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A Photoplethysmographic Monitor for Local Pulse Wave Velocity Measurement

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ABSTRACT
Currently, the available technologies that are capable of monitoring pulse wave velocity (PWV) in a patient are uncomfortable and obstructive. Recently, it has been hypothesized the use of photoplethysmographic (PPG) for this purpose and, therefore, the need to capture and understand the hemodynamic variables used in the PPG signal acquirement process, such as the local pulse transit time (PTT) and local PWV. This work aims to verify the feasibility of the PPG technique in the construction of local PTT and PWV monitor, using PPG sensors and low-cost integrated circuits. In this paper, the low-cost term is used as a synonym for retail sensors, available commercially and commonly used in academic projects for the Arduino platform. It is important for the development of wearable technologies that can be used in a future project to monitor PTT and PWV using a minimally obstructive approach.

General Terms
Photoplethysmography, pulse transit time, pulse wave velocity, Arduino.

Keywords
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1. INTRODUCTION
Photoplethysmography (PPG) is a simple, non-invasive, low-cost technique used to monitor blood flow through a light transducer. This technique is used to obtain the pulse wave signal, allowing the analysis of volumetric changes of pulsating blood and, therefore, the expansion and contraction of blood vessels. The pulse waves, measured by a PPG sensor, result from the contraction of the heart when blood is pumped through the body [1]. Therefore, a PPG monitor can be used to measure many clinical parameters, such as arterial oxygen saturation, heart rate, blood pressure, and cardiac output [2].

The pulse transit time (PTT) is a physiological parameter that indicates the time required for the pulse wave to travel a previously defined distance between two points in the same artery. This variable can be obtained by analysis of the electrocardiogram, the PPG signal, and other technologies [3].

A PPG sensor produces a high sensitivity signal, which allows the analysis of morphological characteristics, such as the minimum of a systolic amplitude or peak. A systolic peak is caused by the highest light absorption by hemoglobin, which coincides with the pulse wave arrival time [4]. Thus, two PPG sensors placed along an arterial branch, with a known distance, can measure the PTT between the two locations and, consequently, evaluate the local PWV along with a selected artery site [5].

The PWV from a small arterial segment (less than 50 mm) is known as local PWV. The simplest and standard approach for PWV measurement is based on the two-point method, where the pulse waves are acquired. Two arterial sites are required to sensors' positioning in an arterial branch, which is usually the femoral artery, radial artery, and carotid artery, where arterial pulsations are more apparent [6]. Thus, the PPG sensors are responsible for measuring the transit time of blood pulse waves between two arterial sites simultaneously. Since there is a known distance between these two sensors, it is possible to determinate the local PWV.

However, the PPG signal is highly susceptible to noise caused by the user's movement [7]. Another important aspect refers to the anatomy of the human body and, consequently, the correct sensors' positioning. Low tissue perfusion has a direct impact on a reliable acquisition of the PPG signal. It happens due to the mechanical origin of this biopotential, whose propagation is directly influenced by any factor that may interfere in an individual's vasoconstriction and vasodilation mechanism [8].

Therefore, this work presents a local PTT and local PWV monitor using two PPG sensors positioned in different body sites. Identifying arterial branches where PPG signal acquisition presents high amplitude and low noise interference is important for the proposed technology, as well as the analysis of low-cost sensors to the Arduino platform. The local PTT and PWV results shown in this paper were obtained by analyzing the PPG signal of two sensors in the radial artery.

2. MATERIALS AND METHODS
This system consists of two main components: two pulsesensor.com® PPG sensors and an Arduino development kit, model MEGA 2560 R3. The sensors were connected to the microcontroller's analog inputs for access to the analog/digital converter used for PPG signal sampling. They are 15.8 mm in diameter, and their LED and light photodetector (PD) work at a wavelength in the range of 500 to 504 nm, which corresponds to visible green light. Since the LED and PD are positioned on the same side, it operates in reflexive PPG mode.

The PPG is practical, simple, energy-efficient, and easy to set up. For PPG signal detection, the LEDs and PDs are set up to green wavelengths due to its absorption by the hemoglobin present in the arterial blood. Thus, the amount of light reflected on PD corresponds to the change in blood volume, as shown in Figure 1.

Fig. 1. PPG sensor in reflexive mode

Figure 2 shows the prototype that was designed and developed using two PPG sensors connected to the Arduino microcontroller. The sensors were connected to a 3-way armored cable to improve cable resistance and reduce external interference or signal noise. The armored cable and the Arduino microcontroller were connected to a 3- way P2 3.5mm plug, promoting safety, mobility, and ease of prototype use. For the prototype development shown in Figure 3, it was spent approximately US$ 30.00.

The components used in this project did not require printed circuit boards manufacture, reducing the cost, and especially the time for hardware prototyping, as assembly can be easily done. It is particularly important for healthcare professionals, potential managers of this technology.

Figure 4 illustrates the software interface used to obtain the PPG signals. This program was developed by SOUZA for the acquisition and digitization of biopotentials during the validation of the HRVCam software [9].

First, a boolean variable named flag is declared and acts by controlling the sending of signals to other software, developed for the MATLAB platform, and executed on a personal computer (PC) [10]. When an event occurs, such as sending or receiving a signal sample, an interrupt is created and associated with each of the Arduino analog ports (A0 or A1). If the received value is false, the flag variable is updated, and the signal sending to the PC is canceled. If the value is true, the flag variable is updated, enabling the signals to be sent to the PC running the software shown in Figure 4. Also, it is possible to select the sampling frequency that the microcontroller samples the PPG signals. For this, a conditional structure is declared, the selection of which will depend on the operator in the PC.

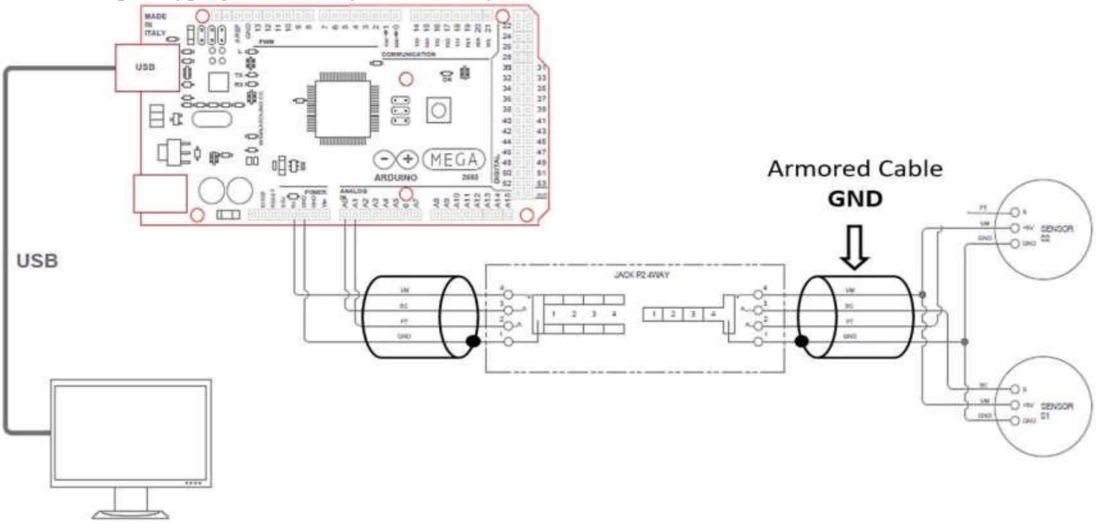

Fig. 2. The prototype of the PPG signal acquisition circuit developed in this project.

Fig. 3. The final prototype.

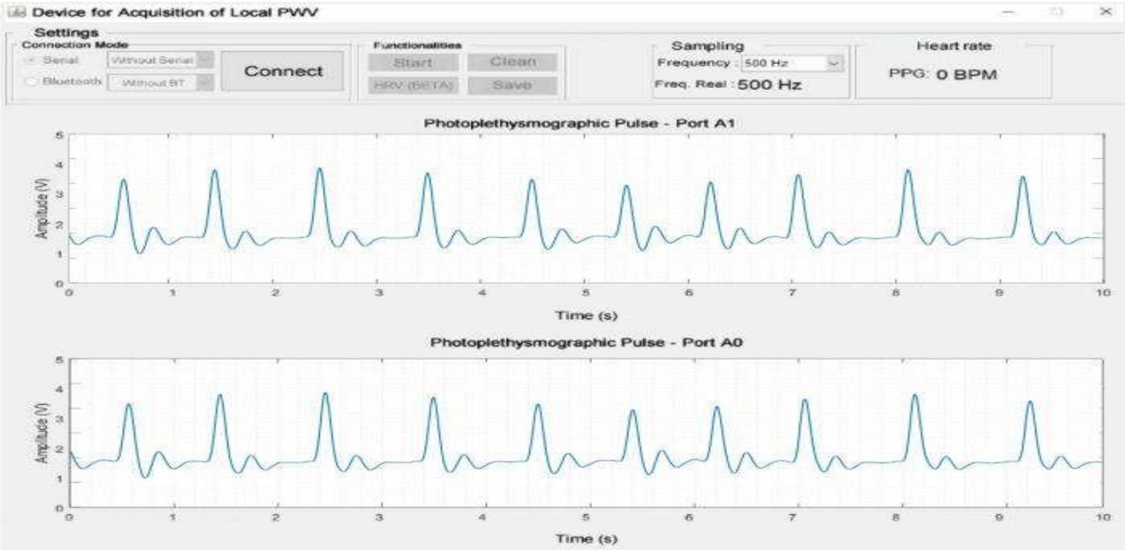

Fig. 4. Software for visualization of data collected by Arduino.

The sampling frequency used during the tests of this project was approximately 500 Hz. At this sampling frequency, the time between samples is 2 ms, allowing the accurate detection of time differences between the pulses of the proximal and distal regions that are greater than or equal to 2 ms.

3. TEST ENVIRONMENT

Figure 5 illustrates the test environment. The image was taken during an experimental procedure, showing a participant submitted to the proposed data collection with the acquisition system.

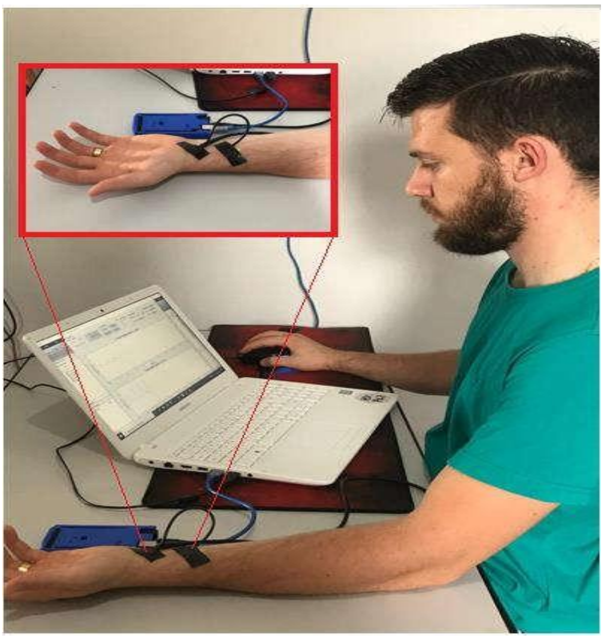

Fig. 5. Test environment for data acquisition.

4. RESULTS AND DISCUSSION

The proposed device measures the local PWV in real-time during signal acquisition and visualization in the software interface [10]. It is only possible because the local PWV monitor allows real-time communication between the proposed acquisition system, shown in Figures 2 and 3, and the software, shown in Figure 4, via USB port.

All results presented in Figures 7, 8, 9, and 10 were extracted from a single research volunteer during data acquisition for the local PWV monitor's test. Two PPG sensors, shown in Figure 7, were installed in contact with the volunteer's skin, in two arterial points, a proximal and a distal, in the same arterial branch, during 1 minute.

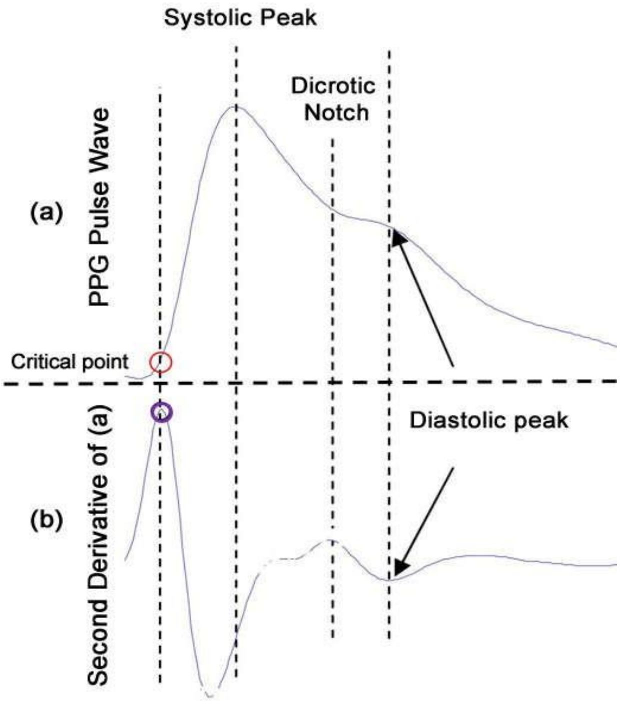

Fig. 6. The critical point (red O) on signal (a), obtained by detecting peaks in the second derivation (b) of the PPG signal, is an event that marks the beginning of systole (purple O) Source: (Adapted from ELGENDI, 2012).

The monitor estimates the local PTT by measuring the time difference between critical points in the second derivative of PPG signal [11], which is equivalent to the time between the beginning of systole in a proximal region and a distal region, as shown in Figure 6. Considering that the sensors are positioned in the same arterial branch, at a known distance, it is possible to estimate the local PWV by local PTT [12].

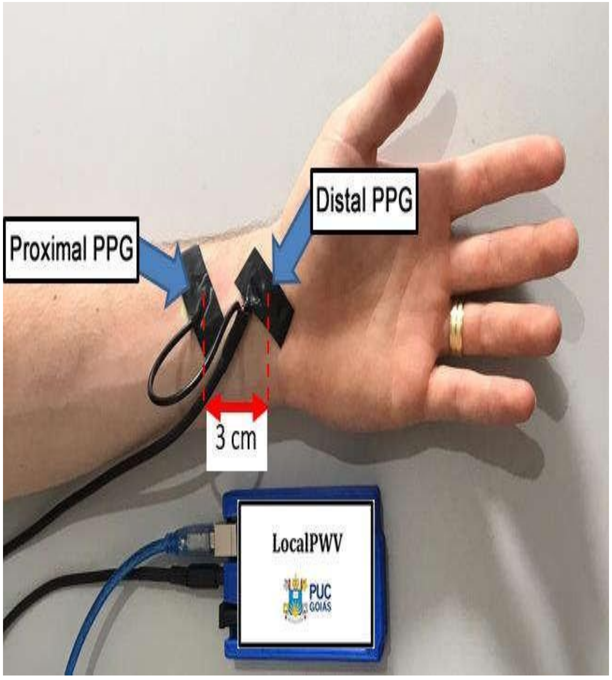

Fig. 7. Example of data collection made during the experiments.

Figure 7 demonstrates how PPGs sensors were placed on the user's skin above the radial artery and how the data acquirement was performed using the proposed monitor. All volunteers were adults aged 22 to 26 years. On average, the data collections lasted 60 seconds, and the pulse waves were acquired in the radial artery and the carotid artery. Thus, the local PTT and PWV were calculated.

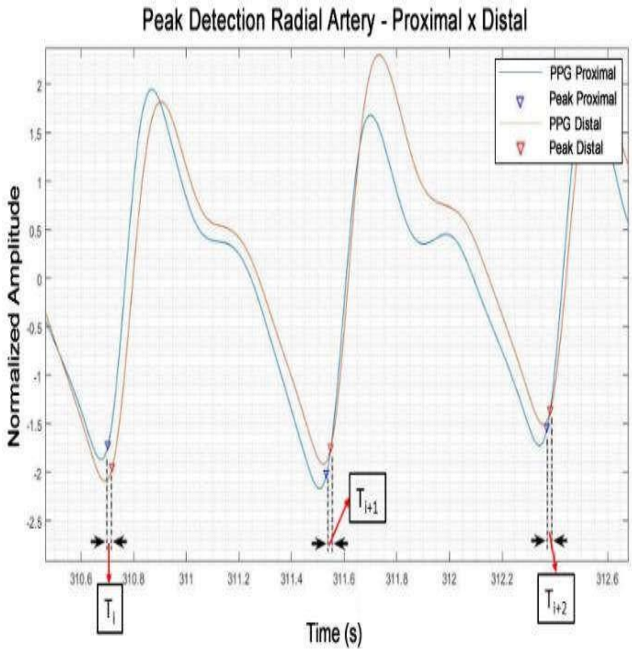

Fig. 8. The time delay between two regions in the same arterial branch, indicated by the black arrows and saved in the T_i vector.

Figure 8 illustrates a measurement between proximal and distal regions. In this PPG signals' plot, it is possible to notice the time delays between the critical points, which are saved in a Ti vector, responsible for saving the time differences.

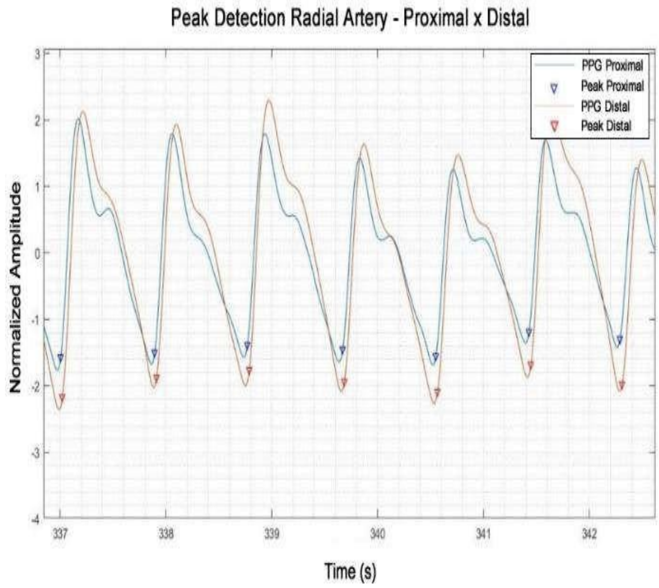

Fig. 9. Detection of critical points on the PPG signals obtained in the left-hand radial artery.

The sensors' position was continuously adjusted until a good quality PPG signal was obtained. Figure 9 presents a plot where two PPG signals were acquired through sensors placed at two arterial points. The proximal and distal sensors were located in the radial artery of the left hand, at a distance of 0.03m. It is also possible to notice the time delays between proximal and distal critical points.

According to Khong [13], local PTT is estimated by then the local PWV was estimated. The mean local carotid local PWV of 25 volunteers measured by the proposed device was 2.63 ± 0.42 m/s.

In the study proposed in this paper, the results suggest that the acquisition of local PTT and PWV were very consistent when comparing them to the experiment presented by Nabeel [14], showing that it is possible to use two PPG sensors for obtaining these physiological variables.

The PPG signals obtained by the pulsesensor® sensors allow the

$$\text{PTTlocal} = \frac{\text{T1} + \text{T2} + \text{T3} + \text{T} \ldots + \text{TN}}{\text{N}} \qquad (1)$$

analysis of the entire cardiac cycle in two regions (proximal and distal) simultaneously, when the transducers are positioned in an arterial

here T is the time interval between the systolic peaks of the proximal and distal pulse wave, and N is the number of critical peaks found. Therefore, an arithmetic average of the time intervals between the systolic pulse wave peaks is calculated [13]. Considering that the sensors are placed in the same arterial branch, whose distance h is known, according to Nabeel [14], the local PWV can be calculated by

section larger than 2 cm.

Since the PPG sensors operate in reflexive mode, the green light beam goes through surrounding tissues to reach deeper arteries. The experiments showed that in these cases, the PPG sensors did not have enough light reflection to return to the pulse wave signal to the photodiode.

Based on the results shown in Table 1, the use of PPG sensors in the

$$PWVlocal = \frac{h}{PTTlocal} \quad (2)$$

radial and carotid artery proved to be a good choice for determining local PTT and local PWV, due to noise immunity, signal amplitude,

In Figure 10, as the sensors are positioned at a known distance of 0.03 m, it was possible to detect the time intervals between the arterial points indicated in Figure 8, thus estimating local PTT and PWV using equations (1) and (2).

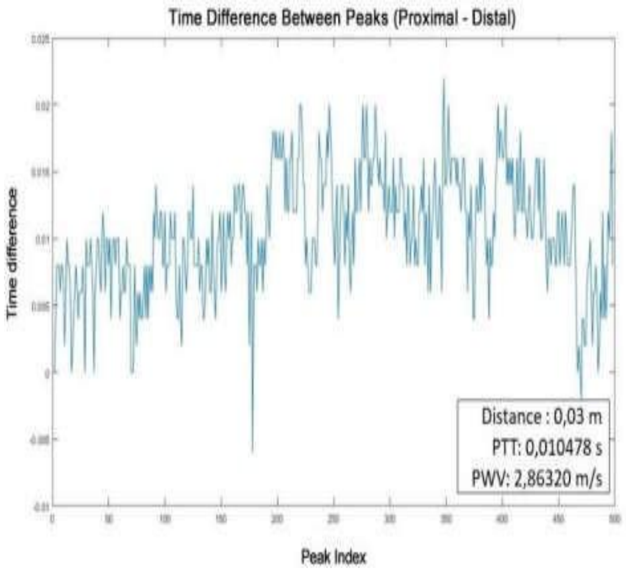

Fig. 10. Local PTT and local PWV values obtained.

Table 1 shows all the data collected during the experiments. Five healthy adults participated in the study, aged between 22 and 26 years old.

Table 1. Values obtained from experiments performed

Experiment*	Age (years)	Height (m)	Weight (kg)	Arterial Region	Distance (m)	Local PTT (s)	Local PWV (m/s)
1	22	1,85	85	Radial	0,03	0,0105	2,86
				Carotid	0,05	0,0342	2,33
				Carotid	0,10	0,0385	2,59
2	22	1,76	72	Radial	0,04	0,0148	2,70
3	26	1,78	85	Radial	0,06	0,0234	2,94
				Carotid	0,08	0,3729	2,14
5	23	1,77	83	Radial	0,05	0,0154	3,23
4	26	1,60	49	Radial	0,05	0,0234	2,13

In the study proposed by Nabeel [11], the experiment was conducted with twenty-five adults (18 men). All volunteers were young and healthy (age = 24.5 ± 4 years), with body mass index = 23.6 ± 4.1 kg/m2). The experiments consisted of collecting thirty seconds of blood pulse signals acquirement in the volunteers' carotid artery, and

user's ergonomics, less obstruction to the user's movements, and shorter distance between the sensors when compared to other arterial points explored in this study.

The experiments also showed that PPG waveforms and the delay between them could be more accurately measured from one proximal arterial point and a second distal point in the same artery. Thus, the greater the distance between the proximal and distal regions, the easier and more accurate is the detection of time intervals between systolic peaks.

It is important to notice that the shorter the distance between the PPG sensors, the smaller the time intervals captured, as shown in Figure 8, and the higher the sampling frequency applied in the collection. Failure to do so may fail to estimate the time interval between critical point events with enough resolution. It happens when attempting to acquire a sample occurs within a shorter time than each acquisition occurs.

However, as this paper intends to develop a wearable acquisition system, several body regions were investigated. Thus, as shown in the results, radial and carotid acquisition was effective for the proposed study.

5. CONCLUSIONS

This work presented a prototype for the acquisition of local PTT, and local PWV variables obtained using low-cost PPG sensors, positioned in different body regions. The results were obtained by positioning the sensors in two arterial regions, which were radial and carotid.

The PPG obtained through pulsesensor® sensors allows the analysis of the entire cardiac cycle simultaneously in two regions (proximal and distal), when the sensors are positioned in an arterial section larger than 2 cm. It allows automatic identification of systolic peaks and the calculation of local PTT and local PWV.

The PTT and PWV have been frequently used to evaluate arrhythmias and especially the aging of the circulatory system. Thus, obtaining local PTT and local PWV using PPG sensors allows the estimation of these physiological variables through a more ergonomic and less obstructive system without the need for vasoconstriction using cuffs, for example.

After identifying some more favorable regions for PPG measurement, future work will focus on two tasks: i) development of wearable monitor to measure local PTT, PWV, and BP; and ii) a validation study of the proposed monitor's technology, initially, in a population without associated heart disease, with reference instruments for PTT and PWV measurements, such as Mobil-o-Graph or sphygmoCor (gold standard).

The main contributions of this study are the development of an embedded system marked by its ease of use and handling, including the possibility of incorporation into a wearable system. Additionally, the evaluation of different arterial regions for the sensors' positioning.

6. ACKNOWLEDGMENTS

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