference device.

2. MATERIAL AND METHODS

HR measurements acquired through a PPG sensor with controlled contact pressure and a ECG-based reference system were performed in order to evaluate how different contact pressure levels affect the PPG signal during different levels of physical activity. Hereinafter, the measurement setup and the activity's protocol are described:

Measurement setup: A PPG sensor equipped with single LED with a wavelength of 520 nm (DFRobot, Be-jimng, China) was integrated in a 3D printed polylactide frame, designed to be worn on the wrist via a bracelet and to host a bottom load cell (FX1901, Meas.Spec., Fremont, U.S.) stack on the PPG sensor itself, as shown in figure 1. Such a configuration let the load cell to provide the contact pressure between the PPG and the skin. Specifically, the printed components are constituted by a frame (Fig. 1, B) and a cell-press (Fig. 1, C). The first component has two main functions: is designed to act as an interface between the PPG sensor and the load cell and to keep the two surfaces parallel. The second component, which has two slots for the 2 cm nylon bracelet, was used to transmit the pressure exerted by the bracelet entirely to the load cell thanks to the matching surface which is specular to that of the load cell. The combination of the two components allows to normally transmit the force generated by the tightening of the strap directly on the load cell and on the underlying PPG sensor.
The calibration of the load cell, which directly provides the value of the pressure exerted by the sensor on the skin in mmHg, was conducted by stacking a series of calibrated masses of 30, 60 and 90 grams on the system.
In order to test higher contact pressures without cause an uncomfortable feeling of constriction on the wrists of the participants involved in the study, the printed circuit board of the PPG sensor has been milled in the lateral sides not involved by the electrical circuits.

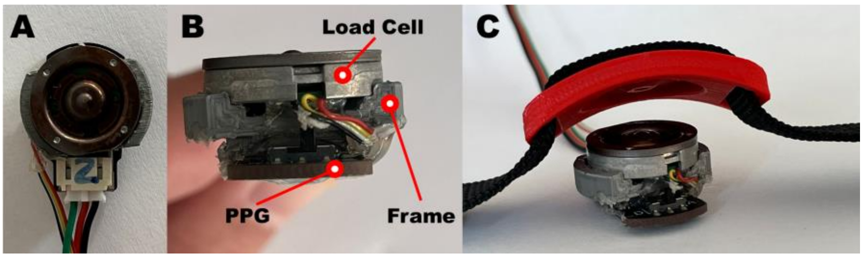

Figure 1. PPG-based device comprehensive of a PPG sensor and of a compression load cell; A top view, B front view and C integration with a bracelet

This has allowed to bring the sensor's area from approximately 460 mm^2 to an area of about 355 mm^2, thus with a reduction of 25%.
The signal provided by the load cell was amplified through the integrated HX-711 (SparkFun Electronics, Niwot, U.S.A.) and all the components were managed by the Arduino Uno microcontroller at a sampling frequency of 80 Hz.
HR reference data were acquired via an ECG-based chest-strap (H9, Polar Electro, Kempele, Finland) and acquired via a mobile app (Elite HRV Inc.) which records a text file containing all the R-R intervals.
All the physical activities were performed on a treadmill (JK Fitness, Movifitness MF Top Slim, Padua, Italy) at different speeds (i.e. 3 km/h, 6km/h and 8 km/h) with the slope fixed at zero degree.
Blood pressure were register before every physical activity section through an automatic oscillometric device (Omron, M2, automatic).

Activity's protocol: The following protocol was approved by the bioethical committee of the University of Palermo and registered with the protocol number 43288-2023; the tests were carried out during spring and early summer of 2023. The protocol has designed in accordance with the standard ANSI/CTA-2065 [12], proposed and released in 2018 by the Consumer Technology Association, as it aims to define the process to test and validate the accuracy of a device for HR monitoring under different conditions.
Twenty-five subjects (10 males and 15 females, age 23 ± 2,6 years, range 22-36, height: 170 ± 8 cm weight: 66,8 ±10,7 kg) after signing the informed and the data consents were enrolled for the study. None of the enrolled subjects reported any known cardiovascular diseases nor reported taking any medication that can influence the main parameters of the cardiovascular system.
All the tests, which had an overall average duration of around 60 minutes each, were conducted within a laboratory with a room temperature ranging from 21 to 24 °C for all the tests.
After collecting the consensus and the anthropometric information of each subject, the skin color on each participant's arm was compared with the Fitzpatrick chromatic scale: 3 subjects presented a skin classification of type 1, 8 subjects presented a skin classification of type 2 and 14 subjects a skin classification of type 3.
Before the beginning of the test, a first blood pressure measurement (BP_1) was recorded. Then, the study coordinator asked each participant to wear the Polar H9 chest strap and then to sit and rest in a chair while placing the prototypal bracelet at the wrist and ensuring it to be tight at the first contact pressure of 20 mmHg (CP_1). The wires from the bracelet were then fixed on the arm, by using an adhesive, tape to prevent any unwanted displacement of the system during the physical activity. Thus, each subject began the planned activity as depicted in figure 2.

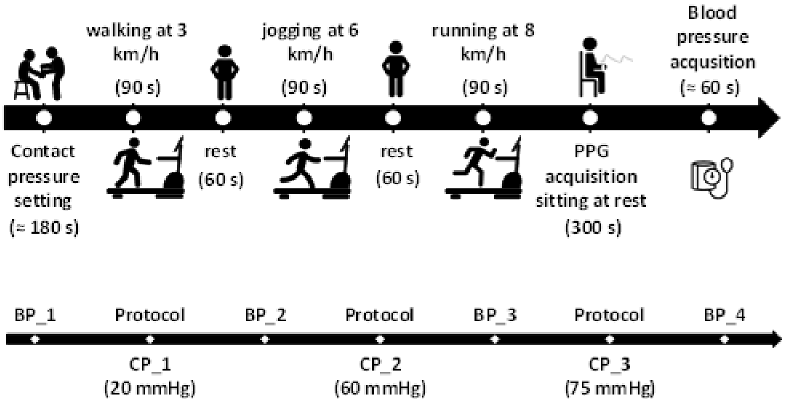

Figure 2. Description of the protocol (upper image) and summary of contact pressures tested and blood pressure acquisitions made for each subjects (lower image).

Data analysis: ECG and PPG data were processed offline with Matlab; a band-pass between 0.5 and 5 Hz was applied to the digitized PPG waveform as well as a Hampel filter to detect and remove any outliers. The two datasets (ECG and PPG) were synchronized by means of minimum bpm error to find the maximum correlation values, and then, a PPG signal was used to extract waveform features as the peaks.
The HR was quantified both for every single pair of consecutive peaks and by using a moving average from a variable subset of data ranging linearly from 5 at 60 bpm up to 13 at 150 bpm.
ECG and PPG derived HR were finally compared (25 subjects, 9 different tests for each person), and the parameters of interest were assessed and specifically, the Mean Absolute Percentage Error (MAPE), the Mean Absolute Error (MAE) and finally, Bland-Altman graph was implemented.

3. PRELIMINARY RESULTS AND DISCUSSION

After having set the contact pressure before the physical activity session, this changed, even significantly, during the test due to the movement of the arm and muscles. However, at the end of the test, the value returned within ± 5 mmHg of the set value, demonstrating that the tightening system did not loosen during the execution of the tests.
PPG and ECG signals recorded from a single random subject are presented, as an example, in figure 3.

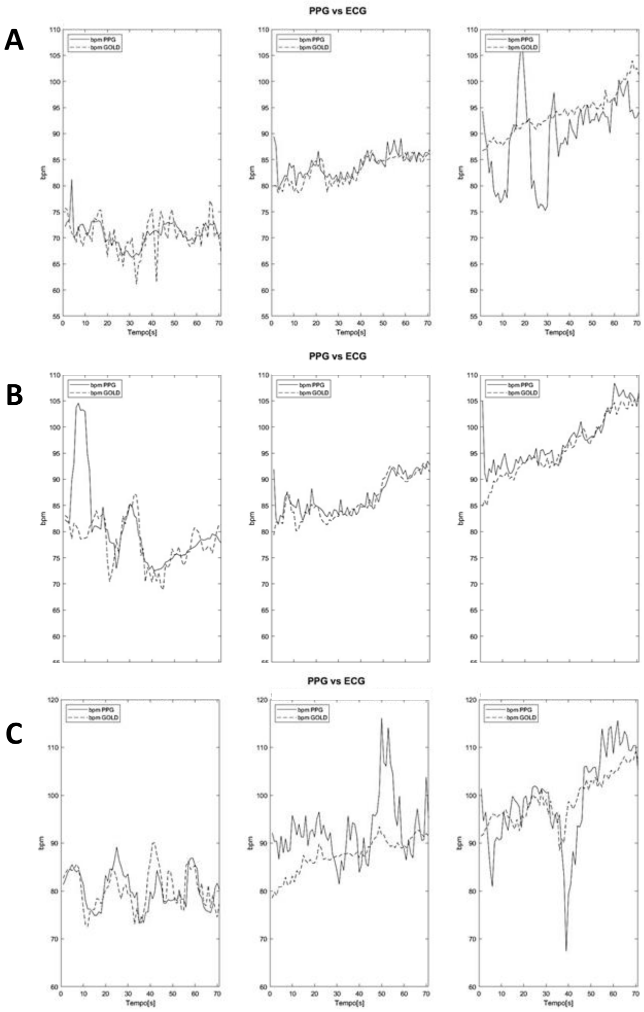

Figure 3 Filtered and synchronized PPG (continuous line) and ECG (dashed line) acquisitions at each speed and for every contact pressure (CP), to evaluate qualitatively the correlations between ECG and PPG. Line A: 20 mmHg at 3,6 and 8 km/h; Line B: 60 mmHg at 3,6 and 8 km/h; Line C: 75 mmHg at 3,6 and 8 km/h;

To establish the agreement between the PPG-based device with respect to the gold standard (i.e., ECG device) the MAPE was calculated for all the subjects. As reported in table 1, it is possible to observe, as expected, that the highest values of MAPE are achieved at 8km/h.

	MAPE (σ)		
	20 mmHg	**60 mmHg**	**75 mmHg**
3 km/h	7.0 % (4.7)	8.4 % (6.3)	16.2 % (9.5)
6 km/h	11.3 % (8.8)	9.6 % (5.7)	16.8 % (9.2)
8 km/h	29.3 % (12.27)	33.3 % (11.3)	34.6 % (9.7)

Table 1 Mean absolute percentage error (MAPE) of PPG and ECG at each velocity and for each contact pressure

It is also possible to observe that the worst results at any speed are obtained with the highest contact pressure of 75 mmHg. As reported in literature [4], theoretically the optimal contact pressure can be achieved at the transmural pressure, which likely is lower than 75 mmHg. In addition, 75 mmHg is a rather high contact pressure and probably the worst results obtained at this pressure are due to two main reasons: the average diastolic blood pressure of participant through all the test session was lower than 75 mmHg and thus, this pressure compress the capillary bed during part of the cardiac cycle. The second reason may be that at such high contact pressure there is any attenuation of the bouncing due to the physical activity which may interfere with the acquisition.

Similar results were achieved at 20 and 60 mmHg, where the MAPE is slightly lower at 3 and 8 km/h. The comparison of the two signals was then deepen through the Bland-Altman technique (Fig.4) as prescribed by the CTA-2065 standard [12].

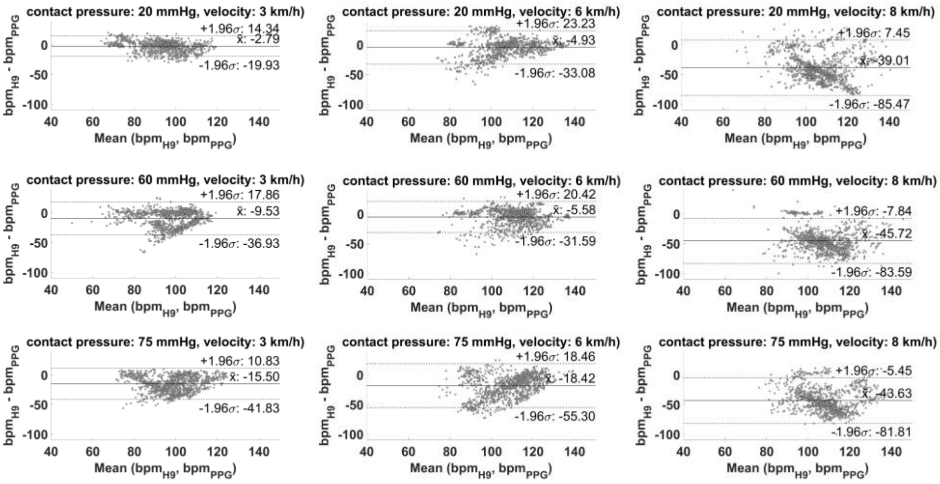

Figure 4. Bland Altman plot of PPG and ECG acquisition at each speed and for each contact pressure.

As obtained in a previous similar study [9] the individual optimal contact pressure was assessed. Only in two subjects the best MAPE was achieved at 75 mmHg (at 3 and 8 km/h) whereas a good balance was found between 20 and 60 mmHg. Basing on the individual optimal contact pressure, a MAPE of 5.9%, 7.9% and 26% were obtained at 3, 6 and 8 km/h respectively. This underline a intersubject variability and suggest that an individual optimal contact pressure may improve the accuracy of the PPG system during physical activity.

4. Conclusion

PPG sensors have a great potential in detecting cardiovascular parameters and thus, scientific community have extensively performed new studies in order to increase the metrological performance of the sensor. Among several sources that affect PPG signal, CP between the sensor and the skin greatly influences the PPG signal quality, compromising the overall reliability of the system and preventing its widespread use during the typical daily activities.

To assess the most convenient contact pressure related to a specific physical activity intensity, 25 subjects were enrolled in a study where 3 contact pressures at 3 different speed of physical activity were tested.

Results show that the contact pressure has a significant effect on the evaluation of the HR. Specifically, 75 mmHg it is an excessive pressure which gave poor results for all tests.

The other 2 contact pressures (i.e. 20 and 60 mmHg) provide almost equivalent results for the walking activity (3km/h) while 60 mmHg provided better results for 6 km/h, due to the reduction of motion artefacts.

With a higher HR accuracy, a PPG-based HR sensor, integrated in a wristband, can be effectively used for monitoring athletes, workers and in general, for the personal health management for a safer and healthier lifestyle.

Although future studies on a larger cohort of subjects are needed to further strengthen our results, this study could contribute to enhancing PPG-based device behaviour and accuracy in the monitoring of HR.

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