Movement, Sweating, and Contact Pressure as Sources of Heart Rate Inaccuracy in Wearable Devices

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Abstract

Wearable devices enable continuous heart rate (HR) monitoring through photoplethysmography (PPG). The impact of wrist-worn devices' sensor contact pressure and sweat, and of their interaction with movement, on HR monitoring is unclear. HR was recorded in 17 healthy individuals using two smartwatches, Garmin Vivoactive 4 (GV) and Fitbit Sense (FS), concurrently with ECG at rest and during controlled arm movement at three increasing intensities. Recordings were repeated after reducing contact pressure by loosening the wristband by one or two notches and using one or two drops of saline solution to simulate sweating. In optimal conditions, the mean absolute percentage error (MAPE) was (median [interquartile range]) 4.3% (1.4%, 7.7%) and 3.1% (1.6%, 5.0%) (p=0.58), for GV and FS, respectively. Loosening the wristband by 1 notch increased MAPE for FS during rest (p=0.021), moderate (p=0.004) and vigorous (p=0.002) movement, but not for GV, for which loosening the wristband by 2 notches increased MAPE during moderate (p=0.015) and vigorous (p=0.008) movement. Simulated sweat increased MAPE during moderate movement using FS (p=0.002), and during vigorous movement for both devices. In conclusion, contact pressure and sweating can increase HR inaccuracy even during rest and moderate movement.

1. Introduction

Wearable devices for health monitoring have the potential of transforming healthcare. Smartwatches measure heart rate (HR), heart rate variability and other health parameters through photoplethysmography (PPG) [1], [2]. Resting heart rate, heart rate variability and hear rate recovery are established physiological parameters which provide insight into cardiac autonomic modulation and have significant prognostic value [3]. Accuracy of wrist-worn devices in measuring heart rate has been investigated under different conditions, including rest and different types and intensities of physical activity [4], [5]. The identification of sources of inaccuracy in PPG-derived heart rate monitoring is instrumental in improving its accuracy. Apart from motion artifacts, which represent the main source of inaccuracy, previous studies have highlighted several physiological and external factors that may affect the PPG waveform and impact on heart rate monitoring [6], but their effect on consumer-graded wrist-worn heart rate monitors remains undetermined. The aim of this study was to assess the impact of wristband fit and simulate sweating on heart rate monitoring and their interaction. The hypothesis of the study is that loosening the wristband and increasing sweat would reduce heart rate accuracy and that interaction with motion artefacts further reduces accuracy.

2. Methods

Seventeen young healthy adults (n=9 women, age 21±1.3 years [mean ± standard deviation], height 166±9.1 cm, body mass 61.9±8.4 kg) were recruited.

A 3 Lead ECG Holter monitor (eMotion Faros, sampling frequency 500 Hz) was used to measure the reference heart rate (Figure 1). Two consumer-grade smartwatches (Garmin Vivoactive 4 and Fitbit Sense) were placed at random on the left and right wrists according to manufacturer's instructions. The protocol included 5 sessions, each one lasting 2 minutes. During the first session, wrist-worn devices were worn ensuring optimal contact between the optical sensor and the skin. After starting the recording, participants were instructed to stand still for 30 seconds (first epoch), after which, they were instructed to move their arms with intensity increasing every 30 seconds (epochs 2, 3 and 4) to mimic walking (low intensity movement), fast walking (moderate intensity movement) and running (vigorous intensity movement). This was then repeated 4 times: 1) After loosening the wristband by one notch. 2) After loosening the wristband by two notches; 3) After tightening the wristband (baseline condition) and adding 1 drop of physiological saline to mimic sweat; 4) Adding a second drop of physiological saline while maintaining the wristband tighten in its baseline condition. Each session was recorded on the wrist-worn devices as an activity. A graphical representation of the protocol is shown in Figure 1.

 ISSN: 2325-887X DOI: 10.22489/CinC.2022.232

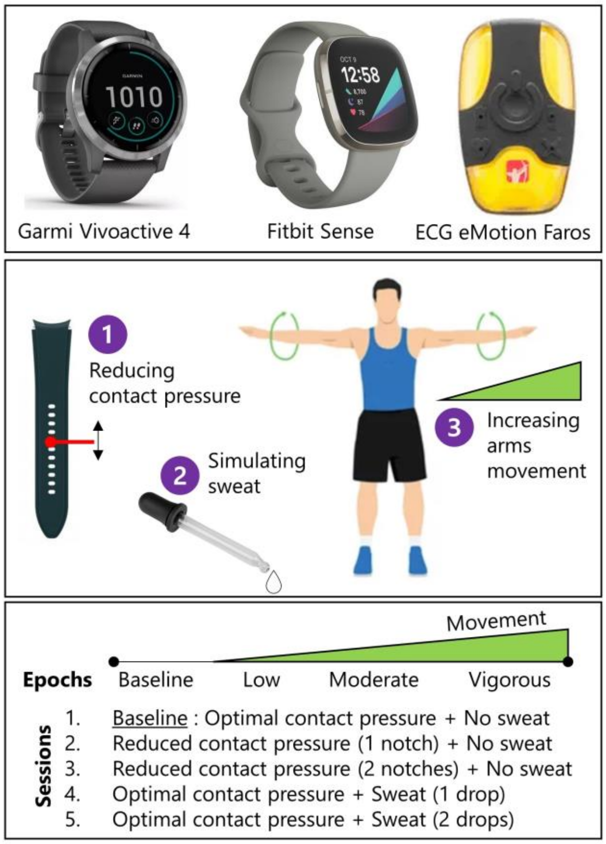

Figure 1. Illustration of the protocol

Raw ECG data were exported and analyzed using bespoke algorithms developed in our group to measure beat to beat RR-Intervals, as in previous studies [7]. Heart rate time series were downloaded from the manufacturers' portals and were sampled at 1 Hz for both Fitbit and Garmin devices. The mean heart rate was computed for all 30-second epochs by averaging the heart rate samples within the epoch after excluding samples from the first and last 5 seconds. In the case of heart rate derived from the ECG, before computing the mean heart rate, a moving median filter with a window of 5 beats was used to remove outliers in the beat-to-beat time series.

Heart rate accuracy was measured using the mean absolute percentage error (MAPE), defined as:

$$e_{i,j,k}^{d} = 100 \times \frac{\left|\overline{HR}_{i,j,k}^{d} - \overline{HR}_{i,j,k}^{EGC}\right|}{\overline{HR}_{i,j,k}^{EGC}}$$

Where d represents a device (Fitbit or Garmin), while i, j and k represent a given subject, session, and epoch, respectively. The symbol $\overline{HR}$ indicates that MAPE is

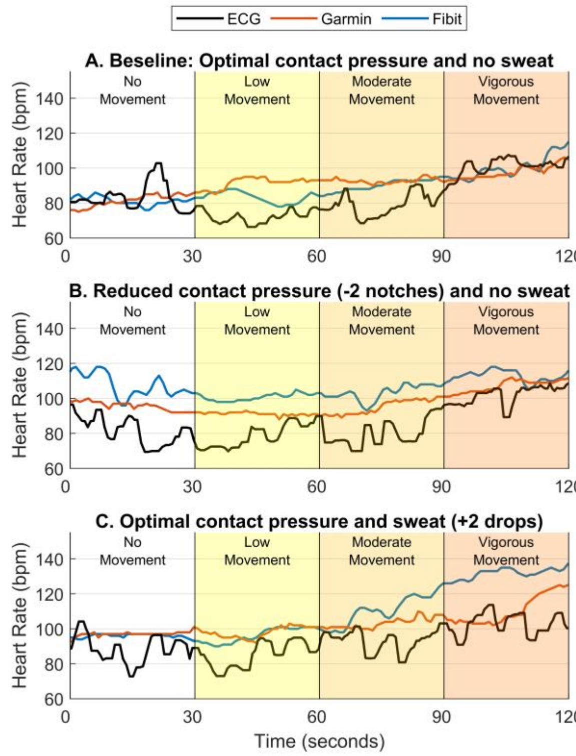

Figure 2. Heart rate profile for a representative participant during 3 sessions (Baseline, reduced contact pressure and presence of sweat) and 4 epochs: No arm movement, and low, moderate, and vigorous arm movement. Heart rate profile from the ECG was filtered using a moving median filter (5 beats), while heart rate from wrist-worn devices was unprocessed.

derived from mean heart rate estimates. The Wilcoxon signed-rank test (uncorrected for multiple comparisons) was used to assess whether MAPE increased during each condition with respect to baseline at rest (i.e. no saline and optimal contact pressure, $e_{i,j=1,k=1}^{d}$). In further analysis, changes in MAPE were assessed with respect to MAPE registered at baseline but for the same level of movement intensity (i. e. $e_{i,j=1,k}^{d}$).

3. Results

A representative example of heart rate trends derived from the ECG and wrist worn devices during three sessions for one subject are shown in Figure 2. In absence of movement (first epoch), the heart rate profiles overlap during baseline conditions (Panel A), but they show differences when contact pressure was reduced (Panel B) or sweat was simulated (Panel C).

The reference mean heart rate at baseline was (median [interquartile range]) 89 (79, 94) bpm across all recordings. Mean heart rate derived from Garmin and Fitbit was similar, at 82 (77 – 91) bpm and 87 (81 – 96) bpm, respectively. MAPE at baseline was 4.2% (1.5%-7.8%) for Garmin and 3.1% (1.6% - 5.0%) for Fitbit. Median MAPE increased with the intensity of arm movement, reaching 9.3% and 10.2% for Garmin and Fitbit, respectively, at the maximum intensity (including recordings with reduced contact pressure and saline).

Figure 3 shows MAPE as a function of the experimental conditions. With preserved contact pressure and no saline (blue boxplots), vigorous arm movement increased MAPE for Garmin (10.3% [5.0% - 16.9%], P=0.01) compared with rest; the increase for Fitbit was less marked (4.9% [2.2%-17.0%], P=0.07). Reducing contact pressure increased MAPE for both devices compared to baseline resting conditions (black stars). An increase in Fitbit's MAPE was observed in all experimental conditions, including after loosening the wristband by 2 notches at rest (MAPE=4.4% [3.1%-26.8%], P=0.015). An increase in Garmin's MAPE was observed at any intensity of arm movement (e.g., MAPE=7.4% [1.8%-14.8%], P=0.039, during low intensity arm movement), but not at rest (MAPE=3.0% [1.9%-8.0%], P=0.25) after loosening the wristband by 2 notches. Adding two drops of saline solution to simulate marked sweating increased MAPE with respect to rest when there was moderate arm movement. Comparison with recordings obtained at the same intensity of arms' movement (red stars) showed that both reduced contact pressure and sweat increased MAPE for Fitbit but not for Garmin.

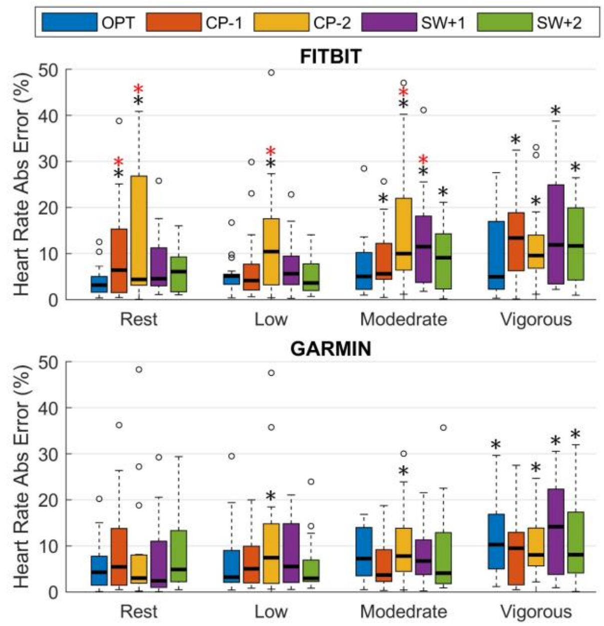

Figure 3. Mean absolute percentage error (MAPE) in heart rate measurements using a Fitbit (above) and Garmin device (below). Lines and bars represent median and interquartile ranges, while whiskers and circles represent range (excluding outliers) and outliers, respectively. * P<0.05 using Wilcoxon signed-rank test compared to resting baseline conditions (optimal contact pressure and no movement). * P<0.05 using as reference recording obtained with optimal contact pressure and no-sweat but same level of arm movement. OPT=optimal contact pressure; CP-1 and CP-2: reduced contact pressure by loosening the wristband by 1 or 2 notches, respectively. SW+1 and SW+2: Simulating sweating by adding 1 or 2 drops of saline solution, respectively.

4. Discussion

The aim of this study was to assess the impact of contact pressure, arm movement and sweat on the accuracy of heart rate monitoring using wrist-worn devices and their interactions. The main finding was that both reduced contact pressure and simulating sweating increased heart rate errors. The effect of contact pressure was more pronounced for the Fitbit Charge than the Garmin Vivoactive 4. This may be in part explained by the fact that the distance between wristband notches on the Fitbit's wristband is greater than on the Garmin's wristband (4 mm vs 3 mm). Furthermore, the optical sensor protrudes out of the back of the Garmin device while it remains level on the back of the Fitbit device. This may improve contact between the skin and the sensor in the Garmin device, thereby reducing the impact of loosening the wristband. These differences prevent us from making a direct comparison of contact sensitivity of the two devices. Although contact pressure is a recognized factor affecting the morphology of the PPG signal, few studies have assessed its impact on heart rate accuracy [8] and to our knowledge, this is the first study assessing the impact of contact force on consumer-graded devices. Our data agrees with a previous study using an experimental PPG device coupled with a force sensor, which reported that accuracy in heart rate monitoring decreased for reduced contact pressure during low, moderate and vigorous physical activity [8].

We found that simulated sweat also increased errors and there was some evidence that the effect was more pronounced when accompanied by arm movement.

The practical ramification of these data is that users of wrist worn devices should ensure that the device has good contact pressure to obtain accurate heart rate tracking and that sweating may impair device accuracy.

Conclusions

Reduced contact pressure and sweating increases heart rate inaccuracy of consumer-graded wrist-worn devices. These effects may be exaggerated when there is arm motion.

Acknowledgements

AJ was supported by a BHF PhD Studentship (FS/19/63/34902C). This work was supported by a grant from the UK Medical Research Council and National Institute for Health Research (MC_PC-20051). MO is supported by a BHF Accelerator award (AA/18/6/34223).

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