BioWatch - A Wrist Watch based Signal Acquisition System for Physiological Signals including Blood Pressure

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***Abstract*— A wrist watch based system, which can measure electrocardiogram (ECG) and photoplethysmogram (PPG), is presented in this work. By using both ECG and PPG we also measure pulse transit time (PTT), which studies show to correlate well with blood pressure (BP). The system is also capable of monitoring heart rate using either ECG or PPG and can monitor blood oxygenation by easily replacing the PPG sensors with a different set. In this work, we investigate methods to train a fitting function to convert a PTT measurement to its corresponding systolic BP. We also validate measurements on different postures and show the value of calibrating the device for each posture. This system, called BioWatch, can potentially facilitate continuous and ubiquitous monitoring of ECG, PPG, heart rate, blood oxygenation and BP.**

I. INTRODUCTION

Daily monitoring of vital signs outside of a hospital environment can help early diagnosis of chronic ailments as well as promote healthier lifestyle changes. A device built for this purpose should not only provide accurate and reliable readings of physiological phenomena but also be easy to use in a convenient form factor that does not unduly burden the user for daily use. With this in mind, we focused our research on developing a non-invasive wearable blood pressure monitoring device using pulse transit time (PTT).

According to several recent studies, PTT is highly correlated with systolic blood pressure (SBP) [1], [2], [3]. Measuring PTT is very convenient since it is noninvasive and the sensing can be continuous. Many previous studies have been using separate systems for ECG and PPG and they are not independently wearable [4] [5]. There are some studies [6] [7] which tried to introduce wearable blood pressure (BP) measurement devices; however the wearable solution in [6] is still not convenient enough because of its wired connection extension to the other arm, which will be uncomfortable if worn all day and [7] did not provide a clear validation on the measured BP. In this paper we present BioWatch, a wearable device in the form of a wrist watch that can monitor the user's heart rate, blood oxygenation and BP non-invasively. Wireless measurement in a wrist watch form factor will be a convenient solution for daily personal monitoring of BP. Fig. 1 shows the relative convenience of a wrist watch based system. Shown on the left is a person wearing BioWatch and on the right is a person wearing wet electrocardiogram (ECG) electrodes and a finger based photoplethysmogram (PPG) sensor in a traditional setup.

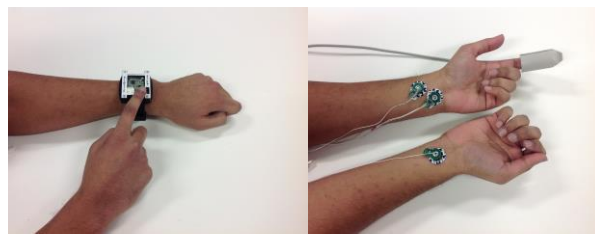

Fig. 1: Wrist watch based system compared to a system with wires

As the human body is complex, there are many physiological factors, such as physical characteristics of blood vessels, which influence PTT. This makes accuracy of BP estimated from PTT difficult. Estimation of absolute BP needs calibration and recently, a one point calibration is proposed in [8]. However, most studies for PTT-BP relation are done using only one posture and they developed PTT-BP equations for the general population, which needed recursive calibration to each individual using traditional cuff measurements. Here, we developed and calibrated the PTT-BP equation to each individual and each posture. We collected both PTT and reference SBP for each subject in this study and used fitting functions to develop an equation. In this study, we also validate the calculation of BP through measurement of PTT using different postures of the human body and show how calibration to each posture is important.

II. PULSE TRANSIT TIME

A. Definition

Pulse transit time (PTT) is the time taken for the blood to travel from the heart to a specific location for each heartbeat. It can be defined as the time between the ECG 'R peak' and the corresponding maximum inclination in the PPG [9], as illustrated in Fig. 2.

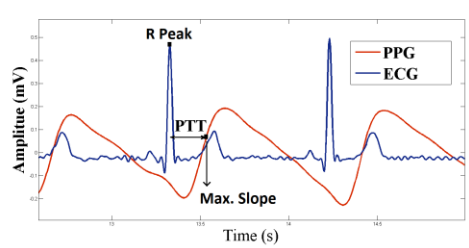

Fig. 2: PTT from ECG & PPG

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B. Measuring Pulse Transit Time

Both ECG and PPG signals are passed through band pass filters (details in section IV-A and IV-B). We are interested only in the ECG's R-peak, so after filtering the signal's peak is detected easily. Once each R peak of the ECG and corresponding point of steepest slope of the PPG is detected, then the time difference between these points gives the PTT.

III. BioWatch System

A. Hardware

The platform used for BioWatch is designed by our lab, the Embedded Signal Processing Lab (ESP), in partnership with Texas Instruments (TI). BioWatch comes with two analog front ends (AFE): the TI ADS1292 for acquiring ECG signal and the TI AFE4400 for reading PPG. Both of them are controlled by the TI MSP430 microcontroller. Dual mode Bluetooth from BlueRadios is used for data communication to a PC. The board is battery-powered and can recharge the battery through a micro-USB interface. The AFE4400 which collects the PPG data is currently connected to a flat reflective PPG sensor which uses green LEDs and a photo diode. The PPG sensor used here is an add-on board and can easily be replaced with PPG sensors of different colored LEDs for blood oxygenation monitoring applications. We designed our own custom dry ECG electrodes which consist of spring loaded gold plated fingers and a flat metal surface soldered on top of it. Two of the ECG electrodes are placed at the bottom of the BioWatch and the third one is on top and the electrodes are directly connected to the inputs of the ADS1292. Fig 3 shows the front and back of the BioWatch.

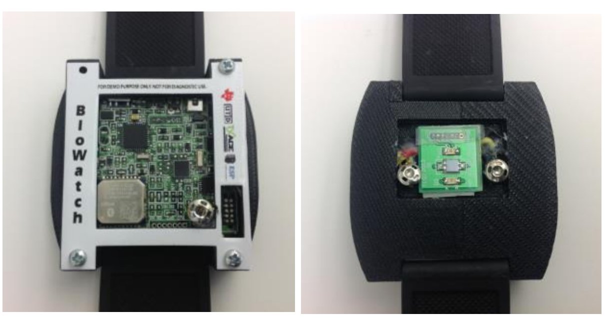

Fig. 3: BioWatch (front and back) designed in our lab

B. Operation

BioWatch is worn on the wrist like a normal wrist watch. The watch band itself does not have any effect on PPG or PTT because the PPG sensor is completely cased inside the watch case made of plastic. But it is important that the watch is worn reasonably tight to make sure that the PPG data is collected properly. While measuring the PTT, users are encouraged to keep their arm, with BioWatch, across the chest to get a more stable and accurate measurement. The user has to touch the top ECG electrode of the BioWatch with the other hand, to measure the ECG signal. PPG signals can be collected without this additional touch. The PC front end, designed using LabVIEW, uses MATLAB scripts for all the signal processing. Once data collection is initiated from PC both ECG and PPG are sampled at 122Hz and sent continuously to PC where data is either continuously processed for PTT/BP measurement or saved for offline processing. For this study, validation of BP was done offline. Fig 4 shows the ECG signal collected from BioWatch.

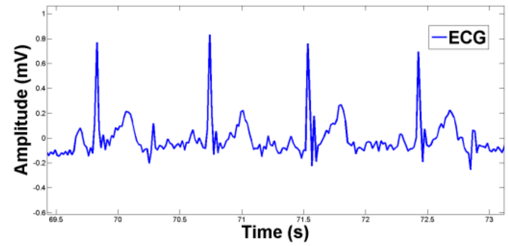

Fig. 4: ECG signal from BioWatch

IV. Methods

A. Detecting the R peak

The ECG collected is passed through a zero phase band pass filter with passing band between 10Hz to 30 Hz. Once this is done we detect all the R peaks of the signal using the 'findpeaks' function in MATLAB.

B. Detecting the point of maximum slope

The PPG collected goes through a zero phase band pass filter between 0.5Hz to 7Hz. After detecting the R peak of the ECG the algorithm looks for the steepest slope in PPG for the next few milliseconds depending on the R-R interval. Ideally, the steepest PPG slope will be within 70% of the R-R interval. Slope is measured by subtracting each sample from the previous one. The samples which give the highest difference correspond to the maximum slope.

C. Computing PTT

As described in Section II A, PTT is the time between the ECG R peak and the corresponding point of maximum inclination in the PPG. Once we have detected these for each R-R interval, the corresponding sample numbers are subtracted. This is then multiplied with the time between each sample.

D. Translating PTT to BP

In order to train the conversion of measured PTT to BP, we collected both PTT and arterial blood pressure (ABP) using a reference device for different subjects. The SBP is then calculated as the highest value of ABP for each R-R interval. We also calculate the pulse wave velocity (PWV), as shown below.

$$PWV = \frac{d}{PTT} \quad (1)$$

Here d is the distance from heart to the wrist and is calculated as 50% of the height of the individual.

For the training of a new equation to estimate BP using PTT, we used curve fitting and regression techniques. Using these, we translated our measured PWV to the training data set of BP obtained from the reference device. The fitting function obtained from this procedure was then tested on another set of data to see how closely the calculated BP, using the PTT and fitting function, matched the reference BP. This would provide a validation for the BP as measured by BioWatch against a standard BP measurement device (detailed in Section V-A).

One common fitting function is polynomial regression as described below:

$$y = a_0 + a_1 \times x + a_2 \times x^2 + \dots\dots + a_k * x^k \quad (2)$$

Here, k is the order of the fitting function, x is the PWV and y is the BP measure. We trained polynomial equations of orders 1 and 2. In [9], BP is calculated as 70% of the total pressure drop (ΔBP) in the body, where ΔBP is calculated as shown below.

$$\Delta BP = \frac{1}{2}\rho \frac{d^2}{PTT^2} + \rho g h \quad (3)$$

where ρ is the density of the blood, d is the distance from heart to the wrist, g is the gravity of earth and h is the height difference between the two sites. We trained a generalized equation based on this BP model. The equation we used was

$$y = ax^2 + b \quad (4)$$

where x is the PWV y is the BP measure and a, b are constants which need to be determined after the training. Finally, we also evaluated two other exponential equations to see which would be the best fit for the data set. Table I summarizes all the equations used to train the fitting function. Parameters a, b & c are determined after the training. Taking into account the eventual need to run the algorithm in a microcontroller we chose simple equations for now, leaving more complex equations for future analysis. Another reason for preferring generalized simpler equations is to avoid over-fitting. We also mainly considered polynomial and exponential equations since many previous works like [8] & [9] used similar models.

Table I : Different fitting functions used for training

Fitting Eq. No:	Equations
1	$y = ax + b$
2	$y = ax^2 + bx + c$
3	$y = ax^2 + b$
4	$y = ax^b + c$
5	$y = ae^{bx}$

Once these equations were derived their effectiveness was tested on the testing data. For this, the data set is divided into 10 segments and 9 were used for training. The effectiveness of the equation is tested on the untrained segment. A 10-fold cross validation is done to see how close the calculated BP is to the actual BP. This procedure is repeated for all 3 postures. As we are interested in the absolute value of the BP the objective is to minimize the root mean square error (RMSE) between the calculated BP and the actual measured BP.

V. Experimental Setup

A. Measurement Procedure

For our analysis we collected data from 4 individuals. BioWatch was worn on their left arm to collect ECG & PPG, while the right arm and the right wrist was used to collect beat-to-beat ABP from the radial artery using the Colin Continuous Blood Pressure Monitor, CBM-7000. This device is itself calibrated to a standard BP cuff at the beginning of each measurement cycle and then continues to collect indirect ABP from the wrist using its wrist-worn module. ABP is recorded on the PC through BIOPAC MP150, which also records another ECG signal from the subject simultaneously. By aligning the ECG from both BioWatch and BIOPAC we were able to align the two sets of data. In sitting and standing positions, the subject put their left arm across the chest and the right arm on a platform keeping it at the chest level. While in supine position both the left hand and the right hand were kept on two different platforms keeping them at the chest level. Since in this experiment the right arm was used to collect the ABP, we used a wire connecting from the top ECG electrode to the right hand to complete the electrical connection for ECG on the BioWatch.

B. Protocol

Once the subject is seated comfortably, the data collection is started. We designed the protocol such that the BP measurements during normal conditions as well as during abrupt changes could be validated. For introducing sharp changes in the BP, the Valsalva maneuver [10] was introduced during the data collection. The Valsalva maneuver required the subject to exhale against the closed airway after the maximal inhalation (at the maximal lung volume) to induce the required change. For the first 4 minutes of data collection, the subject is at rest. After that, the Valsalva maneuver was performed 5 times with 45 seconds to 1 min gap between each one. The collected data was imported to MATLAB for further processing. Once the data was aligned, PTT was calculated. Using this PTT and our trained equation we calculated systolic BP. The corresponding systolic BP is also obtained from the ABP device for comparison. For validation we found the RMSE between the calculated BP and the real measured BP. Fig.5 shows the PTT and BP measured simultaneously during the Valsalva maneuver and Fig 6 shows the fitted BP and systolic BP for the Valsalva maneuver.

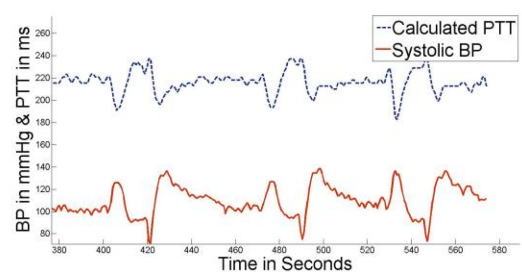

Fig. 5: PTT & BP collected simultaneously

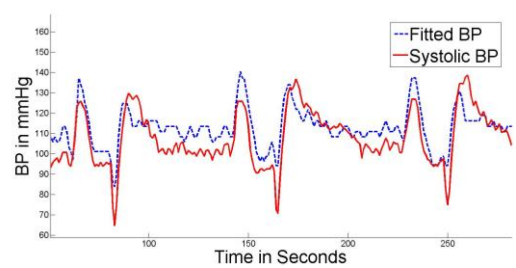

Fig. 6: Fitted BP & corresponding Systolic BP

VI. DISCUSSION OF RESULTS

A. Root Mean Square Error

The RMSE between the calculated BP and the actual measured BP was calculated for each of the postures and the averaged results across all subjects for each of the fitting functions is shown in Table II. The results showed low average RMSEs ranging between 8mmHg to 11mmHg across all postures. This validates the feasibility of PTT-based BP measurement on a wrist-based device. The results also show no significant differences between the performances of the various options for the fitting function. Fig 7 shows the plot of PWV against the actual systolic BP and the fitted BP from 5 fitting equations on one subject.

Table II : RMSE between calculated BP and measured BP

Fitting Function:	RMSE for Different Postures in mmHg (mean$\pm std$)		
	Supine	*Sitting*	*Standing*
1	**8.18±1.57**	**9.25±0.84**	**10.39±1.67**
2	**8.17±1.48**	**9.24±0.96**	**10.21±1.41**
3	**8.22±1.66**	**9.27±0.86**	**10.27±1.66**
4	**8.12±1.42**	**9.62±0.88**	**10.03±1.52**
5	**8.26±1.70**	**9.27±0.87**	**10.23±1.67**

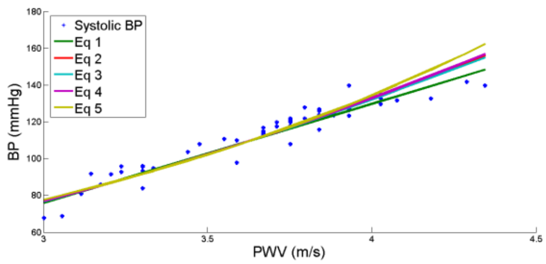

Fig 7 : PWV Vs actual systolic BP & Fitted BP

B. *Posture Specific Calibration*

To examine how important it is to train the equation to a specific posture, we calculated the BP from PTT in 2 different ways. For each subject, we first trained the BP-PTT equation on data from each posture and tested the equation on the untrained data of the same posture as already shown in Table II. Secondly, we trained the equation on data from all the postures of the same subject and tested it on the untrained data of each posture of the same subject. After calculating the RMSE for both cases we calculated the percentage increase in the error when using data trained on all the postures as opposed to training on only the specific posture. The results, listed in Table III, showed a significant increase on RMSEs when not using posture-specific training data. For fitting equation 1, parameter 'a' ranged from 40 to 52 and 'b' ranged from -15 to -48 across different postures of the same individual.

Table III: RMSE from equation trained on all postures and percentage increase on RMSE when compared to posture specific trained BP

Fitting Function	Percentage increase on RMSE in mmHg					
	Supine		*Sitting*		*Standing*	
	RMSE	*% increase*	*RMSE*	*% increase*	*RMSE*	*% increase*
1	**13.77**	**68.45%**	**12.55**	**35.73%**	**15.28**	**47.07%**
2	**13.67**	**67.31%**	**12.79**	**38.43%**	**15.34**	**50.21%**
3	**13.79**	**67.85%**	**12.61**	**36.10%**	**15.20**	**48.02%**
4	**13.60**	**67.55%**	**13.06**	**35.75%**	**15.28**	**52.34%**
5	**13.81**	**67.18%**	**12.62**	**36.06%**	**15.17**	**48.30%**

VII. CONCLUSION

In this paper, we presented a wrist-based platform for physiological signal acquisition. The platform uses dry ECG electrodes and flat reflective PPG sensors. We trained various fitting functions to convert PTT to systolic BP. These were validated on a testing data set which showed low RMSE between the calculated BP from BioWatch and that of a reference device. We also came to the conclusion that calibration to each posture can greatly improve accuracy. In future work, we will collect data on more subjects and assess the significance of individual-specific calibration as well. BioWatch could potentially provide a convenient, wearable solution for daily acquisition of ECG, PPG, heart rate, blood oxygenation and BP data.

VIII. ACKNOWLEDGMENT

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