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A Preliminary Study on Arterial Stiffness Assessment Using Photoplethysmographic Sensors [†]

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Abstract: Cardiovascular diseases represent the cause of 31% of all global deaths. Unfortunately, there are many difficulties in diagnosing them in a preventive, non-invasive and inexpensive way. However, there are important risk markers, including arterial stiffness. The current reference technique for assessing aortic stiffness is the measurement of Pulse Wave Velocity, and a commonly used mathematical model is the Moens–Korteweg equation, which relates Pulse Wave Velocity to arterial stiffness. A pair of photoplethysmographic sensors was used in this study to estimate Pulse Wave Velocity and, consequently, arterial stiffness on silicone phantom models with different geometric and mechanical properties. These models were placed in an experimental in vitro system that simulated the physiological conditions of a cardiovascular apparatus. The PPG sensors were positioned at three specific distances to determine a possible optimal distance for the estimation of arterial stiffness. The purpose of this study is to enhance the use of PPG sensors for monitoring the mechanical properties of blood vessels and, thus, to prevent potential cardiovascular pathologies.

Keywords: photoplethysmography (PPG); optical sensors; arterial stiffness; young modulus; pulse wave velocity; pulse transit time; experimental setup

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1. Introduction

Cardiovascular diseases (CVDs) are the leading cause of death worldwide, as reported by the World Health Organization, with an estimated 17.9 million deaths per year [1], affecting both developed and developing countries [2]. Among the most important risk markers of CVDs is arterial stiffness [3]. Arterial stiffness represents a physiopathological process related to aging, in which, with advancing age, the arteries undergo a process of dilation and stiffening, with important hemodynamic consequences [4]. These age-induced changes are significantly accelerated in the presence of CVDs and are themselves risk factors for both the onset and progression of cardiovascular diseases [5]. Indeed, arterial stiffness can be related to hypertension [6,7], atherosclerosis [8] and other cardiovascular conditions and, as recent studies have shown, an increase in arterial stiffness can be considered a predictor of major cardiovascular events such as heart attacks and strokes [9]. Therefore, accurate and continuous measurement of arterial stiffness is essential and should become part of the clinical routine. Most methods of measuring arterial stiffness are based on the measurement of Pulse Wave Velocity (PWV), i.e., the speed at which the pressure wave propagates along a blood vessel. PWV can be expressed as a function of the geometric and mechanical parameters of the blood vessel wall with the Moens–Korteweg equation.

In recent years, wearable devices such as smartwatches and smartbands have been increasingly used due to their ability to continuously and non-invasively monitor various physiological parameters, such as heart rate, respiratory rate and blood oxygenation [10]. The basis of these devices is photoplethysmography (PPG), a non-invasive optical technique that detects blood volumetric changes during the cardiac cycle. PPG sensors have the advantages of being extremely small, and therefore easily integrated into wearable devices to collect and process data in real time [11], and low costs, as the main components of PPG sensors are a light-emitting diode (LED) and a photodetector for the detection of the light signal.

Using an innovative approach, a pair of PPG sensors were used to estimate PWV, which is directly related to arterial stiffness, on silicone phantom models with different mechanical and geometric properties simulating different health states of blood vessels.

The aim of this study is to improve the use of PPG sensors for adequate monitoring of the mechanical properties of blood vessels, in order to prevent potential cardiovascular diseases.

2. Materials and Methods

In this study, an in vitro experimental setup, based on arterial simulators for biomedical applications present in the literature [12,13], was designed to simulate physiological conditions of the cardiovascular system. The four silicone phantom models, representing the different physiological conditions of the blood vessels (two softer models to represent healthy blood vessels, with two stiffer models for diseased blood vessels), were inserted into the circuit in order to estimate the PWV and, subsequently, the arterial stiffness, using PPG technology.

The experimental setup (Figure 1) is composed of six main components interconnected by silicone tubes and plastic connectors: a pulsatile pump (P01-48x360F; LinMot, Spreitenbach, Switzerland), a compliance chamber, an electromagnetic flowmeter (Optiflux 5300C; Krohne, Duisburg, Germany), a pressure transducer, the silicon phantom model and a fluid collector. Peripheral resistance and systemic pressure were varied using an adjustable valve placed at the outlet of the silicon model.

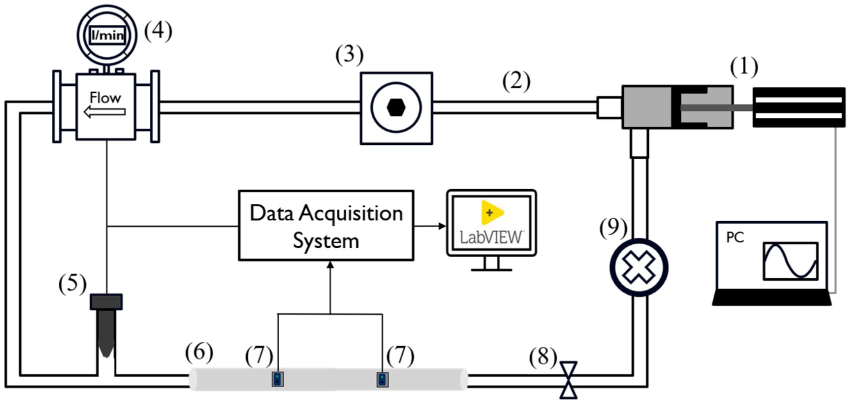

Figure 1. Experimental setup scheme. The numbers reported refer to the following components: pulsatile pump (1), silicone tubes (2), compliance chamber (3), flowmeter (4), pressure transducer (5), silicon phantom model (6), PPG sensors (7), adjustable valve (8), and fluid collector (9).

A baseline fluid dynamic condition was set using a physiologic flow waveform with systemic pressure of 120/80 mm Hg, systolic duration of 300 ms, cardiac output of 5 L/min, and heart rate of 90 beats/min. Data were collected from two PPG sensors (DFRobot, Beijing, China), using a 520 nm wavelength, and placed above the surface of the phantom models at distances of 10, 15 and 20 cm. Signals were acquired using a data acquisition board (NI USB-6009, National Instruments, Austin, TX, USA) for real-time acquisition with a 5 kHz sampling frequency and a dedicated algorithm implemented through LabVIEW software (version 2021, National Instruments, Austin, TX, USA). Post-processing was conducted using MATLAB software (version R2022b, The MathWorks Inc., Natick, MA, USA), applying a FIR bandpass filter to the raw signals.

The mathematical model used in this study to calculate the PWV is the Moens–Korteweg Equation (1):

$$PWV = \sqrt{\frac{Eh}{2r\rho}} \tag{1}$$

This equation ideally relates the PWV to the circumferential Young's modulus of the tube wall, E, the wall thickness, h, the fluid density, ρ, and the tube radius, r.

PWV also equals the ratio of the distance Δs between two recording sites to the transit time Δt of the pulse along the tube segment considered (2):

$$PWV = \frac{\Delta s}{\Delta t} \tag{2}$$

Measurement acquisitions were performed 10 times for 3 min for each experiment, for a total of 120 tests, and the experimental value obtained was compared with the Young's modulus value derived from tensile tests on the four models.

The following variables were evaluated for each test from the PPG signals: the PTT, estimated using a peak-to-peak method [14], the PWV, Young's Modulus and the pressure.

To characterize the mechanical properties and determine Young's moduli reference values of the four silicone phantom models (Table 1), uniaxial tensile tests were conducted for each model.

Table 1. Mechanical and geometrical properties of the four models and experimental Young's modulus values.

N.	Radius (mm)	Thickness (mm)	Tensile Test (MPa)	Experimental Value 10 cm (MPa)	Experimental Value 15 cm (MPa)	Experimental Value 20 cm (MPa)
1	4.30	1.30	2.10 ± 0.23	2.68 ± 0.83	2.04 ± 0.15	2.00 ± 0.19
2	7.50	1.50	2.70 ± 0.14	2.40 ± 0.72	2.63 ± 0.24	2.78 ± 0.28
3	4.00	1.00	4.00 ± 0.29	3.17 ± 0.51	4.04 ± 0.51	4.20 ± 0.58
4	8.00	2.00	5.65 ± 0.43	0.71 ± 0.65	5.74 ± 0.65	6.18 ± 0.82

3. Results

Table 1 shows the mechanical and geometrical properties of the four silicone phantom models and their experimentally obtained Young's moduli, along with the reference values derived from the tensile test. Preliminary results showed that at a sensor distance of 15 cm and 20 cm, the system provided the best performance in estimating Young's modulus, compared to the reference values obtained from the tensile test. The worst performances were obtained at a sensor distance of 10 cm.

A first observation is the increase in the standard deviation as the stiffness of the models increases.

4. Discussion

The primary objective of this study is to estimate the arterial stiffness of four silicone models, inserted into a portion of the laboratory-produced arterial flow simulator, using two PPG sensors positioned at three fixed distances. As with conventional arterial stiffness measurement methods, Young's modulus was estimated from PWV, according to the Moens–Korteweg equation.

Preliminary results showed that at a distance of 15 cm and 20 cm the system provided the best performances in estimating Young's Modulus, compared to the reference values. The results were consistent with similar studies in the literature [15]. Although some cases showed a clear percentage of error, the overall results, which are still under analysis and refinement, confirm the validity of the adopted methodology. The worst performances were found when the distance between the sensors was 10 cm, obtaining higher percentage errors than the reference values of the tensile test and higher standard deviations than the other two cases (15 cm and 20 cm).

A plausible explanation for the bad performance at the distance of 10 cm is the influence of the light reflection from the second PPG sensor on the signal of the first sensor. In this study, the Pulse Transit Time, measured for the calculation of the PWV, was estimated following the processing on Matlab using the peak-to-peak method with the findpeaks algorithm, which involves the detection of the maximum peaks of the PPG waves of the two sensors.

However, this method has limitations, and alternative approaches are foreseen in the future, such as the calculation of the PTT based on the tangent method, i.e., from the time difference between the points of maximum slope of the ascending phase of the signal [14].

Future refinements will be made to improve the system both in the setup and in the computational algorithm, and further studies could be conducted with variations in physiological conditions, such as heart rate and blood pressure, to better understand their impact on arterial stiffness measurements. Furthermore, a Monte Carlo analysis could allow us to better investigate those factors that influence arterial stiffness, such as the radius and thickness of the blood vessel.

In conclusion, PPG sensors have great potential in detecting arterial stiffness non-invasively. Further refinements in the experimental setup and in the computational algorithms will be performed to improve the accuracy and reliability of the measurements.

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