Naptics: Convenient and Continuous Blood Pressure Monitoring during Sleep

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Normal circadian rhythm mediates blood pressure during sleep, decreasing in value in healthy subjects. Current methods to monitor nocturnal blood pressure use an active blood pressure cuff that repeatedly auto-inflates while the subject sleeps. Since these inflations happen in intervals of thirty minutes to one hour, they cause considerable sleep disturbances that lead to false measurements and impact the person's quality of sleep. These blood pressure samples are also just spot checks and rarely exceed 10–15 values per night.

We present *Naptics*, a wearable device woven into shorts. Naptics passively monitors the wearer's blood pressure throughout the night—continuously and unobtrusively—without disturbing the user during sleep. Naptics detects the micro-vibrations of the wearer's body that stem from the heartbeat and senses the optical reflections from the pulse wave as it propagates down the wearer's leg. From the timing between these two events, Naptics computes the *pulse transit time*, which correlates strongly with the user's blood pressure.

Naptics' key novelty is its unobtrusive approach in tracking blood pressure during the night. Our controlled evaluation of six subjects showed a high correlation ($r = 0.89$) between Naptics' calibrated mean arterial pressure and cuff-based blood pressure. Our in-the-wild evaluation validates Naptics in tracking five participants' blood pressure patterns throughout four nights and compares them to before and after cuff measurements. In a majority of the nights, Naptics correctly followed the trend of the cuff measurements while providing insights into the behavior and the patterns of participants' nocturnal blood pressure. Participants reported high sleep quality in sleep diaries after each night, validating Naptics as a convenient monitoring apparatus.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing systems and tools**; *Ubiquitous and mobile devices*;

Additional Key Words and Phrases: Blood pressure, nocturnal hypertension, pulse transit time, continuous physiological sensing, wearable device, unobtrusive monitoring

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1 INTRODUCTION

Monitoring blood pressure serves as a significant indicator for assessing a person's health. In particular, blood volume and arterial blood pressure as the conjunction of arterial resistance and cardiac output serve as a critical signal in the evaluation of a person's cardiovascular system. While in-clinic blood pressure monitoring remains

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the cornerstone of hypertension management, at-home monitoring can give a more complete picture of heart health and can potentially detect masked hypertension, which is only evident *outside* the clinic [1].

The most common form of at-home monitoring involves merely an oscillometry-based blood pressure cuff. A user attaches the cuff multiple times a day to prepare a measurement and holds still while the cuff self-inflates and the device records the user's systolic and diastolic blood pressure as well as their pulse rate. This form of blood pressure tracking is inexpensive, patient-friendly, and accurate [6]. However, cuff-based measurements are limited in effectiveness to times *during* the day when this obtrusive method of taking a reading is tolerable.

In a healthy individual, blood pressure follows a circadian rhythm and tends to dip between 10–20% below day-time values at night [5]. Such blood pressure decreases during the night are typically associated with a withdrawal in sympathetic tone, decreasing heart rate, and peripheral resistance [34]. Persons that exhibit a drop in blood pressure during the night ("dippers") have significantly lower total mortality and cardiovascular events such as stroke, heart failure, or coronary disease than persons with constant day-time and night-time blood pressure ("non-dippers") or increased night-time blood pressure ("reverse dippers") [7, 29]. Even when compared to patients with essential hypertension (i.e., hypertension with no known secondary cause), the lack of dipping blood pressure values are associated more closely with cardiovascular events [8, 28, 48]. Such a lack of dipping blood pressure values during the night can result from disorders such as sympathetic imbalances, decreased sodium excretion, sleep apnea, and insulin resistance [33].

In contrast to daytime blood pressure monitoring, measuring blood pressure values during sleep poses a substantial challenge. Since oscillometric cuffs require *manual* application, they help to monitor blood pressure only during the day and cannot observe blood pressure changes during sleep. Furthermore, proper diagnosis of hypertension and risks associated with hypertension requires measurements throughout a *24-hour period*. This 24-hour period is essential, because a patient may experience nocturnal hypertension without exhibiting signs of hypertension during the day [33], which makes monitoring blood pressure during sleep crucial for *holistic* assessments. Therefore, monitoring blood pressure at night not only improves hypertension assessment but is critically informative as nocturnal readings are superior to daytime blood pressure when assessing cardiovascular risk [41].

Unfortunately, while current 24-hour monitoring devices are obtrusive and inconvenient, they are the only metric for diagnosing those patients who have an increase in blood pressure during the night but normal levels during the day (i.e., isolated nocturnal hypertension) [33]. The typical means of 'continuously' monitoring a patient's nocturnal blood pressure is to strap a semi-automated cuff-based blood pressure monitor to their arm. The cuff auto-inflates during the night during preconfigured intervals and, similar to daytime readings, applies a considerable amount of pressure to the arm, which can be painful and as a result often wakes up the patient during the night [16]. According to the European Society of Hypertension, ambulatory blood pressure cuffs should take a measurement every thirty minutes [39]. This periodic arousal causes the user's quality of sleep to suffer and often severely impacts their performance during the following day.

In this paper, we introduce *Naptics*, an unobtrusive textile device embedded into a pair of shorts that continuously senses and monitors a person's blood pressure behavior during the night.

1.1 Naptics: Convenient and Continuous Nocturnal Blood Pressure Monitoring

As shown in Figure 1, Naptics is a wearable device woven into a pair of compression shorts. Naptics is in constant contact with the body and passively monitors blood pressure throughout wear by recording pulse transit times (PTT [37]): the timing interval for a forward-going pulse wave to travel between two arterial sites. Naptics detects the micro-vibrations of the body associated with cardiac ejection using an accelerometer, while optical sensors detect each pulse wave as it propagates down the leg through the femoral artery. The delay between these events is the pulse transit time, which correlates strongly with a user's blood pressure [32, 37]. Naptics' observation of

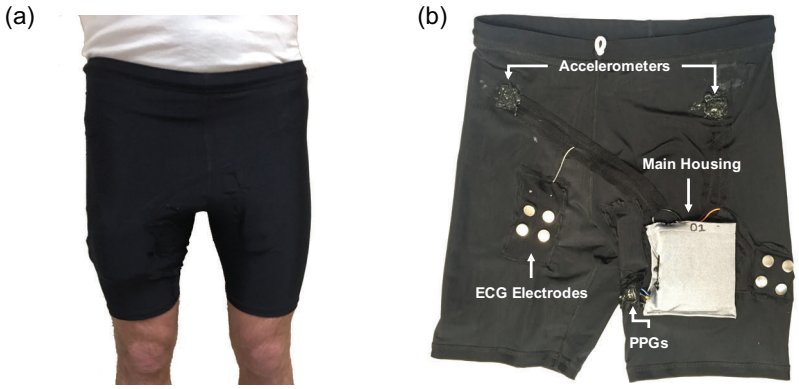

Fig. 1. a) Naptics is a wearable device woven into a pair of compression shorts to *continuously* monitor the wearer's blood pressure during the night. b) Naptics incorporates a series of physiological sensors, including electrocardiogram (ECG), ballistocardiogram (BCG) using sensitive accelerometers, multiple optical photoplethysmography (PPG) sensors, as well as a pulse oximeter and a temperature sensor. Naptics continuously records the measurements of all sensors and derives the wearer's pulse transit time, a metric that correlates highly with a person's blood pressure [10, 24, 32, 37]. Naptics saves all records on a storage card along with timestamps from a real-time clock.

the femoral artery has the potential to record aortic pulse transit times, which most strongly correlate with a user's *central blood pressure* [21].

Naptics' form factor is flat and modular, supporting bending and a limited amount of stretch through cable slack to account for motion during sleep. Naptics detects the wearer's motions during sleep, from which it extracts sleep phases, turns, and breathing rates. Temperature and blood oxygenation sensors supplement all nighttime recordings with continuous measurements. Naptics runs for over 10 hours on a single charge and includes charging components and a USB port for recharging during the day.

Naptics unobtrusively and passively monitors blood pressure during the night. Unlike cuffs or related PTT-sensing devices, Naptics *conveniently* monitors blood pressure with no interference during sleep, obtaining BP behavior at a beat-to-beat sampling rate. In line with recent studies that point to the *variance* of a user's blood pressure as the more indicative marker of autonomic cardiac regulation than the cuff-based averages [43], Naptics is optimally equipped to inform this metric about a person's health.

Naptics' *continuous* approach to sensing supersedes the state of the art in nocturnal monitoring in resolution and frequency, forgoing the need to trade off convenience (e.g., number of inflations) with resolution. Naptics can detect events and patterns in a wearer's nocturnal blood pressure that may get lost between two automated cuff measurements, such as a shortened rapid eye movement (REM) sleep lasting fewer than 7 minutes [11]. Since Naptics does not impact the wearer's sleep quality or sleep duration, it can serve as a measurement instrument that patients may wear for a series of nights *in a row*, removing measurement error or detecting medication responses that are essential to detecting, diagnosing, and treating patients.

Unlike previous PTT-sensing devices, Naptics samples pulse waves on the femoral artery. Naptics is capable of taking *aortic* PTT measurements by sampling at the *I* wave of the wearer's BCG and by monitoring a PPG sensor near the beginning of the femoral artery. Larger diameter arteries such as the aorta have a lower variability of elasticity independent of BP when compared to smaller arteries such as the radial artery, allowing for a higher correlation between the inverse of PTT and blood pressure. A previous study showed improved correlation to blood pressure when measuring PTT through a central artery compared to PTT through more distal arteries [21].

To complement Naptics' operation, a user measures their blood pressure using a conventional apparatus, such as an oscillometric cuff, before sleep at night as well as first thing in the morning after waking up. These measurements provide Naptics with absolute blood pressure measurements that we use to retrospectively anchor all recorded pulse transit time values and thus translate them into absolute blood pressure levels.

We validated Naptics in two folds. Our first evaluation establishes Naptics as an accurate measurement apparatus for pulse transit times with a strong correlation to 6 participants' absolute cuff-based measurements (Mean Arterial Pressure $RMSE = 3.4$ mmHg) during standardized perturbation procedures. In our second evaluation, we deployed five Naptics prototypes to participants and studied their performance in-the-wild over the course of four nights each. Participants' Naptics devices correctly tracked absolute blood pressure trends throughout the study (with only four outliers) and, more importantly, provided detailed insight into the behavior of participants' blood pressure during their nights. For all nights, participants reported high sleep quality through the use of sleep diaries, supporting our design intention of *convenient* monitoring. No Naptics prototype produced any side effects such as pain due to repeated cuff inflation, sleep loss, or tiredness during the following day.

While we designed Naptics specifically for nighttime use during sleep, our prototype records all metrics throughout *wear*, i.e., during the night and the day. Since the compression shorts have all the components embedded in the fabric, users may wear the shorts underneath regular clothing. Therefore, Naptics has the potential to serve as a 24-hour monitoring device that is with the user at all times, unobtrusively recording values.

1.2 Contributions

We make the following contributions in this paper:

(1) A technique to *continuously* record the wearer's pulse transit time through simultaneous monitoring of BCG and PPG during sleep, which records cardiac events at a proximal and a distal location, respectively. The resulting measurements of nocturnal PTT give insight into the wearer's night-time hemodynamics and can assist in diagnosing hypertension, managing medications, or determining cardiovascular risk.
(2) Naptics, a prototype device that unobtrusively integrates with a convenient shorts-based form factor and that does not interfere with normal sleeping patterns. This increases the reliability of true nocturnal measurements compared to cuff-based disruptions. Naptics also integrates physiological sensors such as temperature and pulse oxygenation that are useful in monitoring sleep behavior and quality.
(3) Two evaluations that establish the feasibility of our method and prototype in a six-participant controlled lab evaluation and that demonstrate the promise of our approach during a five-participant in-the-wild evaluation over the course of four nights, resulting in insightful and fine-grained blood pressure patterns, all while participants rated sleep quality as high in sleep diaries.

2 RELATED WORK

2.1 Nocturnal Blood Pressure Monitoring

The current gold standard of arterial blood pressure in a clinic is intra-arterial blood catheterization, which is invasive and requires trained personnel. Catherization requires a strain gauge tipped catheter to be inserted into an artery to make direct contact with the fluid. For nocturnal measurements, only sleep studies that require absolute blood pressure administer this procedure [14, 19].

For nocturnal blood pressure measurements at home, the typical means is a semi-automated cuff that patients wear around their upper arm. During the night, the cuff auto-inflates during preconfigured intervals, typically every thirty minutes. Similar to daytime use, the resulting amount of pressure can be uncomfortable, thereby disrupting sleep, often waking up the patient [16], which can disrupt a person's circadian patterns and may influence dipping [2]. More noticeably, this also severely impacts the patient's quality of sleep and their level of

performance during the following day. Ambulatory blood pressure monitoring is thus typically limited to once every three to six months [39].

Common less obtrusive systems for nocturnal blood pressure monitoring employ the volume-clamping method [15]. A small cuff wrapped around a finger inflates and deflates during each cardiac cycle to continuously record blood pressure. While they utilize a pressure cuff, these devices disturb sleep less than an oscillometric cuff and provide an accurate blood pressure reading [15, 43]. However, the cost and bulk of volume-clamping monitors limit them to either research laboratories or clinics [40].

2.2 Pulse Transit Time

Pulse transit time (PTT) is the time delay for the pressure wave following a heartbeat to travel between two arterial sites. The speed of this forward-going wave is dependent on the stiffness of the arteries with a stiffer artery propagating the pulse wave faster. Since arterial stiffness is proportional to blood pressure, PTT is therefore inversely correlated to the person's blood pressure according to the following equation [37].

$$BP = \frac{K_1}{PTT} + K_2 \tag{1}$$

where K_1 and K_2 are subjected-specific parameters. This method requires the measurement of the pulse wave at two distinct locations—one distal and one proximal to the heart—along the arterial tree to obtain the two timing references for PTT calculations. Ideally, the proximal timing reference would be close to the heart and the distal timing reference would be in a convenient location farther down the arterial tree such as the radial or femoral artery.

Conventional technologies such as optical sensors can measure the pulse at distal locations such as near the foot [4] or the hand [45]. Sensing of the proximal pulse near the heart can be challenging with techniques including seismocardiogram (SCG) [50], impedance cardiogram (ICG) [44], and carotid photoplethysmogram (PPG) [20]. While all these techniques have potential to provide reliable proximal timing, they would likely require the use of two independent units or for the user to preform a particular maneuver, which could be difficult during sleep.

The most common surrogate for a proximal timing reference is electrocardiogram (ECG), the electrical activity of the heart. Wearables frequently incorporate ECG due to the ease of measurement. Zheng et al. developed a PTT based system that uses a combination of ECG and PPG around the arms to estimate blood pressure during the night [51]. However, measurements utilizing ECG are not valid metrics of PTT but of pulse arrival time (PAT) with the ECG providing the initial timing reference for PAT. This misconception is due to the often overlooked time delay between the onset of the R-wave and the ejection of the blood from the heart, also called the pre-ejection period (PEP). In differing scenarios, PEP can either increase or decrease independently of changes in BP. A watch-based system can monitor the micro-vibrations associated with a heartbeat and thus PTT; though, it has only validated in a standing position [49]. Arm position and strap tightness during sleep can vary, potentially corrupting measurements.

Although previous works proposed wearable devices to unobtrusively sense blood pressure using the pulse transit time (e.g., [10, 24]), they are unsuitable for use during sleep. SeismoWatch [10] is an active watch-based system and requires the user to manually place the device on the sternum while actively applying pressure through the wrist. Glabella [24] is a passive pair of glasses that continuously tracks blood pressure, but it is inadequate for wear during the night due to the form factor, sensing modality, and sensing location. Such restrictions limit both devices to day-time measurements only.

Naptics extracts pulse transit time values from the delay between ballistocardiography events and pulse wave events at an arterial site. This method has previously been demonstrated to work using stationary scales to sense BCG and PPG sensors to measure the pulse wave in the user's foot. This technique of using BCG and PPG for PTT extraction was shown to be a better estimation of blood pressure over conventional pulse arrival time methods

[32]. Naptics integrates the acceleration sensor directly in the pair of shorts and couples it with the wearer's torso, while optical sensors observe pulse wave reflections on the femoral artery on the wearer's thigh.

2.3 Sleep Monitoring

Monitoring of pulse transit time has been shown to provide some assessment of sleep quality, primarily as a measure of obstructive sleep apnea or similar respiratory disorders. The airway obstruction increases respiratory efforts and can cause an exaggerated decline in blood pressure. Thus, PTT can be indicative of respiratory efforts [47].

Sleep stages and sleep-related disorders can be evaluated using BCG measurements. The lack of attached electrodes gives BCG an advantage over techniques such ECG or polysomnography (PSG) that are commonly used in sleep studies to assess sleep stages. Sensors can be directly integrated into the sleeping environment to prevent disturbances during sleep. Previous studies used pressure sensors in an air mattress [12], load cells in the legs of a bed [13], and piezoelectric film sensors in a mattress pad [42]. Analysis of the spectral component of BCG heartbeats led to three-stage classification (wake, REM, non-REM) of sleep [31].

3 IMPLEMENTATION

3.1 Naptics Prototype

Overall, our goal in designing Naptics was to obtain a form factor that is comfortable to wear for the user while continuously recording meaningful physiological data at representative sites on the body. We arrived at a prototype that is unobtrusive, compact, and comfortable, which we achieved by integrating flat sensing and processing electronics into a pair of shorts. The shorts limit the interference with the wearer's sleep to a minimum and passively collect data through an entire night's sleep with no requirement for user interaction.

3.1.1 Physiological Measurements: Pulse Wave (PPG) and Oximetry Measurement on the Femoral Artery, BCG and ECG for Cardiac Events, PTT between BCG and PPG. To monitor pulse transit time, Naptics primarily observes the BCG signal from the wearer's heart and the PPG reflections from the wearer's femoral artery. Monitoring the femoral artery allows for a majority of the PTT to occur while the pulse wave is in the aorta. Larger arteries such as the aorta are more representative of central pressure and have a low variability of elasticity independent of blood pressure.

Naptics computes the PTT delays as follows: Integrated sensors in Naptics monitor the arrival of the pulse wave at multiple locations on the arterial tree. PTT relates to blood pressure using the Bramwell-Hill Model, a modified version of the Moens-Korteweg equation that compares the arterial stiffness directly to the pulse wave velocity [9]. With a constant distance between sites and blood pressure corresponding proportionally to arterial stiffness, the inverse of PTT can be used to approximate blood pressure [37].

Our device focuses on obtaining the PTT from a combination of the ballistocardiogram (BCG) and photoplethysmogram (PPG) measurements, similar to previous stationary prototype scales [32], but with wearable, body-attached acceleration sensors in different locations and optical sensors for monitoring pulse waves. The BCG records the most proximal timing of the pulse waves. As the blood is ejected from the left ventricle to the aorta during each cardiac cycle, a reactionary force occurs and causes full-body vibrations. The traditional waveform is composed of the I, J, and K waves with the I wave typically corresponding to the initial cardiac ejection of blood [27]. Unlike ECG-based measurements that include pre-ejection activity, a 'noise' factor in estimating blood pressure, BCG represents the actual beginning of the pulse wave propagation, making it ideal for PTT measurements [30]. With regards to the more distal measurements, Naptics uses PPG sensors to optically capture the pulse wave, monitoring changes in arterial blood volume [3]. Previous studies commonly used PPG sensors as a timing reference for PTT [18, 38].

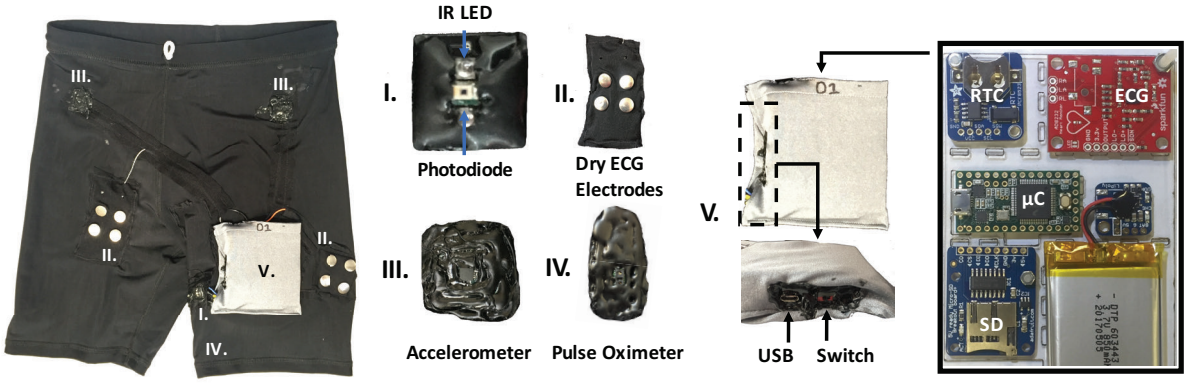

Fig. 2. Naptics integrates (I) photoplethysmography sensors, (II) dry ECG electrodes, (III) low-noise 3-axis accelerometers, and (IV) a pulse oximeter, all sewn to the inside of compression shorts. (V) The main unit houses the sensor boards, a real-time clock (RTC), an SD card writer, and a Teensy 3.2 microcontroller (μC).

Figure 2 shows the components we integrated into each pair of Naptics shorts. Naptics electronics design splits the device into a main component and satellite sensors.

3.1.2 Electronics Design. As shown in Figure 2 (left), each Naptics device is powered by a Teensy 3.2 (PJRC, Sherwood, OR) microprocessor that interfaces with all other components and samples data from all sensors at 1,000 Hz. The Teensy connects to a real-time clock (DS1307, Maxim Integrated), which is powered by a coin-cell battery to store accurately timestamped recordings to an SD card throughout operation and across charging cycles.

An 850 mAh lithium-polymer battery powers the device. Naptics supports battery charging through USB using a Microchip Technology charger IC (MCP73831). Naptics uses approximately 80 mA of power, allowing for over 10 hours of continuous run-time, which is sufficient battery life to capture a single night of sleep.

As shown in Figure 2, Naptics includes a variety of sensors, which we list below, along with the potential insights their signals may provide.

Sensor	signal and potential insights
Accelerometer	ballistocardiogram (BCG), motion activity to separate sleep poses, breathing rates, indicator of motion artifacts in other signals
LED + optical sensor	photoplethysmogram (PPG)
Electrodes	electrocardiogram (ECG)
Pulse oximeter	red and IR PPG to derive oxygen saturation

Two accelerometers (LIS344ALH, STMicroelectronics, Geneva, Switzerland) attach to the upper portion of the shorts near the belt line with one on either hip. These inertial sensors, when pressed against the body, record the full body vibrations associated with the BCG. By having two sensors placed on either of the hips, Naptics can measure regardless of the position of the body. The accelerometers will also provide information regarding body motions such as breathing, turns, getting up, walking, and lying back down, which can provide information on sleep cycles, sleep phases (e.g., Actiwatch Spectrum [46]), and quality of sleep.

Four photoplethysmograms attached in a row transversely along the inside leg of a Naptics shorts cover the location of the wearer's femoral artery. Each PPGs sensor consists of a pair of infrared light-emitting diodes

(IR LEDs) (VSMF2893GX01, Vishay Semiconductors, Malvern, PA) and a photodiode (SD040-101-411, Luna Optoelectronics, Roanoke, VA). We chose an IR LED to achieve deeper penetration than colors with lower wavelengths such as green or red [35]. IR LEDs more accurately capture deeper arteries, such as the femoral artery. The cathode of each photodiode is biased at 2.5 V, while the anode is connected to a transimpedance amplifier (G = 110 dB) with a lowpass cutoff at 8 Hz followed by a first-order bandpass filter ($BW = 0.7 - 8$ Hz, G = 59 dB). This array of four PPG sensors ensures adequate coverage of the inside of the thigh to monitor the femoral artery.

Distal to the PPG sensors is a pulse oximeter (MAX30100, Maxim Integrated, San Jose, CA). This component comprises a red LED, an IR LED, and a photodiode. It serves two purposes: (1) providing SpO_2 readings throughout the night and (2) sampling the wearer's pulse waves at a more distal location than the four PPG sensors. The additional pulse wave can establish a second timing reference for further potential PTT calculations (e.g., similar to Glabella [24]).

Three pairs of electrocardiogram (ECG) electrodes are attached on the inside of each Naptics shorts to monitor the electrical activity of the wearer's heart, to acquire a timing reference, and to measure heart rate and heart rate variability. An AD232 (Analog Devices, Norwood, MA) connects to three sets of metal snaps that act as dry electrodes for measuring the ECG. Although wet electrodes would provide a better coupling to the skin, dry electrodes allow the user to put on and remove the prototype comfortably. The metal snaps provide a smooth interface to the skin, therefore eliminating any discomfort. A set of four dry electrodes rests on each of the wearer's legs to interface with the thighs and to establish the lead. The third set of electrodes is in contact with the back of the wearer's right leg and acts as the right leg drive to reduce common-mode interference.

3.1.3 Mechanical Design and Assembly. A pocket on the lower right leg above the quadriceps houses the main unit that included the Teensy board, ECG board, real-time clock, battery/battery charger, and SD card reader. We chose the positioning of the main unit on the shorts to prevent the majority of users from lying directly on it. Simply relocating the main unit will prevent potential issues for users who sleep in a prone position with their stomachs face down (7% [25]).

Laser-cut flexible Nylon sheets cover both sides of all components in the main unit to prevent breaking, protect against impact, prevent direct contact, and support lying on all elements. To provide comfort for the user and another layer of protection, we added a thin foam pad on either side of the main unit. These layers of plastic and foam also create a layer of thermal insulation between the skin and the battery or MCU that users might perceive as warm.

As shown in Figure 2 and 3, we underfilled hot glue to the surrounding area around the LEDs and photodiodes for all optical sensors to reduce skin irritations caused by sharp edges [24]. We then reheated the hot glue with a reflow gun to smooth out the surface and to allow the glue to mold around the diodes, which produced a smooth surface.

3.2 Signal Processing

Figure 3 shows a block diagram of our signal processing pipeline. As a first step to extract PTT, we partition the signals into individual beats. After bandpass filtering the signals, a thirty-second window with 50% overlap separates the data. We then process each window separately. Since the PPG sensors proved the highest signal quality among the heart rate-related sensors (e.g., BCG, dry-electrode ECG), a simple peak detection algorithm applied to PPG reliably located each cardiac cycle. Using the PPG peaks as the fiducial marker, the separated beats formed an ensemble average, removing any zero-mean noise and extracting the signal's periodic waveform as seen in Figure 4. We compare this average signal to the removed noise to establish a signal-to-noise ratio (SNR) and use the peaks of the PPG signal with the highest SNR as the timing references for separating the beats for

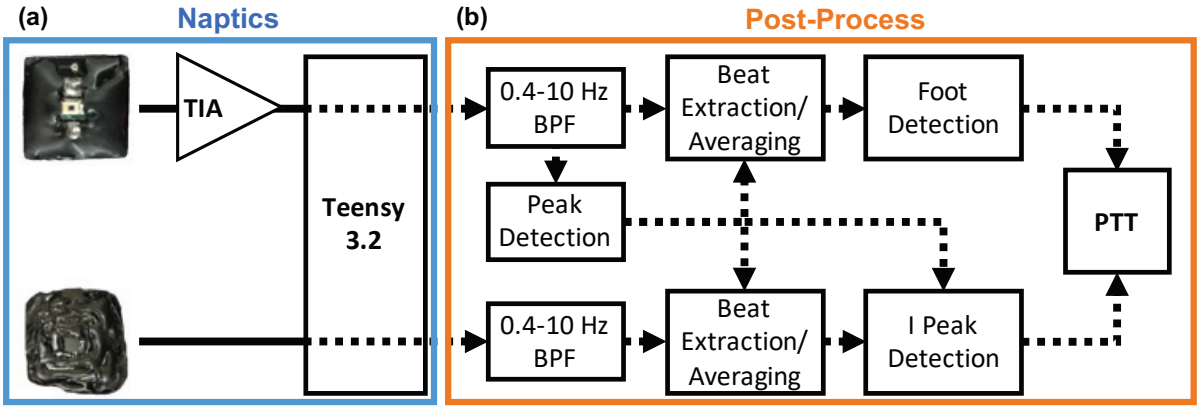

Fig. 3. Block diagram of front-end circuitry and back-end processing to extract PTT.

that particular window. If the SNR of the PPG sensors is deemed too low, we consider the entire window to be corrupted and remove it from further processing.

We then derive an ensemble average from each signal. A window 500 ms before and 500 ms after the peaks of the highest SNR PPG extracts each cardiac cycle from the two BCG, SpO_2, and four PPG signals. The difference between the individual signals and the ensemble average of the entire thirty-second window represents the noise for that signal. The average of the beats not deemed noisy form the final ensemble average for that winding. If either the number or the total SNR of the remaining beats is too low, we remove the signal.

The foot of the averaged PPG values represents the arrival of the pulse wave at that particular site. The intersection of the horizontal projection going through the beat's minimum and a projection tangent to the maximum derivative represents the foot. This timing reference from the PPG sensor with the highest SNR is then used to extract features from the BCG, in particular, the *I* wave. The closest non-negative maximum peak before the distal timing reference is the supposed *J* wave. The previous minimum peak then represents the *I* wave.

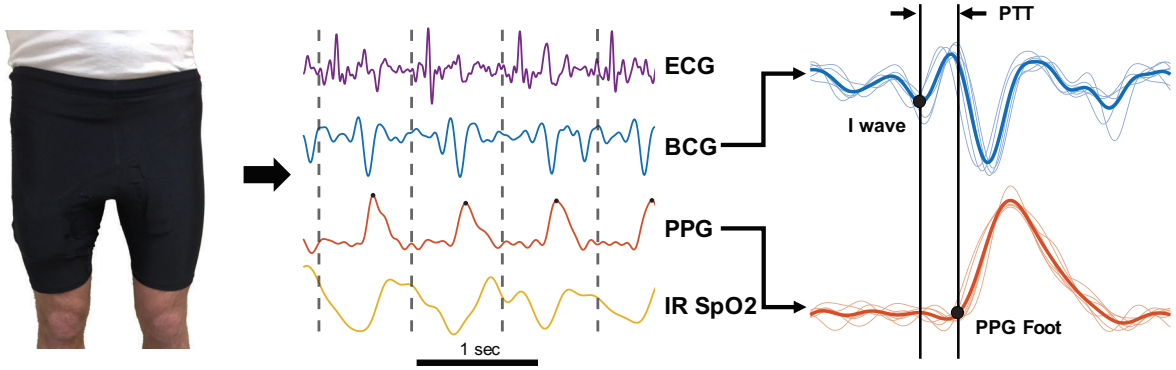

Fig. 4. Naptics continuously records the electrocardiogram (ECG), ballistocardiogram (BCG), photoplethysmogram (PPG) and pulse oximetry during the night. The peaks of the PPG separate the heartbeats, and ensemble averages of the PPG and BCG are computed. Features from these averages are used to determine the pulse transit time (PTT).

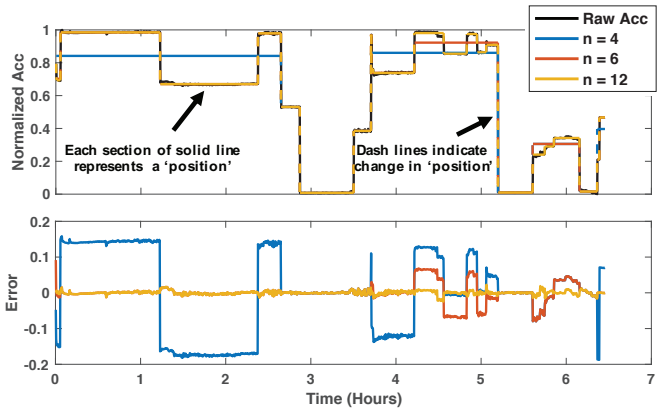

Fig. 5. Clustering separates the accelerometer data into different 'poses.' The error, or the differences between the average accelerometer at each 'pose' and the raw accelerometer data, decreases with each increase in number of cluster.

The timing between the I wave and the foot of the PPG is used as the PTT for the window, corresponding to the timing between the initial cardiac ejection and the arrival of the pulse wave to the PPG site. This process is repeated on each 30-second window to get a PTT trend over the course of a night.

While wearing Naptics, motion artifacts or sensor misalignment may change the distance between the two timing references, skewing PTT measurements. Such changes in distances occur during sleep, where motions are involuntary, and body pose can vary unknowingly. Both the accelerometers and optical sensors are susceptible to these motion artifacts. Changes in the sleeping pose can affect the transfer function between the heart and the accelerometer. During a shift in poses, the location of the optical sensors on the body might change, thus moving the sensing site. Both these movements can shift the PTT values independent of changes in blood pressure, potentially leading to false predictions.

To adjust for these influences on PTT that are independent of changes in blood pressure, we separate PPT signal based on 'poses' determined by the accelerometer as shown in Figure 5. A complete-link clustering with n clusters applied to the average of an accelerometer's three axes separates the recordings to n 'poses.' The root mean squared error (RMSE) between the average accelerometer at each 'poses' and the raw three-axis average shows how well the clustering separated the 'poses.' The number of clusters n increases incrementally until the RMSE is below a threshold. This method allows for separation of 'poses' while allowing for slight movements that are common during the night.

Combinations of the two BCG signals and four PPG signal create eight PTT curves. Starting with PTT signals during the first two 'poses,' we fit a second-degree polynomial to all combinations of the PTT signals and compute the RMSE. The combination with the lowest RMSE represented the start of the reconstructed PTT signal. We again fit a second-degree polynomial to the reconstructed PTT and the PTT curves from the next 'pose' and added the PTT curve that gave the lowest RMSE to the reconstructed PTT. We repeat this process for the remaining 'poses.'

To construct a calibration curve relating PTT to BP, we used linear regression to fit PTT^{-1} to BP. The resulting coefficients represented K_1 and K_2 seen in equation 1. To provide an estimated blood pressure, we applied the calibration curve to the PTT values.

Alternative signal sources for PTT measurements. In addition to computing PTT based on BCG and PPG offsets, Naptics is capable of deriving more than a single PTT measurement. Since the optical sensors are located in

different locations on the wearer's leg and thus on separate sites of the arterial tree, any two of the sensors can measure PTT. SpO_2 to PPG PTT or PPG to PPG PTT can be used to either validate other PTT measurements or to replace corrupted data.

4 CONTROLLED LAB EVALUATION: COMPARING NAPTICS TO A BLOOD-PRESSURE CUFF

We ran a controlled study to assess the accuracy of Naptics as a blood pressure monitor. We designed the study for Naptics to record data while altering blood pressure in a controlled manner while recording the changes with an FDA-approved commercial cuff-based oscillometric device. The resulting correlation between PTT and blood pressure values determined the feasibility of Naptics as a blood pressure monitor.

4.1 Procedure

We recruited six young and healthy subjects for this study (2 female, ages 21–26). Before the study began, we explained the operations of Naptics and the intent of the study. Participants put on Naptics, and we placed a blood pressure cuff on their upper left arm.

To synchronize the blood pressure cuff with the data recorded on Naptics, we tapped the accelerometer on the left hip three times at the beginning and end of the protocol. Additionally, we performed a single tap on the accelerometer immediately after initiating the blood pressure cuff measurement. After the first three taps, the subject began to exercise on an exercise bike for two minutes. Then the participant got off the bike and laid down in a supine position on a leveled table with their head supported by a pillow. We manually initiated the blood pressure cuff six times with a minute between measurements. The number of readings gave sufficient time for the subject's blood pressure to recover to a baseline state. After these recordings, the participant performed a cold pressor test by dipping the right hand in a bucket of ice water for one minute. The cold pressor test raises blood pressure by invoking a sympathetic response and causing vasoconstriction. The subject then removed their hand from the bucket, followed by two blood pressure measurements.

We removed the SD card and downloaded and processed the recordings. Using the beats 10 seconds and 40 seconds after initiating the BP cuff for ensemble averaging, the timing references extracted from BCG and PGG formed the PTT. Using the PTT and BP data, we created a calibration curve and estimated BP for each PTT value.

4.2 Results

Figure 6 presents blood pressure versus estimated blood pressure via PTT for systolic (SP), mean arterial (MAP), and diastolic (DP) pressure along with Bland-Altman plots for each pressure value. After calibration, the total RMSE was 7.7 mmHg, 3.4 mmHg, 2.4 mmHg for SP, DP, and MAP, respectively. The 95% confidence interval is 15.5, 6.9, and 4.8 mmHg for SP, MAP, and DP, respectively.

Table 1 presents the mean and standard deviation of the blood pressure cuff reading and blood pressure estimations after PTT to blood pressure calibration. Both MAP and DP estimations resulted in an RMSE less than 5 mmHg. DP estimations gave the lowest RMSE for most subjects; however, exercise had a minimal effect on DP, and caused the lowest the range of pressure values for all subjects. The table also shows the correlation coefficient (R) for individual and group data. MAP estimations produced the highest correlation to cuff-based blood pressure measurements, consistent with previous studies [30]. Systolic estimations produced the lowest RMSE and R values. This result follows physiological expectations because the foot of the PPG wave – the feature we extracted for obtaining PTT values – represents the arrival of the pulse waveform during diastolic pressure [37].

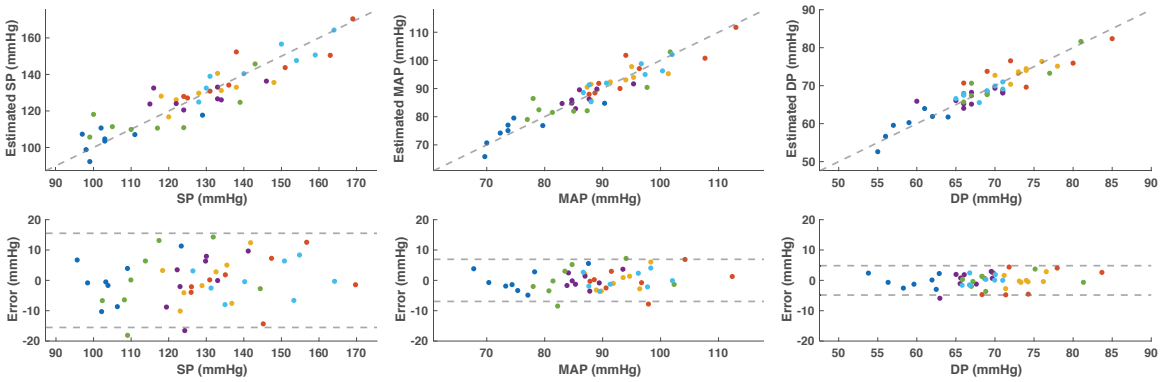

Fig. 6. Correlation and Bland-Altman plots for systolic (SP), mean arterial (MAP), and diastolic (DP) pressure.

Table 1. Root mean squared error (RMSE) and correlation coefficient (R) between estimated and cuff-based blood pressure measurements

	Systolic Pressure			Mean Arterial Pressure			Diastolic Pressure		
Participant	BP Cuff	RMSE	R	BP Cuff	RMSE	R	BP Cuff	RMSE	R
1	105 ± 11	6.8	0.72	76 ± 7	3.4	0.84	60 ± 5	2.1	0.90
2	142 ± 17	7.4	0.88	96 ± 9	4.0	0.89	73 ± 6	3.8	0.77
3	130 ± 10	6.9	0.69	93 ± 5	3.1	0.73	74 ± 3	1.5	0.73
4	128 ± 11	8.4	0.52	87 ± 4	2.2	0.79	67 ± 3	2.6	0.55
5	117 ± 17	10.2	0.76	86 ± 9	4.7	0.84	70 ± 6	2.1	0.92
6	145 ± 14	5.4	0.91	94 ± 6	2.6	0.89	68 ± 3	1.5	0.75
Group	127 ± 19	7.7	0.75	89 ± 10	3.4	0.83	69 ± 6	2.4	0.77

4.3 Discussion

This study shows promise in Naptics in accurately tracking blood pressure trends during the night. While in a supine position, Naptics reliably recorded the BCG and PPG in all subjects, allowing for the extraction of timing references for PTT calculations. Calibrated BP from PTT and blood pressure measurements from a blood pressure cuff exhibited a strong correlation between PTT and all three pressure references.

Since the study used both Naptics and a blood pressure cuff, difference between the two devices became evident. The study lasted approximately fourteen minutes, allowing for a maximum of ten cuff measurement. With thirty-second windows, Naptics has the potential to record twenty-eight PTT measurements, a dramatic improvement. Additionally, Naptics proved to be more reliable during the study. Multiple times during the study, the blood pressure cuff reported an error after inflation and deflation, requiring readjustment of the cuff on the arm to obtain a reading. The participants received only basic instructions on the operations of Naptics. Even with these simple instructions, all participants correctly wore Naptics to obtain clean BCG and PPG signals.

4.4 Limitations

While performing this study in a controlled setting produced ideal results, discrepancies may exist when transitioning to an at-home environment. In this study, all participants remained still in a supine position on a stable table. Unlike during sleep where users are allowed to toss and turn, the participants remained still, resulting in

little to no motion artifacts. Even with these limitations, the study proved that Naptics tracks blood pressure accurately and has the potential to be used in an at-home setting.

An obvious limitation is that the study used only young and healthy subjects in addition to the small subject population and a low number of blood pressure readings. Future work will expand the study to validate Naptics in both healthy and unhealthy populations.

5 IN-THE-WILD EVALUATION

The purpose of this study was two-fold. First, it was to assess the shorts' ability to obtain useful data during the night while not interfering with the user's sleep. Second, we wanted to track PTT during the night and find a correlation between PTT and blood pressure values before and after sleep, measured by an FDA-approved commercial cuff-based oscillometric device. For both purposes, we chose to run this study with external participants in an in-the-wild fashion during their regular days.

5.1 Task

Participants had three tasks during the study. Over the course of four nights, each participant wore a Naptics prototype while sleeping and turned it on to start measurements just before sleep. Subjects were asked to not change any sleeping habits during the study (i.e., initial sleeping position, time asleep, the method of awakening, etc.). On average, participants slept for 7 hours each night with the time asleep ranging from 5 hours to 9 hours. Participants' second task was to record blood pressure values using a cuff-based monitor before going to bed and directly after waking up for each night of participation. The third task was to fill out a sleep diary before and after sleep [36], which included questions on eating, drinking, and napping during the day as well as sleep quality, the mood on final awakening, and alertness of final awakening.

5.2 Procedure

While recruiting participants, we explained the purpose of our evaluation and demonstrated the operation of our wearable prototype pants. We also walked participants through the operation of the blood pressure cuff and demonstrated how to take measurements correctly. To ensure proper operation, we requested participants to take a measurement to show understanding of use. Finally, we explained the diary questionnaire to participants and gave them a Naptics prototype, a blood pressure cuff, and printed instructions as a reminder how to use both. We emailed participants the instructions again and received the devices back after the study.

Before the study, we manufactured Naptics prototype pants in various sizes to support participants with different body dimensions. Participants started the evaluation on a Wednesday and wore the prototype for two consecutive nights. Participants then wore the prototype for another two consecutive nights starting Monday the following week. We did not conduct the evaluation during the weekend, as weekend activities might have prevented us from collecting a reasonable number of hours during wear and might have impacted the compliance in wear and proper cuff operation.

After the study, we downloaded and processed all recorded data as described above.

5.3 Participants

We recruited five participants for this evaluation. Three participants were male (ages 25–31), and two were female (ages 25–30). All participants had either type II or III skin according to the Fitzpatrick skin type scale and reported no medical conditions related to our evaluation, such as hypertension. Each participant received $200 as a gratuity for their time.

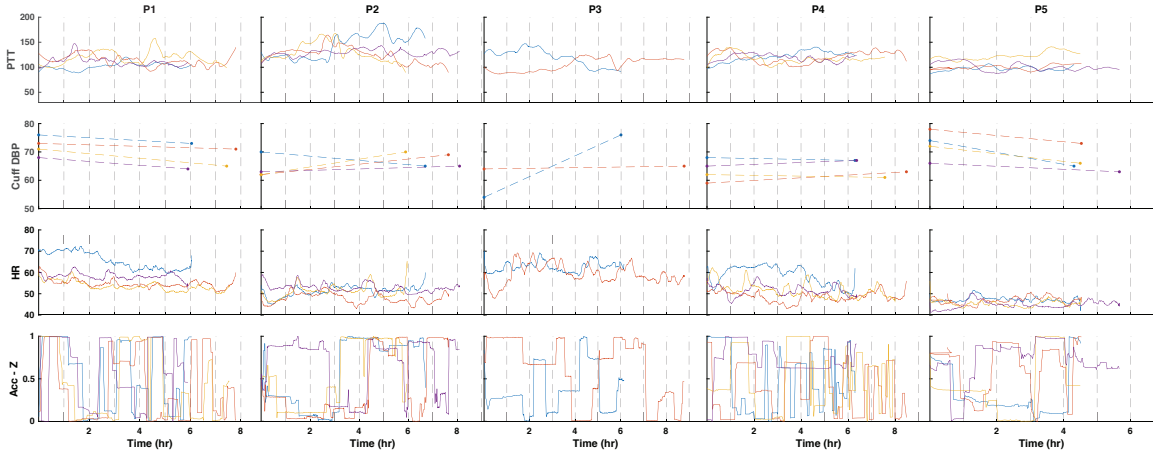

Fig. 7. All plots resulting from all 5 participants for each of the 4 nights. The rows correspond to pulse transit time (PTT), two diastolic blood pressure values (DBP) recorded by participants once before and once after sleeping, heart rate levels, and accelerometer activity. The accelerometer plots indicate the moments at which a participant turned during the night.

5.4 Results

Figure 7 depicts all the measurements obtained by Naptics, including PTT, cuff diastolic blood pressure (DBP), heart rate (HR), and the Z-axis of the accelerometer. Four of the five participants were able to complete all four nights of the study. Due to a technical error, one subject (P3) was only able to complete three of the nights, resulting in a set of measurements from 18 complete nights. Using the first 5 minutes of PTT values as the baseline, the average PTT values increased for 15 of the 18 nights, revealing indications of dipping. The changes in the accelerometer data revealed the sleeping 'positions' for the participants. Most positional changes (63%) occurred during the last half of sleep, consistent with standard sleep stages [11].

To validate the captured records, we compared the shift in the first five minutes of PTT measurements while the subject was asleep and the last five minutes of sleep to the oscillometric blood pressure reading at night and in the morning.

Table 2 shows the night and morning readings. For 14 of the 18 nights, PTT changed in the opposite direction as diastolic blood pressure, i.e., as expected according to a person's circadian rhythm. For participants' systolic blood pressure measurements, only 12 of the 18 nights followed the trend.

Figures 8 and 9 show high-order polynomial fits over PTT values for three nights while subjects were asleep. Using the absolute values measured by the oscillometric cuff before and after sleep in conjunction with the PTT recordings at the beginning and end of sleep, we calculated a PTT calibration curve specific to each participant and night. The figures also show the result of PTT measurements during the nights applied to the curve. The red dots represent the DBP readings before and after sleep, which we use to retroactively offset and stretch the PTT series.

Figure 8 shows a clear "dipper" with PTT values increasing within a few minutes of falling asleep. After around two hours, the PTT values returned to the baseline levels but increased again soon after. The trend continued throughout the night with decreasing dipping amplitude. The first dip led to an increase in PTT by 20 ms while the last few dips only resulted in a PTT increase of approximately 10 ms.

Table 2. Changes in blood pressure and PTT between pre-sleep and post-sleep measurements

	Night	PM Systolic	PM Diastolic	PM PTT	Δ Systolic	Δ Diastolic	Δ PTT (ms)
P1	1	120	76	95	8	3	-11
	2	116	73	126	3	7	7
	3	113	71	109	10	6	-2
	4	108	68	94	-3	4	-12
P2	1	119	70	152	5	5	-9
	2	117	62	111	1	-7	18
	3	110	62	113	3	-8	10
	4	113	63	109	-6	-2	-25
P3	1	86	54	126	-15	-22	34
	2	102	64	98	5	-1	-20
	3	89	58	*	4	3	*
P4	1	108	68	100	9	1	-9
	2	97	59	127	-2	-4	6
	3	100	62	101	3	1	-17
	4	99	65	107	-5	-2	-22
P5	1	108	74	91	6	9	-13
	2	97	78	92	3	5	-11
	3	100	72	93	12	6	-16
	4	99	66	108	11	3	-12

Figures 9 shows PTT trends of a participant on two distinct nights. During the first of the two nights, PTT initially decreases but returns above baseline for a majority of the night. During the beginning of the second night, a similar trend is evident with PTT increasing in the first two hours; however, PTT only returns near baseline momentarily before returning to below baseline levels.

Derived metrics: Heart-rate variability, blood oxygenation, breathing rates. Figure 9 also shows the metrics Naptics additionally records from the optical and acceleration sensors. We pick the same nights for P4 and illustrate participants' heart rate variabilities, pulse oxygenation, as well as breathing rate throughout the night. Heart rate variability seemed to decrease with when blood pressure raised, potentially due to an increase in sympathetic

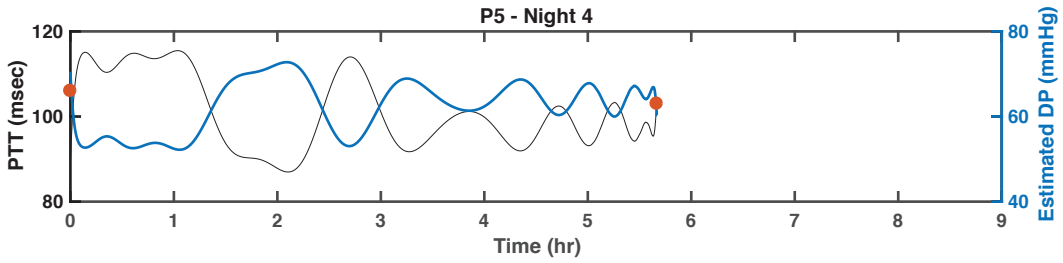

Fig. 8. Full PTT recordings for one night. Blood pressure results from retrofitting PTT curves to the absolute before and after recordings from the cuff-based device.

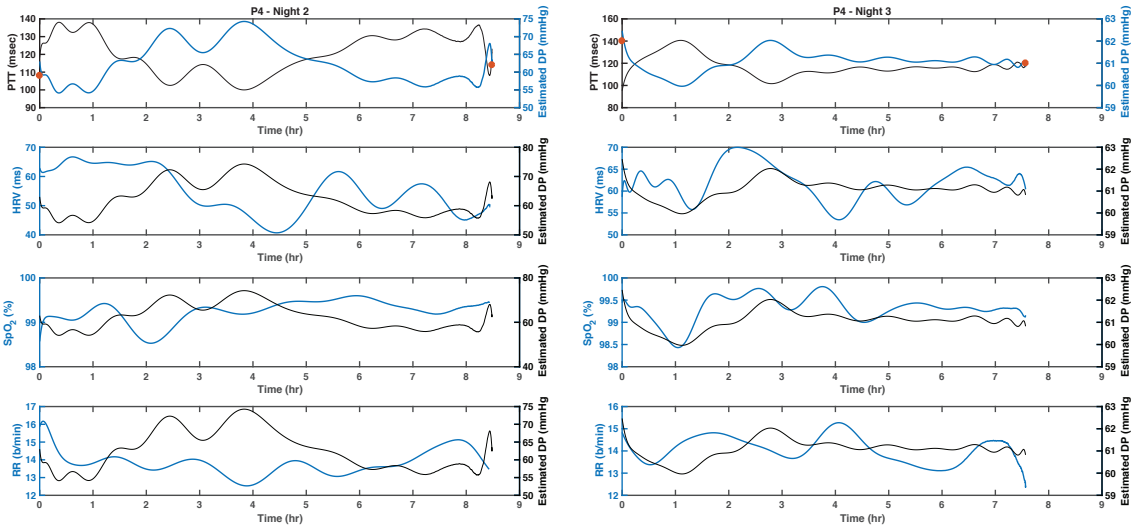

Fig. 9. PTT trends of a participant on two distinct nights along with heart rate variability (HRV), pulse oximetry (SpO_2), and respiration rate (RR)

tone. Breathing rate decreased at the beginning of each night, and stayed below the beginning-of-sleep levels for the majority of the night.

Sleep Diaries. The sleep diaries provided feedback from the participants on sleep quality and state after awakening. On a scale from 1 to 10, the participant's sleep quality averaged 7.3, the mood of awakening averaged 6.5, and alertness upon awakening averaged 6.8. When asked how many times awoke due to discomfort or physical complaint, only one participant on one of the nights indicated discomfort.

We also solicited feedback from participants on their use of Naptics and a comparison to the use of the blood pressure cuff. P2 experienced little interference during sleep while wearing Naptics. "After putting on the pants, I quickly forgot about the devices on my body and slept as peacefully as usual." P3 made a direct comparison between the two devices. "As someone who's had to sleep with a conventional cuff for blood pressure monitoring, it was a joy to sleep through the night without being constantly woken by noise and constriction."

5.5 Discussion

Our evaluation validates Naptics and its promise to unobtrusively and continuously monitor blood pressure patterns throughout the night with little to no disturbances in sleep. Naptics successfully acquired timing references at two distinct sites using inertial and optical sensors in a single device. It is worth noting that Naptics performed all monitoring passively without forcing the users to change their sleeping habits.

For most of the subjects, Naptics tracked the changes in blood pressure from the beginning of sleep to the end. By fitting these measurements to a calibration curve, Naptics revealed the patterns of blood pressure throughout participants' nights. However, finding absolute blood pressure may not be necessary to classify dipping. Traditionally, comparisons made between nocturnal blood pressure and daytime blood pressure determine if the participant is a dipper. With Naptics, a comparison of PTT values between the start of the night and different intervals in the night could determine the dipping status. For example, if the PTT remains constant or decreases during the night, the participant is likely considered a non-dipper.

Our in-the-wild evaluation also showed the potential of Naptics to be used for monitoring sleep states. The oscillations shown in Figure 8 follow trends similar to the different sleep stages throughout the night, as the participant enters and exits REM sleep phases. In a healthy, young adult such as the participant, the human body quickly enters a deeper stage of sleep (NREM) after only a few minutes of the onset of sleep with blood pressure dipping soon after. After around two hours, the body transitions to REM sleep, and blood pressure increases. This process of NREM and REM continues throughout the night in decreasing time intervals. Naptics captured this pattern as shown in the plot, with the timing in between events agreeing with those seen in healthy subjects [11]. Our results also show the potential of improving sleep stage classification when combined with a heart rate monitor and a motion sensor, both of which our prototype devices incorporates.

As we showed during our evaluation, the ability to conveniently and passively take blood pressure measurements allows participants to continuously monitor their blood pressure levels over multiple *consecutive* nights. This capability, in particular, is difficult for current blood pressure cuffs to provide. We believe that the ability to continuously monitor a series of nights throughout a week or even more will allow for a more accurate understanding of a subject's nocturnal blood pressure behavior. Figure 9 shows two different nocturnal readings from Naptics. During the first night, the estimated blood pressure increased above baseline, indicating non-dipping; however, in the second night, blood pressure mostly remained below the baseline value. A cuff-based monitoring procedure, in contrast, would give conflicting results depending on the measurement night. Allowing for monitoring multiple nights, as possible with Naptics, thus will enable clinicians to make better-informed decisions when diagnosing hypertension.

Regarding the sleep diaries participants provided, the results indicate that Naptics did not cause any discomfort that would cause the wearer to wake up. The participants' ratings also indicated that the wear of Naptics had little to no effect on their overall sleep quality or duration during the night. However, a more longitudinal evaluation, such as the typical two-week sleep study, would be required to statistically quantify the effect of Naptics on sleep quality.

5.6 Study Limitations

5.6.1 Number of Participants and Nights. Our in-the-wild evaluation was limited to five participants and four nights each. While a thorough assessment of Naptics for the detection of nocturnal hypertension would undoubtedly involve a more significant number of participants, in part some with known symptoms, our evaluation already produced insights that a traditional cuff-based study would likely have missed. We were able to run this evaluation in pairs of consecutive nights without impacting the quality of participants' sleep and the quality of the following days. Typical nocturnal evaluations need to resort to monitoring nocturnal blood pressure levels for a single night once every three months, which is a sampling frequency that is significantly below Naptics' capabilities and highlights the promise of our technique.

Another limitation of our study we learned about was from P2, who on two nights took blood pressure readings, then laid down, watched TV, and only then turned on their Naptics device and fell asleep. While this temporally offset the cuff reading and our first PTT measurement, likely introducing some inaccuracy for the particular night, this limitation will disappear in a proper sleep study with an automatically self-inflating cuff.

Expanding on this aspect, in the mornings, participants might have gotten up and then taken their morning blood pressure reading. A person's orthostatic hypotension could interfere with the reading in case their blood pressure did not restore within a short amount of time due to the postural change [24]. However, all of our participants were below the age of 32, and orthostatic hypotension is more common in older participants.

For a valid sleep study involving nocturnal blood pressure monitoring, a study has to be designed to minimize sleep arousal. While the most common means is an ambulatory blood pressure cuff, a previous study [23] reported some degree of arousal in 64% of cuff inflations. A more viable option is a continuous blood pressure cuff based on

the volume clamp method. This option provides beat-to-beat blood pressure reading and minimizes discomfort [26].

5.6.2 Discontinuities in Computed Data Curves. While the recorded data streams of all sensors were individually continuous and consistent in their signal types, the derived PTT metric showed inconsistencies in the signal at those times when participants turned in bed. An explanation for this behavior is that due to changing the pose in bed, the PPG sensor on the wearer's femoral artery slightly shifts to another location on the leg. Such a shift is likely always lateral to the artery since the compression pants restore the central position along the artery. Each Naptics device includes four PPG sensors to account for small motions during pose changes. Another explanation is that the wearer might have shifted their weight onto an accelerometer, damping the sensed vibrations to a level that is indistinguishable from noise. Naptics accounts for this scenario by incorporating a second accelerometer at the other end of the shorts. While our processing incorporates the multiple sensors to mitigate the effects of the shifts, limitations do exist with the method. Due to the increasing number of series towards the end of a night (i.e., participants turning and thus causing jumps in the signal), this process weighs the beginning of the series (i.e., longer stretches) more heavily, thus potentially following a trend that does not represent the blood pressure trend during the frequent-motion intervals.

5.6.3 The Challenge of True *Blood Pressure Validation.* Previous evaluations compared prototype devices capable of measuring pulse transit times to a means of obtaining absolute blood pressure levels. Such absolute monitors included (mobile) oscillometric cuffs for periodic spot checks that participants could self-administer [24] or stationary medical devices that obtain continuous blood pressure values during in-lab evaluations [10, 32, 37]. The latter involved a continuously inflated cuff around a participant's finger.

Similar to previous studies, our evaluation also included a self-administered cuff. We took several precautions to ensure correct use. We demonstrated the proper use of a cuff to participants before the study, including a resting position, uncrossed legs, measuring at the level of their heart, and always assuming the same pose. We then asked participants to demonstrate to us how they would take a reading. Finally, we sent daily reminders to participants with illustrated instructions on proper cuff application.

Assuming correct application, the cuff-based ground truth measurements provide suitable absolute baselines for PTT devices during the *day*. During the night, however, self-inflating cuffs almost certainly wake up a participant due to the substantial pressure applied to their arm. Because of the typical 20-minute intervals of self-inflation, this considerably interferes with a participant's sleep pattern, possibly preventing them from reaching deeper sleep states, which, in turn, *affects* their blood pressure levels. Put differently, using a cuff-based apparatus for ground truth measurements limits the *external validity* of a sleep study, since blood pressure levels recorded during such a night do not reflect a participant's regular nocturnal levels.

Apart from applying the cuff correctly, additional factors might have affected the measurements of the oscillometric cuffs that we treated as 'ground truth.' If an external stimulus such as an alarm clock, another person, or outside noise woke up a participant abruptly, blood pressure levels could have substantially increased for a period that could last for as long as 15 minutes [22].

In our evaluation, we validated the recorded and reconstructed PTT series in two ways. First, we compared the overall pattern of PTT curves with the before and after cuff-based recordings. We assumed correct cuff applications by participants as well as proper compliance during the study (e.g., measuring blood pressure in the same pose when going to sleep and waking up and right before switching on a Naptics device, etc.). This form of validation required a single invalid night to be discarded (row highlighted with '*' in Table 2). Of course, it is unclear if the reconstructed PTT series is inaccurate for this participant during that night or if the participant took a cuff measurement considerably before they activated their Naptics device or after they had woken up. Second, we retrofit the recorded PTT series to absolute blood pressure values using participants' before and after cuff recordings for each night, offsetting and stretching the PTT curve. If the resulting blood pressure curve

reaches levels are physiologically impossible (e.g., diastolic blood pressure dipping below 30 mmHg or exceeding 120 mmHg), we know that the recorded PTT series is inconsistent with the measured cuff blood pressure levels, in which case we would need to discard that particular night.

6 CONCLUSION

We presented Naptics, a continuous and unobtrusive wearable device that passively monitors blood pressure patterns of the wearer throughout the night. Naptics compares to automated nocturnal blood pressure monitors that self-inflate periodically every 30 minutes and thus cause a repeated and considerable amount of pressure on the person's arm. The constriction of the arm often causes the user to wake up, which severely impacts their quality of sleep during the night as well as their performance during the following day. In contrast, Naptics' sensors respond to optical reflections and accelerations, which allows the device to passively collect data without interfering with the user's sleep. Our controlled in-lab evaluation showed a high correlation ($r = 0.89$) and low error (RMSE = 3.4 mmHg) for the values computed by Naptics during standardized perturbations with the six participants' absolute cuff-based blood pressure measurements. Our in-the-wild evaluation with five participants during four nights showed Naptics' capability of tracking absolute blood pressure levels when supplemented with one before and one after measurement from an oscillometric cuff, which was self-administered by participants when they were awake.

Despite the small number of participants, our results have already uncovered compelling patterns in the levels of participants' blood pressure levels throughout the night. The curves we obtain from Naptics indicate whether a person is a "dipper", following the expected circadian rhythm of blood pressure, or if their levels exhibit a different behavior, indicating a potential for nocturnal hypertension.

Notably, Naptics has the potential to act as a continuous and repeated monitoring tool to provide physicians with a more comprehensive set of values when monitoring a patient's blood pressure levels. Specifically, Naptics' ability to monitor consecutive nights with little to no impact on a patient's quality of sleep is a unique characteristic that even clinical evaluations *cannot* afford. The results of our study show the significance of this feature in that two consecutive nights already surface different patterns, which is noteworthy as nocturnal hypertension (much like hypertension itself) is not guaranteed to occur during any one night.

Our evaluation also demonstrated the potential of Naptics to serve as a convenient and continuous monitor apparatus that is not limited to specific intervals. Until nighttime equipment such as sleep masks, medical instruments for continuous monitoring that are attached in clinical settings, or continuous monitors that are wearable but limited to daytime use (e.g., Glabella [24], DualBlink [17]), Naptics affords *continuous wear* throughout the day and the night. The use of compression pants not just ensures Naptics' optimal sensor contact, but also allows users to wear Naptics under other garment, such as regular pants.

Encouraged by the results of our evaluations, we plan to refine our prototype into a smaller and more integrated platform (e.g., [17, 24]) that can be deployed in other form factors such as belts or leg straps. This would further reduce the footprint of a device and its potential interference with the user's sleep, while simultaneously increasing the robustness of the device. Such a belt device would have the potential to perform continuous and unobtrusive 24-hour monitoring, a capability that is ultimately useful in diagnosing hypertension in suspected patients with the possibility to extend such monitoring phases to several days or even weeks as monitoring becomes passive and convenient for the patient.

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