Beat-Wise Effect of Heart-Paced Walking on In-Ear Photoplethysmography

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Abstract

Wearable technologies enable continuous, non-invasive monitoring of cardiovascular health, promising for tracking dynamic responses during exercise. Photoplethysmography (PPG) is a simple and cost-effective sensing modality, but its accuracy during movement remains a challenge. This study investigates motion-induced hemodynamic effects on in-ear PPG pulse wave morphology during heart-paced walking. We hypothesize that motion artifacts partly arise from physiological effects induced by body motion, such as blood inertia and wave reflections. The 12 healthy participants (6 female, 28±2 years) walked on a treadmill, guided by auditory signals to synchronize their steps to either systole (R-wave) or diastole (45% RR interval) of the cardiac cycle, while recording in-ear PPG, electrocardiogram and chest acceleration. PPG pulse wave amplitude and morphology varied significantly during heart-paced walking. Diastolic stepping resulted in a consistent morphology downward deflection after 50% RR interval, while systolic stepping yielded a 0.06 V higher peak-to-peak amplitude (Cohen's d=1.08). Our findings highlight the potential of in-ear PPG to capture physiological changes during dynamic conditions and raises questions about pulse wave morphology in the periphery during walking. Further studies are needed on extracting motion-induced hemodynamics in less controlled conditions.

1. Introduction

Wearable hemodynamic sensors have the potential for continuous and non-invasive monitoring of vital signs, offering effective cardiovascular health tracking and facilitating timely interventions in patients with hypertension and heart failure. The current home-based assessment of clinically relevant hemodynamics is based on scale-based weighing and cuff-based blood pressure. None of these methods allow hemodynamic monitoring during daily life or physical activity, a missed opportunity considering that exercise capacity is a prognostic risk factor and, in the case of heart failure, is the cardinal symptom and marker of disease severity. A versatile alternative are wearable hemodynamics-based sensors, as they can be deployed at any body locations where blood vessels touch the surface such as the ear, head, finger, wrist, and leg enabling embodiments suitable to the older population with high prevalence of cardiovascular disease.

Today, wearable hemodynamic monitors provide reliable heart rate (HR) estimates. At the same time, the indirect measurement principle of tonometry and photoplethysmography (PPG) challenges their ability to accurately estimate blood flow and pressure [1]. Here we focus on PPG-based measurement, which is a simple and inexpensive optical measurement method widely used to monitor the pulse wave in the peripheral circulation [2], indicative of blood flow. A particularly stable placement for pulse wave measurement is the ear, given the recent success of lifestyle wearables such as headphones. The ear offers multiple viable locations for PPG measurement due to its rich vascularization. In-ear PPG is commonly acquired in the ear canal, which has a good sensor-skin contact, shielding from ambient light and reduced motion artifact when compared to other body location [3]. However, even under these promising conditions, reliable PPG pulse wave measurement during movement has proven extremely challenging.

Ear-based PPG is highly susceptible to motion and facial artifacts [4]. However, because of difficulties to measure invasively, we know very little about physiologically expected cerebral blood flow and pressure during walking. We hypothesize that in-ear PPG pulse wave is affected by motion-induced hemodynamic effects such as blood inertia and wave reflections. We hereby distinguish between motion artifacts due to measurement challenges and actual motion-induced hemodynamic effects to the pulse wave from walking. Consequently, the 'real' pulse waveform might include not only a cardiac, but also a motion-induced component resulting in altered morphology to the commonly known resting PPG waveforms. The aim of this study is to systematically quantify the beat-wise motion-

induced effects on the PPG pulse wave measured in the ear during heart-paced walking.

2. Methods

2.1. Measurement set-up

The in-ear PPG signal is acquired with a custom-made device, placed inside the ear, with the sensitive side facing the tragus and kept in place with soft silicon ear-plugs. We used a reflective optical sensor (TCRT1010, Vishay, USA), with an infrared emitter at 950 nm and a phototransistor. A resistor of 150 Ω is positioned between the anode and the power supply and a 5 kΩ resistor between the collector and the power supply. The conditioning circuit consists of an inverting band-pass filter, with cutting frequencies F_{c1} = 1.45 Hz, and F_{c2} = 18.56 Hz, with gain G=78 (MCP6002, Microchip Technology, USA). The circuit has been secured on a pair of over-ear headphones, wore during the experiment.

We acquired simultaneous (Cometa Srl., Italy) electrocardiogram (ECG) and the electromyogram (EMG) from a chest sensor, equipped with inertial measurement units (IMU). All data and the PPG amplified signal were wirelessly transmitted for acquisition at 2 kHz.

2.2. Experimental protocol

Twelve healthy subjects participated in the study (6 female, 28±2 years). Ethical approval for the study was obtained from the Swedish authorities (2023-00426-01), and all participants provided written informed consent. To guide heart paced walking, participants wore a chest strap (Pulson, USA) equipped with ECG and IMU sensors. The device played auditory tones timed to coincide with the R wave (systole) or at 45% of the R-R interval (diastole) were generated and played.

The experimental protocol consisted of a resting period (seated and standing) followed by treadmill walking. For the walking phase, subjects walked on a treadmill for a total of 15 minutes. The initial 3 minutes served as a warm-up, followed by two 3-minute bouts each of systolic and diastolic stepping, totaling 12 minutes of heart-paced walking. Subjects were instructed to look straight and keep their head still.

2.3. Data processing

The main intention of the data processing pipeline was to identify beats with maximum similarity both in terms of phase between the step and the heart beat, but also with minimal movement artifacts. The following steps were followed: 1) identification of phase between stepping and heart beat (diastolic, systolic), 2) rule-based exclusion of any non-physiological beats, 3) cross-correlation. The data were processed using custom code in MATLAB R2024b (The MathWorks, Natick, MA).

Pre-processing: Pulse wave and ECG signals were digitally filtered with band-pass between 0.5-7 Hz (pulse wave) and 0.5-50 Hz (ECG). R-peaks in the ECG have been identified using the Pan-Tompkins algorithm [5]. As a movement signal, the vertical chest acceleration was used. **Pulse-wave analysis:** Pulse-wave signals were normalized over the RR-interval and interpolated to 200 evenly spaced points. The mean waveform was computed by point-by-point averaging the selected waveforms point by point. For each individual waveform, the minimum, maximum, and peak-to-peak pulse wave amplitude were extracted. **Phase identification:** Step timing is defined as the time instant in which the acceleration crosses 1 g on a positive axis [6]. To determine the step timing relative to the cardiac cycle, the phase was calculated as the percentage of the RR interval at which each step occurred. Steps occurring at 0% ±15% of the RR interval were classified as systolic stepping, while those at 45% ±15% were classified as diastolic stepping. **Rule-based beat exclusion:** Each pulse waveform has been extracted from the signal with a window starting from the R-peak to the next R-peak. As an initial step to filter out non-physiological artifacts, only waveforms with an onset temporally close to the R-peak and a consistent systolic upstroke were selected (rules-based method). **Cross-correlation:** In the final step, pairwise cross-correlation was used to extract the 10 most similar pulse waveforms per participant and phase based on their correlation score. **Convergence:** We report the reduction in beat-wise variability by computing the standard deviation across the waveforms for all participants. **Statistical analysis:** Peak to peak amplitude differences in resting sitting, resting standing, diastolic and systolic stepping were investigated with a linear mixed-effects model controlling for baseline inter-subject variability and varying heart-rate. Effect size has been estimated with Cohen's d coefficient. Results were considered statistically significant at $P \leq 0.05$. Mean and standard deviation (STD) were calculated for all parameters of interest.

3. Results

All subjects completed the experiment and a total of 11'888 beats was acquired during heart-paced walking. Convergence analysis showed a significant decrease in STD over the pulse waveform after each filtering step, Figure 1.

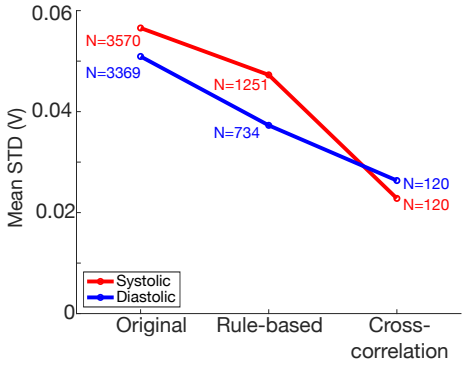

Figure 1. Convergence of similarity across pulse waveforms. N=total number of waveforms at each step.

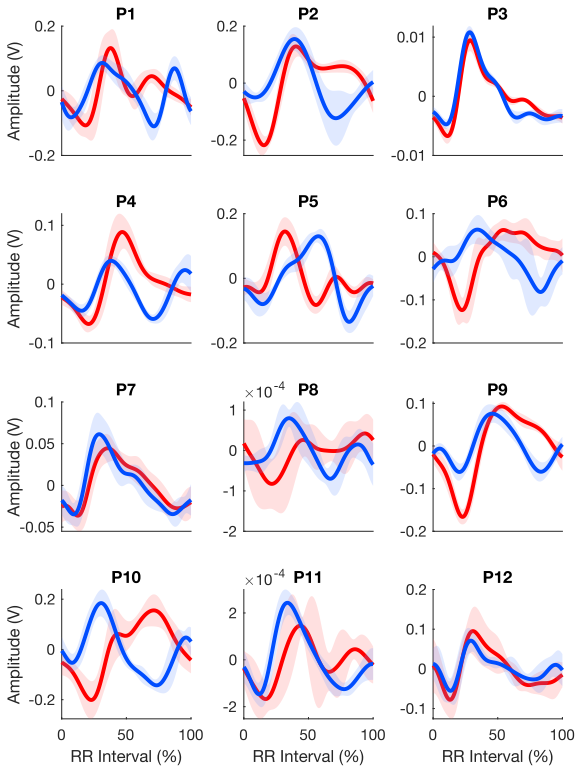

Figure 2. Pulse waveforms (mean, STD) during diastolic and systolic stepping (N=10). Diastolic stepping: 45% ±15%, systolic stepping: 0% ±15% of the RR interval.

Figure 2 illustrates the mean pulse waveforms during systolic and diastolic stepping. The degree of variability across subjects, indicated by the STD, reflects differing levels of morphological consistency. For most subjects, the STD remains stable throughout the waveform; however, subjects P8 and P11 exhibit increased variability, particularly during systolic stepping. Diastolic stepping is characterized by a consistent downward deflection occurring after the midpoint of the cardiac cycle (50% of the RR interval) in the majority of subjects (P1, P2, P4, P6, P8, P10, P11).

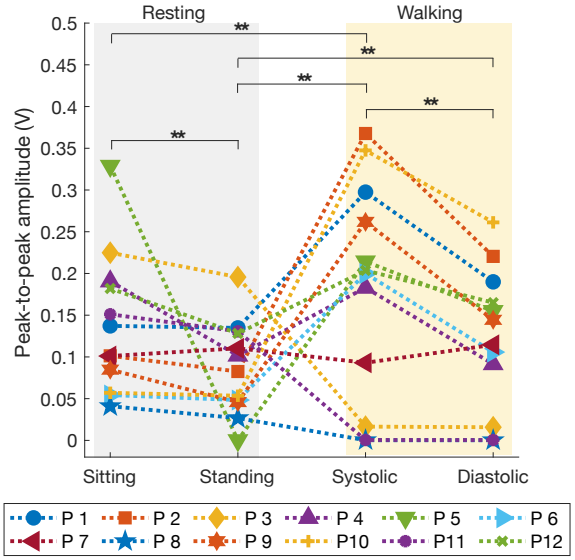

Figure 3. Mean pulse wave peak-to-peak amplitude during resting vs. walking, comparisons among all conditions. **: $p \leq 0.01$

Pulse wave amplitude varies across conditions and with the RR interval, as shown in Figure 3. Standing results in a mean decrease of 0.02V in amplitude compared to sitting, while systolic stepping leads to a significant increase of 0.07V ($p \leq 0.01$). Diastolic stepping shows a smaller, non-significant increase of 0.02V compared to sitting. Amplitude is positively associated with RR interval, with an average increase of 0.12V per unit increase in RR. Comparing stepping phases, diastolic stepping results in a significantly lower amplitude than systolic stepping by 0.06V on average ($p \leq 0.01$, d=1.08), with no significant interaction with RR interval. Notably, resting while standing results in the lowest amplitude across all conditions ($p \leq 0.01$). The amplitude trend is consistent across all subjects, except for P3, P7, P8, and P11, who exhibit an inverse pattern when comparing standing and walking.

4. Discussion

In this study, we present a systematic beat-wise quantification of motion-induced hemodynamics effect on the PPG pulse wave measured in the ear during heart-paced walking. Our results show that walking alters peripheral pulse wave morphology, particularly during diastolic stepping, where a bi-phasic waveform is notable. Peak-to-peak pulse wave amplitude is significantly lower during diastolic stepping compared to systolic stepping with a large effect size.

Motion artifacts in PPG signals have been widely investigated because they constitute a major limitation for

application in clinically important settings such as exercise. For this reason, many groups have explored methods to remove motion artifacts, both motion-induced hemodynamics and measurement noise, using advanced signal processing and accelerometers as references to isolate cardiac signals [7, 8]. However, this is the first study to explore to what extent pulse waveform changes originate from the dynamics of the cardiovascular system rather than sensor-based measurement artifacts. Our results show that in-ear hemodynamics are modulated by motion, which raises questions around both the physiological implications of this effect, but also appropriate PPG signal processing approaches. How should we clinically interpret peripherally measured hemodynamic waveform during exercise?

Heart-paced walking offers the unique opportunity to quantify the contribution of motion to in-ear hemodynamics and isolate it from cardiac contributions, if collected in a highly time-synchronized manner. The 1:1 ratio allows for phase binning and averaging of a substantial quantity of similar beats. We showed that walking affects pulse wave amplitude to a different extent, depending on where the stepping falls within the cardiac cycle. The tightly controlled experimental conditions result in high confidence in our results. In this way, our results inform the understanding of motion-related influences on the PPG signal providing insights which go significantly beyond prior studies. Recent work has provided a comprehensive datasets for studying facial motion artifacts and expressions [4], but studies involving walking often lack controlled, repeatable movement. In the future, our data set may inform signal processing algorithms for analysis of in-ear PPG measurements. However, disentangling the hemodynamic effects induced by motion from measurement related movement artifacts remains a significant challenge.

In order to isolate motion-induced signals from measurement artifacts, we selected only the most similar beats for analysis, based on the assumption that motion modulates beat-to-beat waveform shape. In this way, we might be ignoring transient effects. Hardware issues may explain the unexpected decrease in amplitude from rest to exercise observed in subjects P3, P7, P8, and P11. Further studies are needed to extend these findings to uncontrolled walking settings and understand the clinical implications.

5. Conclusions

Motion-induced hemodynamic effects are present in beat-wise in-ear PPG during heart-paced walking, resulting in a bi-phasic waveform and reduced peak-to-peak amplitude during diastolic compared to systolic stepping.

Acknowledgments

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