In-Ear PPG for Vital Signs

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Earables are now pervasive, and their established purpose, ergonomy, and noninvasive interaction uncover exciting opportunities for sensing and healthcare research. However, it is critical to understand and characterize sensory measurements' accuracy in earables impacting healthcare decisions. We report a systematic characterization of in-ear photoplethysmography (PPG) in measuring vital signs: heart rate (HR), heart rate variability (HRV), blood oxygen saturation (SpO_2), and respiration rate (RR). We explore in-ear PPG inaccuracies stemming from different sensor placements and motion-induced artifacts. We observe statistically significant differences across sensor placements and between artifact types, with ITC placement showing the lowest intersubject variability. However, our study shows the absolute error climbs up to 29.84, 24.09, 3.28, and 30.80%, respectively, for HR, HRV, SpO_2, and RR during motion activities. Our preliminary results suggest that in-ear PPG is reasonably accurate in detecting vital signs but demands careful mechanical design and signal processing treatment.

Earables are becoming a permanent augmentation of the human ear, offering meaningful and engaging hearing experiences and enhancements. Recently, sensory research in and around the ear has sharply risen as earables can transform how we perceive and experience sound, i.e., spatially aware, distraction-free, and personalized. However, earables can also revolutionize personal health and clinical research by enabling noninvasive, continuous, and accurate health monitoring. Due to its proximity to brain and eyes, earables can be used to monitor a plethora of biomarkers like eye-movements,[1] cerebral activity (EEG),[2] or heart-related photoplethysmography (PPG) signals.[3] Indeed, in the pervasive computing literature, we have already seen ear-worn devices applied for continuous monitoring of cardiovascular functions,[4] heart rate and stress,[3] sleep,[2] measurement of oxygen consumption[5] and blood flow,[6] and tracking dietary and swallowing activities.[7]

The growing interest in using earables for healthcare and clinical research has naturally accelerated sensory earables development. We have seen several research-grade earables in the literature today, enabling electrooculography (EOG), electroencephalogram (EEG), and PPG.[2,3,5] Although remarkable in their propositions, significant research challenges still exist concerning the accuracy, reliability, and validation of the data generated by these technologies. To this end, we report a preliminary exploration of in-ear PPG toward the design of a sensory earable for vital signs monitoring. PPG is an optical method for detecting blood volume changes under the skin. Our decision to study in-ear PPG draws upon a set of technical-, biological-, and usability-oriented observations.

Technically, PPG is relatively straightforward to implement and mechanically integrate into an earable, requiring only LEDs and photodiodes. Next, unlike EOG or EEG, PPG's output signal is easy to interpret. Finally, PPG signals can derive various vital signs, including heart rate, heart rate variability, blood oxygen saturation, and respiration rate (RR). Biologically, several blood vessels surround the human ear, and some directly connect to main arteries (i.e., carotid artery). This unique property is critical and very beneficial for the goodness of an optical-based PPG sensor that measures blood volume changes. In addition, the head is generally less susceptible to motion artifacts due to the musculoskeletal system's natural vibration damping. Usability-wise, modern earables are lightweight, ergonomically comfortable, and noninvasive. These properties are imperative to ensure continuous

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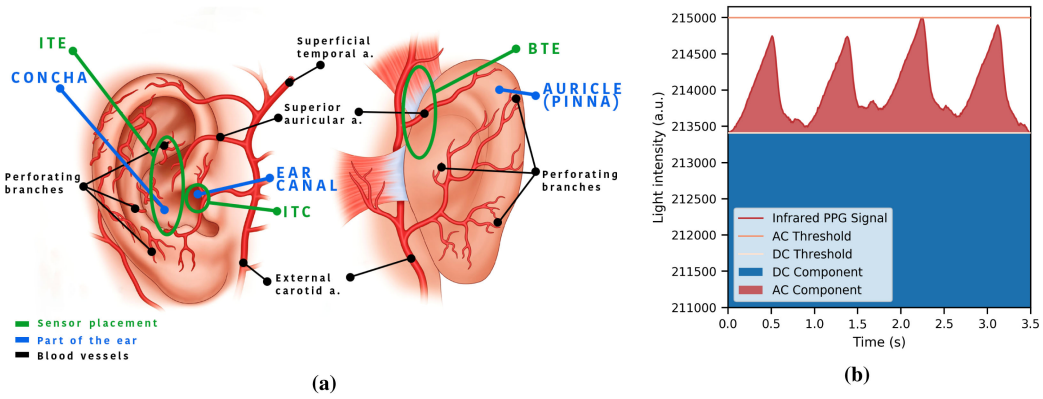

FIGURE 1. (a) Anatomy of the human ear with annotated the chosen sensor placements. (b) Example of a PPG waveform.

and longitudinal usage of earables, and PPG, due to its mechanical simplicity, is the most appropriate sensor for seamless integration to existing forms.

The accuracy of PPG measurements has been a subject of extensive research in recent studies,[8] as PPG is a common feature in various wrist-worn consumer-grade wearables. In medical settings, prior research studied PPG on the tip of fingers, forehead, or ear lobes. These studies mainly quantified PPG signals' inaccuracies stemmed from diverse skin types and motion artifacts.[9] Key insights of these studies suggest that PPG signal is relatively accurate across skin tones, and the accuracy drops up to 30% in the presence of motion artifacts. There have been several attempts to study in-ear PPG; however, these explorations looked primarily at single sensor placement, e.g., from the ear canal[3] and from behind the ear.[6] To date, no studies have systematically validated in-ear PPG under various motion conditions across a range of different positions. To this end, we are interested in providing evidence toward answering 1) Where is the optimal placement of an in-ear PPG sensor? and 2) What is the impact of motion artifacts at different placements?

To answer our first question, we revisit established literature on ear anatomy to identify three plausible locations in and around the ear as sensor placement alternatives, namely, behind the auricle or pinna (referred to as behind-the-ear, BTE); the concha (in-the-ear, ITE); and the first part of the ear canal (in-the-canal, ITC). We then collect PPG signals across these locations from 12 individuals to generate four vital signs—heart rate and heart rate variability, blood oxygen saturation, and RR. We quantify in-ear PPG's quality in inferring these vital signs by comparing the extracted signals with ground truth collected with medical-grade devices. Our analysis shows that ITC represents the best location with the least error variation. We then sought to answer our second question by analyzing the goodness of the in-ear PPG signal under the presence of motion artifacts (speaking, walking, and running). Our results suggest that ITC presents the smallest errors and the least intersubject variability across the motions under examination. However, it is nonetheless heavily impacted by motion artifacts (errors up to 29.84, 24.09, 3.28, and 30.80%, respectively, for HR, HRV, SpO_2, and RR) due to the signal crossover as reported in past studies, albeit for different body placements.

EAR ANATOMY AND PLACEMENT

The ear is the human sensorium dedicated to hearing. It is composed of three regions: outer ear, middle ear (i.e., where sound waves are modulated), and inner ear (i.e., where modulated sound waves are transmitted to the brain). We focus our attention on the outer ear, easily accessible for the placement of ear-worn devices.

To identify plausible placements for a PPG sensor in the outer ear, two aspects shape our design considerations: quality of signal and device comfort. From a signal quality perspective, a PPG sensor detects changes in blood volume flow, and as such, it is essential to place it in an area well supplied by blood vessels. The main components of the outer ear are the *auricle* (or pinna), the visible part of the ear; the *concha*, the depression in the auricle leading to the ear canal orifice; and the *ear canal* itself [see Figure 1(a)]. All three areas are supplied with blood by branches of the external carotid artery, a major artery of the head and neck. Several capillaries called *perforating branches* [see Figure 1(a)] supply blood to the auricle (on both sides, behind as well as in the proximity of

the ear canal orifice) and the concha. In addition, behind the auricle flows the *superior auricular artery*. Another major blood vessel in the very proximity of the ear, particularly the ear canal, is the *superficial temporal artery*.[10] The high concentration of blood vessels in the outer ear naturally poses multiple alternatives for a PPG sensor placement.

To minimize our search space, we turn our attention to ergonomic comfort. Ideally, the earable should enable continuous monitoring in natural situations while ensuring ease of use and comfort for prolonged use. Borrowing from rich literature on earables, including hearing aid ergonomics,[11] we identify three plausible alternatives: 1) behind the auricle, 2) in the concha, or 3) inside the ear canal.

Hence, as shown in Figure 1(a) in green, we choose three vantage points defined as BTE leveraging the superior auricular artery; ITE for the perforating branches, and ITC for the superficial temporal artery.

We exclude other areas of the ear such as the lobe or behind it (i.e., the skin of the neck), even if supplied by the same main artery, because placing an earable on these areas is unnatural and potentially uncomfortable, especially for prolonged use.

PPG AND VITAL SIGNS

Photoplethysmogram (PPG) is an optical measurement technique consisting of an LED and a photodetector used to derive a heart rate signal by detecting blood volume changes in the region under examination. There are two types of PPG sensors: one measuring light transmission through the tissues (used on the extremities as fingertips and earlobes) and the other measuring the light reflected by the tissues (as in smartwatches and wrist-worn fitness trackers). In our work, we leverage a light reflectance PPG sensor given its simplicity in being integrated in an earable form, since it does not require the placement of electronic components on two opposite sides of the skin.

Concretely, a light reflectance PPG sensor measures how light intensity varies whenever there is a blood volume change. Bones, muscles, and tissues absorb light at a constant rate. Therefore, arterial blood volume variations directly map into a decrease in the light intensity (i.e., the voltage of the signal) measured at the photodetector.[12] The constant amount of light absorbed by tissues and bones is known as the dc component (or nonpulsatile component) of the PPG signal, while the modulated component is referred to as the ac component (or pulsatile component)[13] [see Figure 1(b)].

The wavelength of the light used in PPG sensors typically ranges between 500 nm (green color) and 1100 nm (infrared). Red and infrared (IR) lights are absorbed less by the water present in the human tissues compared to green light. Hence, light in the red–IR spectrum penetrates more in the skin, reaching deeper blood vessels. Estimating heart rate requires only one light source (e.g., red) since it can be estimated only from the ac component by measuring the time between consecutive peaks. Instead, SpO_2 measurements rely on the ratio of oxygenated and deoxygenated hemoglobin, and hence require two different wavelengths. Red and IR LEDs are typically used to estimate SpO_2 from PPG.[12]

Vital Signs Estimation With PPG

PPG signals are commonly used in medical and free-living settings to extract vital signs, i.e., reliable biomarkers to indicate health outcomes. The most common types of biomarkers extracted from PPG can be grouped as those related to *cardiovascular activity* (e.g., heart rate, heart rate variability, blood pressure, hyper- and hypovolemia), *respiration* (heart rate signals are modulated by respiratory activity[14]), and *blood oxygen saturation* (SpO_2). These biomarkers constitute an enormous wealth of information, allowing medical practitioners, for instance, to infer the fitness of a patient, the presence (or absence) of respiration as well as cardiovascular conditions, and their mental health (stress, cognitive load, and mental fatigue).[15] In this work, we study three vital signs and the respective processing pipelines we have developed to extract them from raw PPG signals.

Heart Rate (HR) and Heart Rate Variability (HRV)

HR measures the heart contractions that push blood through the arteries. HRV is the variation in the time interval between consecutive heartbeats (contractions). In medical settings, HR is usually measured either with a finger pulse oximeter or with ECG and ranges between 60 and 100 beats per minute (bpm) in healthy subjects. HRV is extracted from the R-peaks detected in an ECG signal and is often used when referring to a person's fitness and mental health. High interbeat interval (IBI) denotes high fitness (700–1000 ms), while lower HRV often indicates a higher stress level.

Extraction pipeline: As depicted in Figure 2(a), we start by processing both the raw IR PPG and the raw ECG (our ground truth signal) with a bandpass and a notch filter, respectively. This step preserves the information content at typical heart rate frequencies and

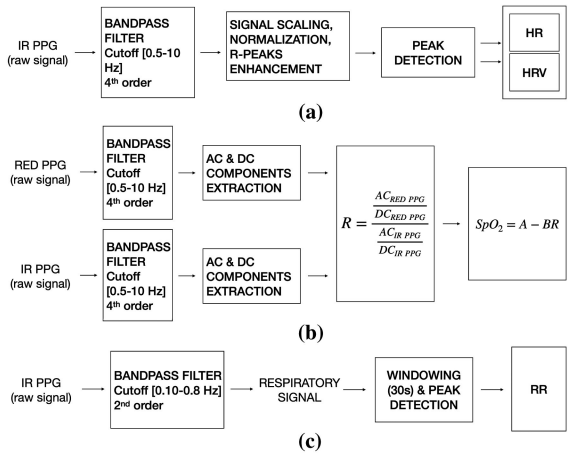

FIGURE 2. Processing pipelines used to extract vital signs. (a) Pipeline for resting heart rate and heart rate variability. (b) Pipeline for blood oxygen saturation. (c) Pipeline for respiration rate.

discards higher frequencies. The filtered signals are then scaled and normalized, and the R-peaks amplitude is enhanced. From the resulting signals, we detect all the peaks corresponding to heart beats and compute the mean HR and HRV.

Reporting metrics: We use *mean bpm* for HR, as the average HR during a session and *mean IBI* for HRV, as the average time between successive heartbeats (taken across a session).

SpO$_2$

Blood oxygen saturation indicates the percentage of oxygen-saturated hemoglobin in the blood. In healthy subjects, it usually is between 95 and 100%. SpO$_2$ is commonly measured with finger pulse oximeters.

Extraction pipeline: To extract SpO$_2$ from PPG, we first filter the PPG readings with the same bandpass filter used to preprocess the data before extracting HR and HRV. We then isolate the ac (pulsatile) and dc (nonpulsatile) components.[13] We adopt the window minimum approach[12] and compute R, the ratio of the ratios of the ac and dc components of the red and IR PPG signals [see Figure 2(b)]

$$R = \frac{\frac{\mathrm{AC}_{\mathrm{RED\ PPG}}}{\mathrm{DC}_{\mathrm{RED\ PPG}}}}{\frac{\mathrm{AC}_{\mathrm{IR\ PPG}}}{\mathrm{DC}_{\mathrm{IR\ PPG}}}}. \quad (1)$$

We then calculate the SpO$_2$ by applying the following equation:

$$\mathrm{SpO}_2 = A - BR \quad (2)$$

where A and B are calibration coefficients[16] we empirically set as $A = 120$ and $B = 24$.

Reporting metrics: We use *mean spo2* for SpO$_2$, as the average percentage of oxygen saturation during a session.

Respiration Rate (RR)

RR is the number of breaths a person takes per minute. In adult subjects, it usually varies between 10 and 20 breaths per minute.

Extraction pipeline: We extract an RR following a frequency-based approach[14] [see Figure 2(c)]. First, we extract a respiratory signal from the raw IR PPG signal. Considering a normal breathing range is 10–20 breaths per minute,[17] the nonrespiratory frequencies are removed with a bandpass filter. Once left with the respiratory signal, we segment it in 30-s-long windows, find the peaks, and compute the breath per minute value for every window.

Reporting metrics: We use *mean rr* for an RR, as the average number of breaths per minute within a session.

EXPERIMENTAL SETUP

Study Population

Twelve individuals (two females, 24–40 years of age, mean = 30.4) were recruited to participate in the study. None of the participants had any heart or respiratory condition and were in good health. All participants were briefed about the study and voluntarily consented to take part in it (no compensation was offered). The study received IRB approval before its beginning.

Devices

To collect PPG signals from the ear, we use a Cosinuss Two,[a] which features an IR and a red PPG sensor on the same ear-tip. The raw data for both wavelengths are provided by the device with a sampling rate of 100 Hz. We modify the Cosinuss' ear-tip to provide better adhesion with the skin for the BTE and ITE conditions, and use surgical tape for attachment. For the ITC condition, we mount the ear-tip on an existing earable (i.e., eSense[18]) to mimic an off-the-shelf earbud.

For ground truth purposes, we use a portable ECG (heart's electrical activity) chest band (Zephyr Bioharness 3.0[b]) and a medical-grade pulse oximeter to be worn on the finger (Masimo Health MightySat-Rx[c]).

[a]https://www.cosinuss.com/
[b]https://www.zephyranywhere.com/
[c]https://www.masimo.com/

FIGURE 3. On the left, a participant wearing the ITC PPG; and on the right, the devices used in the data collection (clockwise: Zephyr Bioharness 3.0, Masimo Health MightySat-Rx, Cosinuss two tip on eSense for ITC, and modified Cosinuss two tip used for ITE and BTE).

We use the ECG signal to derive the ground truth for HR and HRV while RR and SpO_2 are provided directly by the Zephyr and the pulse oximeter, respectively.

The participants wore the portable ECG band and the pulse oximeter, respectively, on their chest and index finger for the whole experiment. Synchronized data from our PPG sensor and the ground truth devices have been collected for the entire duration of the study. The devices used during the data collection are depicted in Figure 3.

Data Collection Protocol

Given our objective of assessing PPG positioning around the ear and the impact of motion, we collect PPG data from the three locations identified earlier (ITC, ITE, and BTE), first in a resting condition (without any movement) and then under three motion conditions of increasing intensity: speaking, walking, and running. Walking and running represent typical sources of noise for optical-based heart rate monitors, as shown by previous research.[9] The speaking condition is instead unique to earables. The complex muscle movements while talking are likely to cause significant deformations of the tissues around the ear and in the ear canal, with potential negative effect on the recorded PPG signal.

For the resting and speaking conditions, we followed the wearable device validation guideline stipulated by the Consumer Technology Association[19] and measured PPG while seated in the upright position. During the resting condition, the participants were asked to breath normally without moving, while during the speaking condition they were asked to read aloud an article provided by the investigators. For the motion conditions, the participants were asked to walk and run at a comfortable pace around the room ensuring that the intensity was higher for running compared to walking. We measured an average acceleration of $0.17\ g$ ($\sigma = 0.05\ g$) and $1.04\ g$ ($\sigma = 0.11\ g$) while walking and running, respectively.

For each motion condition, we recorded 5 minutes of data at the three sensor placements we identified. The length of the sessions was chosen so that they were long enough to observe changes in the characteristics of good-quality vital signs, without being too tedious for the data collection volunteers.

Data Analysis

The PPG data are processed following the pipelines described in the previous section to extract the four biomarkers we are considering. The PPG-derived biomarkers are then compared to the values obtained from the ground truth devices. We compute the relative error as the difference between the ground truth value and the PPG-derived value for each biomarker. We chose to look at the relative error to be able to observe whether the data present trends (e.g., PPG consistently over/underestimating the HR).

RESULTS

We begin by reporting our observations concerning placement variabilities and then reflect on the impact of motion artifacts on the accuracy of PPG-derived vital signs.

Benchmark of In-Ear PPG Placement

Figure 4 illustrates the inaccuracies we observed in the PPG-derived vital signs in comparison with ground truth. We notice that all three positions show comparable performance for different vital signs concerning accuracy. However, one-way repeated measures ANOVA tests performed on the three locations show significant differences on the mean error of each vital sign with test statistic F ranging from 11.0 for RR to 141.2 for HR with p-value < 0.05.

Looking closely at Figure 4, the ITC position shows the least variability (smaller interquartile range). Overall, we can observe that in-ear PPG shows acceptable performance to extract reliable HR, HRV, and SpO_2 with errors ranging across ± 0.5 bpm, ± 5 ms, and $\pm 2\%$, respectively. For instance, errors of a few milliseconds when estimating IBI for HRV are acceptable given that they account for about 1% of the actual IBI of healthy subjects at rest—usually being between 700 and

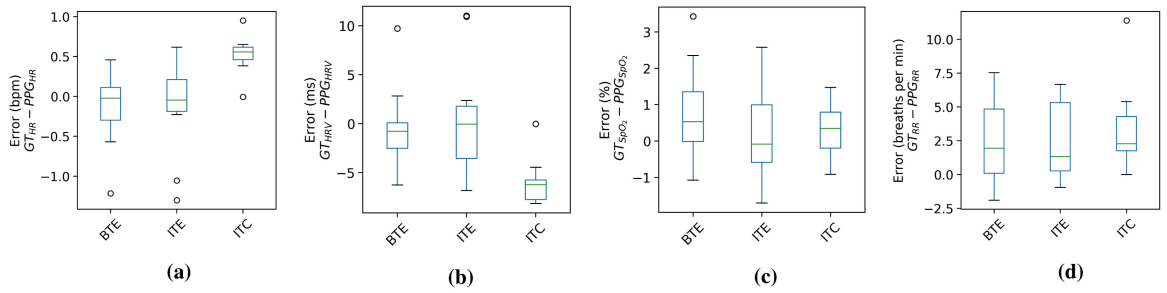

FIGURE 4. Impact of different ear-placements on the goodness of PPG-extracted biomarkers in a resting condition. (a) Resting heart rate. (b) Heart rate variability. (c) Oxygen saturation. (d) Respiration rate.

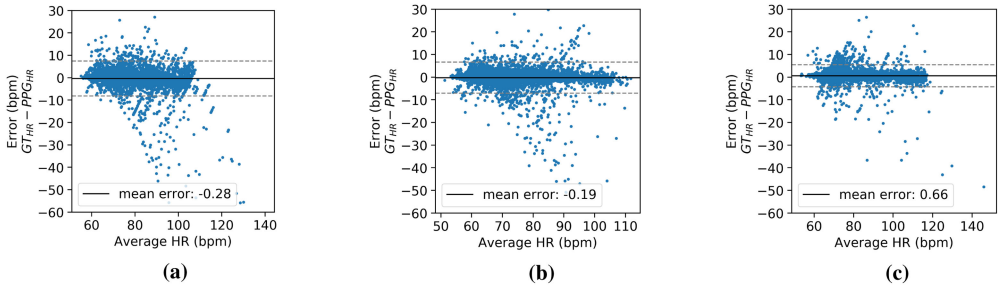

FIGURE 5. Difference between ground truth and PPG heart rate plotted against the mean of the two measurements (Bland–Altman plot). In the interest of space, only data for HR is shown. The solid black line represents the mean error, and the dashed gray lines the 1.96 SD boundaries (95% limits of agreement). (a) Resting heart rate BTE. (b) Resting heart rate ITE. (c) Resting heart rate ITC.

1000 ms, depending on age and medical conditions. Similarly, for SpO_2 data, medical-grade pulse-oximeters usually have a 2% accuracy, which is in line with what we observe for the ITC location.

However, for the RR, we notice a relatively larger error across the three locations, with a mean error around three breaths per minute and large variation. This represents a 30 to 15% error on average if we consider typical breathing rates of 10–20 breaths per minute at rest.[17]

To further analyze the data we employ Bland–Altman (BA) plots, which depict the difference between ground truth biomarker and PPG-extracted biomarker on the *y*-axis ($\mathrm{ECG_{HR}} - \mathrm{PPG_{HR}}$) and their average on the *x*-axis ($(\mathrm{ECG_{HR}} + \mathrm{PPG_{HR}})/2$). Instead of using the mean value of each biomarker during the entire session, for this analysis, we use the biomarker values computed with a one-second granularity. BA plots are typically employed to study the agreement between two measurement methods and allow us to investigate how the two measurements of a biomarker differ (i.e., *y*-axis) at different magnitudes of the biomarker (i.e., *x*-axis).

Figure 5 depicts the BA plots for the HR in three locations. While in the interest of space we only report the BA plots for HR, we observed similar patterns for the other biomarkers. The plot shows how the mean error of HR is consistently small across all three locations. Diversely from ITE and BTE, where the data-points are sparse and the confidence intervals large (± 1.96 of the standard deviation of the error), for the ITC location the majority of data-points fall within the confidence intervals around the mean error. The BTE and ITE locations show larger errors as the HR increases (i.e., in the range 70–100 bpm), with several data-points showing negative errors. This implies that HR estimated from PPG tends to overestimate the actual value in this range. This result suggests an overall agreement between the PPG and the ground truth readings at rest, confirming our previous observation of less error variability for the ITC location.

Key takeaways: Our analysis suggests that, in a resting condition, while there is marginal difference in the median error across the three locations, the ITC position represents a good placement option for in-ear PPG, as it shows consistently the least variation.

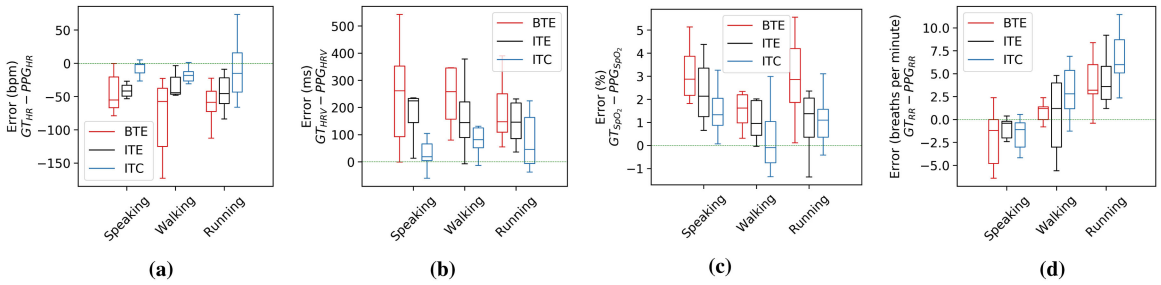

FIGURE 6. Impact of different external artifacts (i.e., speaking, light motion, and intense motion) on the goodness of BTE, ITE, and ITC PPG-extracted biomarkers. (a) Resting heart rate. (b) Heart rate variability. (c) Blood oxygen saturation. (d) Respiration rate.

We argue that this is enabled by the ITC location and the form factor of the corresponding device, i.e., an ear-tip. We could observe that, even when participants wear the ear-tip naturally without special care from the investigators, it automatically ensures good sensor-to-skin contact and improved shielding from ambient light. Devices built for the other locations instead currently provide less tight contact to the skin, thereby resulting in higher variation across wearing events.

Our results also highlight that the PPG-extracted RR has a large error margin. We consider this error could be mitigated with more sophisticated processing techniques or by leveraging other sensing modalities [e.g., inertial measurement unit (IMU)-based breathing detection[20]].

Impact of Motion Artifacts

The form, functions, and applications of an earable naturally imply suspected measurement errors of in-ear PPG, which are typically caused by motion artifacts, i.e., sensor displacement due to head and body movement. Consequently, we sought to understand how the PPG sensor suffers from these artifacts. Specifically, we investigate the impact of three motion activities that are commonly performed while wearing earables—speaking (micromotion), walking (mild motion), and running (intense motion).

Figure 6 illustrates the box plots of the errors between ground truth and PPG-extracted vital signs for different artifacts, across the three locations. At a glance, we notice that the median error for the ITC location tends to be lower than the other locations for the three motion conditions. This is further confirmed when comparing the mean absolute errors of the various biomarkers. For instance, HR extracted from the ITC location shows a 12.52, 27.14, and 29.84% error, respectively, for speaking, walking, and running. These figures are substantially lower than those of the other two locations: 62.60, 105.98, 56.62% and 58.29, 58.66, 44.00%, respectively, for BTE and ITE (similar differences can be observed for HRV and SpO_2). An exception to this is the RR for which ITC shows similar or slightly higher median errors (with BTE showing a lower mean absolute error). For the RR, we also notice a clear trend where the error increases with the increase of motion intensity.

ITE and BTE instead show high median errors and large variations across all three motion conditions, suggesting that they are less suitable locations for in-ear vital signs measurement, even in the presence of moderate motion (e.g., speaking and walking). This could be a consequence of the difficulty in attaching the sensor firmly in these locations and the more pronounced deformation of the skin and tissues during motion activities, which results in corrupted PPG signals.

Notably, the estimation of SpO_2 shows a similar median error across the three motions with relatively limited variability for all three locations. We hypothesize that this relative consistency in SpO_2 measurements is due to the fact that participants' oxygen saturation did not change significantly during the data collection period; hence, only a limited range of values could be recorded (e.g., between 96 and 100%). We leave the investigation of other SpO_2 ranges through the use of specialized equipment to future work.

Key takeaways: Our results suggest that in-ear PPG, despite being located on a more stable part of the body (i.e., the head compared to the wrist), is still significantly affected by motion, with absolute errors for ITC up to 29.84, 24.09, 3.28, and 30.80% for HR, HRV, SpO_2, and RR, respectively. Based on our population, ITC seems to provide the lowest errors across the motion conditions, with ITE and BTE showing large errors even with moderate motion. This is probably

due to a poorer adhesion with the skin for the ITE and BTE locations compared to ITC, which benefits from the enclosed space of the ear canal. These observations call for attention to sophisticated signal processing pipelines mitigating signal cross-over issues, ideally guided by additional sensing modalities (e.g., colocated IMU) and advanced industrial design to ensure stability and good skin contact, especially for the BTE and ITE placements.

OUTLOOK

Our results distilled that the ITC placement is a plausible design choice. However, we need to cater for a careful mechanical design for robust data acquisition and signal processing to mitigate motion artifacts. We reflect on these two aspects in this concluding section.

Form Factor and Ear-Tip Design

From a mechanical construction perspective, ITC placement of a PPG sensor uncovers interesting design challenges. On the one hand, this placement liberates us from a specific form design, as ear-tip or earmold is a default feature of any earable, be it a lifestyle earbud or a medical-grade hearing aid. Besides, ITC placement ensures good skin contact and shielding from ambient light—both imperative to achieve a robust sensing performance.

However, on the other hand, designing an ear-tip with an integrated PPG sensor is exceptionally challenging. First, the ear-tip has to guarantee good sealing for robust data acquisition. Second, the ear-tip must have a stable and steady fit across users to ensure minimal sensor displacement, minimizing motion artifacts. Finally, the ear-tip must be comfortable for prolonged use. However, this well-sealed, stable, and comfortable fit must not come at the expense of additional occlusion effects beyond what is mitigated today with state-of-the-art audio engineering, e.g., pass-through audio. Besides, given every single human ear is different in size and shape, it is incredibly hard to design a cost-effective and universal ear-tip with integrated PPG using existing materials, e.g., rubber, silicone, or foam. Consequently, we call attention to material engineers and industrial designers to carefully consider the facets mentioned previously in developing next-generation sensory ear-tips.

Signal Processing Pipeline

The accuracy of wrist-worn PPG under motion artifacts has been extensively studied in recent literature, with results reporting up to 30% of error rate in extracting vital signs.[9] Even though the head is the stationary part of the human body, we still noticed a similar error margin with in-ear PPG. This signal cross-over effect is caused by the fact that a PPG sensor mistakenly detects the cardiovascular cycle in the presence of a periodic signal caused by repetitive motion, for instance, walking or running. Contemporary mitigation strategies consider wavelet transformation, independent component analysis, template matching, and adaptive filtering techniques. While these techniques are certainly useful, we advocate for adaptive and context-aware signal processing strategies. In particular, we suggest using motion sensing to remove motion artifacts. Given that the PPG signal is correlated with motion intensity and that an IMU is a common feature in modern earable, we can leverage motion-awareness to trigger PPG operations, thus avoiding corrupted PPG segments while saving energy. Finally, we can synthesize corrupted PPG signals considering recent signal trends and motion correlations over small temporal windows.

We acknowledge that the relatively small size of the participant population and the preliminary investigation of SpO_2 ranges can be regarded as limitations of our study. Nonetheless, we anticipate that our reported characterization of in-ear PPG, under various motion conditions across a range of different positions and their implications, represents a starting point toward the development of accurate and robust sensory earables, and their equitable use in healthcare and clinical research applications.

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