BEAT: Barometric Compensation for Wrist-Height Effects in Oscillometric Blood Pressure Measurement

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***Abstract*—Wrist blood pressure (BP) readings depend on the height of the cuff relative to the heart. Maintaining the wrist at heart level can be difficult for users with restricted arm movement. BEAT (Barometric Elevation and Attitude Tracking) uses one detachable barometric–inertial module to estimate the hydrostatic offset. The user briefly holds the module at heart level to record atmospheric pressure, then attaches it to the wrist cuff. The difference between the stored reference and the wrist pressure provides a signed height estimate for correcting oscillometric BP. We evaluated baseline agreement with an Omron monitor using 15 paired readings from three participants. Two participants also completed five trials in each of three arm positions. Across these positions, compensation reduced systolic mean absolute error (MAE) relative to each participant's mean heart-level Omron reading from 7.61 to 3.33 mmHg (56.2%). Diastolic MAE decreased from 6.79 to 4.42 mmHg overall, although it rose from 4.70 to 4.92 mmHg with the wrist above the heart. These results describe feasibility in the tested positions. Clinical accuracy and usability in people with limited mobility require separate evaluation.**

***Index Terms*—Blood pressure monitoring, hydrostatic pressure compensation, oscillometry, wearable devices, barometric sensing.**

I. Introduction

Hypertension remains a critical global health concern, affecting an estimated 1.4 billion adults worldwide in 2024 [1] and serving as a primary risk factor for stroke and cardiovascular disease. Effective management relies heavily on accurate, frequent, and reliable home-based blood pressure (BP) monitoring [2]. Among the available technologies, automated oscillometric devices have largely replaced traditional mercury sphygmomanometers due to their ease of use [3]. Wrist-worn monitors, in particular, offer superior portability. However, their clinical reliability is compromised by the hydrostatic pressure effect.

From a fluid dynamics perspective, the blood column between the heart and the wrist exerts a pressure governed by the equation $\Delta P = \rho g \Delta h$. According to the American Heart Association (AHA) guidelines, any vertical deviation from the heart level introduces a systematic error of approximately 0.77 mmHg per centimeter [4]. In a study of 721 home users, 621 had wrist measurement errors of at least 5 mmHg in magnitude, including 455 with errors of at least 10 mmHg [5]. This positional sensitivity poses a significant challenge for specific patient populations, such as those suffering from paralysis or muscle weakness, who often find it physically impossible to maintain a steady, heart-level posture during measurement. Wrist-cuff results in a high-risk population also varied with arm position [6].

Existing attempts to mitigate posture-induced errors have primarily relied on accelerometers to infer the arm's orientation. However, these inertial-only methods are fundamentally limited; they can detect the angle of the arm but cannot uniquely determine wrist-to-heart height from wrist angle alone. While recent advanced approaches have utilized deep learning models to predict arm poses [7], their accuracy depends on the estimated geometry of the arm. In contrast, barometric pressure sensors offer a direct physical measurement of elevation changes [8].

To bridge this gap, we introduce BEAT, a system featuring a single detachable barometric-inertial sensing module. A key innovation is the time-multiplexed calibration workflow: the user first calibrates the system by placing the detachable sensor at the heart level to establish a zero-reference atmospheric baseline. Once re-attached to the wrist cuff, the system dynamically calculates the vertical displacement h based on the pressure differential between the stored baseline and the real-time wrist altitude [9]. This arrangement allows the arm to rest away from heart level once calibration is complete. Usability with limited mobility remains an open question.

The primary contributions of this work are three-fold:

- Hardware Design: A modular architecture featuring a single detachable sensor for sequential heart-level and wrist-level sensing.
- Compensation algorithm: A signed correction that converts the pressure difference between the sequential heart- and wrist-level readings into an adjustment for wrist BP. Inertial measurements provide motion and orientation information.
- Experimental evaluation: A heart-level comparison with a commercial monitor followed by repeated measurements in three postures. We report both systolic and diastolic errors, including postures in which compensation offered little benefit.

We hypothesized that correction would reduce the average absolute difference from the heart-level reference across the three tested postures (H_1). The project page provides a demonstration. The code repository contains the firmware, desktop acquisition software, and figure-analysis scripts.

II. Methodology

A. System Architecture and Sensing Modalities

The BEAT system is designed around a decoupled, modular architecture to minimize interference between pneumatic actuation and high-precision sensing. The system consists of two

This work was developed in the Fundamentals of Sensing Technology (ME323) course.

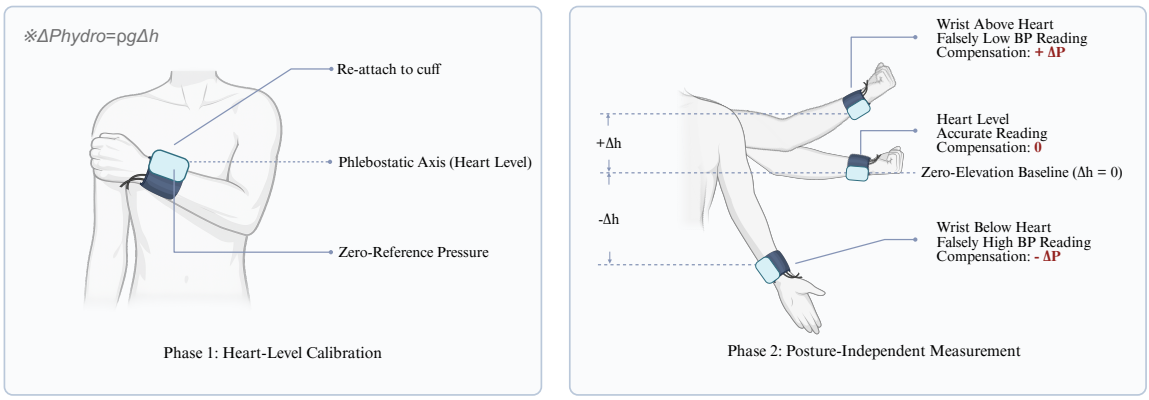


Fig. 1. Two-phase BEAT workflow. During calibration, The detachable sensing module is placed at the heart level to establish a reference atmospheric pressure (P_{ref}). During measurement, the module is re-attached to the wrist cuff to dynamically compensate for the hydrostatic pressure offset ($\Delta P = \rho g \Delta h$) caused by real-time vertical displacement.

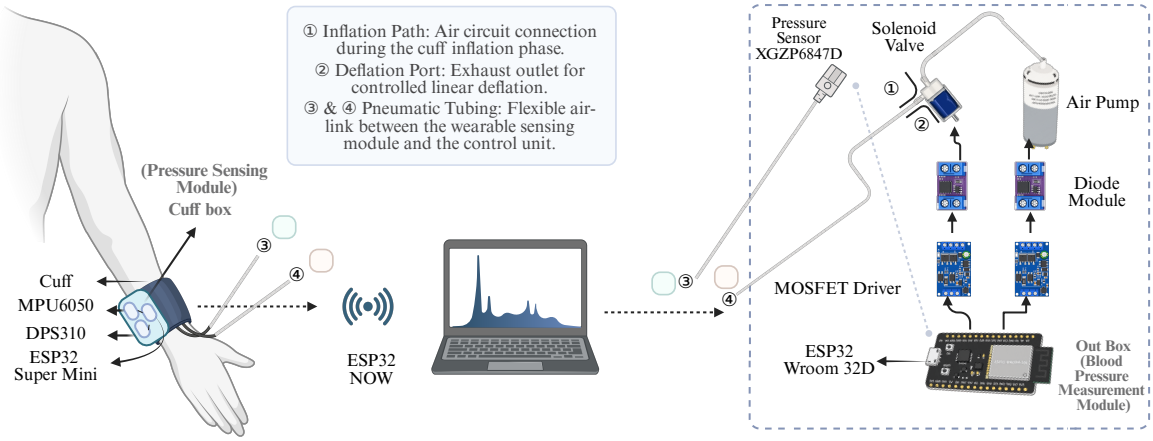


Fig. 2. BEAT hardware and communication paths. The wrist unit contains a DPS310 barometer, an MPU6050 inertial sensor, and an ESP32. ESP-NOW links it to the pneumatic controller, which operates the pump and valve and reads the cuff pressure sensor.

primary functional units: a pneumatic measurement unit and a detachable sensing module, as shown in Fig. 2.

The pneumatic unit integrates a micro-air pump, a linear solenoid valve, and a piezoresistive pressure sensor (XGZP6847D) managed by an ESP32 microcontroller to execute standard oscillometric inflation/deflation cycles.

The detachable sensing module carries an Infineon DPS310 barometer and a six-axis MPU6050 inertial measurement unit (IMU). The former measures atmospheric pressure for the height estimate, while the latter records acceleration and angular motion. The firmware configures the barometer for 64 samples/s with 64-fold pressure oversampling and schedules a wireless update every 100 ms. These settings distinguish sensor sampling from the nominal 10 Hz transmission rate. Using the same barometer at the two sites avoids an offset between independently calibrated sensors. The user can establish the heart-level reference before assuming the posture used for the cuff measurement.

For data acquisition, the wrist ESP32 sends barometric and inertial measurements to the pneumatic controller through ESP-NOW. The peer-to-peer link permits the detachable module to move between the chest and wrist without a data cable. A link update and a cuff-pressure sample have different sampling schedules. The software uses the pressure reference and the wrist measurements to calculate the hydrostatic term associated with the BP estimate. End-to-end latency and inter-device timing error were not characterized in the pilot.

B. Operational Workflow: Time-Multiplexed Calibration

The two-phase workflow (Fig. 1) separates the calibration site from the measurement site. A tilt measurement on its own cannot determine wrist height when the shoulder or torso changes position. Sequential pressure measurements supply a reference for that displacement without requiring the user to hold the cuff at heart level throughout the inflation cycle.

1) Phase 1: Heart-Level Zero-Reference: The detachable module is first placed at the participant's heart level, using the phlebostatic axis as the vertical landmark. The experimental protocol specifies a 2 s reference interval for recording atmospheric pressure, P_{ref}. The duration is a software setting and differs across prototype versions. Averaging several readings reduces short-term fluctuations. Reference drift or a change in air pressure between calibration and measurement still enters the estimated displacement [9].

2) Phase 2: Posture-Independent Measurement: After calibration, the module is re-attached to the wrist cuff. During the BP measurement cycle, the system continuously monitors the real-time pressure at the wrist, P_{wrist}. The vertical

displacement h relative to the heart is derived using the barometric formula:

$$h = \frac{P_{ref} - P_{wrist}}{\rho_{air} \cdot g} \tag{1}$$

where ρ_{air} is the ambient air density and g is the local gravitational acceleration. Pressure is expressed in pascals and height in metres.

C. Pulse Signal Extraction and Conditioning

Cuff pressure $P_{total}(t)$ contains a slowly varying inflation baseline and smaller arterial oscillations. In the released Figure 3 analysis, the sampling rate is estimated from the acquisition timestamps. A third-order Butterworth band-pass design with nominal cutoffs of 0.45 and 4.0 Hz is applied forward and backward to the recorded signal. The filtered component is used to identify pulse peaks. Their amplitudes are interpolated and smoothed along the cuff-pressure axis to construct the oscillometric waveform envelope, $E(P_{cuff})$. The fit constrains the two sides of the envelope so that a terminal pump spike does not determine its maximum. This forward–backward filtering step operates on a recorded trace.

D. BP Estimation and Multi-Sensor Fusion Algorithm

The Maximum Amplitude Algorithm (MAA) is implemented to estimate initial values. The MAP is defined as $MAP = \arg\max_{P_{cuff}} E(P_{cuff})$. SBP and DBP are identified where the envelope amplitude drops to K_s and K_d of the peak A_{max}:

$$\begin{aligned} E(SBP_{est}) &= K_s A_{max}, \quad SBP_{est} > MAP, \\ E(DBP_{est}) &= K_d A_{max}, \quad DBP_{est} < MAP, \end{aligned} \tag{2}$$

The fixed ratios depend on the estimator and measurement phase [10]–[12]. The released inflation analysis used for Fig. 3 specifies $K_s = 0.70$ and $K_d = 0.55$. Thus, reproducing the figure requires selecting the inflation estimator. Other branches in the repository use different settings for deflation. The threshold crossings estimate SBP and DBP from the envelope and are distinct from the subsequent height correction.

E. Fused Hydrostatic Compensation Algorithm

The correction is defined relative to the heart-level reference acquired before each measurement. Placing the detachable module at the phlebostatic axis anchors its local pressure reading to the starting height. The same module then measures pressure during the wrist measurement. This procedure assumes that ambient pressure is sufficiently stable over the interval between the two measurements and that the heart remains near its reference height.

When the wrist changes position, the DPS310 measures the pressure difference $\Delta P_{air} = P_{wrist} - P_{ref}$. Equation (1) uses the local hydrostatic approximation over the arm-height range. Defining positive h as a wrist above the reference makes the direction of correction explicit:

$$\Delta P_{air} = -\rho_{air} g h. \tag{3}$$

For h in metres, the signed correction P_{hydro} in mmHg follows by converting $\rho_{blood} g h$ from pascals to mmHg. With nominal blood density and gravitational acceleration, the correction per centimetre is approximately 0.77 mmHg [4]:

$$P_{hydro} = \frac{\rho_{blood} g h}{133.322 \text{ Pa/mmHg}}. \tag{4}$$

The same signed pressure adjustment applies to both systolic and diastolic wrist estimates:

$$BP_{corrected} = BP_{raw} + P_{hydro}. \tag{5}$$

An elevated wrist gives $h > 0$ and a positive correction because local hydrostatic pressure is lower. A hanging wrist gives $h < 0$ and a negative correction. At the calibration height the term is zero. The IMU provides motion context for interpreting a recording. An acceleration threshold or rejection rule was not validated in the reported trials.

III. Experiments

A. Experimental Protocol

To evaluate the BEAT system's posture-independent performance, we conducted a two-phase pilot study involving 3 healthy volunteers (age: 22.4 ± 1.3 years). All three participants were members of the project team and agreed to participate and to the publication of their blood pressure measurements as reported here. All trials were performed in a controlled laboratory environment at 24 ± 1°C, using the American Heart Association (AHA) screening guidelines [13] regarding arm positioning, cuff sizing, and subject resting state.

1) Phase 1: Baseline Agreement at Heart Level: Three participants each performed five heart-level comparisons. At this height the hydrostatic term is zero, so the comparison assesses the cuff hardware and oscillometric estimator together. For each pair, the uncorrected BEAT reading was compared with the corresponding Omron HEM-series reading. This phase gives a baseline for interpreting the posture experiment. Differences between successive cuff readings can also reflect physiological variation and the reference instrument.

2) Phase 2: Evaluation Across Wrist Positions: To quantify the effectiveness of our hydrostatic compensation algorithm, a subset of 2 subjects underwent an extended multi-posture protocol. Each subject performed 5 repeated trials per posture: *Standard Seated* (P1), *Seated Higher* (P2, +25 cm elevation), and *Active Standing* (P3, arm hanging). The protocol allowed 120 seconds between consecutive trials. Posture-affected Omron readings were collected for reference, though as identified by Byrd and Brook [4], these measurements are inherently susceptible to a hydrostatic error of approximately 0.77 mmHg/cm. Thus, the comparator for each participant was the mean of their five heart-level Omron measurements, allowing us to evaluate whether our system could effectively "re-anchor" wrist-level BP readings to the established physiological zero-point.

B. Evaluation Metrics and Statistical Analysis

The analysis addresses two questions: how closely individual BEAT and Omron readings agreed at heart level, and how much compensation changed the absolute difference from a participant-specific heart-level reference. The AAMI/ESH/ISO validation framework [14], [15] distinguishes mean signed

error from the dispersion of those errors. Our small repeated-measures comparison supplies descriptive estimates for this prototype.

1. Error quantification. In the baseline analysis, the signed error is BEAT minus the paired Omron reading. In the posture experiment, the reference is each participant's average of five heart-level Omron readings for the respective BP component. MAE is the average magnitude of the trial errors. We calculated MAE for each position and across all 30 participant–posture trials. Equal numbers of repeats mean that each participant and posture contributes equally to the overall value.

2. Agreement analysis. The Bland–Altman plots show the signed difference against the average of each baseline pair. The plotted limits equal the pooled mean difference plus or minus 1.96 sample standard deviations. Because the 15 pairs came from three people, the limits describe the dispersion observed in these recordings. A repeated-measures agreement study with more participants would be needed to estimate population limits.

3. Exploratory paired comparisons. At baseline, a two-sided paired t-test compared BEAT with Omron. In the posture analysis, the paired quantities were the raw and corrected *absolute errors* from the same trial. We retain the nominal trial-level p-values for reproducibility. Both tests pool repeated measurements within individuals, so they do not establish participant-level significance. We interpret effect size and direction by posture. The repository provides Python code for signal processing and figure generation.

IV. Results

A. Signal Processing and Baseline Comparison

At heart level, we compared the uncorrected wrist estimates with the corresponding Omron readings. Across postures, we compared both raw and corrected estimates with each participant's mean heart-level reference. These comparisons answer different questions: a signed mean difference can be small even when individual discrepancies are appreciable, whereas MAE gives equal weight to errors in either direction.

The reliability of oscillometric estimation depends on the pulsatile component of the cuff signal. Figure 3(a) shows the inflation baseline with superimposed arterial oscillations. Panel (b) shows the filtered signal and detected peaks, including the terminal interval affected by pump motion. Panel (c) shows how the reconstructed envelope determines the estimated MAP and the two amplitude thresholds used to locate SBP and DBP.

Fifteen paired measurements from the three participants contributed to the heart-level comparison (Fig. 4). The mean signed difference was 1.40 mmHg for both SBP and DBP. A positive value indicates that BEAT read higher on average. At heart level the hydrostatic term is zero, so these differences also occur before any height correction is applied. Individual pairs fell on both sides of zero. We report their spread separately below because neither a small mean difference nor a visually tight cluster establishes equivalence to the reference device.

B. Statistical Agreement at Heart Level

To further evaluate the baseline agreement between the proposed BEAT system and the Omron reference, Bland-Altman analysis was performed using the 15 measurements

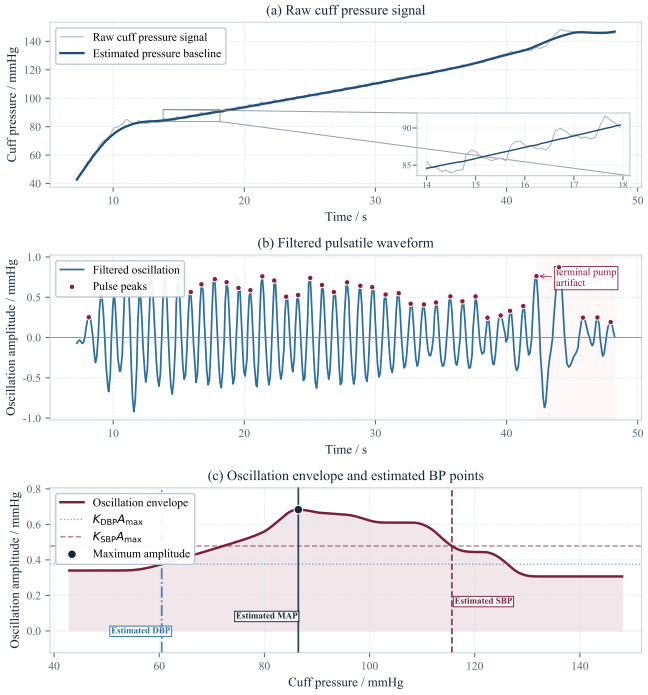


Fig. 3. Oscillometric signal processing. (a) Raw cuff signal and baseline. (b) Filtered waveform with detected peaks. (c) Oscillation envelope used to estimate SBP/DBP.

obtained from all 3 subjects at the heart level (Fig. 4). The difference was defined as the BEAT measurement minus the Omron reference measurement.

Across the 15 baseline pairs, the mean absolute difference was 2.20 mmHg for SBP and 1.93 mmHg for DBP. The five DBP differences for participant 3 were -1, $+3$, -2, $+1$, and -1 mmHg: their signed mean was zero, although their mean absolute difference was 1.60 mmHg. This illustrates how readings on either side of the reference can cancel in the signed average shown in Fig. 4.

For SBP, the mean bias was 1.40 mmHg, with 95% limits of agreement (LoA) ranging from -2.64 to 5.44 mmHg. For DBP, the mean bias was identically 1.40 mmHg, with 95% LoA ranging from -1.98 to 4.78 mmHg. As illustrated by the scatter distribution, the individual differences vary around the mean. Potential contributors include the inherent beat-to-beat physiological variability, cuff-fitting differences across the 3 subjects, and minor pneumatic noises typical of portable prototypes.

The trial-level paired tests yielded nominal p-values of 0.0199 for SBP and 0.0072 for DBP. These results quantify the offset relative to the within-sample dispersion under a trial-independence assumption. They do not test equivalence between instruments. The 1.40 mmHg mean difference is a signed bias, whereas the posture errors below are MAEs. Formal validation requires a specified reference protocol and participant distribution [14], [15]. Neither can be inferred from the size of the observed bias alone.

C. Measurement Accuracy Across Various Postures

To evaluate the robustness of the barometric compensation, measurements from the subset of 2 subjects (yielding 10 trials

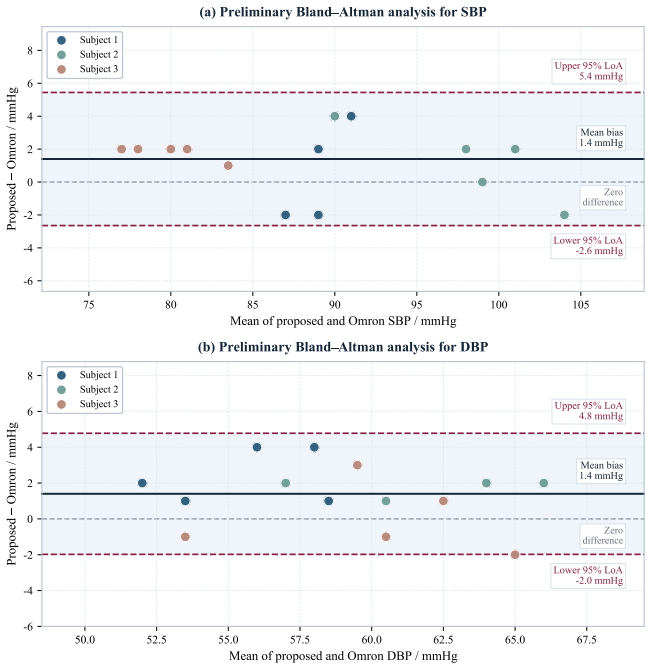


Fig. 4. Bland-Altman plot comparing BEAT system measurements against the Omron heart-level reference for SBP and DBP. The solid line represents mean bias, and dashed lines indicate 95% limits of agreement.

per posture) were analyzed across three arm postures: "Wrist Above Heart", "Heart-Level Posture", and "Wrist Below Heart". Given the short, one-hour experimental window where subjects remained in a resting state, the Omron measurements obtained at heart level were established as the within-session comparator (heart-level Omron reference). Omron readings acquired at non-heart-level postures were not treated as ground truth but rather as posture-affected negative controls to illustrate hydrostatic bias.

Fig. 5 presents the uncompensated (BEAT Raw), compensated (BEAT Corrected), and posture-affected Omron readings across the three positions. Without barometric compensation, the BEAT Raw measurements deviated from the heart-level reference due to hydrostatic pressure. For systolic blood pressure (SBP), the proposed compensation algorithm reduced the overall mean absolute error (MAE) by 56.2% (from 7.61 mmHg to 3.33 mmHg, $p < 0.001$). Posture-specific improvements were substantial: SBP MAE decreased from 9.00 mmHg to 3.54 mmHg (60.7% reduction) in the above-heart posture, and from 9.60 mmHg to 2.22 mmHg (76.9% reduction) in the below-heart posture. As expected, readings at heart level remained unchanged (MAE = 4.24 mmHg), requiring no compensation. The posture-affected Omron readings exhibited a high overall MAE of 9.65 mmHg, consistent with sensitivity to wrist height and possible changes in BP between postures.

For diastolic blood pressure (DBP), the overall MAE was reduced by 34.9% (from 6.79 mmHg to 4.42 mmHg, $p = 0.031$). In the wrist-below-heart posture, the DBP MAE notably decreased from 12.10 mmHg to 4.76 mmHg (60.7% reduction). However, in the wrist-above-heart posture, the DBP MAE increased slightly (4.70 mmHg to 4.92 mmHg). Possible explanations include less distinct diastolic envelope crossings at elevated postures and sampling variability. The data do not distinguish these possibilities given the small sample size ($N = 2$) of this pilot feasibility study.

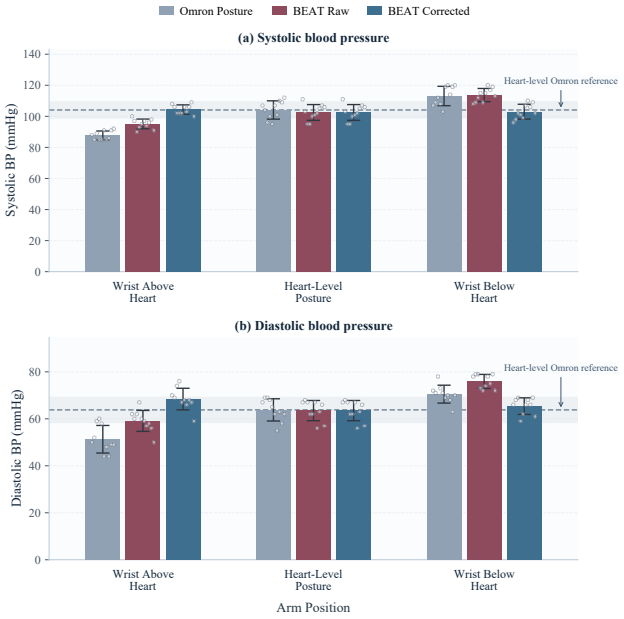


Fig. 5. Posture compensation results for (a) systolic and (b) diastolic blood pressure across three arm positions. The dashed horizontal line and shaded band show the pooled mean and one sample standard deviation of the heart-level Omron readings. Bars and error bars show means and sample standard deviations, and dots represent individual readings. The "Omron Posture" bars serve as posture-affected negative controls, illustrating hydrostatic bias when measured away from the heart level. "BEAT Raw" and "BEAT Corrected" denote the proposed system's measurements before and after barometric compensation.

V. Discussion

A. Posture-Invariant Blood Pressure Monitoring: Key Findings

The primary objective of this pilot feasibility study was to evaluate the BEAT system's capacity for posture-invariant BP monitoring via real-time barometric elevation tracking. Our preliminary results (Fig. 5) show that wrist position changes the discrepancy from the heart-level comparator when the wrist deviates from the heart level, as evidenced by both the uncompensated BEAT Raw readings and the posture-affected Omron negative controls. By applying dynamic, real-time hydrostatic compensation ($\Delta P = \rho g \Delta h$), the BEAT Corrected measurements were shifted toward the heart-level reference on average. The observed reduction in overall SBP MAE (56.2%, $p < 0.001$) was driven by the elevated and hanging wrist positions. The zero correction left the heart-level readings unchanged. Inertial pose estimation [7] and correct wrist positioning [2] address the same error through different mechanisms.

B. Consistency and Advancement Relative to Existing Research

Our findings are consistent with the hydrostatic mechanism described by Byrd and Brook [4]. Colburn et al. [7] estimated the correction using wearable inertial sensors and a learned model of arm position. BEAT obtains an independent height cue by returning the same barometer to two locations in sequence

(Fig. 1). This approach avoids estimating arm geometry but depends on the quality of the initial reference and its stability until the wrist reading. Prior work on wearable barometers identifies environmental pressure fluctuations as a source of error [8], [9]. A direct comparison of the two approaches under identical conditions remains open.

C. Divergent Findings and Physiological Considerations

It is worth noting that some studies using different populations, such as those by Babbs [16] on mathematical modeling, have suggested that arterial stiffness and wave reflection dynamics can significantly influence BP readings. While our study focused on a homogenous cohort of young adults to isolate the barometric compensation effects, the slight residual errors observed may be attributed to these physiological factors. In subjects with advanced arterial stiffness, the relationship between cuff pressure and brachial pulse oscillations may vary. Peripheral systolic amplification can also differ between the brachial and radial arteries [17]. Height correction alone does not separate these physiological effects from cuff or estimator errors.

D. Limitations and Future Research Directions

Despite these advancements, our study has certain limitations. First, three participants contributed baseline pairs and only two contributed posture data. Five repetitions per condition help characterize variation within an individual but do not increase the number of independent participants. A fixed seated heart-level reference also cannot track genuine BP changes on standing. Simultaneous or bracketed reference measurements would help separate those changes from a height error. Second, the "human-in-the-loop" requirement for manual calibration at the heart level may limit usability for patients with extremely restricted mobility. To address this, future iterations of BEAT will investigate an "auto-zeroing" protocol, potentially leveraging long-term barometric trends to perform background recalibration. Regarding the signal artifacts observed during the terminal phase of inflation, future research should explore advanced signal decomposition techniques (e.g., Empirical Mode Decomposition) to further improve the signal-to-noise ratio.

VI. Conclusion

BEAT combines a detachable pressure reference, an inertial sensor, and a wrist cuff to estimate BP at the height of the heart. In the two-participant posture experiment, compensation reduced systolic MAE from 7.61 to 3.33 mmHg and diastolic MAE from 6.79 to 4.42 mmHg relative to participant-specific heart-level Omron averages. Elevated-wrist DBP was the exception, with slightly greater absolute error after correction. The prototype allows the wrist to move away from heart level after calibration. The remaining questions are whether the benefit extends to new users, whether it persists under changing environmental pressure, and whether people with restricted arm movement can reliably perform the calibration.

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