Document Version
Final published version

Citation (APA)
Bangari, R., Knop, T., Steenbergen, W., Bhattacharya, N., & Chizari, A. (2026). Influence of external contact pressure in reflection mode photoplethysmography: a multidimensional manufacturing approach. In G. Vargas (Ed.), *Design and Quality for Biomedical Technologies XIX* Article 138400A (Proceedings of SPIE; Vol. 13840). SPIE. https://doi.org/10.1117/12.3091708

Influence of external contact pressure in reflection mode photoplethysmography: a multidimensional manufacturing approach

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ABSTRACT

Background: Optical wearable sensors provide crucial information on cardiovascular biomarkers used to estimate heart rate variability, blood oxygen saturation, and arterial blood pressure. However, environmental factors, including external contact pressure, can significantly affect the quality of the acquired signal but have been poorly studied. **Objective**: In this work, we investigate the influence of external contact pressure on the photoplethysmography (PPG) signal in reflection mode. By systematic application of external contact pressure to the fingertips of volunteers, we aim to examine how such pressure affects the morphological features of a representative cardiac cycle. **Methods**: We designed, and 3D printed a mounting system to apply controlled pressure to the fingertips of volunteers. This system generated a controllable force using a spring mechanism coupled with a rotating screw. First, we quantified the spring constant and the pressure it applies per revolution. Then, using a PPG sensor operating at a wavelength of 660 ± 20 nm, we recorded raw photocurrent signals from three healthy adults. Using our proposed signal processing algorithm, we created ensemble-averaged representative cardiac cycles. **Results**: We calculated the spring's constant within the mounting system as 339.3 N/m. Using this system, we applied external contact pressure values from 20 to 180 mmHg. Our results show that the amplitude of systolic peak, dicrotic notch, and diastolic peak for this external contact pressure range continuously rise with a factor of 2.5, 5, and 2, respectively. **Conclusion**: Our 3D printed mounting system provided a reliable means of applying controlled and reproducible external contact pressure to the fingertips of adult volunteers. We conclude that such contact pressure substantially influences the amplitude of the obtained PPG photocurrent, being a crucial factor in optical wearable sensor design. **Significance**: Our findings pave the way for determining the optimal level of external contact pressure, as an environmental factor. Such optimal pressure should balance user comfort with the quality of the measured PPG signal, thereby supporting the reliable estimation of cardiovascular parameters.

Keywords: external contact pressure, signal processing, photoplethysmography, cardiac cycle, optical wearable sensors, medical sensor design, additive manufacturing.

1. INTRODUCTION

Cardiovascular diseases (CVDs) are the leading cause of mortality worldwide, responsible for an estimated 17.9 million deaths annually, which is roughly 32% of all global deaths.[1] CVD is a broad term that encompasses disorders of the heart and blood vessels, including coronary heart disease and cerebrovascular disease.[2] Monitoring vital signs such as heart rate variability, arterial blood pressure, and blood oxygen saturation (SpO_2) has been shown to aid in the early detection and prevention of CVDs.[3,4] In this context, wearable optical sensors used in both clinical evaluation and daily life play a key role.[5,6] These sensors include photoplethysmography

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Design and Quality for Biomedical Technologies XIX, edited by Gracie Vargas,
Proc. of SPIE Vol. 13840, 138400A · 2026 Published by SPIE
1605-7422 · doi: 10.1117/12.3091708

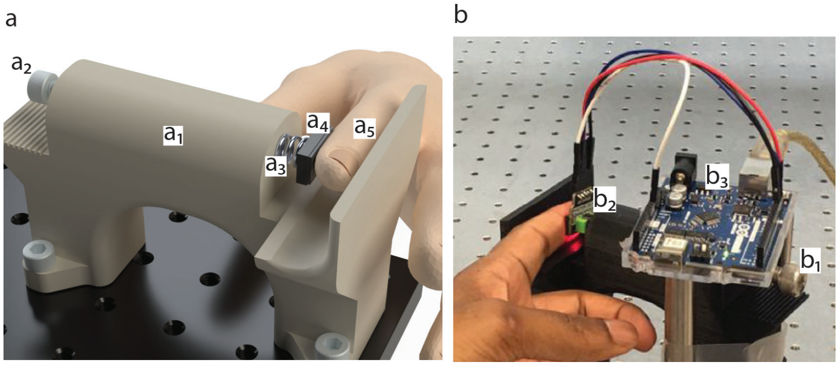

Figure 1. a: Demonstration of the envisioned final design of the 3D-printed mounting system for the systematic study of external contact pressure in reflection mode photoplethysmography (PPG). a_1: the designed mounting system; a_2, b_1: rotating screw to control the applied contact pressure; a_3, spring driven by the rotating screw; a_4, b_2: optical transceiver (i.e., PPG sensor); a_5, volunteer's finger subject to external contact pressure. b: Realization of the experimental setup using the 3D-printed mounting system. b_3: microprocessor for data acquisition from the sensor and data transfer to the work station.

(PPG) which works based on light absorption changes with blood volume during the cardiac cycle; and speckle-plethysmography (SPG) which estimates relative blood flow from light scattering fluctuations.[7,8] However, despite advances in optical wearable sensors, their robustness and reliability under varying environmental and contact conditions (e.g. external contact pressure, motion artifacts, and temperature) remain underexplored.[9,10] Improved understanding of these factors can support the design of medical optical sensors with optimal signal acquisition and accurate cardiovascular parameter estimation.

In this study, we investigate the influence of external contact pressure on photocurrent fluctuations induced by cardiac cycles in reflection-mode Photoplethysmography measured at the fingertip. To achieve this, we first introduce a mounting system that enables controlled pressure application and precise finger placement. We then characterize its rotating screw mechanism, which incorporates an embedded spring. Next, we propose a signal processing pipeline for the automatic calculation of ensemble-averaged cardiac cycles representing each measurement. Finally, we examine the relationship between morphological features of the cardiac cycles and the applied external contact pressure.

2. MATERIALS AND METHODS

2.1 Design of a mounting system for pressure application

A holder was designed in Solidworks and 3D-printed using Polylactic Acid (PLA) and featured a cylinder oriented perpendicular to a curved wall. An M6 screw (6×120 mm^2) was positioned inside the cylinder, with a spring placed around it. At the distal end of the screw–spring assembly, a MAX30101 PPG sensor (Maxim Integrated) was mounted and operated at 660 ± 20 nm wavelength of LED light source. The space between the sensor and the curved wall was designated for placement of the index finger (see Fig. 1).

2.2 Volunteer measurements

Three healthy adults participated in the study, in which raw photocurrent signals were recorded from fingertip reflection-mode measurements. Each recording took 90 seconds with a data acquisition rate of 1 kHz averaged every 14 samples with maximum LED current of 50 mA. The first 30 seconds of the recordings was not used to ensure exclusion of instabilities within the PPG signals. The applied external contact pressure range for each subject was 20 to 180 mmHg with a step size of 20 mmHg and 90 seconds of resting time between each pressure application.

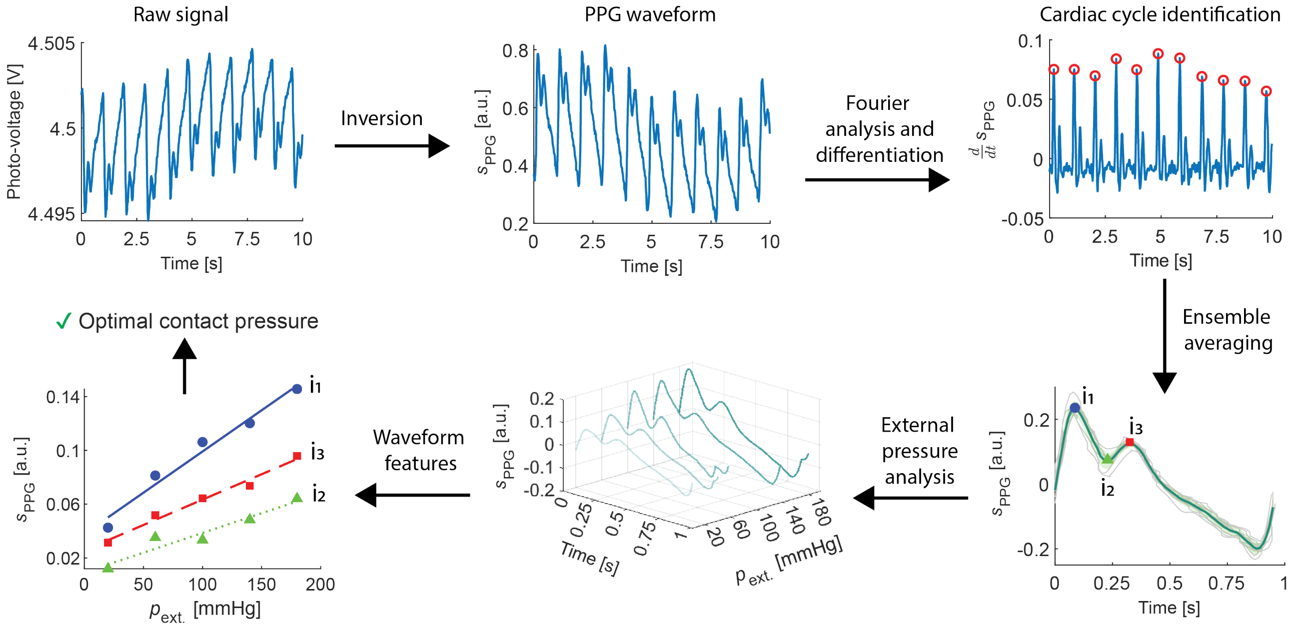

Figure 2. Data analysis procedure for study of external contact pressure in reflection mode photoplethysmography (PPG). Top left, raw photo-detector signal obtained from a fingertip measurement. Top middle, inverted raw signal (PPG waveform) demonstrating the cardiac cycles. Top right, automated detection of the onset of the cardiac cycles by DC-removal and time differentiation of the PPG waveform. Bottom right, ensemble averaging of individual cardiac cycles from a 60 seconds measurement. Bottom middle, ensemble averaged PPG signals as a function external contact pressure. Bottom left, amplitude of the marked features (i.e., systolic peak (i_1), dicrotic notch (i_2), and diastolic peak (i_3)) as a function of external contact pressure with corresponding linear fit functions.

2.3 Data processing pipeline

Prior to each recording, we adjusted the fingertip location relative to the PPG optical transceivers and ensured the detection of cardiac cycles in preview mode at zero external contact pressure. For each measurement, we recorded the temporal voltage, which was transferred to a workstation through an Arduino processing unit using an in-house code developed in MATLAB (see Fig. 2(top left)). This raw signal $V(t)$ was first DC-removed and normalized ($V_{\mathrm{norm.}}(t)$), and then converted to a PPG waveform[11] as $S_{\mathrm{PPG}}(t) = 1 - V_{\mathrm{norm.}}(t)$ (see Fig. 2(top middle)). To suppress undesirable frequency components in the signal resulting from noise and motion artifacts, a band-pass filter was applied to the PPG signal in the range of 0.5–10 Hz.[12]

For automated detection of the onset of cardiac cycles, the first-order time derivative of the filtered PPG signal was calculated. As shown in Fig. 2(top right), distinct local maxima were apparent in the resulting signal. These peaks were automatically annotated using a local peak detection function in MATLAB. Based on these annotations, individual cardiac cycles from each measurement were grouped, and a representative ensemble-averaged signal was calculated by temporal averaging (see Fig. 2(bottom right)).

3. RESULTS AND DISCUSSION

3.1 Characterization of the mounting system

To define the applied contact pressure as a function of screw revolutions, we measured the applied mass as a function of screw displacements resulted by its revolution (rotation) in a controlled experiment. We displaced the screw in 10 steps towards the contact force resulting in compression of the spring by 1.4 mm per step. We measured a mass difference of $\Delta m = 0.4$ kg at the maximum displacement of $\Delta x = 14$ mm. Thus, the total applied force was $\Delta F = \Delta m\ a = 3.9$ N assuming ($a = 9.8$ m/s^2). Thus, according the Hooke's law, the spring constant k was calculated as $\Delta F/\Delta x = 339.3$ N/m, after calculating the slope of the linear fit function

$\Delta x/\Delta m = 0.029$. We set an area of $A = 181.7$ mm^2 for the optical sensor to contact the skin. Thus, the applied external contact pressure was calculated as $\Delta P = \Delta F/A$ which equals to 11.7 mmHg per 1 mm displacement of the screw. Note that each 360° revolution of the screw resulted in its 1.2 mm displacement.

3.2 Amplitude of morphological features

A representation of the ensemble-averaged waveforms as a function of applied contact pressure is shown in Fig. 2(bottom middle). As the contact pressure increases, the morphological features within the cardiac cycles become more distinct. To quantify this observation, we selected three key points on each cardiac cycle (i.e., systolic peak, dicrotic notch, and diastolic peak) and calculated the amplitudes of these features as a function of contact pressure (see Fig. 2(bottom left)). The ratios of this increase at 180 mmHg relative to 20 mmHg were calculated as 2.5, 5, and 2 (a.u.) for the systolic peak, dicrotic notch, and diastolic peak, respectively. In addition, High linear correlations were obtained, with the goodness-of-fit (R^2) of the fitting functions being 0.97, 0.92, and 0.98 for the systolic peak, dicrotic notch, and diastolic peak, respectively. This suggests that higher contact pressure leads to higher PPG signal quality. However, increasing contact pressure can cause user discomfort and may even lead to arterial wall collapse if the applied external pressure exceeds the arterial blood pressure.[13] Arterial wall collapse occurs when the transmural pressure becomes negative, that is, when the external contact pressure exceeds the arterial blood pressure. This leads to distortion of the natural blood flow, which in turn alters the measured temporal cardiac cycles. Therefore, in practical system design, a trade-off must be made between signal quality and user comfort. In addition, in-vitro testing during normothermic machine perfusion[14] can provide insights for determining an upper bound for the contact pressure, which we plan to explore in future research.

Although a maximum external contact pressure of 300 mmHg has been explored previously,[15] we limited the pressure to 180 mmHg in this study to prevent discomfort for the volunteers, avoid potential damage to the hardware, and prevent negative transmural pressure. While an optimal contact pressure of 112 mmHg for wearable PPG has been reported in the literature,[16] this value largely depends on the wavelength of the light source used as well as the criteria applied to assess PPG signal quality. Therefore, this value should be recalculated based on the specific optical sensor being designed. The results of this study inform the design of optical wearable sensors capable of reliably estimating parameters for cardiovascular sensing applications, including those used in surgical settings.[17]

ACKNOWLEDGMENTS

This research is supported by NWO-Talent programme Veni TTW 2024 from the Dutch Research Council with the grant ID https://doi.org/10.61686/ONJFB45923.

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