

# In-Ear Pulse Wave Amplitude Recordings During Synchronized Walking

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## Abstract

One way to improve hemodynamic efficiency is the synchronization of the stepping with the diastolic phase of the cardiac cycle (diastolic stepping) minimizing peak pressures on the heart level. At head level, we expect maximized blood flow in diastolic stepping and minimized blood flow in systolic stepping. This study aims to verify suggested blood flow patterns via analysis of the pulse wave (PW) amplitudes in the ear during synchronized walking. Four participants (2 men, 2 women,  $27 \pm 3$  years) walked on a treadmill at a comfortable speed, guided by auditory signals (Pulson, USA) to perform diastolic and systolic stepping. PW amplitudes were continuously measured in the ear using an optosensor (TCRT1000, Vishay, USA) and compared to heart rate (HR) from an ECG chest strap (Movesense, Finland). Results showed that the PW amplitude increased by  $20 \pm 16\%$  across all subjects during diastolic stepping compared to systolic stepping, with lower HRs detected from the optosensor ( $0.73 \pm 1.4$  beats/min) than from the ECG. The findings suggest that synchronized walking modulates PW amplitude during diastolic stepping with different extent across subjects. A more stable sensor configuration should be considered in the future to increase signal robustness. Further studies will investigate the observed tendencies in more subjects to understand patient-specific variability.

## 1. Introduction

Sufficient blood supply is essential for maintaining optimal perfusion throughout the body, especially during endurance sports and in individuals with impaired heart function. During routine daily activities, such as locomotion, hemodynamics is directly influenced by heart's pumping action, which delivers blood to contracting muscles, and by the skeletal muscle pump, which, in turn, enhances venous return to the heart [1]. Synchronization is defined as a 1:1 ratio between the heart and gait cycle [2], with steps aligning to specific phases of the cardiac cycle. Diastolic stepping refers to a step synchronized with cardiac relaxation, while systolic stepping corresponds to a step

occurring during cardiac contraction. Diastolic stepping has been shown effective in promoting lower leg muscle perfusion [3] and enhancing cardiac output [4], while systolic stepping has been associated with increased heart rate (HR) at constant work load [5]. Synchronized walking has also been shown to modulate arterial pulse pressure at the heart level, with high pulse pressure occurring during systolic stepping, and low pulse pressure resulting during diastolic stepping [6].

If muscle perfusion and central arterial pressure enclose locomotor information, we could expect an influence on cerebral perfusion as well. However, the effects of synchronized walking on perfusion at the head level remain unknown, as does the potential clinical significance of such effects. Given the opposing directions of blood flow toward the limbs versus the brain, we hypothesize that synchronized walking may have opposite effects on pulse wave (PW) amplitude in these regions, as shown in Figure 1. Specifically, we expect an increase in PW amplitude during diastolic stepping at the head level.

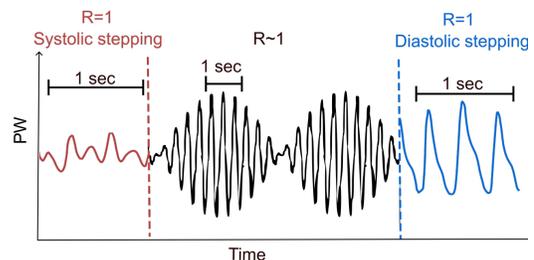


Figure 1. Hypothesis of hemodynamic modulation at head level during synchronized walking, adapted from [6]. R=1 meaning heart cycle and gait cycle being synchronized.

As there is currently no evidence of walking-related flow modulation at head level, the objectives of this study are to:

1. Design and validate a PPG-based in-ear device for blood flow measurement;
2. Investigate blood flow variations in the ear during diastolic vs. systolic stepping.

## 2. Methods

### 2.1. Device

A custom-made device has been designed to acquire and process the PW time series. The sensitive part of the device is a reflective optical sensor (TCRT1010, Vishay, USA). This sensor is made of an infrared emitter at 950 nm and a phototransistor. Its compact dimensions (LxWxH in mm:7x4x2.5) make it ideal for integration into small design, such as an in-ear application. A resistor of 180  $\Omega$  has been positioned at the anode and a 6.8 k $\Omega$  resistor at the collector to limit the inflow current from the power supply. The conditioning circuit includes high pass filtering with cutoff frequency  $C_f = 0.23$  Hz, differential amplification (AD623AN, Analog Devices, USA) and low pass filtering with cutoff frequency  $C_f = 2.3$  Hz. The signal has been sampled at 100 Hz (GD32VF103, GigaDevice, China) and sent to a laptop via universal asynchronous receiver-transmitter (UART) communication. The microcontroller also provided the single power supply 0-3.3 V to all the electronic components. A custom graphical user interface (GUI) has been programmed in Python (v3.10.9, USA) to real-time plot the data and store them to a text file.

### 2.2. Experimental design

Four healthy subjects (2 male and 2 female, 27 $\pm$ 3 years) with no history of cardiovascular diseases participated in the study. All participants wore a chest strap (Pulson, USA) enabling auditory step synchronization, equipped with a sensor to monitor HR via electrocardiogram (ECG) and foot strike via accelerometry. The data were wirelessly transmitted in real-time to a tablet (Apple iPad, Cupertino, CA) and pre-processed with proprietary software (Pulson, USA). The software generated auditory tones timed to coincide with the 25% of the R-R interval (ventricular systole) or at 45% of the R-R interval (diastole). These tones were played to the participants through a loudspeaker. To validate the in-ear measurement, participants wore a chest strap (Movesense, Finland) to record time-series ECG at 125Hz. The optosensor was positioned on the tragus, which has previously shown the least variability compared to the back of the ear and the concha [7]. The experimental protocol included a first 2 minutes warm up walk on a treadmill, then diastolic stepping (5 min), constant stepping (5 min, placebo) and systolic stepping (5 min) on a treadmill with constant speed and inclination through the whole experiment. The placebo consist of synchronization to their own step rate (SR) and they were blind to the protocol for the entire duration of the experiment.

### 2.3. Data processing

The data were processed using custom code in MATLAB R2022a (The MathWorks, Natick, MA).

#### 2.3.1. Heart rate validation

To validate the PW measurements, we compared the HR detected from the chest strap to the HR computed from the PW. The two signals were first digitally filtered between 0.4-10 Hz (PW) and 0.1-40 Hz (ECG). The HR was computed through R-peaks detection (Pan Tompkins [8]) in the ECG and onset detection in the PW. The ECG was manually time-aligned to match the HR variations of the two HR series and cut to fit the length of the PW recording. In order to find a threshold for acceptable vs. non acceptable signal quality, we performed linear regression between the two HR series of subject 1 (S1) and found a good agreement ( $r^2=0.85$ ), while Bland-Altman analysis revealed a confidence interval of  $\pm 5.2$  bpm. This confidence interval for beat-to-beat agreement between the two HR series within this confidence interval was classified as acceptable signal.

#### 2.3.2. Pulse wave analysis

The proprietary software automatically computes the phase between heart cycle and gait cycle. The software computed phase was used to extract a set of consecutive waves in the dataset that corresponds to diastolic stepping (delay between R-peak and stepping in the range 35-55% of the R-R interval) and systolic stepping (delay between R-peak and stepping in the range 0-20% of the R-R interval). The set with longest number of consecutive waves for each subject was used for amplitude calculations. Pulse wave shape homogeneity was visually assessed by segmenting each wave with a fixed-length window and overlapping them using the PW onset as reference point. The amplitude was instead calculated as the peak-to-peak difference between the systolic peak and PW onset.

## 3. Results

Demographic and physiologic data from subjects are presented in Table 1.

Table 1. Demographic characteristics of the participants, starting HR (beats/min). HR: Heart rate.

Subject	Age	Gender	Starting HR
S1	27	Male	75
S2	23	Female	80
S3	28	Male	100
S4	32	Female	90

### 3.1. Heart rate validation

Heart rate validation resulted in the following signal quality observations: S1 had 95% of acceptable signal, Figure 2, S2 had 64%, S3 had 82%, and S4 had 71% over each whole recording. The HR measured from the in-ear sensor was  $0.73 \pm 1.4$  beats/min lower than the HR obtained from the chest strap ECG, suggesting that some beats were missed by the PW sensor due to signal quality issues.

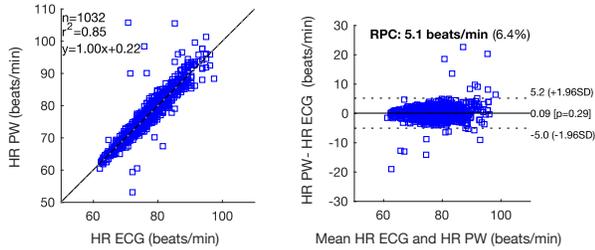


Figure 2. Regression analysis and Bland Altman plot, S1.

### 3.2. Pulse wave analysis

The PW amplitude results modulated by the walking pattern, showing a periodic alternation of high and low pulse pressure, as presented in Figure 3. This pattern suggests a varying phase between locomotor and cardiac contributions and therefore inadequate rate synchronization (see Figure 1,  $R \approx 1$ ).

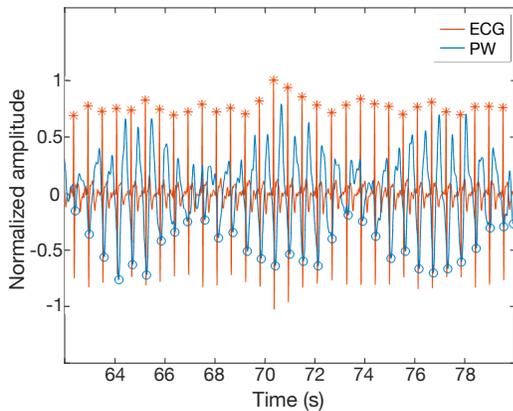


Figure 3. PW modulation during synchronized walking, S2. PW:Pulse Wave

An example of PW shape homogeneity is shown in Figure 4. The PW shapes shows that there is some inter-subject variability. The onset and the front overlap suggests good repeatability.

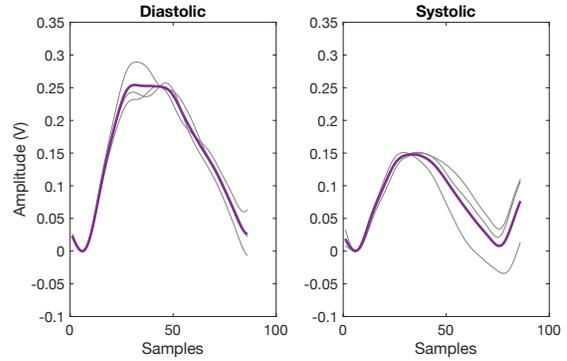


Figure 4. PW in diastolic vs. systolic stepping, S1. PW:pulse wave.

The amplitude variation for each subject is presented in Figure 5. The PW amplitude was found to be  $20 \pm 16\%$  greater during diastolic stepping compared to systolic stepping across all subjects, indicating greater cerebral blood flow during diastolic stepping.

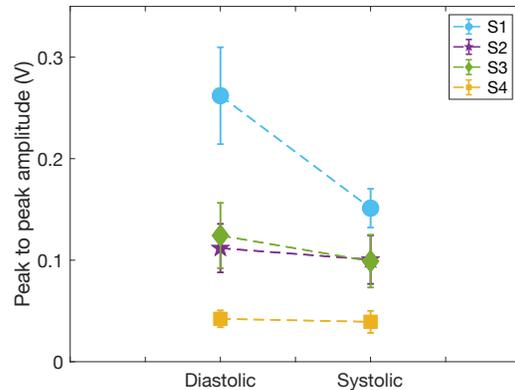


Figure 5. Mean amplitudes and standard deviation of measured pulse wave amplitude across all subjects.

## 4. Discussion

To the best of the author's knowledge, this is the first study investigating the PW amplitude at head level during synchronized walking. Our primary findings demonstrate that the PW amplitude is directly influenced by walking, with a periodic widening and narrowing, which is commonly identified as beating phenomenon [9]. This modulation may arise from the accessory wave generated in the great vessels with each heel strike.

Previous studies have explored the beating phenomenon during running by tracking arterial blood pressure [6, 9]. In our study, we focused on synchronized walking. Despite the smaller impact of heel striking during walking

compared to running, we observed a similar PW modulation pattern. In [6], it was shown that walking produces biphasic waves with low pulse pressure during diastole and uniphasic waves with higher pulse pressure during systole when measured on heart level. Contrary to this, we found an inverse effect at head level, with higher PW amplitude during diastole and lower amplitude during systole. Additionally, in this study, we did not observe any differences in the PW shape, with all waves resembling the uniphasic waveform. This could be attributed to the different acquisition site involving smaller vessels compared to interarterial recordings, where high frequency components are already dampened out. It may also be attributed to our conditioning circuit, where the 2.5 Hz low-pass filter may have removed some of the high-frequency components in the PW shape.

In this study, we focused exclusively on relative changes in peak-to-peak amplitude and did not quantify absolute blood flow changes. As a result, no conclusions can be drawn regarding the clinical impact of diastolic versus systolic stepping on cerebral perfusion. Future studies could employ techniques such as intracranial Doppler or Near-Infrared Spectroscopy (NIRS) to directly monitor blood flow during synchronized walking. While HR and its possible influence on the blood flow was not directly accounted for, it may constitute a confounding factor and should be considered in future investigation.

For proof of concept, young and healthy subject were included, while most other studies of cardiac and locomotor coupling focus on older adults. Even in this young cohort, we found modulation and inter-person variability in the extent of PW modulation. We expect the extent of these variations to be dependent on the synchronization success, on the individual walking pattern, and the elastic properties of the cardiovascular system.

## 5. Conclusions

Supporting the hypothesis that synchronized walking modulates hemodynamics, we found an increase in PW amplitude during diastolic stepping, suggesting improved cerebral blood flow. The variability in the results highlights the need for further validations with a larger cohort and a more stable sensor placement to reduce signal artifacts and improve reliability across different subjects.

## Acknowledgments

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