Glabella: Continuously Sensing Blood Pressure Behavior using an Unobtrusive Wearable Device

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We propose Glabella, a wearable device that continuously and unobtrusively monitors heart rates at three sites on the wearer's head. Our glasses prototype incorporates optical sensors, processing, storage, and communication components, all integrated into the frame to passively collect physiological data about the user without the need for any interaction. Glabella continuously records the stream of reflected light intensities from blood flow as well as inertial measurements of the user's head. From the temporal differences in pulse events across the sensors, our prototype derives the wearer's pulse transit time on a beat-to-beat basis.

Numerous efforts have found a significant correlation between a person's pulse transit time and their systolic blood pressure. In this paper, we leverage this insight to continuously observe pulse transit time as a proxy for the behavior of systolic blood pressure levels—at a substantially higher level of convenience and higher rate than traditional blood pressure monitors, such as cuff-based oscillometric devices. This enables our prototype to model the beat-to-beat fluctuations in the user's blood pressure over the course of the day and record its *short-term* responses to events, such as postural changes, exercise, eating and drinking, resting, medication intake, location changes, or time of day.

During our in-the-wild evaluation, four participants wore a custom-fit Glabella prototype device over the course of five days throughout their daytime job and regular activities. Participants additionally measured their radial blood pressure three times an hour using a commercial oscillometric cuff. Our analysis shows a high correlation between the pulse transit times computed on our devices with participants' heart rates (mean $r = 0.92$, $SE = 0.03$, angular artery) and systolic blood pressure values measured using the oscillometric cuffs (mean $r = 0.79$, $SE = 0.15$, angular–superficial temporal artery, considering participants' self-administered cuff-based measurements as ground truth). Our results indicate that Glabella has the potential to serve as a socially-acceptable capture device, requiring no user input or behavior changes during regular activities, and whose continuous measurements may prove informative to physicians as well as users' self-tracking activities.

CCS Concepts: • **Computer systems organization → Embedded systems**; *Redundancy*; Robotics; • **Networks →** Network reliability;

Additional Key Words and Phrases: Physiological sensing, blood pressure monitoring, pulse transit time, cuffless sensing, heart rate monitoring, continuous tracking, wearable device, unobtrusive wearable, convenience, in-the-wild user study

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1 INTRODUCTION

Monitoring cardiovascular activity serves as a significant indicator for assessing a patient's health [26]. Arterial blood pressure as the conjunction of arterial resistance and cardiac output serves as a key signal in the assessment

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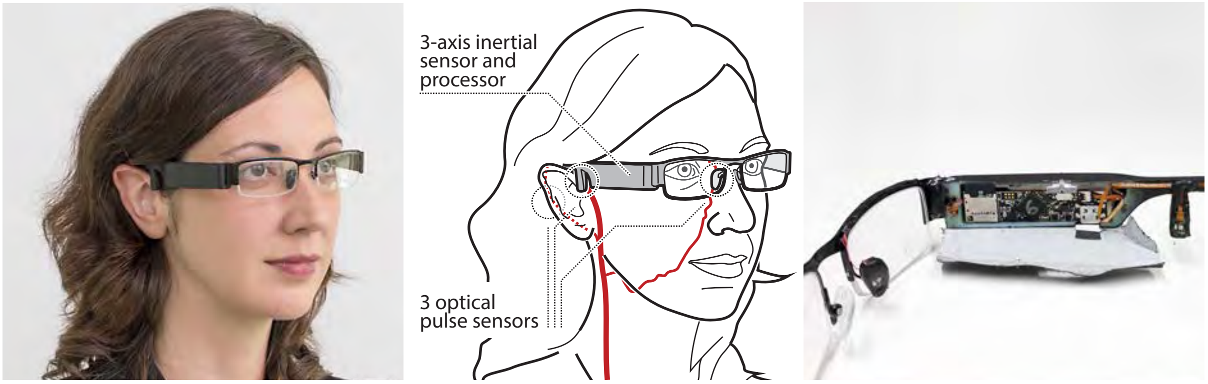

Fig. 1. Our wearable glasses prototype *Glabella* incorporates optical sensors to continuously measure and store the user's pulse waves at three different sites on their face. Our device additionally comprises inertial sensors and a processing unit that compares the continuously recorded pulse waves to extract the user's pulse transit time—the delay between the moments at which the blood ejected from the heart reaches the three sites. Pulse transit time functions as a proxy measurement to monitor the short-term behavior of the user's systolic blood pressure, to which our evaluation shows a significant correlation during in-the-wild use.

of the cardiovascular system. The gold standard of measuring systemic arterial blood pressure, specifically the maximum (systolic) and minimum (diastolic) pressure during a cardiac cycle, is invasive and performed in a clinical setting. Recent semi-automated cuff-based blood pressure monitors increase the ease of use and allow patients to regularly record and monitor their values themselves at home.

Blood pressure measurements are subject to seasonal effects, habits, time of day, and other factors [28]. Therefore, patients with known conditions or those who are receiving treatment are encouraged to monitor their blood pressure on a regular basis [29]. Continuously recording a patient's values either in ambulatory settings (e.g., walk-up clinics, pharmacy stores, etc.) or using personal monitors at home, in turn, helps physicians manage and adjust patients' prescriptions according to patients' responses to the treatment.

In addition to seasonal effects, a patient's blood pressure naturally varies throughout the day, from higher values in the morning to dropping values in the evenings and typically lowest readings during sleep at night. Even *shorter-term events* additionally influence a person's blood pressure, such as eating and drinking [33], events at work [15], exercise from light postural changes [11] to more demanding activities [30], and not least medication intake. All these potential influences make it desirable to *continuously* monitor the behavior of a patient's blood pressure throughout their day to record how fast it responds and recovers from such short-term events. Importantly, such data collection is ideally unobtrusive without interfering with users' regular habits, in particular in light of the inaccuracies that accompany clinical measurements (e.g., white-coat hypertension [31]). While some continuous solutions exist (e.g., non-invasive 24-hour blood pressure monitors [19]), they naturally trade off measurement accuracies against usability and convenience, thereby imposing restrictions on patients to go about their regular activities. Consequently, some users may exhibit a lack of discipline in regularly measuring their blood pressure, rendering the data collection on their cardiovascular activity incomplete.

Blood pressure is traditionally captured using a mechanical device, such as an oscillometric cuff, which includes a pump and a cuff users need to wear around their arm. While the device captures accurate blood pressure values, its application can be cumbersome; since the cuff has to be attached, correctly oriented, and detached manually, users will naturally limit the frequency of recording their blood pressure values, often to only once or twice a day. The literature, however, suggests that more frequent observations may be beneficial for understanding the correlations between daily activities and patterns with cardiac health [24, 37]. By continuously observing the body's blood pressure response to various stimuli, we are equipped with an opportunity to uncover new insights as to how an individual may respond to certain foods and drugs, observe patterns of blood pressure variability throughout the day, and potentially provide new understanding of a multitude of pathologies.

In order to gain such insights, it is necessary to develop more continuous blood pressure monitoring technologies. One promising method is measuring the *pulse transit time* (PTT), which is the time that it takes a pulse wave generated by a heartbeat to travel down the arterial tree between two or more sites of the body. Unlike a traditional oscillometric cuff, PTT measurement does not require the use of a cuff and can be measured *continuously* during each beat. However, typical methods for measuring PTT either require the use of ECG and pulse sensing, which necessitate cumbersome electrodes, or active interaction with a device that potentially obstructs regular activities to accomplish a measurement.

In this paper, we take a different approach. We introduce *Glabella*, a lightweight wearable approach to continuously tracking the behavior of a user's blood pressure. Our prototype device integrates three pulse sensors into a pair of glasses as shown in Figure 1. Our device measures the wearer's pulse using photoplethysmography on three locations of the user's head, which produces three slightly offset pulse signals. From the offset in these waves, Glabella computes the pulse transit times between the locations, thereby *continuously* monitoring the behavior of the wearer's blood pressure on a beat-by-beat basis—unobtrusively, conveniently, and throughout their regular day.

1.1 Glabella: Continuously monitoring beat-to-beat pulse transit time

As shown in Figure 1, Glabella is a standalone device and runs an entire day on a single charge to continuously record the wearer's motions and pulse transit time. Figure 2 shows a preview of our prototype's operations, including the types of signals our prototype collects, processes, and stores. The majority of the signal processing serves to extract the key signal: the wearer's pulse transit time, measured as the temporal difference in pulse arrival times between two sensors: between the preauricular skin pit on the wearer's angular artery and either the orbital region on the wearer's superficial temporal artery or the area behind their ear on the occipital artery (see Figure 1 for the arteries).

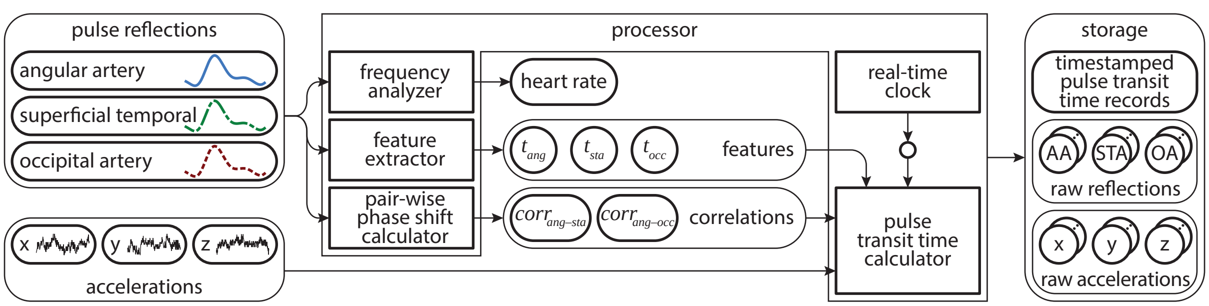

Fig. 2. Overview of the wearable platform we built: Each prototype senses the reflections of the wearer's pulse in three locations as well as the 3D inertial motions of the head through the frame. From the input signals, the prototype extracts the wearer's heart rate and the temporal features in the pulse reflections, from which we calculate the pulse transit time for each beat. Analyzing device motions and the cross-correlation across the reflections allows us to reject inaccurate candidate beats in the raw pulse signals. Finally, Glabella stores the raw signal streams along with the computed features, heart rates, and pulse transit times on an SD card.

We believe that the form factor of our prototype strikes a good balance between wearability and sensing a rich signal; while glasses are exceeded only by wrist watches in the convenience of wear and social acceptability, glasses are constantly worn on the body. Coincidentally, they reach across multiple arteries at different distances from the wearer's heart, making them optimal for sensing pulse transit times in a usable and ordinary form factor. This is a key feature that current wrist-worn devices do not afford. The redundancy in signals Glabella records through multiple sensors equips us with a tool to assess the quality of the signal while sensing from signal similarities in addition to motion artifacts that Glabella detects through inertial sensors. Importantly, unlike watch-based pulse transit time sensors, Glabella requires no explicit input or postural configurations from the wearer (e.g., reaching across to touch the watch with the opposite hand [32]), but instead senses continuously *without* user interaction. Finally, Glabella rests on the wearer's nose and ears, thereby making suitable contact with the skin with constant force due to gravity, and thus does not need to be adjusted in tightness through a strap or otherwise. This side effect of constant force results in a particularly reliable signal acquired from the angular artery that is suitable for comparison across an even longer-term period.

Our in-the-wild evaluation of Glabella found significant correlations of the heart rate and pulse transit times collected by our prototype with the blood pressure levels recorded by a commercial cuff-based oscillometric device. Four subjects participated in our evaluation and wore a custom-fit Glabella device during their regular activities over the course of five days while recording their blood pressure using a cuff-based monitor three times an hour.

1.2 Contributions

We make the following contributions in this paper:

(1) A wearable device that continuously records the wearer's pulse and pulse transit times at a high frequency. Recording the pulse transit time enables the device to predict and monitor the behavior of the wearer's systolic blood pressure on a beat-by-beat basis throughout the day. The frequent nature of sampling has the potential of helping in detecting short-term anomalies in an individual's blood pressure, such as temporary hypotension and hypertension, response and recovery times to medication, food intake, activity, as well as other events during the day.
(2) A standalone and socially-acceptable form factor with all components integrated to minimally if at all impact the user's daily patterns. Users are not required to remember to measure or consciously stop their activities to take a measurement. Our device does not require being semi-permanently attached to or removed from the user's body, such as ECG electrodes.
(3) An in-the-wild evaluation of our prototype over the course of five days, during which participants continuously wore a custom-fit Glabella prototype and recorded their heart rate and blood pressure using a commercial cuff-based oscillometric device.

2 RELATED WORK

The basis of this work relies on unobtrusively estimating blood pressure fluctuations by measuring pulse transit time (PTT). The following section presents the mechanism behind PTT and the medical relevance of this measurement. Followed by an overview of the exploration in the ubiquitous computing and mobile health research community on the use of PTT as a way of incorporating blood pressure monitoring into the new generations of smartphones and wearables [27].

2.1 Pulse arrival time

Pulse arrival time (PAT) is the amount of time it takes a blood pressure wave generated by the beat of the heart to travel down the arterial tree to a point of the body. PAT is inversely related to blood pressure; the higher the blood pressure, the shorter the PAT. Mukkamala et al. presented a thorough survey on pulse arrival time, its various implementations as well as correlations to blood pressure found in the related work [21]

To measure PAT, two events have to be measured: when the heart beats and when the pulse wave arrives at a location on the body. The typical method is to instrument the person with electrodes to measure their electrocardiogram (ECG) and monitor when their heart beats by recording the R-wave. Simultaneously, the person's finger is typically instrumented with an optical pulse sensor that measures the photoplethysmogram (PPG) at the finger tip. The ECG sensor observes when the heart beats and the PPG sensor measures when the pulse wave arrives at the distal location.

While PAT is inversely correlated with blood pressure, it requires calibration to directly estimate absolute blood pressure values. This is because the propagation time of the pressure wave depends on the distance of travel and arterial stiffness. Whereas the distance of travel is held constant by always measuring the PPG at the same place, arterial stiffness is subject to change. For example, as humans age, arterial stiffness tends to increase, which is typically a slow process, such that a calibration will be consistent for at least a few months. The correlation strength of PAT and blood pressure has been demonstrated by various research efforts.

Work done by Allen et al. in the early 1980s recorded correlations between PAT and blood pressure as measured by an arterial catheter in three hypertensive subjects and systematically varied their blood pressure through different stress inducing conditions [1]. Gesche et al. later developed a model to predict systolic blood pressure from arterial pulse arrival times [8]. By using a one-point calibration to create the predictor, their system achieved correlations of 70% and higher.

However, the use of PAT, even when calibrated, has been demonstrated to not be a highly reliable measure of absolute blood pressure. Various investigations have shown that it is a strong measure of variability and rapid changes in blood pressure [25, 35]. Mukkamala et al.'s overview over such accomplishments also discusses the main challenges in this domain [21].

As an example of a consumer device, Withings Body Cardio Scale seamlessly integrates ECG electrodes into the scales on which users can step each morning to record PAT [39]. While the scales offer convenient measurement and monitoring of this metric, they are naturally not mobile and provide only selective measurements in the mornings. Presumably because of the challenges in calibration with absolute blood pressure values, Withings displays pulse arrival times as the useful unit for consumers, arguing for its own relevance to assessing cardiovascular health.

The challenge of monitoring PAT using ECG and PPG is that ECG recordings do not capture the precise moments at which the blood is actually ejected from the heart, but rather when the heart depolarizes at the start of a contraction [7]. This period from depolarization and aortic valve opening (i.e., cardiac ejection) is referred to as the *pre-ejection period* (PEP), and is not constant beat to beat. As a result, the ECG-to-PPG measurement of PAT is inherently noisy due to this pre-ejection variable that can be independent of blood pressure (i.e., vasoconstriction, stress, or neural-hormonal factors).

2.2 Pulse transit time

The variability of the pre-ejection period can be counteracted by switching the measurement to *pulse transit time* (PTT) instead, which is the time delay for the pressure wave following a heart beat to travel between two arterial sites. PTT is therefore also inversely correlated to the person's blood pressure [21]. The measurement of PTT varies from that of PAT in that different arterial events are used to establish the timestamp at a proximal location. One such method is known as ballistocardiography (BCG), which measures the slight vibration propagated to the rest of the body by the reaction force caused by cardiac ejection [14]. Another method measures the vibrations of the surroundings of the heart in response to the heart's mechanical activities and is known as seismocardiogram (SCG) [12]. Both these measurements are directly caused by the physical contraction of the heart, avoiding the uncertainty of the pre-ejection period that comes with an ECG measurement, and have shown useful correlations with absolute blood pressure measurements [13].

Another way of counteracting the issue of non-constant pre-ejection periods is to measure PPG at two sites of the body, ideally along the same artery at a known distance from each other. Because the blood that the pressure wave propels to both sites in the body originates from the same source, PTT can be measured using the difference in arrival time of the pulse wave at the two locations. This is typically done on the wrist and the finger of the same hand [18] or on the finger and the toes [23].

In order for PTT to actually become useful for continuous blood pressure monitoring outside the hospital, natural living environments of daily life, the measurement techniques of PTT need to be more unobtrusive and socially acceptable. Our work expands on the use of multi-site PPG measurements to derive PTT, but avoids measuring in unobtrusive locations, such as the finger and the toes, which restricts movement and is typically covered by clothing, respectively. Instead, we opt for measurements on the facial arteries and integrate our system into a pair of glasses, making the use of the system possible in normal everyday life.

2.3 Blood pressure monitoring in mobile health

The gold standard of measuring *continuous* blood pressure is intra-arterial blood pressure monitoring using catheters in a clinical setting. Implants have the potential to take continuous measurement outside the clinic [17], but require a separate device for communication and raise usability challenges [9].

Currently, blood pressure monitoring in everyday use relies on using cuff-based oscillometric devices. Off-the-shelf devices are cheap and simple to use, such that patients who need to monitor their blood pressure can easily acquire a device and start monitoring their values.

However, the use of a cuff is disruptive to daily activity and takes at least a few minutes. More importantly, such devices require correctly putting on the inflating cuff, making it not suitable for use outside the home. As a result, the recommended device use is to measure the blood pressure at the same time everyday, once or twice a day. Although useful for monitoring long term trends of the person's blood pressure, the infrequency of such measurements renders short-term monitoring impossible.

The growing adoption of ubiquitous computing platforms, such as smartphone and wearable devices has opened up a new platform for incorporating measurements of blood pressure that is always available. This is made possible by using pulse transit time as the basis for measuring blood pressure, which does not require mechanical hardware such as a cuff and a pump.

2.3.1 Smartphone-based blood pressure monitoring. Multiple research and commercial efforts have attempted to incorporate blood pressure monitoring into smartphones. For example, Chandrasekaran et al. demonstrated the use of an external microphone to measure PCG and the use of the smartphone camera and flash to perform PPG measurements [4]. In a five people study, they were able to predict systolic blood pressure accurately within ± 5 mmHg for their recorded samples. Although it is reasonable to imagine a user could carry a microphone during daily activities for this measurement, the need to place the microphone onto the chest makes the measurement more obtrusive and disruptive.

Products, such as Wello and Kito+ by Azoi inc. incorporate PAT measurements into a phone case that provides ECG and PPG measurements. By installing this case on the phone, a person can monitor their blood pressure by simply holding the phone with both hands, covering the ECG pads with their finger and the optical sensor with one of the fingers, a common hand pose while using the phone. The grab has to be sustained over the course of data collection and the recorded physiological signal that is PAT includes the aforementioned undesirable variability of the pre-ejection period.

A more software-driven approach relies on avoiding the use of external hardware, such as an ECG and try to measure PTT using sensors already available on the smartphone. Although not directly developed onto a

Fig. 3. The iterative evolution of our Glabella prototypes. While the first two prototypes consisted of Arduino-based components to study and evaluate the feasibility of our approach in pilots, Versions 3–5 miniaturize the form factor into an integrated device that comprises all components on two separate types of boards: the main board, which sits inside the glasses frame, and the sensor boards that connect through flex PCB cables.

smartphone, Liu et al. demonstrated the measurement of PTT with a custom FPGA based two camera system that mimics the operations of a phone's front and back camera [16]. By placing one camera on an artery at the temple and another camera on the finger, the system measures PPG at two locations, and calculates the PTT. Although smartphones are mobile and often with the user, making such measurements more convenient and potentially more readily available and thus frequent, they are by nature not continuous; the user still needs be explicitly using the phone to measure their blood pressure, incurring an interruption to their regular activities.

2.3.2 Wearable consumer and research devices for blood pressure monitoring. Wearable devices provide a different opportunity for monitoring blood pressure. Devices, such as smartwatches are worn throughout the day, and are always in contact with the body. It is now typical for smartwatches to have PPG sensors incorporated into the surface that is in constant contact with the wearer's wrist, which makes PPG measurements continuous on such devices.

By incorporating ECG measurements using two metal contacts on the watch, one contacting the wrist, another pointing away to be touched by the other hand, Samsung has demonstrated PAT measurements using an ECG and PPG pair [32]. BioWatch is a similar example of the same mode of operation [36]. All such watch-based implementations suffer from the same limitation of providing convenient but not continuous monitoring, similar to the various smartphone embodiments of PAT and PTT monitors.

Winokur et al. developed a hearing aid-like device that measures single-point ECG, BCG, and PPG through a connection to a PC [38]. The proposed device requires the user to wear an ear plug and an ECG electrode below the nape and has the potential to continuously measure PAT and PTT an ECG electrode, though further miniaturization would be required to make it comfortable for long-term use and visually unobtrusive. Our system is similar to Winokur et al.'s approach in terms of the head-mounted mechanism, but uses multi-site PPG to avoid the use of ECG and is incorporated into a single device.

Constant et al. built a custom frame-enclosed wearable prototype for PPG-based pulse monitoring [5]. The prototype wirelessly integrates with a smartphone app and was designed for the use during activities, such as driving. During an evaluation, the authors found that the device provides comparable performances to a 2-lead ECG during activities, such as chewing, talking, walking, blinking and breathing. With Glabella, we take Constant et al.'s system one step further, integrating multiple sensors and correlating their measurements along with device motion for the purpose of continuously recording pulse transit times.

3 IMPLEMENTATION

We iteratively designed the final prototype of our Glabella glasses as shown in Figure 3. The goal of our design was to achieve a small, lightweight, and unobtrusive wearable form factor that directly integrates into the frame of a pair of glasses. The dominant goal was a socially acceptable overall form factor that would allow for data

Fig. 4. Breakout view of a Glabella prototype. Two sensor boards are integrated into the glasses frame, one is seamlessly integrated into a nose pad. The main board includes storage and processing components and hides in the side frame alongside the battery.

collection during the wearer's day without causing distraction to either the wearer or surrounding people. At the same time, our goal was to create a device that lasts a full day on a single charge while collecting continuous measurements at high sample rates.

3.1 Capture device

Our final prototype consists of the components shown in Figure 4. We customized one side of the glasses frame to accommodate all components and to be able to scale to different head dimensions during manufacturing. The frame houses our main board and the main battery, while two sensor boards attach further down the frame. A third sensor board integrates with one of the nose pads to sample reflections from the wearer's angular artery. All sensor boards connect to the main board using custom flex PCB cables.

3.1.1 Electronics Design. For our final prototype, we designed a custom circuit board to miniaturize and integrate all electronics apart from the sensing components as shown in Figure 5. The main components are the ARM Cortex M3-based PSoC microcontroller (Cypress CY8C5888LTI-LP097), which is the main processor on our device, the external real-time clock (Maxim Integrated DS1344D-33+T&R), a 3-axis, 12-bit digital accelerometer (NXP MMA8652FCR1), as well as a micro USB connector, a micro SD card slot, an on-off switch, and a coin-cell battery to power the external real-time clock. The device supports battery charging through USB using a

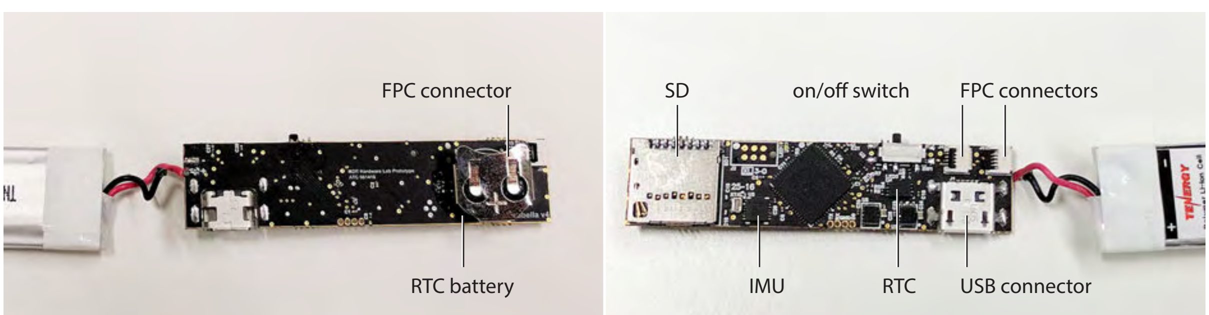

Fig. 5. Glabella's main board and main components.

Fig. 6. Glabella's sensor boards incorporate a photodiode, a corresponding and spectrum-matching green LED, and a small opamp circuit. The PSoC-integrated ADC on the main board digitizes all signals in synchrony. (Left) Custom FPC cables connect the two sensor boards in the frame to the main board. (Right) Thin magnet wires connect the sensor board that is embedded in the nose pad to the main board, routed along the frame for minimal visibility.

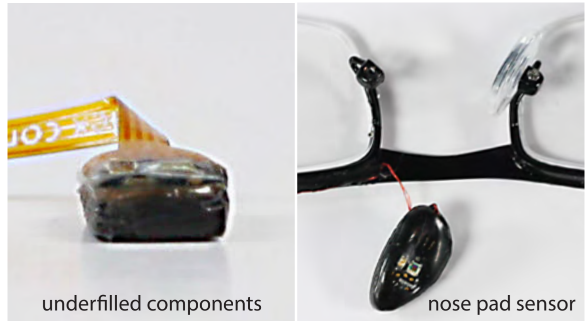

Fig. 7. To limit the exposure of our sensor boards to the user's skin and protect them from external influences, such as sweat, we *underfilled* all components using fine traces of hot glue that we manually reflowed. Using an underfill keeps the main components of the sensor board exposed to make direct contact with the wearer's skin, such that the LED and the photodiode optimally inject light into the skin and observe optimal reflections, respectively.

Microchip Technology charger IC (MCP73832-2ACI/MC). A 305 mAh lithium-polymer battery powers the device, which runs for approximately 15 hours.

Figure 6 shows our sensor board. It comprises a photodiode (Broadcom APDS-9008), a corresponding and spectrum-matching green LED, a small opamp IC (Microchip Technology MCP6001T-I/OT) and amplification and filter circuit. The filter circuit is designed to adapt the gain to changing brightness intensities and to remove the DC bias of the reflections, as well as to block frequencies above 50 Hz in the raw signal. The photodiodes on the sensor boards directly connect to the microcontroller through our custom flex PCB cables, where the PSoC-integrated 12-bit ADC samples the reflection signals in a synchronized manner.

3.1.2 Mechanical Design. We use off-the-shelf glasses as base frames (KHAN, Small Rectangular Clear Glasses Flex Frame) and 3D printed a custom side frame from digital ABS [34] on a Stratasys Objet Connex 500 printer to

Fig. 8. Mechanical design of the frame. The ABS-printed frame is parametric for easy adjustment to each wearer's head dimensions. Cavities accommodate the main board and the sensor boards. The groove along the frame routes FPC cables between all boards. We close the frame using black tape.

house all components as shown in Figure 8. While we modeled the frame to roughly resemble the shape of the opposite frame, we kept the model parametric, because the locations of all sensor boards have to be adjusted to the wearer's head dimensions much like prescription glasses. The case features openings for the USB connector and the on-off switch, for which we printed a hat to extend beyond the case for easier operation. We sealed the frame by lightly attaching the battery and board with hot glue and wrapping it in robust and skin-friendly tape. A small layer of black hot glue inside the frame hinge prevents the frame from closing while providing a good amount of compliance to prevent breaking.

Glabella's integrated sensor boards are shown in Figure 6. Since they make constant contact with the wearer's skin, polishing their finish posed a challenge. To obtain an optimal signal, the sensor needs to rest as closely against the skin as possible. Similarly, the LED needs to be against the skin to prevent crossover light leakage directly into the sensor. Covering both components in a blob of transparent glue will lead to internal reflections as may surface covers, both of which have diminished the signal to noise ratio during our prototyping and testing efforts. At the same time, our sensors needed to resist water damage due to potentially profuse sweat and be smooth enough to not cause itching or scratching to the skin.

Figure 7 shows our solution to this challenge. We underfilled all components, such that the glue extended exactly to the top surface of the LED and photodiode. This smoothly enclosed all components and prevents direct exposure while keeping the distance between the LED and the user's skin or the photodiode and the user's skin at zero.

For the nose pad sensor, we modeled a separate volume to resemble a traditional nose pad and simultaneously accommodate our sensor board as shown in Figure 7. This custom pad also includes a mount for the metal mount connecting it to the front frame of the glasses, which allows for adjustment and exhibits spring-like behavior to comfortably adapt to the user's skin.

The total weight of our final prototype is 45 grams including all boards, batteries, mounts, and enclosures. This compares to 37 grams for the unmodified off-the-shelf glasses, which is in the same order of magnitude, making our prototype glasses comfortable for everyday wear.

3.1.3 Device Operation. We designed our prototype devices to continuously sample data from the inertial sensor to record the user's movements and from the photodiodes to measure the amount of reflected light to obtain pulse signals. The microcontroller samples reflections at 5000 Hz and inertial measurements at 200 Hz. The processor buffers all streams of measurements for as long as possible (around 1.5 seconds) and then dumps them to the SD card for additional offline analysis along with the timestamp obtained from the separate real-time clock on the board. To achieve around 15 hours of operation, we had to duty-cycle the sensing, such that our device senses 4 out of 5 minutes throughout the lifetime of the battery. During the remaining minute, the LEDs are turned off, the ADC does not sample reflection levels, and the microcontroller is sent to a soft sleep state.

Our prototype continues this type of processing until the main battery charge runs out, which is stops discharging before running too low through a protection circuit. The separate coin-cell battery ensures that the real-time clock keeps time across days and a discharged main battery, such that logging continues with accurate timestamps once the device has been charged again. Fully charging the Li-Po battery through USB takes around 10 minutes.

3.2 Signal Processing

Each Glabella device logs records of three optical reflections and three accelerometer measurements. We process the data in five steps to extract final pulse transit times to predict blood pressure changes.

Figure 9 shows an example of the raw signal digitized by the microcontroller over the course of 5 seconds. While our sensor board performs coarse analog filtering of the raw reflections from the angular artery (nose location, s_{ang}), superficial temporal artery (STA, just in front of the ear, s_{sta}), and occipital artery (behind the ear,

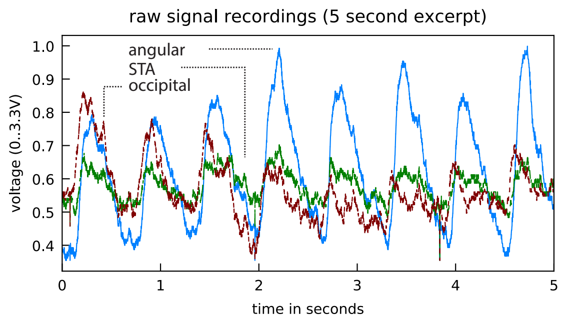

Fig. 9. Raw signal captured by the sensors, here a particularly bad example due to the opamp recovery from railing intensities just before restoring the proper amount of signal amplification.

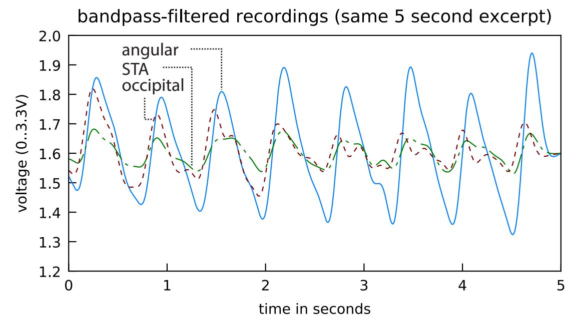

Fig. 10. After applying a 0.4 Hz–8 Hz bandpass filter to the raw intensities, the pulse reflections exhibit clearly their characteristic features, which we consequently detect for extracting timestamps.

s_{occ}), the signal contains noise from sources, such as motion artifacts or potential changes in ambient illumination. In this case, the limited resolution is due to the recovery from a railing signal, for which our opamp circuit requires around 10 seconds to settle again. The inertial measurements a_x, a_y, a_z (not shown) are unfiltered to include even the strongest motions and process all optical reflections accordingly.

First, we apply a 5^{th}-order 8 Hz Butterworth low-pass filter and a 2^{nd}-order 0.4 Hz Butterworth high-pass filter to all three signal streams. This smoothes the signal, removes the DC bias that may temporarily be present (e.g., due to recovering from railing as shown in Figure 9), and produces recognizable pulse reflections as shown in Figure 10. Figure 11 shows a magnification of a 1-second subset of the data, which demonstrates the similarity and temporal offset in signals across the three reflections.

Second, we apply a Fast Fourier transform to each 15-second window of the recordings of each channel and extract the dominant frequency f_{ang}, f_{sta}, and f_{occ} for each window of the signals s_{ang}, s_{sta}, and s_{occ}. If $|f_{ang} - f_{sta}| < \varepsilon$ and $|f_{ang} - f_{occ}| < \varepsilon$, we derive the user's heart rate at that moment from the dominant frequency if the magnitude of the second most-dominant frequency is significantly smaller than the first.

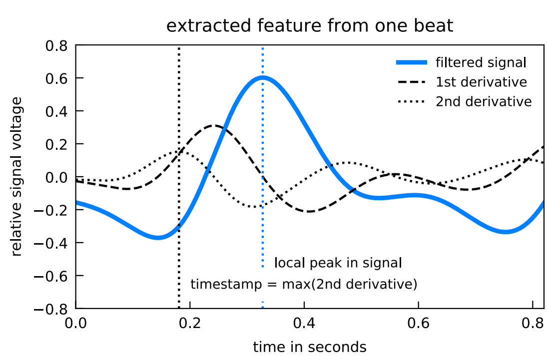

Fig. 11. Illustration of a single beat after applying a bandpass filter. We compute the feature timestamp from the local maximum of the 2^{nd} derivative of each of the signals (dotted vertical line) just before the local peak of the signal (blue dotted vertical line).

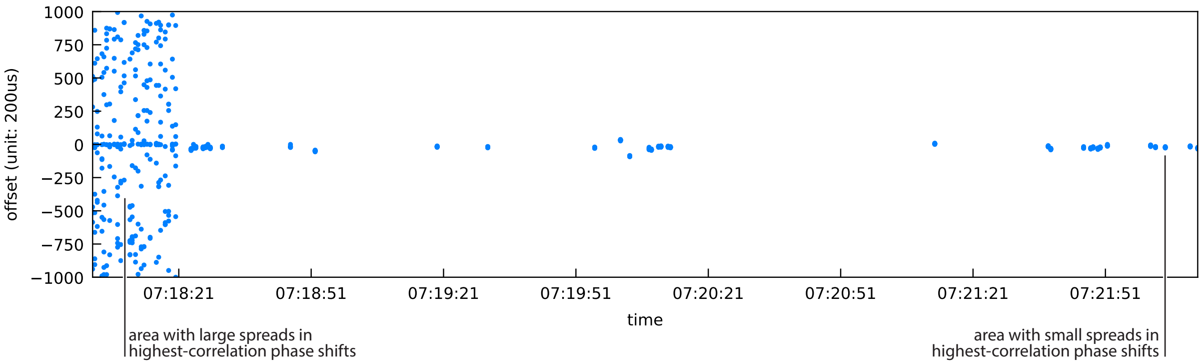

Fig. 12. Plotting the spread of the top 50 phase shifts for two correlated signals for each heart beat reveals periods of low spreads, which we consequently use as beat candidates for PTT computation, as well as large spreads, which we discard. Note that during times when only few phase shifts appear to be visible in the chart (e.g., right part of the plot), they belong to adjacent offsets, thus resulting in a minute vertical spread. Periods without any values represent times when the sensors were off or those during which the device was moving as detected by the accelerometer.

Third, we detect peaks in the one signal that originates from the angular artery-located reflection sensor s_{ang} with a window size of $\frac{1}{5}$ seconds. We then detect the closest peaks in the other two signals s_{sta} and s_{occ} as well as the closest preceding troughs in all three signals. This produces the timestamp of the onset of the pulse wave as well as its maximum. We now extract the features $t_{ang}, t_{sta}, t_{occ}$ from the maximum of the second derivative of the bandpass filtered signal originating from the sensor by the glabella (on the angular artery), temple (superficial temporal artery), and behind the ear (occipital artery) as shown in Figure 11.

Fourth, we apply two steps to verify the validity of the extracted candidate timestamps: 1) We discard candidate timestamps for a beat if the inertial measurements during a 1-second window around the beat exceed a threshold in any of the three directions to account for motion artifacts. 2) We phase correlate the normalized reflection waves of s_{ang} and s_{sta} as well as s_{ang} and s_{occ}, respectively, to determine the maximum magnitude of correspondence and to assess the spread of best-matching phase offsets. If either the former value is below a threshold or the spread of the phase values is too large, we discard the candidate timestamps for this peak. Figure 12 shows a plot of the top 50 correlation phase offsets, which reveals areas of large spreads (to be discarded, e.g., during motion) and small spreads.

Finally, we derive the pulse transit time PTT_{AA-STA} and PTT_{AA-OA} from the differences of the timestamps $t_{ang} - t_{sta}$ and $t_{ang} - t_{occ}$, respectively, as shown in Figure 13. Our lab prototype shown in Figure 14 allowed us to optimize sensor locations to test users for rapid feature evaluation and in-lab testing. For added stability and resolution, we input all such derived pulse-transit times into a moving window average function to obtain a final measurement. These resulting final pulse transit times can now be used as a proxy to monitor the behavior of the user's systolic blood pressure. To obtain absolute blood pressure values, a model needs to be calibrated per-person through correlation with ground-truth recordings [8, 21]. As Mukkamala et al. describe, we determine the quality of our Glabella to ground-truth relationship by correlating $1/PTT$ with absolute blood pressure measurements to determine K_1 and K_2 in

$$BP = \frac{K_1}{PTT} + K_2,$$

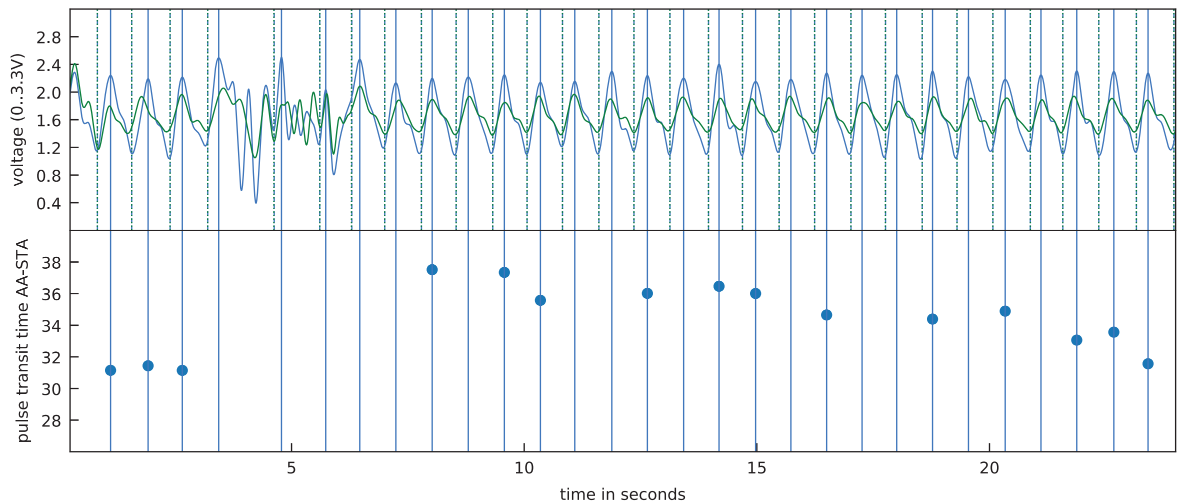

Fig. 13. Two pulse signals over the course of 16 seconds, from which we extract pulse transit times on a beat-by-beat basis. If the feature points around a pulse in the continuous stream of reflections fails our quality control, we skip the computation of the pulse transit time for this beat. In this example, the PTT curve shows the behavior of a person standing up wearing the prototype after leaning back for 5 minutes. This produces a quick drop in relative systolic blood pressure, which quickly recovers to the previous values.

which has been found to linearly relate to a wide range of blood pressure values [20]. Inverting PTT values essentially produces a measure of the pulse wave velocity (PWV), though for our purposes we do not calibrate it to differences in distances from the wearer's heart to the sensors.

4 IN-THE-WILD EVALUATION

The purpose of this evaluation was two-fold. First, we wanted to assess whether our prototype glasses could sustain operation and capture useful data during everyday wear and regular activities. Second, we wanted to determine the correlation between the pulse transit times recorded by our prototype and systolic blood pressure

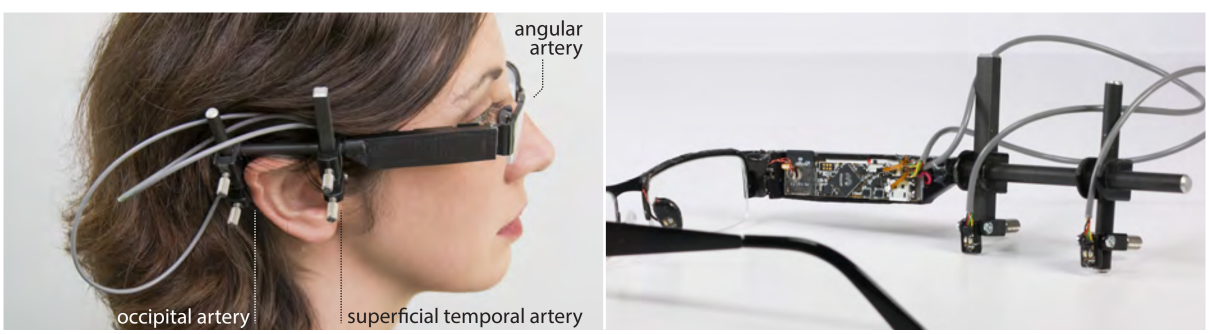

Fig. 14. Our adjustable lab prototype that recorded the pulse waves shown in Figure 13. While Glabella rigidly integrates the two sensor boards inside the frame at user-specific locations, this prototype features adjustable joints for translation, tilt, and rotation to fit a user's head dimensions.

values as 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.

4.1 Task

Participants performed two tasks throughout the duration of the study.

Each participant wore a customized Glabella device over the course of each day of participation, for a minimum of 12 hours, but often covering the duration between getting up in the morning and going to sleep at night. Participants charged the device overnight to be ready for use again the next morning.

Additionally, participants took blood pressure measurements three times an hour at regular intervals for twelve hours each day of participation using a commercial oscillometric cuff. A periodic SMS message every 20 minutes reminded them to take a measurement. We instructed participants to record at least 30 blood pressure measurements per day, but to skip recordings in inconvenient situations that cannot afford interruptions, such as meetings or work situations, driving, and during exercise.

4.2 Procedure

Before the actual evaluation, each participant attended a screening meeting, during which the experimenters explained the purpose and procedure of this study. The experimenters then introduced participants to the Glabella prototype device and answered questions on expectations and study participation. To individually customize glasses frames to each participant's head dimensions, the experimenters measured and recorded the precise locations of each participant's superficial temporal artery and at the location behind their ear in relation to the mockup glasses worn only during the screening as shown in Figure 15. Participants then installed an app on their smartphones to record blood pressure measurements on the oscillometric cuff that we provided and we tested the connection with the monitor and the upload of values to their profile. We then demonstrated the operation of the blood pressure monitor and observed and corrected participants while they performed a measurement.

After the screening sessions, we modified the model of our glasses frame to fit each participant's head dimensions and sent it out for fabrication. Upon return, we assembled each of the four prototypes and sealed them as described before. We then included each participant's Glabella prototype, a charging cable, adapter, and the commercial blood pressure monitor in a box, ready for participants to pick up and begin the study.

Participants conducted this evaluation starting on a Monday through Friday night, which allowed us to cover sampling during their regular weekdays that they spent mostly on campus.

4.3 Interfaces

We collected measurements using two interfaces during this study.

The first interface was a Glabella prototype device, custom-fitted to each participant's head dimensions as shown in Figure 16. The device continuously measured and stored timestamped optical reflections at the location of participants' angular arteries, superficial temporal arteries, and occipital arteries while being worn throughout the days of the evaluation.

The second interface was a commercial cuff-based oscillometric device as shown in Figure 16 (iHealth Sense [10]). The device is clinically accurate, FDA approved, as well as wireless and convenient in operation. To record a measurement, participants wrapped the spring-loaded strap of the cuff around their wrist, tightened it, and initiated a measurement through the app on their smartphone. The cuff then inflated and recorded blood pressure measurements, which were subsequently uploaded to the iHealth Labs cloud backend through the app on their phone. This allowed us to monitor participants' compliance and ensure the cuff's proper functioning throughout the study.

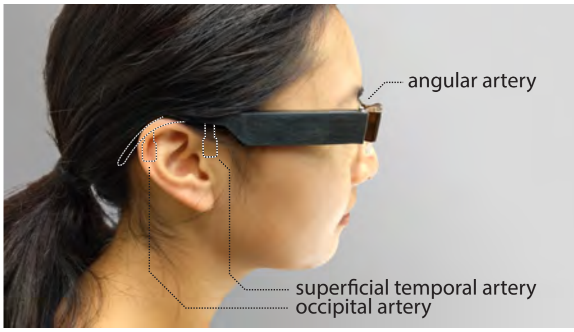

Fig. 15. During the screening session, we measured each participant's head dimensions to precisely fit the sensor on the location of their superficial temporal artery and occipital artery in the 3D printed case, respectively. The sensor on the participant's angular artery was fixed and embedded into the nose pad of the frame.

Fig. 16. Each participant recorded values using two interfaces during the study. Our Glabella prototype glasses continuously recorded the user's pulse reflections at three sites on their head. Three times an hour, participants took a blood pressure measurement using a commercial cuff-based wrist-mounted blood pressure monitor.

While we briefly considered the use of an automatic cuff that periodically inflates, we learned during pilot testing that the device is subject to slipping during regular activities. This sometimes required adjusting the device, manually marking measurements as unreliable, and repeating them at a later stage. Such a self-inflating cuff also posed a challenge to go about regular habits by partially impeding movement as well as inflating during inconvenient moments.

4.4 Participants

We recruited four participants for this evaluation. Two participants were male (ages 40 and 42) and two were female (ages 25 and 39). All participants had Fitzpatrick skin type II and had no known medical conditions related to our evaluation, such as hypertension. All participants worked at Microsoft, though in different capacities and parts of the organization and no participant worked with the research organization. Each participant received $400 as a gratuity for their time, effort, and compliance.

4.5 Results

We now compare participants' measurements using the commercial blood pressure monitor with the pulse measurements of our prototypes. We thereby analyze the results separately for each participant to avoid misleading results and account for individual physiological characteristics [1].

For each blood pressure measurement taken by a participant, we analyze the surrounding ±2 minutes of pulse reflection and accelerometer data recorded by their Glabella device. On a per-beat basis, we evaluate the quality of the signal and discard candidates or extract the PTT features as described above.

4.5.1 Heart rate correlations. Figure 17 (top) shows the summary plot of all heart rates recorded through the blood pressure monitor and those recorded through our prototype devices. What is most evident in the charts is the quality of the signal derived from the angular artery compared to the quality of the signals from the superficial temporal and occipital artery; across all participants, the former resulted in a high coefficient of the correlation of both signals. In contrast, the spread of recorded data points is larger for the signal stemming from the other two sensors as shown by the standard errors. The spread is largest and resulted in a low correlation coefficient for the sensors close to the ear in the measurements of Participants 3 and 4.

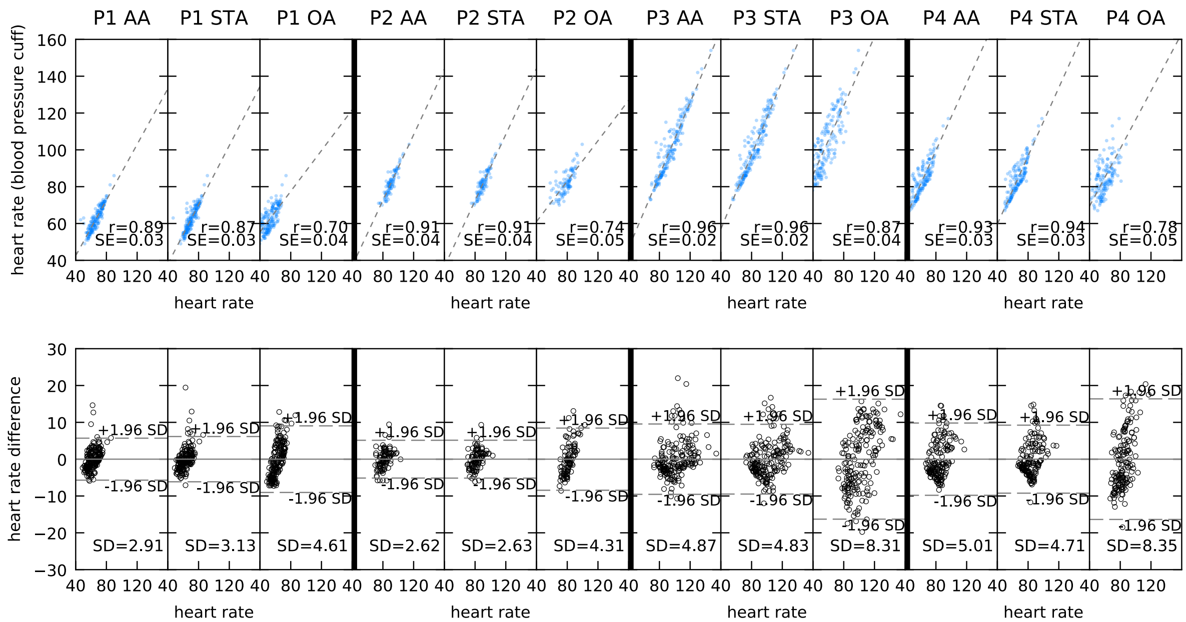

Fig. 17. (Top) Correlation of heart rates measured by the commercial blood pressure monitor and each of the three sensors on our prototype devices sampling the angular artery (AA), superficial temporal artery (STA), and occipital artery (OA). (Bottom) Bland-Altman diagram of errors in pulse measurements using our sensors compared to the values from the blood pressure monitor as ground truth.

Figure 17 (bottom) shows the Bland-Altman diagrams for all pairs of measurements, comparing the differences in observations along the range of heart rates recorded by the blood pressure monitor. Again, this diagram reveals the decreased match and increased error spread in heart rates measured by our prototypes on the occipital artery, as well as lower spreads and more consistent measurements on the angular artery and superficial temporal artery. On average, the standard deviation of deviations in observations was almost twice as large for the sensor on the occipital artery as that for the two other sensors.

Apart from the diverging values, we can see in the diagram that the heart rates participants exhibited over the course of the study varied in different amounts. Whereas for P1 and P2, their heart rate stayed at consistently low values during the moments of measurements, P3 and P4's recorded heart rates covered a larger part of the spectrum.

4.5.2 Systolic blood pressure correlations. We now analyze the correlation of recorded systolic blood pressure measurements and the pulse transit times derived by our prototype devices. Figure 18 shows the distribution of systolic blood pressures measured by all four participants over the course of our evaluation. We can see that from the four participants, the distribution of systolic blood pressures recorded by P2 stands out and is shifted to higher ranges, with a spread in values that is comparable to the other participants.

Figure 19 (top) shows the correlation scatter plot for all recorded systolic blood pressure measurements and the corresponding inverted pulse transit times that our device computed for the temporal difference in features between the sensor sampling the angular artery and the sensor sampling the reflections from the superficial temporal artery. The figure also illustrates the results of a linear regression through all observations, for which

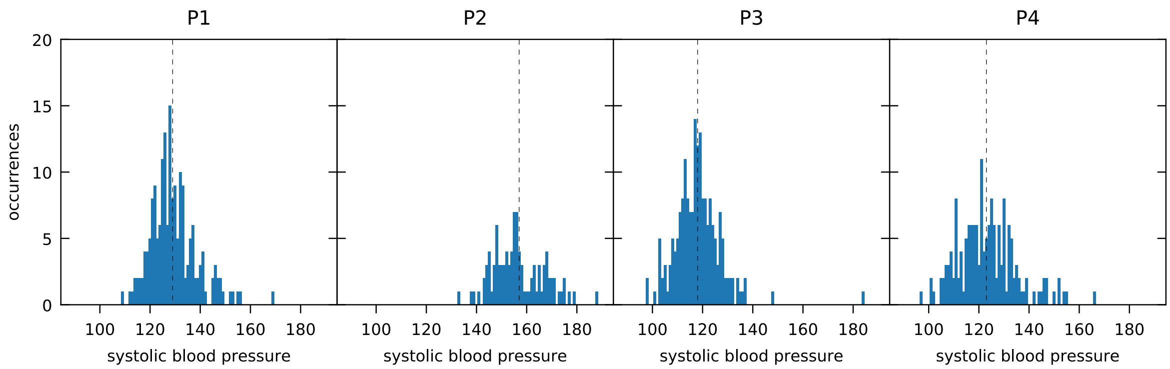

Fig. 18. Distribution of systolic blood pressure measurements across the duration of the study for each participant.

we obtained a correlation coefficient between 0.64 and 0.84. The units of the abscissa refer to the inverted pulse transit time, thus s^{-1}, which is not adjusted for the distance between the sensors. The chart highlights that after discarding samples due to motion and insufficiently strong correlations across sensors, the inverted pulse transit times cover the small range between 18 and 60 s^{-1}.

The bottom plot in Figure 19 again shows the Bland-Altman diagram of the value pairs. The Bland-Altman diagram shows a slight trend for all participants, most pronounced for P1, but also visible in P3's and P4's results. In P1's case, for actual systolic blood pressure values below the 120 mmHg mark, the linear model results in blood pressure estimates that are almost all too low, whereas they are too high for values larger than 140 mmHg. Despite the bias in prediction error, we can see that except for a few outliers, all predictions using the inverted pulse transit time correspond to the recorded systolic blood pressure value within ± 10 mmHg using the linear mapping

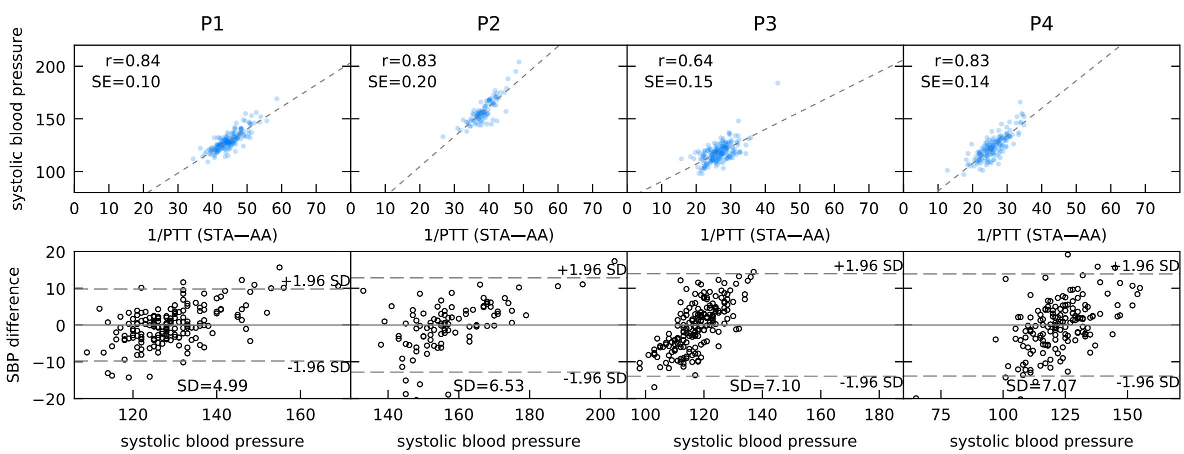

Fig. 19. (Top) Correlations of 1/PTT and systolic blood pressure between the angular artery and the superficial temporal artery, as well as the correlation coefficient for a linear model. (Bottom) Bland-Altman diagram of the errors produced by the linear model in predicting systolic blood pressure values based on pulse transit times along the ground-truth values manually recorded by the monitor.

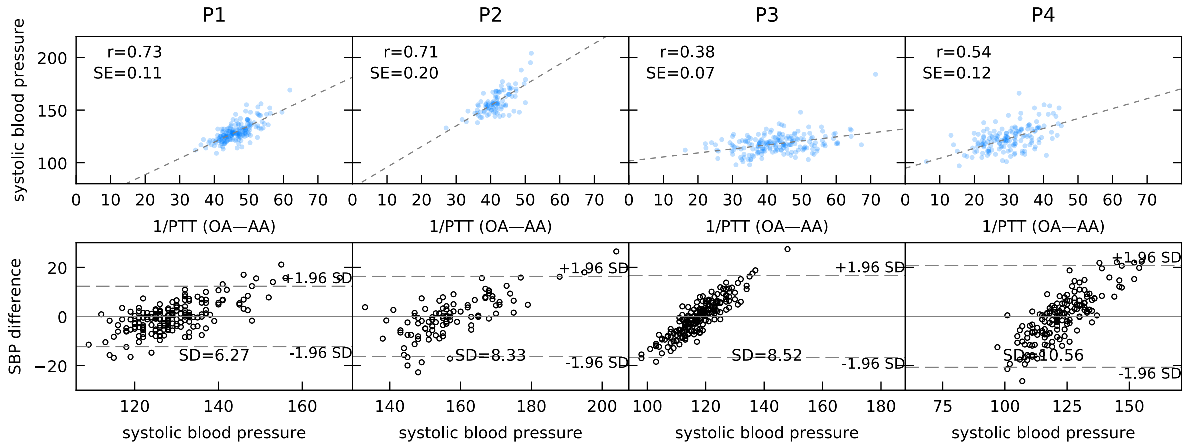

Fig. 20. (Top) Correlations of 1/PTT and measured systolic blood pressure between the angular artery and the occipital artery behind participants' ears, as well as the correlation coefficient for a linear model. (Bottom) Bland-Altman diagram of the errors produced by the linear model along the ground-truth values of the blood pressure monitor.

shown above. As can be seen in the distribution graph of each participant, the typical range of fluctuation is about 40 to 50 mmHg, indicating that the error in prediction by inverse pulse transit time is still capable of distinguishing general trends in blood pressure fluctuations for a given person.

Differences between the optical sensors in our wearable prototype become obvious when comparing the recorded pulse transit times above with those between the sensor on the angular artery and that on the occipital artery (Figure 20). Here, the distance between the participant's heart and either sensor was shorter, thus resulting in slightly shorter pulse transit times observed between the filtered signals. Compared to the previous diagram, the linear model produces higher errors and lower correlation coefficients for all participants.

Similarly, the Bland-Altman diagram reflects the larger error in a higher spread of differences between the model output and the recorded actual systolic blood pressure values. The model outputs based on the pulse transit times between the sensors on these two locations differ from the true measurements by ± 20 mmHg. What is even more evident in the scatter plot is the linear trend in the comparisons of error to systolic blood pressure measurement. This indicates a much lower quality of the model for predictive purposes and confirms the impression above that the sensor on participants' occipital artery produced a lower-quality signal.

5 DISCUSSION

On the highest level, the results of our evaluation show the feasibility of our Glabella prototype device to continuously collect optical pulse reflections at a quality that is adequate to track the wearer's heart rate and extract meaningful differences in time-of-arrival between reflections at the different sensor locations. We have also established the capabilities of our prototype to track the behavior of the wearer's blood pressure passively and conveniently without imposing requirements on data acquisition or demanding user input.

To arrive at *absolute* blood pressure values, the correlations between the inverted pulse transit times and the systolic blood pressure measurements taken by participants show that a simple linear per-user model can predict systolic blood pressure values within ±10 mmHg for the participants in our study. Importantly, the results in this paper assume that participants administered the cuff correctly throughout the study and remained aware of the measurement procedure to record accurate values. Even so, the results we obtained result from the data captured with a platform that is unobtrusive and wearable, and that accompanies the wearer throughout their regular day and activities. This shows Glabella's potential of recording real-time responses in blood pressure behavior to events throughout the day.

The suitable fit of a linear per-user model for the continuous prediction of systolic blood pressure values also shows promise for incorporating all processing directly on the device. Whereas for our evaluation purposes, we processed all recorded streams of data offline to determine each participant's individual model, these could now be deployed to the device and continuously feed into a platform that records physiological data, such as Microsoft Health or Apple iHealth.

Regarding the plots in Figures 19 and 20, the inverted pulse transit time signal we extract from the reflected intensities spans only a limited range of values. In comparing the sensor on the angular artery with that on the superficial temporal artery, the majority of inverted pulse transit times are within a range of only 20–30 values; relayed back to the original measurements, this equates to around 50 offsets in the raw observations at our sample rate of 5000 Hz. This insight shows support for our approach to continuously observe all signals. By averaging across valid pulse transit times and weeding out low-quality candidate samples using the inertial sensors and the assessment of similarity across the optical signals, we achieve a resolution that is higher than that of an individual observation, such as achieved by selective measurements using existing monitors.

The charts also offer insights into the quality of individual signals and sensor locations. Across all observations, the sensor sitting on the angular artery provided the highest-quality signal with the lowest spread, whereas the sensor on the occipital artery produced a higher spread in measurements and thus less consistency. In follow-up examinations of participants' head dimensions and the customized models, we believe this is the result of two interplaying factors: The sensor on the angular artery sits on the wearer's nose, pressed against the wearer's skin through gravity. Except for moments of motion, the force with which the sensor touches the wearer's face is roughly constant. Unlike sensors in watches, this sensor requires no manual adjustment, such as by tightening the strap, which is common in smartwatches to obtain reliable readings.

In contrast to the sensor behind the ear, the other two sensors are pushed towards the users' head, creating two distinct points of contact. In hindsight, this raised a challenge for the third sensor. The current version of our frame is made from little-flexible ABS material and virtually all compliant behavior of the frame results from the hinges. Therefore, the sensor on the superficial temporal artery often made better contact with participants' heads than the sensor behind the ear. This is aggravated by the softness of the surface behind the ear, which is closer to the skull and much less soft and thus a worse support than the surface around the superficial temporal artery. The result is the drop in signal quality that we saw in the evaluation. On top of these aspects, hair falling down behind the ears of participants might have occasionally prevented optimal contact between the sensor and the participant's head. While we encouraged all participants with longer hair to wear a hairpin and pull their hair up to prevent this, we had no way of verifying this part of compliance. Hair might have also slipped down over the course of the day, potentially leading to worse signal qualities.

5.1 Limitations, Applications, and Future Challenges

In addition to the partially suboptimal contact of all sensors with participants' heads during wear, our study has revealed several limitations.

An obvious limitation of our study is the number of participants as well as the ages, weights, and skin types they represented. The plot of recorded systolic blood pressure measurements in Figure 18 shows normal distributions for each participant; although they are offset on the spectrum, each distribution is small in range. Besides, none of our participants had known conditions of hypertension or was actively treated through medication. This factor as well as a higher number of participants is what we are planning to examine in a future study.

Notably, throughout the analysis, we treated the measurements recorded by the commercial oscillometric cuff as ground-truth recordings as mentioned above, with the implicit assumption that the values are accurate. While the type of automated oscillometric monitor we used in our study has been proven to be accurate in use (only 4–5% of recordings producing an error > 3 mmHg [3]), the design of our study naturally left the participant themselves as a potential source of error [22]. Although we repeatedly demonstrated to participants during the screening how to accurately take a measurement and instructed them to patiently wait during the procedure, a chance remains that some of the measurements were subject to noise from simultaneous other activities, such as checking the phone, interacting with a workstation in the office, or other body motions.

Closely related is another limitation of our study that is the lack of a controlled procedure to influence participants' blood pressure levels. Evaluations are commonly conducted in laboratory environments and participants undergo static and dynamic exercises to control the behavior of their blood pressure and thus test out prototype sensors.

To obtain the correlation of pulse transit times and accurate blood pressure measurements, our Glabella devices will need to be evaluated in a clinical setting and the context of invasive measurements. We are currently in the process of preparing such an evaluation with patients in collaboration with an affiliated university hospital.

Another observation of the raw data in our results section shows support for Gesche et al.'s work [8]. Their results indicated that a linear model to predict systolic blood pressure values from observed pulse transit times is an oversimplification; instead, their non-linear model integrates an exponential term that depends on a user-specific parameter. Revisiting the two scatter plots for each participant in Figures 19 and 20 from this perspective, some plots appear to support the presence of an additional factor. As mentioned before, the slight linear trend of data points in all Bland-Altman diagrams further supports the limited nature of the derived models from our evaluation.

In looking at the number of pulse transit time measurements that were suitable in predicting a participant's systolic blood pressure and those that clearly lay outside the valid range (e.g., large negative values or offsets larger than 500 frames) encourage us to reconsider the core feature we have been extracting to calculate pulse transit times. In previous tests, we experimented with the inflection point of the original signal (i.e., the local maximum of the first derivative), the foot of pulse wave, as well as a purely phase-correlation-based prediction, all of which provided less accurate results than our current metric. We plan on reexamining our dataset to experiment with different features as well as a combination of them, such as individual distances between all peaks and troughs of the pulse wave (i.e., the peaks and troughs of reflection waves in addition to systole peaks [2]) and the holistic shape of the wave to begin with.

Finally, our current sensors measure the reflections of green light, which is less prone to observing motion artifacts due to more shallow light penetration, but is visible if the sensors are not aligned correctly with the user's body. We plan on exploring near-infrared emitters and sensors in future versions of our prototype wearable, which simultaneously increases arterial penetration and should further improve our signal.

5.1.1 Applications. Besides the potential implications of our Glabella prototypes for health-related scenarios, monitoring the behavior of blood pressure in response to short-term events, such as postural changes or medication intake, we foresee even wider applications. An emerging trend in the wider human-computer community as well as consumers outside the research domain is self-tracking and reflecting about one's activities for well-being purposes.

We think that Glabella could serve as a convenient and continuous data collection instrument that may allow users to better understand their physiological behaviors and responses with blood pressure behavior being a useful metric for understanding how we respond to certain stimuli. The inertial sensors in our device are immediately suitable for activity recognition, a topic that has been widely explored and has found its way into many commercial products. What such devices have in common with our prototype is the requirement for continuous sensing that must happen in the background; with only periodic measurements that may even have to be performed manually, any sensing instrument is bound to miss the body's detailed responses that we seek to understand better. Glabella requires low user attention and thus does not distract users from their regular activities on which they can remain focused.

In addition to tracking, logging, and later reflecting, by moving the processing onto the device, Glabella could start acting as a direct source of feedback. For example, with this additional physiological metric, we envision the use of our prototype in the context of alertness tracking and decision making, such as by observing users' responses to certain foods and drinks (e.g., recommending against another cup of coffee) or to encourage the user to take a break.

5.1.2 Future Challenges. The results of our evaluation support Glabella as a continuous monitor of blood pressure *behavior*, meaning relative changes in the wearer's blood pressure levels. The main challenge we see resulting from this work is the calibration of models that predict *absolute* measurements. Efforts in the related work have pointed out the potential of calibrating a PTT-based system using few data points (e.g., [8]). In contrast, our method of obtaining all per-participant models implied collecting participants' measurements in an arguably tedious fashion to record ground-truth data. Although we see the potential of Glabella as a convenient and unobtrusive device, the act of calibration so far prevents it from fully redeeming these desirable characteristics.

All calibration efforts for PTT-based systems compare to the traditional cuff, which is a cheap, off-the-shelf device that will produce accurate measurements within minutes. Therefore, we plan on focusing the main part of our future efforts on a reduced calibration procedure for cuffless devices.

Another challenge we face is the continued miniaturization of our prototype. While the device is fully integrated into the frame, wearers may still stand out upon closer consideration, such as during conversations with others. We have already started to work on the next revision of our device with the goal of more robust signal acquisition, power efficiency, and a smaller form factor. We thereby also hope to overcome the current requirement of custom-fitting each device to a wearer's head dimensions, possibly even arriving at the clip-on form factor of our previous work that affords the use with regular glasses [6].

6 CONCLUSION

We presented Glabella, a novel wearable prototype device that unobtrusively and continuously collects the wearer's heart rate at three different sites on their head on a per-second basis. From the difference in pulse arrival times at each of the locations, our prototype derives the user's pulse transit time on a beat-by-beat basis.

Our in-the-wild evaluation of our prototype devices with four participants over the course of five days during their everyday activities showed a strong correlation between the inverted recorded pulse transit times and participant's manually recorded systolic blood pressure, consistently throughout different times of day and days of the week. Our work, therefore, indicates that Glabella is a viable option to continuously monitor a person's systolic blood pressure on a short-term basis, all using a socially-acceptable prototype during each and every moment of their regular day.

We believe that the continuous data that our prototype captures will open up a new perspective on the detailed behavior of the user's blood pressure throughout the day in response to activities, such as eating, walking, resting, working, and so on. The results of our data capture will inform the validity of this novel measurement as a more continuous monitoring method for blood pressure monitoring as compared to currently available technology, which imposes constraints on the user's flexibility and interrupts their activities. With further miniaturization and optimization of signal acquisition and processing, we think that a well-engineered, non-invasive device like Glabella will allow for realistic capturing of data in daily use scenarios to fully understand the fidelity of pulse transit time as an informative signal.

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