Fingertip Impedance Plethysmography: A New Window Into Peripheral Blood Flow

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***Abstract*—This paper presents the first reported measurements of impedance plethysmography (IPG) signals directly from the human fingertip for the purpose of evaluating peripheral hemodynamics. The human fingertip serves as a vital non-invasive access point for cardiovascular monitoring, with photoplethysmography (PPG) widely adopted for its assessment of superficial blood flow. However, the optical sensing depth of PPG limits its capability to fully characterize deeper peripheral hemodynamics. Here, we developed a novel four-electrode fingertip IPG prototype and measurement protocol, enabling the consistent capture of pulsatile impedance waveforms reflecting blood volume changes within the digit. Preliminary data from two participants illustrates clear signal reproducibility and enables the derivation of key pulse wave metrics, including pulse arrival time (PAT). Given IPG's electrical sensing principle, distinct from PPG's optical approach, our findings suggest that fingertip IPG offers a complementary "new window" into peripheral circulation. This work establishes fingertip IPG as a significant advancement for non-invasive physiological monitoring, holding promise for both clinical applications and wearable health sensing.**

***Index Terms*—Impedance Plethysmography, Fingertip, Hemodynamics, Blood Flow, Wearables, Health Sensing**

I. Introduction

The intricate interplay of physiological processes is fundamentally linked to the dynamics of blood flow, with the vascularized extremities offering readily accessible windows into systemic health. As a highly vascularized location, the fingertip is ideal for the non-invasive monitoring of cardiovascular characteristics, exemplified by the widespread use of pulse oximetry (SpO2) in hospital settings [1]. Beyond oxygen saturation, fingertip photoplethysmography (PPG) has been instrumental in unraveling diverse hemodynamic characteristics, from heart rate to more exploratory efforts, including blood pressure [2] and vascular stiffness [3]. However, the optical nature of PPG fundamentally limits its penetration depth, primarily capturing superficial tissue perfusion [4], and thus leaving a critical gap in our understanding of deeper vascular dynamics at this highly relevant anatomical site.

Impedance plethysmography (IPG) offers an alternative approach to measure volumetric changes in a body segment by detecting subtle variations in electrical impedance. This technique has shown promise for evaluating limb blood flow [5], [6]. Recent literature has also highlighted the integration of IPG into wearable systems, demonstrating its potential for continuous and non-invasive physiological monitoring in ambulatory settings [7]–[9]. Despite these advancements, there remains a notable absence of published literature specifically describing IPG measurements from the human fingertip. While a foundational IEEE paper from 1977 [10] evaluated an electrode system for tetrapolar IPG of the finger, it did not investigate fingertip-specific sensing or provide the detailed hemodynamic signal analysis pertinent to contemporary research. Given the fingertip's rich vascularization and PPG's known sensitivity to superficial blood vessels, a fundamental question emerges: does IPG, like PPG, primarily sense superficial blood flow from the fingertip, or does its electrical sensing pathway offer access into deeper hemodynamics? Our recent work [11] measuring IPG and PPG simultaneously on the ventral forearm suggests a divergence in sensing pathways, with IPG signals remaining robust even during vasoconstrictive interventions that diminish PPG, pointing towards distinct measurement depths.

Here, we aim to address this critical knowledge gap by demonstrating the feasibility of measuring IPG signals directly from the human fingertip. Through the miniaturization and specific arrangement of IPG electrodes for this highly vascularized site, we anticipate the presence of a distinct and repeatable IPG signal. This paper presents preliminary results obtained from two participants using a custom-designed fingertip IPG prototype, highlighting the potential of this novel approach for non-invasive hemodynamic assessment.

II. METHODS

A. Prototype Design

A custom IPG prototype (Fig. 1A) was fabricated using 316L stainless steel electrodes, waterjet-cut from a steel sheet (0.79 mm thick) and adhered to an acrylic substrate (8.50 mm thick). The design incorporated integrated connection pads with 10.6 mm diameter Ag/AgCl button contacts for electrical interfacing. To control the sensing area and ensure precise electrical pathways, all non-active metal surfaces were insulated with a transparent acrylic coating. The exposed electrode surfaces were precisely defined: each electrode had an area of 15.6 mm^2, its distal edge was positioned 5 mm from the edge of the acrylic, and all electrodes were arranged within an area of 130 mm^2. The insulating properties of the coated regions were verified using a digital multimeter to confirm electrical isolation from the active electrodes prior

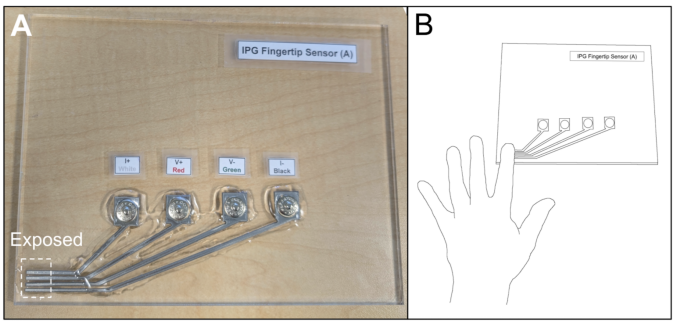

Fig. 1: Fingertip IPG prototype and finger placement. (A) Top-down photograph of the custom IPG prototype with 316L stainless steel electrodes within the exposed area, and their corresponding connection pads. (B) Illustration of left index finger placement over the exposed IPG electrodes on the device.

to experimentation. The electrical pathways between exposed electrodes and the Ag/AgCl button contacts measured $< 1\Omega$ each. The IPG fingertip prototype was secured to a height-adjustable table at a distance of 47.5 mm from the edge closest to where the participant would be seated.

B. Electrical Interface and Signal Acquisition

IPG signals were acquired using a Biopac MP36R data acquisition unit (Biopac Systems, CA, USA) coupled with the SS31L cardiac output module (100 kHz excitation frequency, excitation current = 400 μA_{rms}, continuously applied). This module was directly connected to the prototype's button contacts. Both the impedance (Z) and the first derivative (dZ/dt) were simultaneously recorded at a sampling rate of 2 kHz to capture high-fidelity pulsatile changes indicative of hemodynamic activity.

C. Experimental Protocol

This pilot study involved two healthy adult participants (N = 2; one male and one female). Each participant was comfortably seated with their elbows anchored on a stable table surface to minimize motion artifacts, and was instructed to remain relaxed and still throughout the measurement period. The distal phalanx of the participant's left index fingertip was positioned over the four electrodes of the prototype - as illustrated in Figure 1B - ensuring firm and consistent contact with all active electrode surfaces. A finger alignment guide to facilitate consistent finger placement was placed underneath the transparent acrylic substrate of the prototype.

For each participant, five replicate measurements were performed. Between each repetition, the participants briefly removed their fingertip from the electrodes, stood, sat, and then rested for two minutes before repositioning their finger. This intervention was designed to assess signal reproducibility under conditions simulating short-term natural variations in placement and physiological state. One additional IPG measurement was performed for one of the participants, which included a simultaneous acquisition of electrocardiogram (ECG) using the Biopac ECG lead module and 3M Red Dot 2670-5 gel electrodes positioned on the left shoulder, right shoulder, and right leg, forming a single-lead ECG sampled at 2 kHz. Subsequent to IPG measurements, fingertip skin hydration was measured using a Delfin MoistureMeterSC. Five measurements were taken within three minutes immediately following the final IPG and ECG acquisition. All participants provided informed consent prior to their participation in this study, which was approved by an Institutional Review Board provided by the WIRB-Copernicus Group under the protocol number 1391946.

D. Data Analysis

All data analysis was performed using custom scripts developed in Python. Signal processing of the IPG signal involved bandpass filtering (0.5 to 10 Hz, 8th-order Butterworth, zero phase shift). Since the IPG Z channel was often saturated while the dZ/dt channel remained intact, the IPG signal underwent additional processing. This included integration of the dZ/dt channel to derive a Z channel and baseline flattening using a moving average subtraction method with a window size of 2000 samples. The derived IPG Z signals underwent an additional smoothing using a median filter (kernel size = 21) before peak extraction. Onsets of beats were defined as the minima between peaks. The IPG Z peaks were detected using the HeartPy algorithm [12]. The ECG R peaks were detected using the Pan-Tompkins algorithm. The amplitude was calculated as the difference in magnitude between the onset and subsequent peak for each beat. The time difference from onset to the following peak was also calculated for timing analysis. Beats underwent aggregation and normalization (for both timing and amplitude) to visualize waveform morphology and repeatability. When calculating the amplitude and the time from onset to following peak, only beats above a signal quality index (SQI) threshold of 0.8 [13] were included.

III. Results

A. IPG Repetitions

We successfully acquired IPG signals from the human fingertip using a custom-designed prototype with miniaturized electrodes. Measurements revealed the presence of distinct pulsatile impedance waveforms across both participants (Fig. 2A). Aggregate waveforms across all five repetitions are shown for one participant (Fig. 2B), alongside the distributions of waveform IPG Z amplitudes and timings from waveform onset to peak (Fig. 2C,D). For Participant 1, the mean (SD) IPG Z amplitude was 27.9 mΩ (18.1 mΩ), and the mean (SD) time from onset to peak was 0.26 s (0.13 s). For Participant 2, these values were 315 mΩ (244 mΩ) and 0.41 s (0.20 s), respectively.

B. IPG and ECG

IPG and ECG signals were simultaneously collected from Participant 2, with a representative section of the time series data shown in Figure 3. The IPG pulse wave lagged the

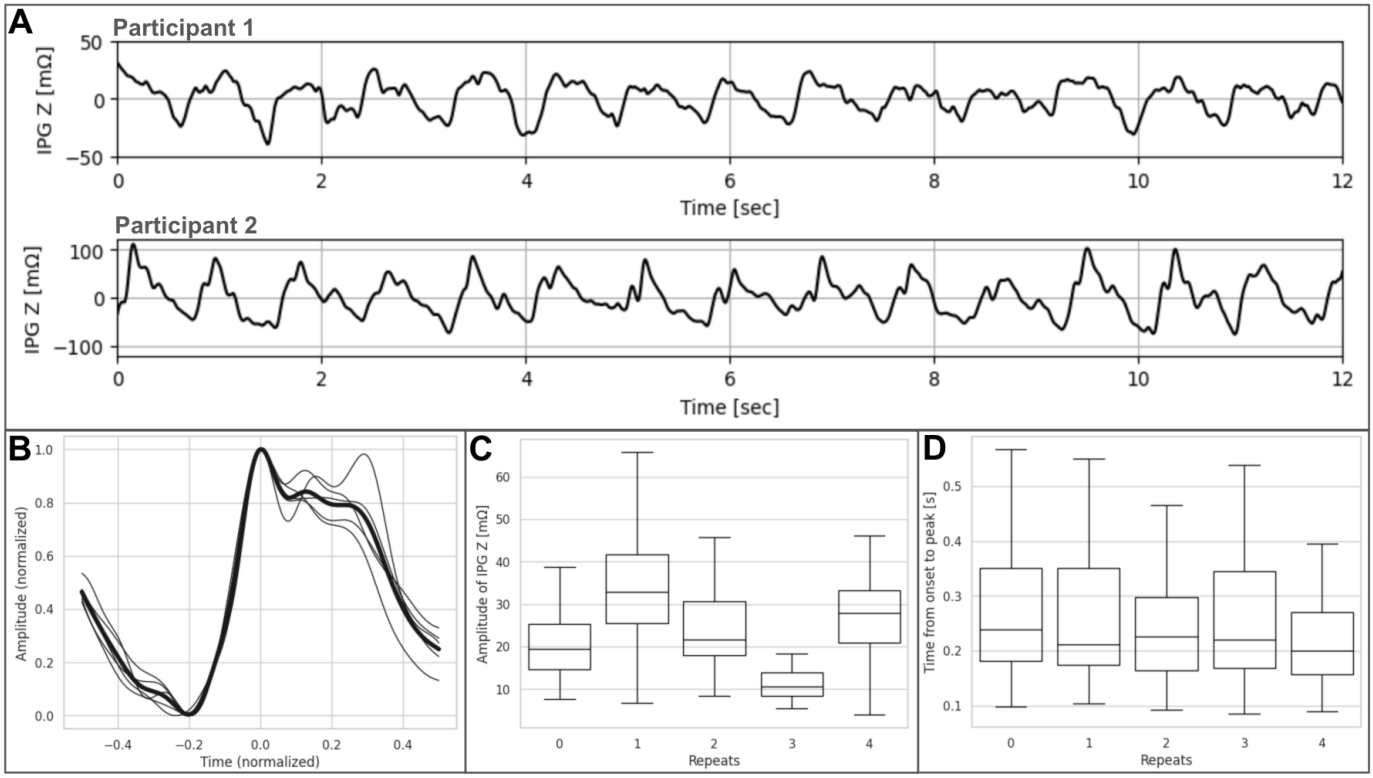

Fig. 2: Reproducibility of fingertip IPG waveforms and derived metrics. (A) Representative time-series sections of IPG waveforms measured from the left index fingertips of two participants. (B) Aggregation of normalized IPG Z waveforms for one participant across five independent collections, demonstrating signal consistency. (C) Distribution of IPG Z amplitude from the aggregated waveforms shown in (B). (D) Distribution of timings from waveform onset to peak for the aggregated waveforms shown in (B).

ECG QRS complex. Pulse wave analysis (PWA) metrics can be derived from the IPG signals when paired with ECG. Specifically, pulse arrival time (PAT) was extracted as the time difference from the ECG R peak to the IPG Z onset. Mean (SD) PAT was 0.19 s (0.035 s).

C. Moisture Meter

Fingertip skin hydration measurements were acquired from both participants. The mean (SD) moisture meter values were 138 a.u. (2.9 a.u.) for Participant 1 and 33.24 a.u. (2.2 a.u.) for Participant 2.

IV. Discussion

This study presents the first reported successful and repeatable signal acquisition of IPG signals directly from the human fingertip, a highly vascularized and clinically significant anatomical site. Our preliminary findings from two participants demonstrate early feasibility of this novel measurement approach, revealing clear and discernible pulsatile impedance waveforms that are consistent with changes in blood volume within the fingertip (Fig. 2). The observed waveform morphology aligns with established IPG principles, and is consistent with signals reported from other peripheral sites using wearable IPG devices [14], [15]. These first observations pave the way for further exploration of fingertip IPG as a

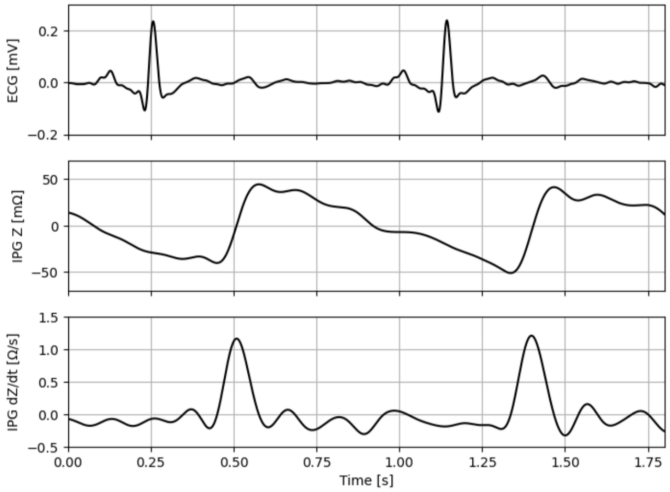

Fig. 3: Time-series section showing simultaneous ECG and fingertip IPG (Z and dZ/dt) measurement from one participant, illustrating the physiological lag of the IPG pulse wave relative to the ECG R-peak.

complementary, non-invasive tool for peripheral hemodynamic assessment.

A key observation was the variation in signal characteristics between participants. Participant 2 exhibited greater variability in IPG Z amplitude across the five replicate measurements compared to Participant 1. While the limited sample size precludes definitive conclusions, these differences prompt consideration of factors influencing signal quality. Contact impedance is a well-known critical determinant in impedance-based sensing [16], with both skin hydration and electrode-skin contact playing crucial roles in minimizing this impedance. The moisture meter readings, which report the tissue dielectric constant, indicated that Participant 2's fingertip skin was substantially drier than Participant 1's. Additionally, Participant 1 had a notably larger fingertip area. It is plausible that the interplay of these factors - potentially leading to differences in electrode-skin interfacing - contributed to the observed variance. Further investigation with a larger and more diverse participant cohort will be essential to decouple these types of influences towards establishing quantifiable relationships with fingertip IPG signal quality and reproducibility.

The simultaneous measurement of IPG and ECG signals from Participant 2, as shown in Figure 3, confirms the expected physiological lag of the IPG pulse wave relative to the ECG R-peak. This critical synchronization enables the derivation of important PWA metrics, such as PAT. Our estimate for PAT from the ECG R-peak to the IPG waveform for Participant 2 (mean of 0.19 s) falls within the expected physiological range for PAT measurements obtained from the fingertip using PPG [17]. This consistency with established methods underscores the potential for fingertip IPG to provide valuable cardiovascular timing metrics. Additionally, the utility of combining optical and impedance-based signals to probe different measurement depths has been explored in the literature [14], suggesting that fingertip IPG could offer unique insights into deeper tissue perfusion dynamics compared to the more superficial information typically captured by PPG [4]. Our recent work on the ventral forearm also indicated a divergence in sensing pathways between IPG and PPG, with IPG signals remaining robust during vasoconstriction interventions that diminished PPG, supporting this notion of distinct measurement depths [11].

A primary limitation of this pilot study is its small sample size (N = 2). While providing proof-of-concept, the generalizability of these findings is restricted. Further research must expand to a larger and more diverse participant pool to account for inter-individual variability in anatomy and physiology, including skin characteristics. A systematic investigation into the impact of factors such as skin hydration and finger size appears a logical next step for optimizing electrode design and measurement protocols. Furthermore, direct comparisons of fingertip IPG with established techniques like fingertip PPG would also be valuable.

Overall, this study introduces a significant advancement in non-invasive physiological monitoring by demonstrating the initial successful and repeatable measurement of IPG signals from the human fingertip. This foundational work supports future, larger-scale investigations into fingertip IPG's potential to complement existing techniques, offer novel insights into peripheral hemodynamics, and expand upon the capabilities of wearable physiological monitoring.

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