Seismo: Blood Pressure Monitoring using Built-in Smartphone Accelerometer and Camera

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ABSTRACT

Although cost-effective at-home blood pressure monitors are available, a complementary mobile solution can ease the burden of measuring BP at critical points throughout the day. In this work, we developed and evaluated a smartphone-based BP monitoring application called *Seismo*. The technique relies on measuring the time between the opening of the aortic valve and the pulse later reaching a periphery arterial site. It uses the smartphone's accelerometer to measure the vibration caused by the heart valve movements and the smartphone's camera to measure the pulse at the fingertip. The system was evaluated in a nine participant longitudinal BP perturbation study. Each participant participated in four sessions that involved stationary biking at multiple intensities. The Pearson correlation coefficient of the blood pressure estimation across participants is 0.20-0.77 (μ=0.55, σ=0.19), with an RMSE of 3.3-9.2 mmHg (μ=5.2, σ=2.0).

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; I.5.4. Image Processing and Computer Vision: Applications

Author Keywords

Physiological sensing; noninvasive blood pressure; pulse transit time; photoplethysmography; seismocardiography; PTT; PPG; SCG

INTRODUCTION

High blood pressure (BP), also known as hypertension, is a medical condition in which the blood exerts high force on the artery walls as it circulates through the body. According to the WHO [21], hypertension causes 7.5 million deaths per year, about 12.8% of all deaths worldwide, and in 2008, around one billion people had hypertension. Frequent monitoring of BP at home has been show to improve the management of
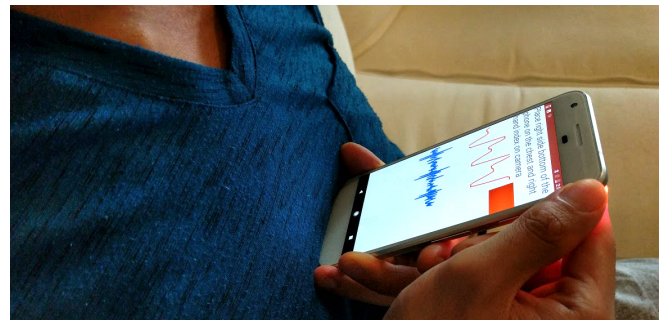
Figure 1. Measuring blood pressure using Seismo, a smartphone application that uses the built-in accelerometer and camera to calculate pulse transit time.

hypertension and effectiveness of treatments over infrequent in-clinic monitoring [1]. Currently, at home monitoring of BP relies on automated oscillometry-based BP arm cuffs for daily measurements. Although this way of automated way of measuring blood pressure enable out of clinic monitoring, they are cumbersome and inconvenient [20, 19].Due to these drawbacks, patients typically only perform arm cuff-based measurements once a day, and thus cannot capture the fluctuations in BP that occurs throughout the day due to exercise, activities, and other stressors.

Advances in mobile technologies now present an opportunity to have always available health monitoring capabilities as more and more people carry a smartphone around with them. Incorporating BP monitoring using only the built-in sensors on all smartphones has the potential of enabling unobtrusive and convenient BP monitoring at home and frequently throughout the day. As a software-only solution leveraging commodity devices that are already disseminated widely, it would be possible to enable higher adoption, and as a result improve the population awareness of their cardiovascular risk.

In this work, we develop and evaluate *Seismo*, a BP measurement technique using the existing sensors on the smartphone. Seismo uses pulse transit time (PTT) – the time taken by the heart's pulse to propagate between two arterial sites – which is inversely related to BP [9, 22, 25]. In particular, Seismo tracks the time when the blood is ejected from the heart as the aortic valve opens and when the pulse arrives at the fingertip. To perform this, Seismo relies on Seismocardiography (SCG), which uses the vibration caused by the movement of

the blood and valve activities as the heart beats, allowing for accurate measurement of aortic valve opening time. The SCG is captured using the phone's accelerometer pressed against the chest (Figure 1). In this position, the user holds the phone with their finger covering the camera, which then captures the photoplethysmogram (PPG) at the finger, thus measuring the pulse as it arrives. This technique conveniently captures both the proximal (close to the heart) and distal (away from the heart) timing all from one device, without the need for any supplemental hardware. Additionally, PTT-based techniques can measure beat-to-beat BP, thus it can more reliably measure short-term BP changes (such as post-exercise), which are difficult to measure using cuff-based devices. One major distinction between Seismo and previous solutions that enable smartphone blood pressure tracking without additional hardware is the use of accelerometer to capture SCG as a proximal timing. Other work has mainly focused on using the sound created by the heart, otherwise known as phonocardiography (PCG). However, the fundamental limitation of using PCG as a proximal timing is that the sound being captured is actually created by the *closing* of the heart valves rather than the *opening*, thus not an ideal reference for when the blood is actually ejected. Although prior work have demonstrated the use of SCG and PPG to reliably capture PTT for measuring BP, they use custom hardware with ultra low-noise accelerometers [3] to resolve the signal, while we focus on using only off-the-shelf commodity smartphones.

To measure the effectiveness of Seismo, we collected data from nine participants in four lab-sessions each. Participants biked at multiple intensities during each session to raise their blood pressure. For each participant, the first session BP measurements are used for calibration and learning. Based on which, the subsequent three sessions of blood pressure measurements are estimated. We note that Seismo struggles to capture reliable SCG and PPG signals from two of the nine participants. One participant has very shaky hands during the measurements, which is accentuated when holding the phone in the measurement position. The other participant has a comparatively weak heart beat, while also having more muscle and fat tissues between the accelerometer and the heart, which significantly reduces the transduction of the signal. Of the seven participants whom Seismo is able to capture clean and extractable signals, Seismo achieves Pearson correlation coefficient scores of 0.20-0.77 (μ=0.57, σ=0.15) and RMSE of 3.3-9.2 mmHg (μ=0.52, σ=2.0) for each participant. This is comparable to prior work [10, 24] that uses custom hardware to measure PTT, demonstrating the feasibility of using commodity smartphones to capture SCG and PPG for BP estimation, while we also identify the limitations of our system.

RELATED WORK

PTT vs PAT
Compared to cuff-based BP measurement approaches, PTT-based techniques provide continuous beat-to-beat BP measurements. A typical method for obtaining PTT [9, 16, 17, 23] is to use the R-wave of the ECG to mark the timing of the genesis of the pulse, and measure the pulse at the periphery (typically at the fingertip) using PPG. However, the ECG R-wave is not a reliable timing marker for the genesis of the pulse [3, 25, 16],

as it marks the electrical stimulation that would then trigger the start of a heartbeat, when the blood leaves the heart.

The time between the occurrence of the R-wave and the actual aortic valve opening (AO) is called the pre-ejection period (PEP). In reality, systems using a combination of ECG and PPG to measure PTT are actually measuring Pulse Arrival Time (PAT=PEP+PTT) to estimate BP, by wrongly assuming PEP to be constant. Previous work has shown that PAT is not an accurate measure to estimate BP [3, 25], as PEP is connected to the nervous system activity and is variable up to tens of milliseconds. Instead, prior work have shown that a better way to resolve PTT is to capture the mechanical vibration at the chest caused by the series of muscular contractions during a heart beat, known as seismocardiography (SCG) [7]. The advantage of SCG is that the signal captures the valve movements of the heart, showing the mitral valve closure time (MC) and aortic valve opening time (AO).
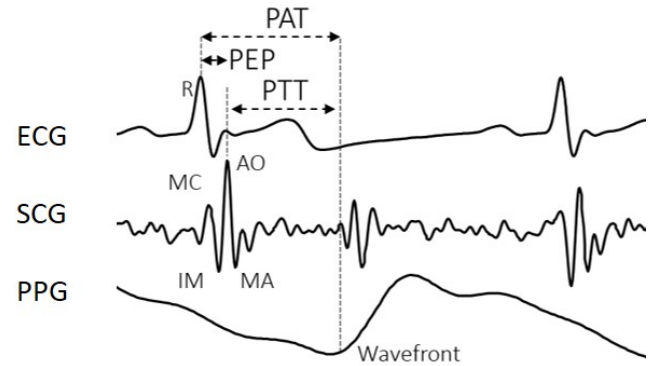

Figure 2. PTT using SCG and PPG as measured by the Seismo system on a Google Pixel phone. ECG based timing results in the inclusion of PEP, and thus measures PAT.

In this work, similar to [3, 10], we rely on SCG instead of ECG to capture the proximal timing of aortic valve opening in order to measure accurate PTT value (not PAT) for BP estimation (Figure 2). PTT-based BP estimation approaches suffer from a few limitations. PTT can only estimate relative changes in blood pressure, *i.e.*, an absolute measure of PTT cannot be extrapolated to an absolute measure of BP. Also, the relationship between PTT and BP is dependent on the physiological properties of an individual. Both of these limitations can be addressed by performing per user calibration, and is an active area of research. Various methods have been proposed to determine the calibration between PTT and BP [16]. The most common is to perform a set of interventions that would perturb an individual's blood pressure. Exercises such as running and biking are effective methods to drastically increase the blood pressure. Other methods include postural changes, valsalva maneuvers, and cold pressor [16]. Finally, another limitation of PTT is that it is most strongly influenced by diastolic blood pressure. As such, in our evaluation we focused only testing the correlation between PTT and diastolic blood pressure. However, because diastolic blood pressure changes and systolic blood pressure changes are often strongly correlated, PTT remains a highly useful for monitoring blood pressure fluctuation.

Measuring BP using Wearable Devices

Researchers have proposed PTT-based wearable devices to continuously sense BP throughout the day [3, 5, 6, 22]. Glabella is a wearable glasses [6] with three optical sensors for PPG to measure PTT on different arterial sites on the face. Fortino and Giampa [5] use a combination of a ring and a wrist band with optical sensors for two separate PPG measurements, while SeismoWatch [3] use a wristwatch form factor with optical and IMU sensor to calculate PTT. SeismoWatch [3] shows the usage of SCG and PPG to accurately measure PTT and predict BP. However, it uses custom wearable hardware with ultralow-noise accelerometer (ADXL354) and IR photodiode arrays to measure SCG and PPG, in order to measure high resolution SCG and PPG values. Previous work has shown that SCG can be accurately measured using smartphone's built-in accelerometer [11, 15], though only examined more measuring heart rate and heart rate variability, not pulse transit time. In our work, we explore measuring SCG from the phone's accelerometer by placing the phone over the chest, and measuring PPG at the fingertip from the same phone's camera (Figure 1), to determine PTT and estimate BP while the user is seated and with measurements taken over clothing. This is of significance because the measurement of PTT necessitates better capturing of distinct time characteristics of aortic valve opening time over just identifying the presence of a heart beat.

Measuring BP using Smartphones

As wearable devices are potentially cumbersome and are not widely adopted, researchers have explored exploiting the ubiquity of smartphones to measure PTT and predict BP [4, 13, 18, 8]. Most of the phone-based BP techniques [4, 8] using a combination of the smartphone's microphone to record the heart sounds created by the closure of the mitral and aortic valves, called phonocardiogram (PCG), and the smartphone's camera to determine the heart beat at the fingertip. As the smartphone microphone is sensitive to noise, a stethoscope-based hardware is usually attached to enhance the smartphone sensing capability [18, 4]. Dias *et al.* [8] has demonstrated the use of the commodity smartphone without any attachments to capture PCG. However, as mentioned previously, PCG does not provide the correct time to determine PTT, as PCG captures the closing of the valves sound, not the opening. There is currently a gap in using built-in smartphone sensors to accurately capture PTT, which our work addresses through the use of accelerometer and camera paired PTT measurement.

SEISMO

Seismo implements the SCG and PPG based PTT measurement method with the built-in sensors of a smartphone. To take a measurement, a user needs to hold the phone in one hand, and press it onto the left side of the chest in one of the two locations: (1) below the pectoral muscles on the sternum, (2) above the pectoral muscles and below the clavicles.

These two positions provide proper ergonomics and access to the heart vibration, and also are less obstructed by body fat compared to other portions of the chest. The user can try placing the phone in both the positions, and our system Seismo will determine the subject-specific location depending on the quality of the signal received. The SCG morphology changes

depending on the position of the recording device (Figure 4). Thus once the chest position is determined, the user needs to place the phone at the same position thereafter. To measure PPG, the user places their index finger of the other hand over the phone's back camera, covering both the camera and flash. In this position (Figure 1), the SCG is measured using the accelerometer Y-axis data (along the height of the phone) and the PPG is measured using the camera data.

The prototype of Seismo is implemented on the Google Pixel phone, which has the BST-BMI160 inertial measurement unit with a stock setting of 250uG/LSB and 400Hz sampling rate. Although it is technically possible to improve the resolution to 61uG/LSB and sampling rate to 2000Hz, we found that the stock setting is good enough for our use case. The phone's back camera operates at a standard frame rate of 30 fps.

The following sections describe the signal processing of the captured SCG and PPG signals in this setup, and the calculation of PTT from the processed signals.

Synchronization

The Android SDK does not guarantee perfect synchronization between different sensor subsystems, hence we need to synchronize the data collected from the camera and the accelerometer subsystems. For the synchronization, the user places the phone on a flat surface for each use, and the phone's speaker plays a series of three beeps (Figure 3). The vibrations caused by the beeps is captured by both the microphone (which is synchronized with the camera subsystem) and the z-axis of the accelerometer (axis perpendicular to the screen).Using a matching filter of the expected vibration pattern, the timing of the beeps was extracted from both the microphone signal and the accelerometer signal. The timing delay is then used to shift the accelerometer signal to synchronize with that of the microphone signal based on the beep timing. We found this timing to be about 170±15ms.
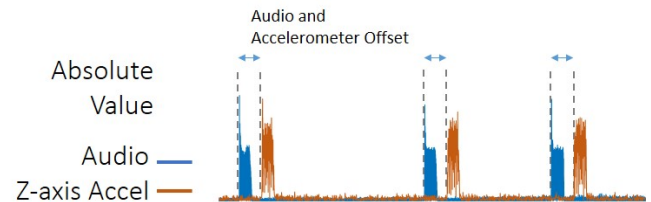

Figure 3. A series of three beeps is played through the phone's speaker to synchronize the camera and accelerometer subsystems.

PTT Calculation

To calculate PTT, we need to measure the time difference between the aortic valve opening (AO) and the pulse reaching the finger. The SCG signal from the phone's accelerometer provides the AO, while the PPG from the camera provides the pulse timing at the finger. PPG has a much higher SNR, compared to SCG. Thus, we first extract the timing of the pulse arriving at the fingertip using the camera data, and use that to search for the position of the AO relative to it. From the camera data, for each heartbeat, we need to find the foot of the PPG waveform, which denotes the end of diastole. First
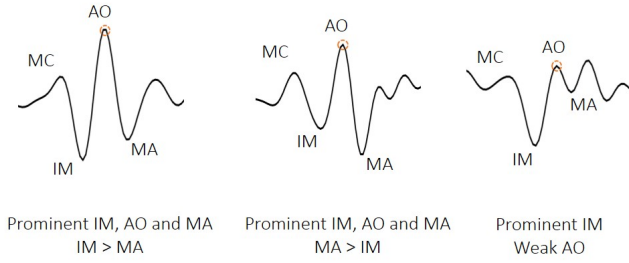
Figure 4. The SCG is produced by the consecutive mechanical movements during a heartbeat (MC, IM, AO, then MA). However, the relative amplitude of each movement changes depending on the person and position of the accelerometer placement.

we calculate the heart rate by taking an FFT of the PPG, and retrieving the dominant frequency. The heart rate is then used to predetermine the minimum spacing between successive pulses. To calculate the actual timing of the pulse wavefront, we use the second derivative of the PPG signal, called acceleration photoplethysmogram (APG), instead of the original PPG waveform. The reason for this is the peak of the APG accentuates when the pulse shows up at the finger. By using the heart rate as the minimum spacing, we then apply a standard peak detection algorithm to capture the peak of the APG.

The Y-axis of the accelerometer records SCG at 400Hz. The accelerometer captures the vibration induced by the mechanical motion of the heart when it beats. The SCG is the low-frequency (0.8-20Hz) component of this vibration. Figure 5 shows the SCG waveform captured by the accelerometer after bandpass filtering. The SCG waveform has a series of characteristic points resulting from the different phases of the heartbeat. A typical SCG captures the mitral valve closure (MC), isovolumetric moment (IM), the aortic valve opening (AO), and maximal acceleration (MA) (Figure 4). As discussed before, the major advantage of SCG is that it can capture AO, which cannot be captured by the sound-based phonocardiogram (PCG) as it measures the high-frequency (30-150Hz) component caused by the closure of the mitral valve. The PCG is sometime coupled to the accelerometer as the accelerometer acts as a contact microphone. To ensure that the timing of the AO is not affected by the PCG, a bandpass filter from 0.8-20Hz is applied to the raw accelerometer signal to remove breathing artifacts below 0.8 Hz and the sound of the PCG signal .

We need to find the timing of the AO point for every beat. Some characteristics of SCGs include: (1) the AO point happens before the PPG signal begins to rise, and (2) the AO point happens after the IM, which typically has the strongest negative amplitude signal before the arrival of the distal pulse. Hence we can use the PPG waveform extracted in the previous step to aid in finding AO point, which is expected to be between two successive APG peaks. We extract all the positive and negative peaks from the SCG prior to each APG peak, the duration being determined by the heart rate. We designate the negative peak with the highest prominence as the IM point. The prominence of a peak measures how much it stands out due to its intrinsic height and its location relative to other

peaks. However, for certain SCG morphologies, in particular those recorded closer to the sternum, the MA point can have a similar prominence as the IM point (Figure 4). To take care of such cases, the algorithm then compares the negative peak ahead of the most prominent negative peak to determine if the most prominent peak is IM or MA. If the peak extracted is from MA, then the peak ahead of it would also have a high prominence. In this case, we compare the prominence of the two peaks and if the ratio of their prominence is above 90%, a threshold that we empirically determined to work well, the algorithm chooses the peak ahead of the most prominent peak as the actual IM. Finally, since the AO point necessarily occurs after the IM, the positive peak following immediately after IM is chosen to be the AO. Finally, the time difference is calculated for each AO and APG peak pair, with the median taken as the PTT.
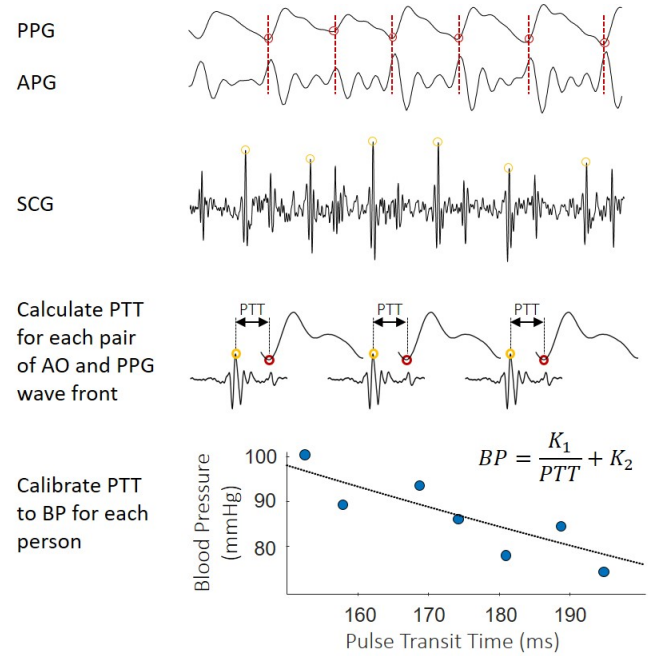

Figure 5. PPG and SCG signals are used to measure the PTT. The maximal point of acceleration of the PPG (APG) is compared with the AO point of the SCG. To convert PTT to BP, an individualized calibration of PTT to BP is generated based on reference recording with a blood pressure cuff.

Blood Pressure Calculation

To calculate blood pressure from the PTT, an individualized calibration for each user needs to be created. In our evaluation, we use the data from the first day of the intervention study for calibration between PTT and BP, and test how well it performs for the remaining three days. A least-square fit is used to fit the PTT measured with Seismo and the ground-truth blood pressure measured by a cuff-based sphygmomanometer, using the Moens-Kortweg equation (Figure 5) to estimate the subject-specific coefficients K_1 and K_2.

EVALUATION: BLOOD PRESSURE ESTIMATION

To validate the performance of Seismo, we recruited nine participants (five female) to perform a series of stationary

Table 1. Participant statistics and results for the 4-day bike study

ID	Age	Sex	Weight [lb]	Height [in]	Day 1 DP [mmHg]	All Days DP [mmHg]	RMSE [mmHg]	R
1	27	F	130	67	81 - 96	75 - 101	5.2	0.63
2	61	F	134	65	92 - 114	91 - 114	5.8	0.52
3	26	F	101	64	68 - 79	68 - 84	3.3	0.68
4	27	M	145	70	84 - 89	75 - 91	3.3	0.20
5	56	M	190	72	90 - 97	80 - 107	4.9	0.59
6	55	F	114	64	62 - 85	62 - 88	4.4	0.77
7	66	M	162	72	79 - 92	79 - 112	9.2	0.45
μ	44		139	68			5.2	0.55
σ	17		30	4			2.0	0.19

bike tasks. All participants were recruited from within the author's institution, with an age range from 26 to 66 years (μ=44, σ=17). Participants were paid 50 USD/session and all protocols are approved by our institution's IRB.

Participants are asked to ride a stationary bike five times, for 2-minutes each. The bike riding intensity varies from 50%, 75%, 100%, 75%, and 50% of the participants' maximum speed. The participant's blood pressure is first taken at rest. Then the participant performs the first 2-minute bike ride at 50% of the maximum speed. Just after the bike ride, their blood pressure is taken again. The participant repeats this until they finish all five rounds of biking. At the end, the participant is asked to rest for two minutes, and their blood pressure is measured again after the rest. In total, the blood pressure and PTT are measured 7 times (once before biking, 5 times after biking at each intensity, and once after two minutes of rest).

The blood pressure is measured simultaneously using Seismo and with a standard blood pressure cuff device (Microlife bp3na1-1x) as ground truth. Both the measurements are started at the same time. The Seismo measurement is taken with the right hand index finger over the camera, while holding the phone at the sternum, or upper chest just below the clavicle (Figure 1). Each Seismo measurement takes 30 seconds. The blood pressure cuff is placed over the left upper arm. The blood pressure cuff measurement typically takes between 30-60 seconds depending on the participant's blood pressure, and provides a measure of systolic and diastolic blood pressure.

The study was conducted in a quiet office, so external vibration is not evaluated by our study. However, during development, we observed negligible impact of surrounding noise, such as speaking, passing cars, and gym activities.

Results

All the participants completed all four days of the bike study. Of the nine participant, two participants are removed from analysis as the data collected from them is inconsistent. One old male participant suffers from severe hand tremor, and as SCG is of similar frequency to his hand tremor, most AO peaks are masked. Another female participant exhibited poor SCG signal both at the sternum and at the clavicle. We suspect this is due to low acceleration caused by dampening by fat and muscle tissues.

After removing the two participants, we have a total of n=196 (= 7 participants x 4 sessions x 7 measurements/session) blood

pressure and PTT measurement pairs for analysis. The average diastolic blood pressure, and average blood pressure fluctuation per participant observed in the study is μ=88±11.5 mmHg. Individual breakdown is shown in Table 1.
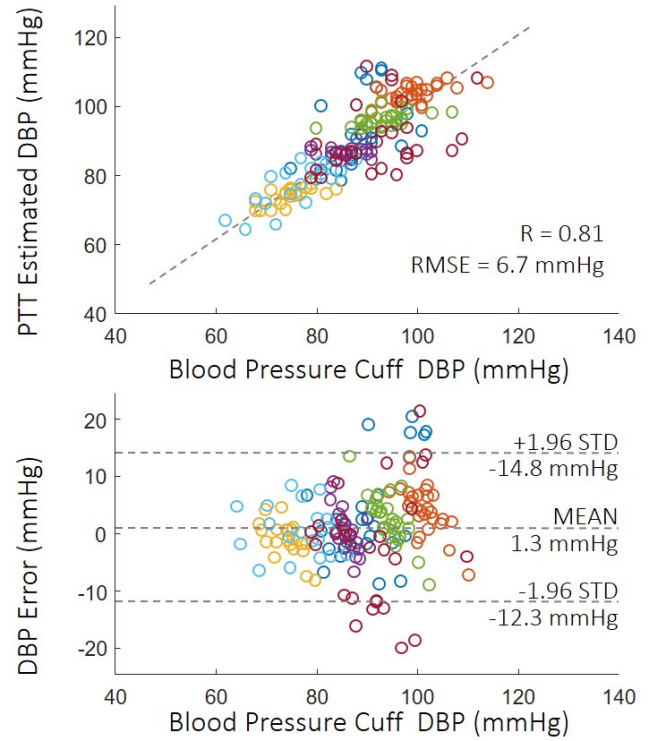

Figure 6. Correlation and Bland-Altman plot between DBP estimated using individual calibration and reference blood pressure measurements of the seven participants included in analysis.

For each participant, the first days' PTT measurement by Seismo and the blood pressure reference measured by the cuff are used for calibration. With this calibration, the subject's blood pressures for the rest of the sessions are estimated from the PTTs measured and compared against the reference cuff-based BP measurements. The calibration performed in our work is limited to the mechanism of BP perturbation caused by exercise, and our work does not include other vasomotor tone modulation induced by cold pressor or stress.

We analyze the relationship between the pulse transit time and diastolic blood pressure (DBP). This is because the foot

of the PPG signal (or peak of the APG signal) measures the arrival time of diastole and not systole. Correlation of pulse transit time with systolic blood pressure (SBP) comes from an associated increase of SBP with DBP, but is not a direct relationship. For this reason, we focus only on the correlation of DBP with PTT. The average Pearson correlation coefficient across all participants is 0.55 and the average RMSE is 5.2 mmHg across participants, with R between 0.20-0.77 and RMSE between 3.3-9.2 mmHg.

Figure 6 shows the calibrated PTT and DBP for all participants. When all participants' estimated blood pressure using the individual calibration is correlated against the reference blood pressure measurement, we find the Pearson correlation coefficient = 0.81 with an RMSE = 6.7mmHg. As seen in the CDF, 67% of absolute errors fall under 5 mmHg, 87% fall under 10 mmHg, and 94% fall under 15 mmHg (Figure 7), with the maximum being 21.3 mmHg.
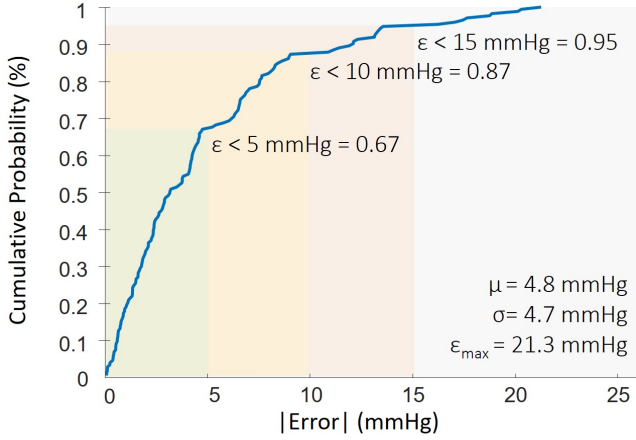

Figure 8. Left: Subject-3 with an R=0.68 exhibiting the expected pattern in both reference blood pressure and PTT changes. Right: Subject-4 with an R=0.20 exhibiting only the PTT showing the expected trend across multiple sessions.

Figure 7. CDF of the absolute error between the estimated DBP from Seismo to the reference DBP from the Microlife blood pressure cuff.

DISCUSSION

Limitations
One of the main limitation of the evaluation is the reference blood pressure. Although the Microlife bp3na1-1x used in the evaluation is rated A/A under the BHS Standard, it is not designed for measuring rapidly changing blood pressure. In comparison, other works [3, 10] that have demonstrated high correlation between PTT and BP during BP perturbation studies instead use a reference system that measures blood pressure continuously, such as a ccNexfin finger cuff (Edwards Lifesciences, Irvine, CA). Such a system can more reliably capture the fast-changing blood pressure after exercise, but it is very expensive and specialized. It is likely that some of the disparity between our results and results from prior work [3, 10] can be attributed to using a different system to measure ground truth. In fact, the participant with the lowest correlation, Subject-4, has sessions where his/her reference blood pressure remain unchanged even after intense biking. When PTT of Subject-4 is measured, it reduces as expected. Figure 8 shows Subject-3 which has the expected trend of both – the reference blood pressure and the inverse of pulse
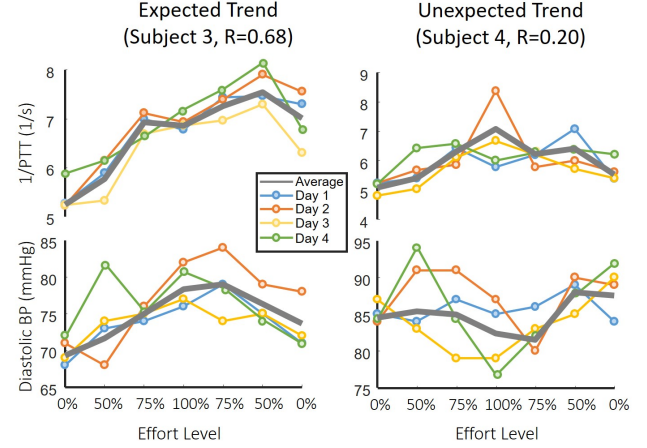
transit time – increasing due to exercise, while for Subject-4, the inverse of PTT is following the expected trend, however the reference blood pressure does not. If we remove Subject-4, the group correlation improves to 0.61.

We compare our system with prior work, using either ECG or SCG as a reference. Although widely used as a method for noninvasive blood pressure monitoring, ECG-based pulse arrival time measurements have been shown to poorly correlate with diastolic blood pressure due to the pre-ejection period [25, 3]. In contrast, techniques that can thus capture the actual timing of aortic valve opening can accurately determine the pulse transit time and thus correlate with blood pressure more reliably. Previous studies using ECG and PPG positioned at the finger/wrist found correlations between PAT and DBP to be 0.40±0.35 [12], 0.26-0.57 [14], and 0.41 [2]. In comparison, our average correlation between PTT and DBP is comparatively high at 0.55 (or 0.61 when removing the outlier Subject-4).

When compared to other methods that accurately capture the aortic opening time, our correlation results are comparable to 0.57±0.13 by [24], 0.62±0.16 by [10], but is comparatively lower than 0.84±0.09 by [3]. Although our system demonstrates a slightly lower accuracy compared with state-of-the-art in prior work, a main contribution of our work is in showing that a smartphone's built-in SCG and PPG measurement can be used in measuring pulse transit time for tracking blood pressure. Compared with SeismoWatch [3], which uses a ultralow-noise accelerometer (ADXL354 with a noise floor $20\mu g/\sqrt{Hz}$, instead of using a dedicated hardware system, Seismo relies on a built-in smartphone accelerometer (BST-BMI160 with a noise floor of $180\mu g/\sqrt{Hz}$), which is a typical sensor for commodity phone hardware. To enable built-in sensors to perform PTT measurements, we came up with a synchronization technique that uses the built-in speaker that is always available on the phone as well.

Of the nine participants in the study, two participants were taken out of the analysis due to poor signal quality. One participant's hand shook while performing the measurement, and the motion artifact often over-shadowed the SCG. The current prototype has the person holding the phone with the screen facing them. This position is ideal since in actual use, it is more suitable for users to be able to see the screen while operating the app. However, for users whose hand shakes, holding the phone in a floating position is difficult. Instead, if the phone were held to the chest with the screen against the chest, the hand would no longer be floating, making the position more stable.

Another participant was removed from the analysis due to low signal strength caused by thicker tissue mass between the heart and the phone's accelerometer. This demonstrates a limitation of the sensor. As the noise floor of the sensor is relatively high compared to that of a low noise accelerometer used by [3], with a low measurable heartbeat acceleration possibly caused by damping by fat tissues, our system was not able to resolve such a signal. This was particularly the case when the participant was at rest. During the high intensity biking efforts, however the participant's increase in cardiac output did allow for a stronger SCG signal, and the sensor was able to reliably detect the SCG.

Incorporating Smartphone Blood Pressure Monitoring to Personal Health Tracking Applications

By only using the built-in sensors of the smartphone, Seismo can monitor blood pressure without any modifications to a smartphone with a camera and accelerometer. We envision such a smartphone based PTT measurement can be useful in a variety of scenarios depending on the availability of resources.

Supplement to At-Home Blood Pressure Cuff

A smartphone solution to measure blood pressure can be a good supplement for patients who are already monitoring their blood pressure with the cuff. Although a person can easily keep a cuff around at home and monitor once or twice a day to gain knowledge of their general blood pressure trends, it is hard to carry a cuff around as they go out of their house or when they travel. Having a smartphone based method can certainly help in such a scenario. Moreover, Seismo can be use for blood pressure monitoring for pre- and post-exercise. Here blood pressure change pre- and post-workout can even act as an additional measure of workout quality beyond heart-rate tracking. Using Seismo, the user can also track their blood pressure recovery time after a cardio workout. One of the advantage to a pulse transit time based blood pressure monitoring is the ability to track blood pressure continuously, something that can not be tracked even if the user had brought a cuff with them to the gym.

Cardiovascular Risk Screening

In order for PTT-based blood pressure monitor to measure blood pressure accurately, the user needs to calibrate it. As such, for users who do not already have access to a cuff, Seismo would not be able to readily translate the measured PTT to blood pressure. However, in this case, Seismo can still offer insight into the person's cardiovascular health. The

relationship between PTT and blood pressure also depends on arterial stiffness. Arterial stiffening occurs naturally as people age, however excessive stiffening usually suggests some form of health risks, such as plaque build-up. PTT has been shown to be a potent index for monitoring arterial stiffness [26] by taking into account arm length, gender, and age. In well-equipped hospitals, an ECG and PPG system is often used to monitor PTT to screen for arterial stiffening. However, this is not available in low resource areas. Using Seismo, reliable PTT measurements can be made available through phones that are already available in these areas to enable arterial stiffness screening.

CONCLUSION

Seismo is a smartphone-based blood pressure monitoring technique that uses the built-in accelerometer to measure SCG and the smartphone's camera to measure PPG, in order to calculate pulse transit time to estimate blood pressure. In our evaluation with nine participants, we observed that two participants exhibited signals that were too noisy for our system to produce consistent SCG signals. Further investigation into different positioning of the phone may improve the motion artifacts that occur due to someone's hand shaking. For participants with a weaker heart beat and more fat and muscle tissues between the accelerometer and the heart impedes the transduction of the SCG. In this case, the high noise floor of the built-in accelerometer suffered in acquisition of the SCG. Of the seven participants that produced clean SCG and PPG signals for further analysis, we found the group correlation to be between 0.20-0.77 with a mean of 0.55. Although this result is a bit lower than prior work that uses similar signal source to infer pulse transit time, upon further investigation, we noted that the participant with the lowest correlation exhibited unexpected reference blood pressure measurements. For this participant, even though their pulse transit time decreased with respect to increase biking effort, their blood pressure did not follow the expected trend of increasing with increased effort. When we look at the group correlation without the worst correlated subject, the correlation becomes 0.61, comparable with most of the related work. Through this evaluation, we show that the built-in sensors of a smartphone can acquire high quality signals for use in pulse transit time based blood pressure monitoring, while also revealing some of the short comings and improvements that can potentially mitigate them.

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