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A multi-channel photoplethysmography array with contact-force regulation for tonoarteriographic imaging

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Abstract

Aim: Photoplethysmography (PPG) has gained widespread popularity as a non-invasive method for potential cuff-less blood pressure (BP) measurement in smart devices. However, the accuracy of PPG-based devices is often hindered by motion artifacts, site variability, and inconsistent contact force (CF). This study aims to investigate the influence of CF variations on PPG signals.

Methods: To address these challenges, we present a novel approach involving a multi-channel PPG array integrated with CF regulation in the form of a wearable wristband. This platform enables the visualization of regional PPG/BP distribution while simultaneously monitoring CF. Moreover, our research explored the relationship between PPG waveform characteristics and CF during wrist extension.

Results: The results of this study reveal that the PPG amplitude (PPGA) and the b/a ratios, computed from the second derivative peaks of the PPG AC pulse wave, exhibit inconsistency in reaction to CF variations. Notably, a shape correlation coefficient of 0.65069 between normalized PPG and flipped CF sheds light on how changes in posture affect PPG measurements.

Conclusions: The proposed platform shows promise in mitigating the effects of CF and spatial positioning on PPG, thereby improving measurement precision and offering a novel approach to image tonoarteriographic (TAG) activities for continuous hypertension management.

Keywords: Contact force, photoplethysmography, tonoarteriographic imaging, hypertension, blood pressure

INTRODUCTION

Cuff-less blood pressure (BP) monitoring devices are increasingly recognized for their potential to revolutionize hypertension management[1]. A critical component of these devices is usually photoplethysmography (PPG) sensor because of its cost-effectiveness and user-friendliness[2,3]. However, despite the advantages offered by PPG, its application has been plagued by unexpected inaccuracies due to various factors, including intricate sensor design considerations, sensor clip pressure, photodiode sensitivity, ambient light conditions, motion artifacts, and variations in measurement sites[4-6].

Notably, recent studies have underscored the critical role of contact force (CF), defined as the pressure applied to a PPG sensor at the measurement site, in the quality and morphology of the PPG signals. Pioneering work by Teng *et al.* in 2007 demonstrated a significant correlation between CF and PPG signals, revealing an optimal or "peak" CF level, emphasizing the necessity of meticulous sensor design considerations[7]. Subsequent research by Grabovskis *et al.* showcased that insufficient contact pressure could adversely affect the alternating current (AC) PPG 2nd derivative peak ratio b/a[8]. Moreover, work by Shimazaki *et al.* unveiled the substantial role of CF in mitigating noise introduced by motion artifacts during physical activity[9]. May *et al.* further refined our understanding by pinpointing an optimal sensor contact pressure range (between 35.1 mmHg and 48.1 mmHg) for reflectance PPG signal measurements based on a specific anatomical model[10]. More recently, Irene Pi and her colleagues further demonstrated that external factors, including touch force and temperature, significantly influence resulting PPG waveforms[11].

In consideration of these findings, the influence of CF emerges as a pivotal factor in developing cuff-less BP measuring devices using PPG sensors[12]. It is also crucial to recognize that PPG signal morphology is influenced by the measurement site, which in turn affects BP estimation accuracy, a phenomenon we have corroborated in our prior research[13,14]. Recognizing the substantial influence of measurement sites on BP evaluation, we have proposed a novel approach known as tonoarteriographic (TAG) imaging system, a cost-effective, wearable, and non-invasive technique used for continuous 2D BP monitoring based on a homemade electronic-optical sensor array[14]. This system includes a wearable multi-channel signal acquisition configuration with 9 PPG sensors, visualizing PPG/BP distribution at the wrist using a multi-channel PPG array and one-lead ECG. Building upon the TAG imaging system foundation, we present an innovative watch band-type multi-channel PPG array with integrated CF regulation to substantially reduce the influence of CF. This innovative platform is designed to counter challenges such as sensor displacement during movement, variations in sensor placement, and inconsistencies in wristband tightness. Consequently, it offers the potential to investigate PPG/BP distribution across different anatomical locations, facilitating two-dimensional PPG/BP measurement while minimizing the effects of CF.

METHODS

The architecture of the multi-channel PPG array with CF regulation is illustrated in Figure 1. It comprises 9 PPG sensors and 4 ceramic piezoelectric sensors, with the PPG sensors arranged in a 3 × 3 matrix configuration to ensure optimal spacing, while the ceramic piezoelectric sensors strategically positioned to prevent any interference with the PPG sensors, thus guaranteeing uninterrupted contact with the specific measurement site. Each PPG sensor, with a 12 mm diameter, consists of a green LED (515 nm AM2520), a photodiode (APDS9008), a low-pass filter (0.05~200 Hz), and an amplifier (MCP6001, gain of *330 times). These sensors detect changes in light transmission resulting from the pulsation of blood vessels in human tissue[15]. The 12 mm diameter piezoelectric sensors convert mechanical stress or vibration into electrical charge or voltage, with a resonant frequency of 9.0 ± 1.0 KHz, resonant impedance not exceeding 500 Ω, and capacitance at 120 Hz. Integrated into an elastic wristband, these sensors establish a secure and conforming interface with the skin[16]. The structural configuration of the platform is showcased in Figure 1A, with the sensor pin information, arrangement, and data transmission workflow depicted in Figure 1B. The VDD and Ground connections were effectively amalgamated, powered by a direct current supply of 5 V. Notably, the signal output from each sensor was independently linked to a 16-channel data collection module (Biopac Systems Inc., USA) at a sampling rate of 2 KHz for subsequent analysis.

RESULTS

The prototype of the platform is delineated in Figure 2A, where the dimensions of the detection sensor are specified as 36 mm^2. Methodical testing procedures were systematically executed under static conditions to evaluate the performance and reliability of the device. During these evaluations, an elastic band was securely fastened around the wrist, ensuring the sensors were evenly positioned over both the radial and ulnar arteries, as well as their surrounding regions. This arrangement facilitated the simultaneous recording of 13 signal channels, which included 4 CF signals and 9 PPG signals, as depicted in Figure 2B. The results indicate variations in the morphologies of CF and PPG signals, which can be attributed to differences in the measurement sites.

To further validate the correlation between PPG characteristics and CF, specifically the PPG amplitude (PPGA) and b/a ratios, we conducted wrist extension experiments. These experiments involved deliberate changes in wrist position to induce variations in CF. Throughout the experiments, we observed a remarkable consistency in the trends and amplitudes across the 9 channels of PPG and the 4 channels of CF signals. For enhanced clarity and precision in representation, we opted to compute the averages of the 9 channels of PPG signals and the 4 channels of CF signals separately. The resulting plots display the average PPG (Avg_PPG) and CF signals (Avg_CF) in Figure 3 To refine the waveforms and minimize noise, a fourth-order low-pass Butterworth filter with cutoff frequencies set at 0.5 was meticulously applied to the digitized PPG (FAvg_PPG) and CF (FAvg_CF) signals, as detailed in Figure 3. This figure demonstrates how CF varies across different anatomical sites, profoundly affecting the morphology of PPG waveforms. Notably, the experiments revealed a clear shape similarity between the changing PPG and CF signals during various observed intervals.

From the analysis of Figure 3, an apparent inconsistency in CFs is observed for identical wrist postures during the wrist extension experiments. This inconsistency can be attributed to challenges in precisely controlling the speed and magnitude of wrist flexion. Notably, calculations of PPGA at various stages revealed inconsistency in PPGA levels during CF regulation, as shown in Figure 4A. This inconsistency suggests that PPGA is influenced by CF variations, and despite adjustments in wrist posture, CF remained inconsistent, resulting in varying PPGA magnitudes. This phenomenon aligns with the observations of Sim *et al.*[17]. To delve further into this observation, we selected five periods of PPG signals to compute the b/a

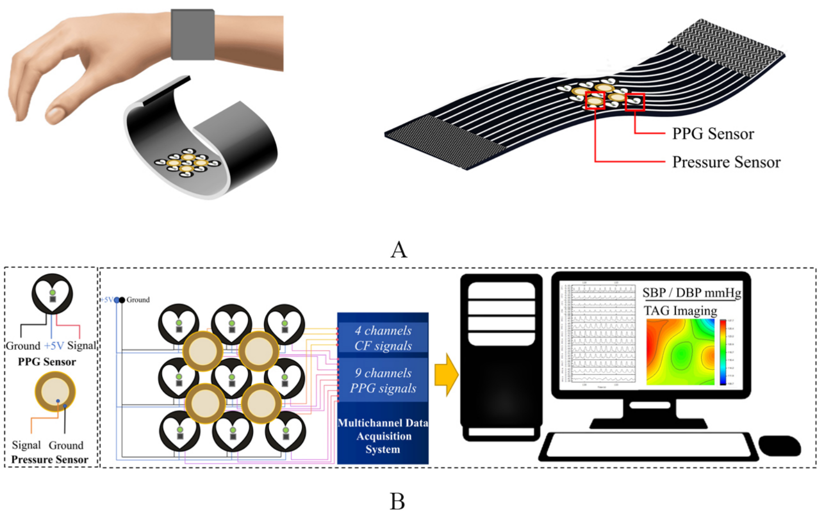

Figure 1. Architecture of the multi-channel PPG array with CF regulation. (A) Structural configuration; and (B) sensor pin information, arrangement, and data transmission workflow. PPG: photoplethysmography; CF: contact force.

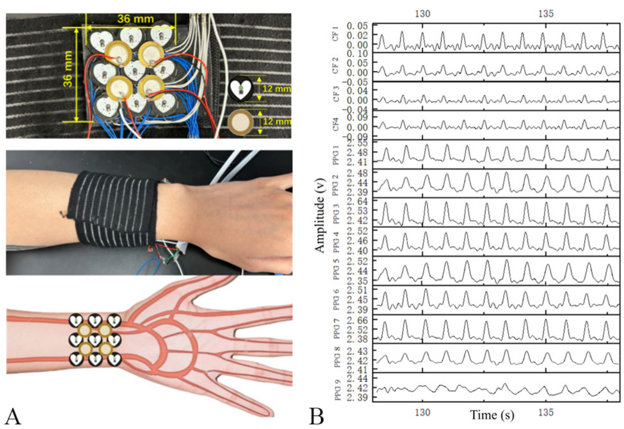

Figure 2. Experimental setup and signal visualization. (A) Prototype of the platform; and (A) visualization of the signals from 13 channels.

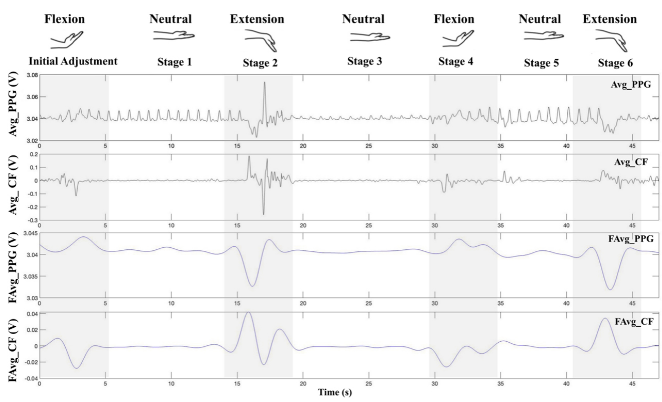

Figure 3. Examining the correlation between PPG waveform characteristics and CF via wrist extension experiments. PPG: photoplethysmography; CF: contact force.

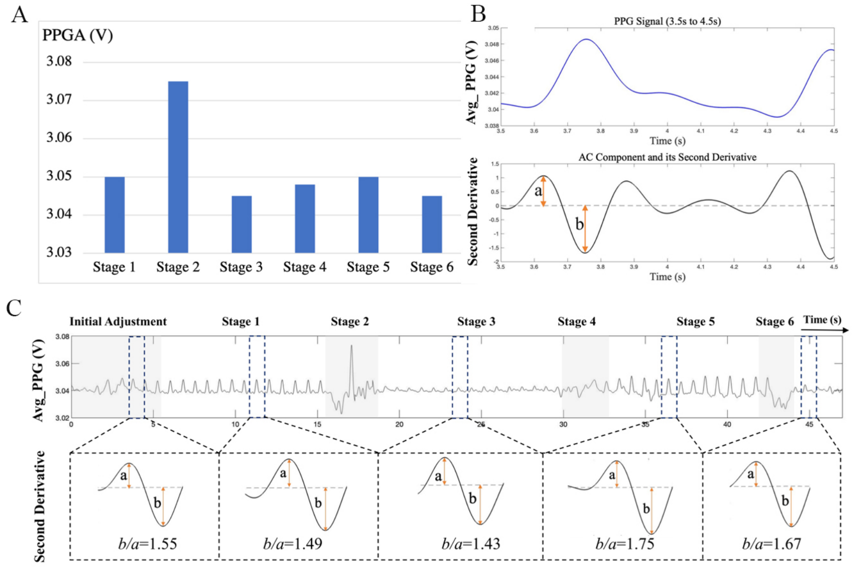

Figure 4. Correlation and inconsistency analysis of CF, PPGA, and b/a ratios in wrist extension experiments. (A) PPGA visualization; (B) 3.5-4.5 s interval for b/a ratio calculation; and (C) segmented time intervals (3.5-4.5 s, 11-12 s, 23-24 s, 36-37 s, 44.5-45.5 s) for b/a ratios calculation. PPG: photoplethysmography; CF: contact force; PPGA: PPG amplitude; AC: Alternating current.

ratios, derived from the PPG AC pulse wave 2nd derivative peaks following wrist extension recovery. These intervals include 3.5-4.5 s, 11-12 s, 23-24 s, 36-37 s, and 44.5-45.5 s. Taking the b/a calculation at 3.5-4.5 s as an example, illustrated in Figure 4B, we observed inconsistency in the b/a ratio under CF variations, as depicted in Figure 4C. This finding aligns with the work of Grabovskis *et al.*[8], who reported strong inconsistency in arterial stiffness (AS) estimates derived from the PPG pulse wave 2nd derivative parameter b/a when recorded under nonoptimal probe contact pressure (CP).

In addition to examining PPG waveform parameters, we explored the shape correlation coefficient between the PPG and CF signals. To ensure consistency in subsequent analyses, we inverted the filtered CF signal. This inversion aligned the waveform direction of the CF signal with the PPG signal. Subsequently, we normalized both the filtered PPG and the inverted CF signals, thereby establishing a foundation for precise correlation analysis, as illustrated in Figure 5. The computed shape correlation coefficient, standing at 0.65069, underscored a significant association between the normalized PPG and CF signals, thus illuminating their interdependence. Moreover, the variability observed in CF for identical wrist postures during the experiment is attributable to the inherent challenges associated with precisely controlling the speed and extent of wrist flexion. The complexity of maintaining exact control results in waveform variations. It is crucial to emphasize that, notwithstanding these fluctuations, the overall trend remains consistent. This consistency reinforces the potential correlation between the characteristics of the PPG waveform and the intensity of the applied CF, a relationship substantiated by insights derived from prior studies[18,19].

CONCLUSION

In summary, the results of our research demonstrate the variability in local PPG measurements across different sites, which potentially influences the accuracy of PPG-based BP estimation. Notably, we observed inconsistencies in PPGA levels and b/a ratios during the regulation of CF, highlighting the sensitivity of PPG to variations in contact conditions. Given the critical nature of PPGA and the b/a ratio as features significantly contributing to BP estimation, especially in frequency domain and statistical features[5], the

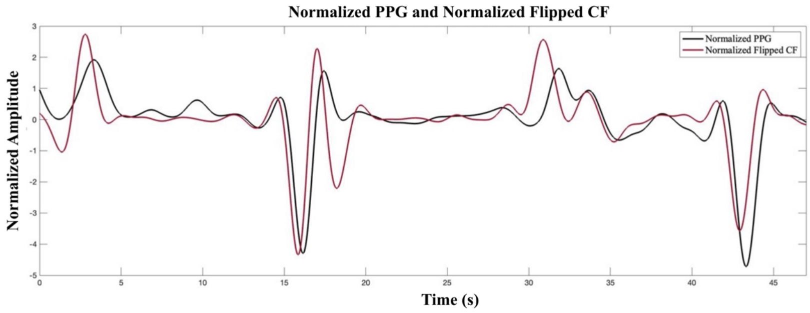

Figure 5. Correlation analysis between normalized PPG and CF signals. PPG: photoplethysmography; CF: contact force.

incorporation of CF is crucial in BP measurement. Careful control of this force is essential to ensure the acquisition of high-quality clinical data from the signals[20]. Furthermore, our findings reveal a correlation between changes in CF and concurrent variations in the PPG waveform at different locations. The integration of CF regulation into a multi-channel PPG system holds promise for enhanced precision and reliability in BP estimation, providing valuable insights into TAG imaging and its interaction with external forces.

However, the limitations of our study must be acknowledged. Our analysis was focused on a specific context, and further research is required to validate the findings in diverse populations and clinical settings on a bigger database. Additionally, the observed correlation between PPG waveforms and CF does not imply causation, necessitating further research to unravel the underlying physical or physiological mechanisms. Our study contributes to the growing body of knowledge about the significance of CF in PPG technologies and suggests that incorporating CF regulation could enhance the utility of these PPG-based systems for cardiovascular care. Future research should aim to explore the clinical ramifications, refine the technology, and evaluate its potential in enhancing patient outcomes.

DECLARATIONS

Authors' contributions

Made a substantial contribution to the conception and writing of the manuscript: Liu ZJ
Contributed to the manuscript's editing: Xiang T, Zhou RS, Ji N, Zhang YT
Approved the final manuscript for submission: Liu ZJ, Xiang T, Zhou RS, Ji N, Zhang YT

Availability of data and materials

Not applicable.

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Conflicts of interest

Yuanting Zhang is the Editor-in-Chief of the journal *CHATmed*; Nan Ji is an Academic Assistant Editor of the journal *CHATmed*. The other authors declare that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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