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# Wearable Blood Pressure Device For Detection of Orthostatic Hypotension

Mariam Hafez
mariam.hafez@uconn.edu

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Mariam Hafez

Thesis Supervisor: Dr. Insoo Kim

Honors Advisor: Dr. Patrick Kumavor

Biomedical Engineering Department

University of Connecticut

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Abstract

Orthostatic hypotension may be described as an inevitable response from the body in the form of a drop in blood pressure after changing positions. This quick drop in blood pressure can cause a syncopal episode, often injuring victims. There are limitations in the currently used cuff-type blood pressure sensor, which is used in healthcare settings, in that it does not continuously measure blood pressure. This research project developed a wearable device that measures heart rate variability (HRV) to detect changes in blood pressure using the correlation between the two measurements. The instrumentation was developed and included a commercially available pulse oximetry sensor (MAX30101, Maxim Integrated, CA), which collected data used to calculate heart rate and HRV. A study was conducted as a series of head-tilt table tests to monitor changes in blood pressure and correlate this with HRV.

# 1. Introduction

## 1.1. Background Research

There are numerous risks associated with high blood pressure, which are prevented through diet and medication. Unfortunately, complications with low blood pressure are not addressed as often as high blood pressure. A dangerous drop in blood pressure can lead to injury from a fall and in severe cases, unconsciousness. Orthostatic hypotension, a particular type of blood pressure drop, is when a person is sitting or lying for a period of time and two to three minutes upon standing, their systolic blood pressure drops about 20 mm Hg [1]. Orthostatic hypotension may be described as an inevitable response from the body to changing positions. Adjusting a body's position from a supine to upright position causes the blood flow in the body to shift as a result. About 500 mL of blood is shifted away from the upper body to the lower body, causing a decrease in overall blood pressure [2]. This quick drop in blood pressure can cause a syncopal episode, often injuring victims.

There are limitations in the currently used cuff-type blood pressure sensor, which is used in healthcare settings, in that it does not continuously measure blood pressure; continuous wearable blood pressure sensors are still in the research phase. In the market, there are fitness tracker watches such as the ThinkBand, which provides "real-time" measurements for blood pressure. These devices, which have similar concepts, provide several blood pressure readings throughout a period of time, instead of continuous measurement. For this reason, this method is not ideal, since a drop in blood pressure can occur between these given blood pressure readings.

Pregnant women often suffer from high blood pressure and are given medication to counteract this. Consequently, blood pressure drops with these medications, often times resulting in hypotension. Orthostatic hypotension in pregnant women is especially severe because

movement of a fetus inside the mother pushes against the mother's blood vessels, causing a sudden drop in blood pressure [3]. Fainting during pregnancy can be attributed to several factors. Fainting spells in pregnant women occur because of diet or hormonal changes, but most importantly they can occur from quick fetal movements and restricted blood flow, which are causes that cannot be controlled [3]. Fainting is harmful to a mother, and in severe cases, fatal to her fetus. Injury from fainting spells is common, since pregnant women cannot control where or how they fall when their blood pressure suddenly drops. If a fall causes injury in close proximity to the mother's uterus, it can result in serious problems for the fetus [4].

Orthostatic hypotension is not limited to pregnant women; postural low blood pressure often accompanies neurological diseases because of medications given to patients such as diuretics and vasodilators which inhibit normal reflexes of the autonomic nervous system. These causes can interfere with the body's involuntary responses, making it difficult to control reflexes, specifically muscle sympathetic nerve activity, during a sudden drop in blood pressure [5]. Causes of orthostatic hypotension vary and finding a way to monitor this to prevent any danger is possible. Although these causes vary, one commonality that can be detected between each case is a drop in blood pressure.

A heart rate variability (HRV) sensor may be used to detect sudden blood pressure changes; this is a more practical approach than the current solutions mentioned previously HRV, a measure of the variability between heartbeats, is correlated with blood pressure [6]. This measurement differs from heart rate, a measure of heartbeat; HRV reveals if a heartbeat is irregular, based on variations. Diet, activity, stress, and sleep can influence HRV, similar to the influence they have on blood pressure [7]. This form of measurement is relevant to use with a wearable device because it is quick to detect and can be implemented to predict blood pressure

changes. Heart rate variability has been studied extensively, and studies show that a negative correlation exists between HRV and blood pressure [8].

Another marker of a sudden drop in blood pressure is a change in skin conductance, which may be measured using a bioimpedance sensor. Detecting hypotension during spinal anesthesia surgery has been a pressing issue in surgical research; patients undergoing this procedure suffer from sudden drops of blood pressure during surgery, causing major long-term complications. This condition is comparable to orthostatic hypotension in pregnant women, since both are characterized by a drop in blood pressure over a short duration. Skin conductance has been studied to monitor this, revealing a correlation between the skin's electrical response and blood pressure changes.

Monitoring orthostatic hypotension has been previously studied, to better understand causes and characteristics of the condition. A pilot study was conducted to predict drops in blood pressure for ten patients, ranging from 23-43 years old. In this study, a mathematical model was derived for predicting when a patient's blood pressure would drop during a certain time interval given their change in heart rate variability. These researchers proposed that blood pressure could be monitored using heart rate variability. The model was found to have an accuracy of 80% for all instances in predicting blood pressure drops with a measurement error of ± 4.5 mmHg, which is less than the error of the blood pressure cuff currently used in medical practices [9]. This is important to consider because it can be modified for the purpose of a wearable device, based on certain disorders and conditions associated with orthostatic hypotension.

HRV is a valuable marker to assess changes in the function of the autonomic nervous system. It is used to study several cardiovascular and nervous disorders, since changes in HRV are linked to changes in the parasympathetic and sympathetic nervous systems [10]. Electrocardiogram

(ECG) can be used to determine HRV using the intervals between the peaks in an ECG, known as RR intervals. Photoplethysmography (PPG) is another measurement that relates to changes in the blood volume in a tissue. This is possible due to a generation of a pulse by the ventricular systole immediately following the QRS wave, or the peak, in an ECG [10]. The generated pulse causes an increase in the blood volume which can be detected by a PPG sensor. The use of PPG can then substitute the use of ECG to determine the peak-to-peak interval for HRV measurement.

### 1.2. Purpose

The purpose of this research project is to develop a wearable device that can measure HRV, to detect changes in blood pressure using the correlation between the two measurements. To hypothesize, the developed instrumentation should be able to reveal a correlation between HRV and a drop in blood pressure.

### 1.3. Aims and Objectives

The main aim of this thesis project is to create a sensor that continuously monitors blood pressure using heart rate variability for detection of orthostatic hypotension. Objectives for this aim include: (1) Develop instrumentation to detect changes in the body's response to a sudden blood pressure drop when standing after a prolonged period of sitting, (2) Recruit eligible subjects and test the proposed study protocol on these subjects to adopt a method to analyze the obtained data, (3) Develop an algorithm that detects changes in blood pressure based on the heart rate variability marker that is correlated, and (4) Validate and retest the instrumentation and algorithm.

## 2. Device Design

### 2.1. Prototype

The device is a wrist band with a Velcro strap as an enclosure for various arm sizes and will incorporate the developed sensor. The enclosure for the sensor was created using a 3D printer and used to secure the sensor on the strap. A microcontroller (STM32L4, STMicroElectronics, Switzerland) will be used to implement the algorithm that is developed to track HRV. The MAX30101 (Maxim Integrated, CA), an integrated pulse oximeter, is used as the PPG sensor. In addition, the board includes a micro SD card for data collection and battery to power the board. A Bluetooth component may be added to make updates or for monitoring purposes to the board through a smartphone.

#### 2.1.1. Instrumentation

The sensor begins recording by flipping the ON switch. The data begins recording after the LED turns red. During recording, the MAX30101 sensor should be in complete contact with the skin, preferably the dorsal aspect of the wrist. A greater signal is detected when the sensor is in contact with the index finger, but this is not practical for the purpose of designing a wearable device. Once the desired recording time is reached, the button on the board should be pressed and the LED will turn green. Following this, the switch should be turned to the OFF position. Once the instrumentation is turned off, the SD card can be removed to be read by the MATLAB code. The file will be saved as PPG.txt on the SD card and can be analyzed.

#### 2.1.2. Enclosure

Several designs for the enclosure were developed. The first design shown in Figure 1 was the initial design. The design was appropriate for the use of the sensor, but the size was too large. This made the enclosure impractical for placement on the wrist since it is too bulky.

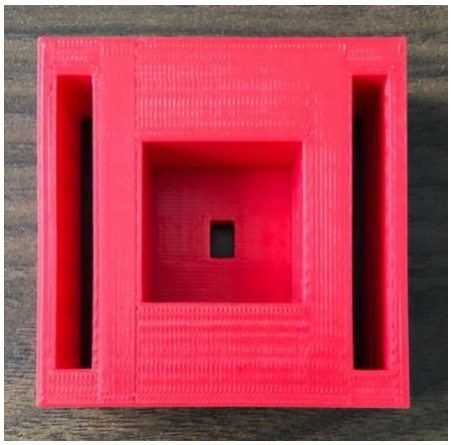

*Figure 1. Initial design of the sensor enclosure.*

The second design that was developed fixed the issue faced with the initial design. This design is shown in Figure 2. The second design was smaller and more compact. However, when testing the instrumentation, no data was obtained. On examination, the bottom side of the enclosure was found to be too thick, allowing for little to no contact between the sensor and the subject's skin. For this reason, the design was inappropriate for its use since the sensor was unable to pick up a signal. When attached to the wrist strap, the space between the sensor and the strap increased, making it even more difficult for a signal to be detected. The second design also did not allow for skin contact when the battery was attached. This is because the battery input added to the dimension of the sensor in one corner of the board.

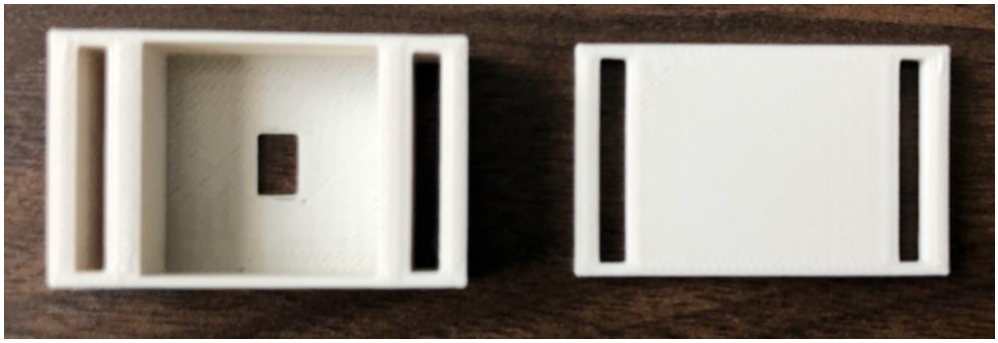

*Figure 2. Second design of enclosure.*

The third design was the most optimal design; it is displayed in Figure 3. It was created with similar dimensions as the second design to make it compact and easy for wrist strap use.

The bottom side of the enclosure was thinned, improving the contact between the sensor and the subject's skin. In addition, extruded cuts were made in areas of both sides of the enclosure to allow for the wrist strap to loop around and increase sensor to skin contact. This design also provides room for the battery to be attached, since a cut was made to hold the battery input in place.


*Figure 3. Final and optimal design of enclosure (a) without sensor and (b) with sensor.*

The final design, including the instrumentation, wrist strap, and enclosure is displayed in Figure 4 below. The SOLIDWORKS design that was created before 3D printing, in Figure 5, shows the enclosure and lid with correct dimensions for proper security and movement when wearing the device.

*Figure 4. Wearable device including all necessary components.*

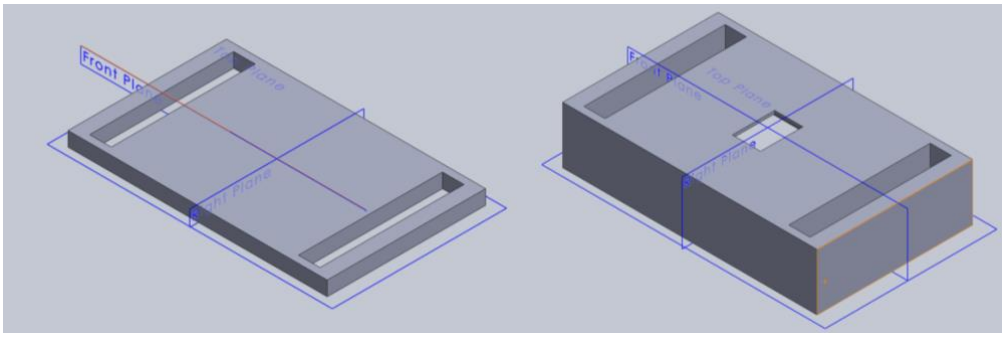

*Figure 5. SOLIDWORKS design of final enclosure and lid.*

## 3. Study Protocol

### 3.1. Study Design

Two commercially-available standard devices will be used to validate the device, a HRV monitor and a blood pressure sensor. HRV will be validated using the Polar H10 sensor, a sensor which monitors heart rate and HRV incorporated in a chest strap as shown in Figure 6 below.


*Figure 6. Polar H10 sensor incorporated in a chest strap.*

This sensor sends the measured data to the Elite HRV application on a smartphone for analysis. Blood pressure will be validated using a cuff-type OMRON blood pressure monitor, a device that is currently used in healthcare settings. The OMRON blood pressure cuff is shown in Figure 7.


*Figure 7. OMRON blood pressure cuff.*

3.2. Subject Characteristics

Subjects will be recruited depending on whether or not they suit the inclusion criteria. The study will be described as a series of head-up tilt table tests to measure blood pressure using a developed instrumentation. Eligible subjects will be asked to participant in the study. Subjects who accept will be notified and will receive an explanation of the study procedure for their purposes.

3.2.1. Inclusion Criteria

Subjects with the following criteria are eligible:

- Age: 20-50 years
- Ethnicity: N/A
- Gender: Female
- Subjects should be able to perform a head-up tilt table test.

#### 3.2.2. Exclusion Criteria

Subjects with the following criteria are ineligible:

- Subjects with any cardiac complications such as arrhythmia, history of myocardial infarction, coronary artery disease, congestive heart failure, hypertension
- Subjects currently taking medication to regulate blood pressure or heart rate such as calcium channel blockers, antidepressants, and vasodilators

### 3.3. Study Procedure

The study procedure follows two parts: a head-up tilt table test to obtain several blood pressure measurements and a test characteristic for orthostatic hypotension [11]. The first part will use the INNOVA inversion table, shown in Figure 8, to allow the subject to lay flat and then be tilted at 30 and 60 degrees. The tilt test is incorporated in the study procedure because it can effectively detect orthostatic hypotension. Prior to the study, the subject will consent to the study procedure explained.


*Figure 8. INNOVA heavy duty inversion table, model ITX9600 [12].*

3.3.1. Part 1

(1) The subject will lay on a flat surface.

(2) The Polar H10 sensor will be strapped around the participant's chest and will measure the HRV continuously throughout the trial. The OMRON blood pressure cuff will be attached around the participant's left arm, level with the subject's heart.

(3) At time 0 minutes, blood pressure (OMRON) will be measured while the subject is lying flat.

(4) At time 3 minutes, the subject's upper body will be tilted at a 30 degree angle. Blood pressure (OMRON) will be measured.

(5) At time 5 minutes, the subject's upper body will be tilted at a 60 degree angle. Blood pressure (OMRON) will be measured.

(6) Part 1 will be repeated 2 times with a 2 minute rest interval between trials.

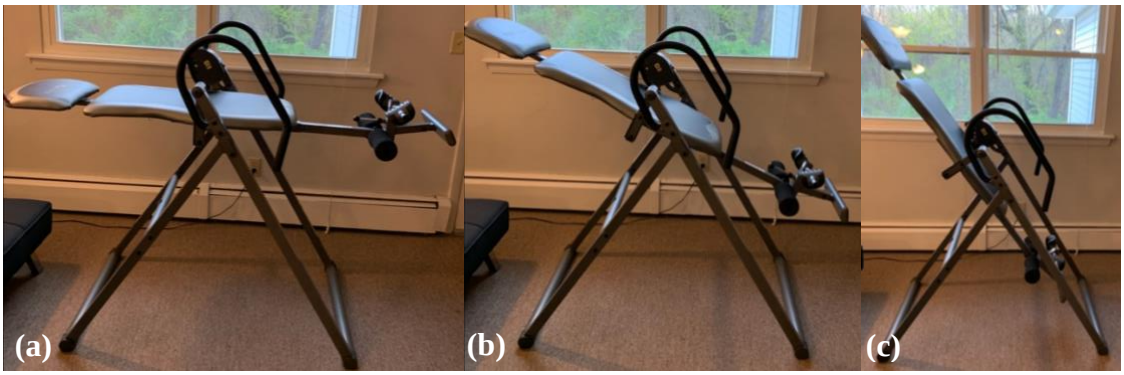


*Figure 9. Tilt table with inversion table (a) lying flat, (b) at 30 degrees, and (c) at 60 degrees.*

3.3.2. Part 2

(1) The subject will lay on a flat surface.

(2) The Polar H10 sensor will be strapped around the participant's chest and will measure the HRV continuously throughout the trial. The OMRON blood pressure cuff will be attached around the participant's left arm, level with the subject's heart.

(3) At time 0 minutes, blood pressure (OMRON) will be measured.

(4) At time 2 minutes, the subject will stand up straight. Blood pressure (OMRON) will be measured. Any signs of dizziness or lightheadedness will be noted.

(5) Part 2 will be repeated 2 times with a 2 minute rest interval between trials.

## 4. Analysis Method

### 4.1. MATLAB

The algorithm for obtaining PPG data was developed in MATLAB. The code collects the raw data from the PPG.txt file and filters it using a bandpass filter. A five second artifact from the data is recognized and removed in the code. The peaks are detected and peak times are used to calculate the RR interval, which is the interval between the peaks. The RR interval is then used to compute HRV, the final measurement, using the following relationship.

$$HRV = \frac{60}{RR\ interval}$$

An example of this MATLAB code is shown in Appendix A.

### 4.2. Elite HRV

HRV data obtained using the Polar H10 sensor is collected via Bluetooth to a smartphone. The sensor is connected to the Elite HRV application on the smartphone which provides real-time HRV readings. Once the recording is complete, the data is exported and can be analyzed using Kubios HRV software.

### 4.3. Kubios HRV

Kubios HRV is a software used to analyze HRV data for scientific purposes. The HRV software collects RR interval data and removes any artifact that could be caused by noise in the

measurement. It provides both time-domain and frequency-domain analysis for a selected time period within the data that is uploaded. The variables obtained from the software can then be used to understand the results for further analyzation.

## 5. Result

*Table 1. Blood pressure readings obtained for the subject study.*

| | | Time (s) | Blood Pressure (mmHg) |
|---|---|---|---|
| Part 1 | Trial 1 | 0 | 108/69 |
| | | 180 | 109/69 |
| | | 300 | 105/78 |
| | Trial 2 | 0 | 103/68 |
| | | 180 | 105/77 |
| | | 300 | 102/80 |
| Part 2 | Trial 1 | 0 | 114/71 |
| | | 120 | 113/100 |
| | Trial 2 | 0 | 117/74 |
| | | 120 | 100/78 |

*Table 2. Frequency correlated with systolic blood pressure drops from Polar H10.*

| | | Time Period | LF | HF | LF/HF |
|---|---|---|---|---|---|
| Part 1 | Trial 1 | 1:30-3:20 | 0.07667 | 0.31000 | 0.24731 |
| | | 4:11-5:36 | 0.07333 | 0.27000 | 0.27160 |
| | Trial 2 | 0:00-2:00 | 0.14000 | 0.31333 | 0.44681 |
| | | 3:00-5:00 | 0.05667 | 0.20000 | 0.28334 |
| Part 2 | Trial 1 | 0:00-1:00 | 0.12000 | 0.19667 | 0.61016 |
| | | 1:12-2:04 | 0.05000 | 0.33000 | 0.15152 |
| | Trial 2 | 0:00-1:50 | 0.05667 | 0.36000 | 0.15741 |
| | | 2:20-4:10 | 0.08667 | 0.15667 | 0.55318 |

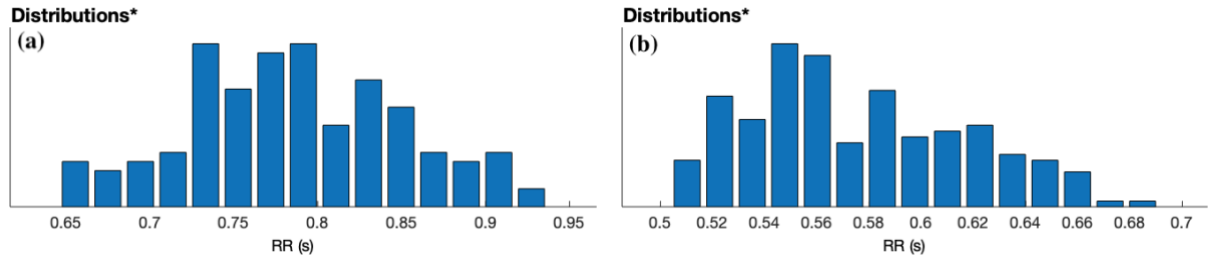


*Figure 10. RR distributions (a) before and (b) after systolic blood pressure drop for Part 2 Trial 2 from Polar H10.*

*Table 3. Frequency correlated with systolic blood pressure drops from MAX30101 sensor.*

| | | Time Period | LF | HF | LF/HF |
|---|---|---|---|---|---|
| Part 1 | Trial 1 | 1:30-3:20 | 0.07000 | 0.34333 | 0.20389 |
| | | 4:11-5:36 | 0.06333 | 0.17000 | 0.37255 |
| | Trial 2 | 0:00-2:00 | 0.05000 | 0.18667 | 0.26785 |
| | | 3:00-5:00 | 0.06333 | 0.19667 | 0.32203 |
| Part 2 | Trial 1 | 0:00-1:00 | 0.05667 | 0.19000 | 0.29825 |
| | | 1:12-2:04 | 0.04667 | 0.28000 | 0.16667 |
| | Trial 2 | 0:00-1:50 | 0.05333 | 0.30000 | 0.17778 |
| | | 2:20-4:10 | 0.12667 | 0.25667 | 0.49351 |

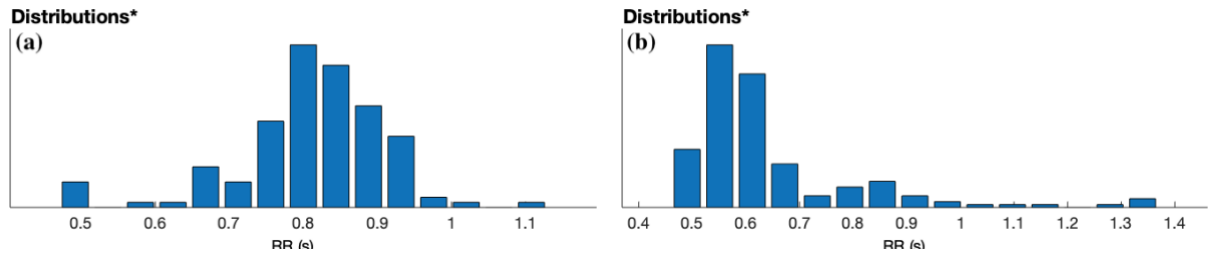


*Figure 11. RR distributions (a) before and (b) after systolic blood pressure drop for Part 2 Trial 2 from MAX30101.*

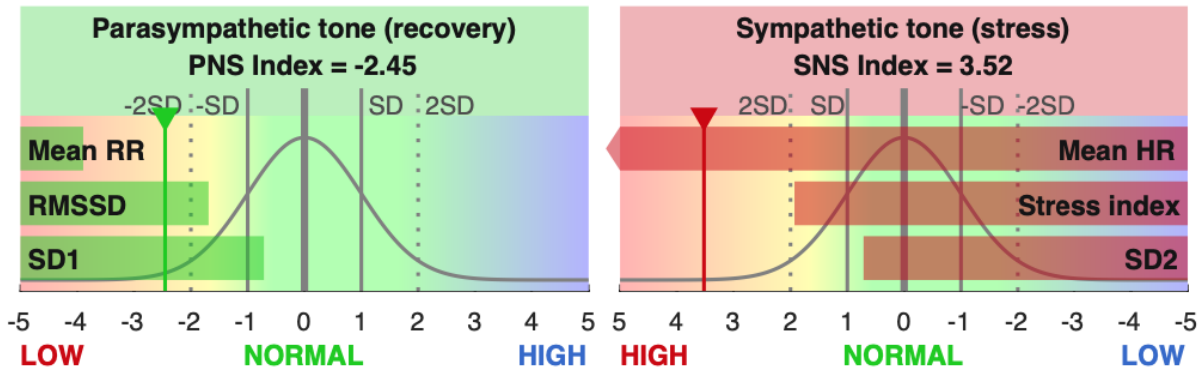


*Figure 12. PNS and SNS indices calculated by Kubios HRV software for Part 2 Trial 2.*

## 6. Discussion

Part 1 of the study involves a modified head-tilt table test using an inversion table to tilt the subject's head. Part 2 involves an orthostatic test in which the subject is laying down and then stands up. Both parts of the study are tests designed to measure the orthostatic changes in the subject. For this reason, if an orthostatic change occurs, the subject's systolic blood pressure should drop approximately 20 mmHg. From Table 1, Part 1 demonstrated a systolic blood pressure drop of 3 mmHg in the first trial and 1 mmHg in the second trial as evidenced in Table 1. However, this is not a significant drop in blood pressure, since the decrease does not represent an orthostatic change. The first trial of Part 2 also demonstrated an insignificant systolic blood pressure drop of 1 mmHg. The most significant systolic blood pressure drop from this subject's study was a decrease of 7 mmHg in the second trial of Part 2. This change can be used to better understand the correlation between blood pressure and HRV.

Figure 10 above displays the RR interval distributions from Polar H10 obtained using Kubios HRV software before and after the systolic blood pressure drop in the second trial of Part 2. There is a shift to the left of the RR interval distribution following the blood pressure change.

This can be correlated to a change in HRV since the RR interval is used to calculate HRV. The same shift occurs in Figure 11 with the RR interval distributions from the MAX30101 sensor. The RR interval distribution shifts to the left, revealing that on average, RR intervals decrease after the blood pressure change.

It is important to correlate the results with what occurs in the body during a blood pressure drop. The physical change in the body's position causes the blood to shift to another part of the body. In this case, the blood moves to the lower extremities, since the study is directed towards an upright movement in both parts. Compensation for this change occurs when the body increases heart rate and constricts blood vessels to allow blood to move to tissues that lack the required amount of blood following this. These signals correspond to the sympathetic nervous system, which can be studied using the frequency domain analysis obtained from Kubios.

High frequency (HF) and low frequency (LF) components of HRV relate to the activity of the autonomic nervous system and are given in Tables 2 and 3 [10]. These frequency components are defined as the frequency of the peaks in each low frequency, 0.04 Hz to 0.15 Hz, or high frequency, 0.15 Hz to 0.40 Hz, band [13]. From Table 2, the results using the Polar H10 sensor as a reliable measurement determine which parameter, or frequency, correlates with the blood pressure drop. The greatest blood pressure drop from the second trial of Part 2 shows the largest change for the LF/HF ratio from 0.15741 before the change to 0.55318 after the change. From this data, a change in LF/HF has the strongest correlation to with a change in systolic blood pressure.

Each frequency component of HRV can be correlated with a certain activity in the body. The HF component is managed by the parasympathetic nervous system and LF by both the parasympathetic and sympathetic nervous systems [10]. The LF/HF ratio is mediated by the

sympathetic nervous system, specifically with sympathovagal activity [14]. This is relevant since communications between the sympathetic nervous system and the vagus nerve is a cause of the drop in blood pressure as a result of an immediate constriction of blood vessels. Specifically, the HF component is also not practical in evaluating the HRV data in this situation since the parasympathetic nervous system does not control the blood pressure drop and the LF/HF ratio is a better fit [13]. The results obtained demonstrate both changes in LF and HF components of HRV, revealing that changes in both the parasympathetic (PNS) and sympathetic (SNS) nervous systems were involved during the conducted study.

To compare the activity of both of these systems, PNS and SNS indices can be observed to understand the level of activity of each system in relation to the normal population average [15]. PNS and SNS indices are shown in Figure 12 for the second trial of Part 2, since this demonstrated the greatest drop in blood pressure among all of the parts of the completed study. The PNS index is given by -2.45 and SNS index is 3.52, meaning that the PNS activity deviated from the normal population by -2.45 standard deviations and SNS activity deviated by 3.52 standard deviations. Indices between -2.00 and 2.00 represent normal PNS and SNS activities since these values are within 95% of the population [10]. Greater deviations can be connected to increased stress, physical exertion on the body, or changes in autonomic nervous system activity. It is also important to note that SNS activity deviated more than PNS activity, by 1.07 standard deviations. This can be attributed to the greater change in SNS activity during a change in body position and the resulting drop in blood pressure. Nonetheless, PNS activity did deviate from the normal population, revealing that the parasympathetic nervous system also played a role during this study.

It is also important to note the difference between peak-to-peak, PP and RR intervals when measuring heart rate variability. In the case of measurement with a PPG sensor, the variability is referred to as pulse rate variability, PRV, since the peak-to-peak intervals are calculated from the PPG signal [10]. The use of PRV to estimate HRV has been shown to be the most accurate for healthy subjects. The two measurements deviate the least when subjects are resting and lacking mental stressors [16]. Thus, PRV is a sufficient measurement for the purpose of the conducted study.

# 7. Conclusion

## 7.1. Significance of Results

The results obtained from the developed instrumentation provide measurements that give an understanding to how the body reacts to a change in position and as a result, a change in blood pressure. Changes in the LF/HF ratio correlate with the decrease in systolic blood pressure in the conducted study. These values give insight to how the sympathetic nervous system responds to changes in blood pressure. Deviations from normal sympathetic activity are also given by the SNS index, which confirms that the change in position and blood pressure in the study can be detected by the sensor.

## 7.2. Future Application

With additional subject testing, more conclusive results can be obtained to further understand the correlation between HRV and blood pressure. Additional subject studies would allow for a more accurate confirmation of the hypothesis. These studies would strengthen the repeatability of the protocol and obtain more data for analysis of the relationship between HRV and changes in the sympathetic nervous system.

As evidenced, the developed protocol as a head-tilt table test did not mimic the sudden drop in systolic blood pressure of approximately 20 mmHg that is characteristic of orthostatic hypotension; this could be a limitation of using one subject for the study. Another limitation is related to the time intervals used in the study. The head-tilt table test was shortened to accommodate subjects during the study. Changes in the duration of this test could have influenced the blood pressure readings that were obtained, since changing body positions after a longer duration influences the magnitude of the change in blood pressure.

The device's wearable property allows a practical use of the instrumentation. To enhance this practicality, the device could upload the recorded data via Bluetooth and detect any changes in HRV that are significant to a drop in blood pressure to alert its user.

## 8. Acknowledgements

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## 10. Appendix

*Appendix A: Code developed for HRV calculation from PPG data.*

```
% Mariam's Data Analysis
% PSD of NBM
clear all;

SPS = 100; % Sampling rate

PPG_file = fopen('PPG1.txt');
PPG_Raw = fread(PPG_file,'ubit32');
fclose (PPG_file);

% Create x-axis timestamp
timestamp = transpose((1:length(PPG_Raw))/SPS);

% Bandpass filtering (0.5 ~ 5 Hz)
PPG_filt = bandfilter (PPG_Raw, SPS) * (-1); % The data is flipped so
multiply (-1)

% Chopped out first 5 seconds that is artifact created by the filter.
PPG_peak = PPG_filt(SPS*5:length(PPG_filt));
timestamp = transpose((1:length(PPG_peak))/SPS);

% Peak detection. Min Peak distance is 0.45 sec, which means that the maximum
heart rate is 133 bpm.
[pks, peaktimes] = findpeaks(PPG_peak, timestamp, 'MinPeakDistance', 0.45);
plot(timestamp,PPG_peak, peaktimes, pks, 'o')
title('PPG Peak detection')
ylabel('PPG'); xlabel('time (sec)')

% Calculate R-R intervals and HRV from 'peaktimes.'
RR = sqrt(sum(abs(diff(peaktimes)).^2,2))*1000; % Calculate R-R intervals
HRV = (60./RR*1000); % 60/R-R intervals for each point
```