Coverage of PPG-based wearable devices in office tasks

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Abstract

This study aims to evaluate the coverage (percentage of usable data) in heart rate (HR) monitoring terms provided by two photoplethysmography-based wearable devices during usual office tasks. These two devices are Polar OH1 (armband device) and Maxim MAXREFDES103 (wrist-worn device). A conventional Holter-type monitor (Medicom MTD) was used as reference. 19 healthy patients were monitored with the three devices mentioned above while performing some office tasks following an ad-hoc protocol during 34 minutes. HR was estimated from both wearable devices separately, and the estimates were compared to the HR estimated with the reference ECG device. Obtained results show that the best average coverage across stages (70%) was given by the Polar OH1 device, while a 50% was obtained by the MAXREFDES103.

1. Introduction

Nowadays, wearable devices are used by a large amount of people. Their high user acceptance makes them very interesting for well-being and clinical applications. However, they are highly vulnerable to artifacts during daily life. Thus, it is relevant to find out the validity of their measures during the different activities in daily life in order to evaluate their potential for a long-term monitoring of physiological parameters. The percentage of data provided by a wearable device that is usable for monitoring a specific physiological parameter is usually referred as coverage on that specific parameter. *E.g.*, the percentage of time during which a wearable device provides an accurate mean heart rate (HR) is usually referred as the coverage on mean HR of that specific device.

In this way, the coverage depends on the physiological parameter that is being monitored, *e.g.*, the beat/pulse occurrence detection requires less signal-to-noise ratio than the beat/pulse morphological features extraction, so a higher coverage can be expected for markers based on beat/pulse occurrence. Furthermore, coverage depends also on the activity that the subject is performing. Thus, the coverages reported in the literature are very variable. In [1], a lab-controlled experiment using a PPG-based wearable device was performed, reporting a coverage of 134 out of 908 segments (14.76%). A much higher mean coverage using a PPG-based wearable (76.34%) was reported in [2], where patients were in bed and in restricted-movement conditions. There are also studies reporting coverage of PPG-based wearable devices during 24-hour of free daily living, such as [3] (24%) and [4] (56%).

This study aims to quantify the coverage during usual office tasks on heart rate (HR) of two wearable devices based on pule photoplethysmography (PPG): Polar OH1 (armband device) and Maxim MAXREFDES103 (wrist-worn device). HR was estimated from each one of the two devices. Then, these estimations were compared to HR estimated from a reference Holter-type electrocardiogram (ECG) monitor (Medicom MTD).

2. Materials and methods

2.1. Data and protocol

19 healthy subjects were involved in the study. 16 were right-handed and the resting 3 were left-handed. All the subjects wore the wearable devices on the left arm/wrist. Wearable PPG and reference ECG signals were simultaneously recorded while the subjects performed five types of tasks that are common in an office environment. Specifically, these tasks were *mechanography*, *use of telephone*, *handwriting*, *use of archives or photocopying* and *other actions* that can be easily performed in an office. All the tasks were performed during 5 minutes with a break of 1 minute between tasks.

The analyzed wearable devices were Polar OH1 and Maxim MAXREFDES103. The Polar OH1 is a PPG-based sensor that is used to measure the HR. It is versatile armband device that has six green LEDs and a photodiode to measure PPG signals (sampling rate: 135 Hz). This device was located on the upper side of the arm, as recommended by the manufacturer.

The MAXREFDES103 is a wrist-worn sensor of Maxim Integrated that is able to process algorithms for health-sensing applications (sampling rate: 136 Hz). It is com-

Table 1. Heart rate (bpm) table of the writing task.

Window m	Medicom $d_{\text{HR}}(m)$	Polar OH1 (CH2) $d_{\text{HR}}(m)$
1	78	72
2	78	78
3	66	66
4	78	72
5	72	78
...	...	...
27	78	66
28	72	72
29	66	66
30	72	72

posed by a sensor board which includes a microcontroller, a 3-axis accelerometer and an optical HR sensor with two green LEDs, one red LED, one IR LED and two photodiodes. The microcontroller process the HR sensor signals. It is possible to program the sensor with owner algorithms for calculating some physiological parameters through the PPG signals measured.

In this study, only the green channels were analyzed, based on the superiority of green wavelength for quality PPG acquisition reported in the literature in most of the cases [5]. That means a total of 3 (green) channels from Polar OH1 and 2 (green) channels from Maxim MAXREFDES103. The devices were placed 10-15 minutes before starting the recording, so the sensors could reach the temperature of the skin.

In addition to the analyzed wearable devices, ECG was acquired by a Holter-type device. Specifically, Encephalan-EEGR-19/26 AT Mini of Medicom MTD was used. This device allows to measure up to 3 orthogonal leads of ECG.

2.2. Heart rate estimation and alignment

In order to evaluate the coverage of the wearable devices, the HR was estimated from each one of the PPG channels of each one of the analyzed wearable devices, and then compared to HR estimated from the reference ECG device. Before this comparison was performed, the different signals from the different devices were synchronized.

The synchronization was based on HR variability (HRV) series. Although HRV extracted from PPG signal (also known as pulse rate variability, PRV) is not exactly the same than HRV (extracted from ECG signal) [6], they are known to be highly correlated [7].

PPG signals were preprocessed by using a band-pass filter (0.03-35 Hz) to considerably attenuate the noise. Then, a pulse detector based on a low-pass-differentiator filter was applied [8], taking the maximun-upslope point as fiducial point. PRV series were extracted from each one of the

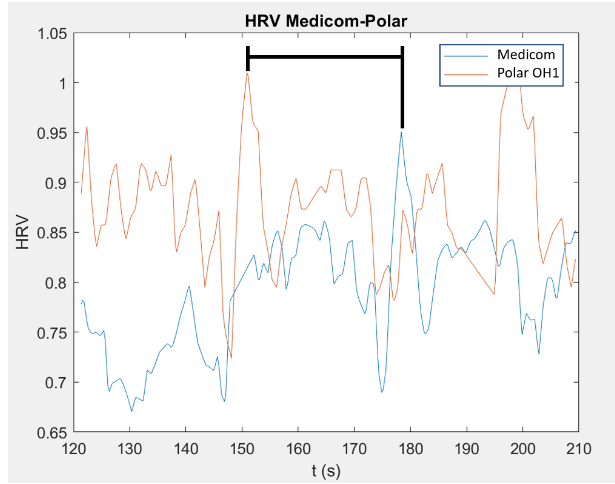

Figure 1. Example of delay between Medicom MTD (reference ECG device) and Polar OH1.

PPG channels of each one of the analyzed wearable devices, by using a cubic-splines-based inverse interval function and a sampling frequency of 4 Hz.

Reference HR series were estimated from the ECG-reference-device lead that was observed to have the best signal-to-noise ratio. In this case, a QRS detector based on wavelets was used [9]. Similarly to the case of PPG signals, HRV series were extracted from the QRS detections by using a cubic-splines-based inverse interval function and a sampling frequency of 4 Hz.

Then, the delay between PPG-based HRV series and rerference-ECG-based HRV series was estimated as the lag where the maximum of their cross correlation occurs. Subsequently, the estimated delay was corrected, performing the synchronization of the signals from different devices. An example of this delay is shown in Fig. 1.

Once the different signals from the different devices were aligned, the mean HR was computed within windows of 10 seconds from the number of beat/pulse occurrences in each window:

$$d_{\text{HR}}(m) = N_m \frac{60s}{10s} \tag{1}$$

where N_m is the number of beats/pulses detected in the mth window.

As the duration of the protocol stages is 5 min, a total of 30 samples of mean HR were obtained for each stage (see Fig. 2). An example of the *handwriting* task is showed in the Table 1 with the mean HR values estimated from the reference ECG signal and from the Polar OH1 (CH2) signal.

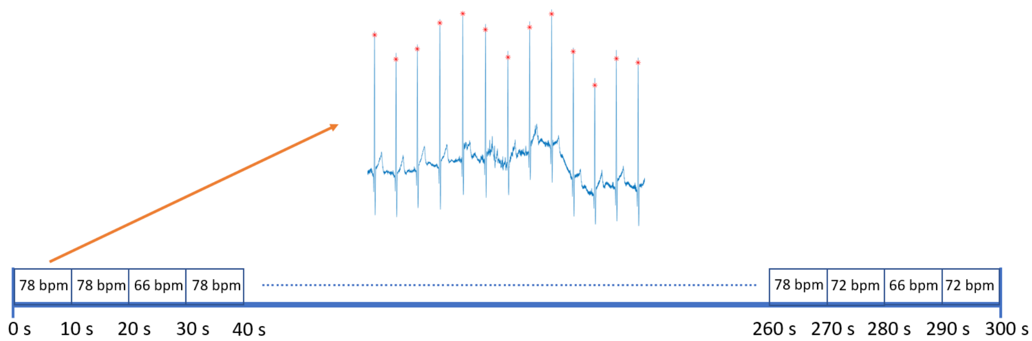

Figure 2. Example of heart rate values calculated in a task.

2.3. Performance measures

The aligned mean HR samples estimated from the different channels of the analyzed wearable devices were compared to those mean HR samples estimated from the reference ECG device. The wearable-estimated HR samples were considered accurate when they differ less than 10% from their corresponding reference HR sample. Note that the mean HR samples were calculated from time windows of length of 10 seconds and thus, an error of 10% would correspond to one pulse missdetection with a hypothetical mean HR of 60 beats per minute. Then, the coverage on mean HR was estimated as the percentage of accurate mean HR samples (according to the criterion explained above) with respect to the total number of samples. *E.g.*, in the case of *handwriting* task shown in Table 1, 29 out of the 30 mean HR samples estimated from the wearable device (Polar OH1) were accurate (differed less than 10% from the corresponding reference HR samples), thus, the estimated coverage is 96.67%.

3. Results

The mean inter-subject coverage for each green PPG channel of the analyzed wearable devices is shown in Table 2. The best coverage values were obtained for the Polar OH1 with more than 50% of mean inter-subject coverage in all the tasks, and around 70% of average coverage considering the entire protocol. The channel 1 has the highest value of coverage in the *handwriting* task (87.19%).

4. Discussion

The coverage on mean HR of two PPG-based wearable devices have been analyzed during common office tasks. The protocol included stages of *mechanography*, *use of telephone*, *handwriting*, *use of archives or photocopying*, and *other actions*. The analyzed devices are Polar OH1 (3 green PPG channels) and Maxim MAXREFDES103 (2 green PPG channels). Mean HR was estimated from the signals recorded by these devices within time windows of 10 seconds, and then compared to the mean HR estimated from a reference ECG signal. Estimated mean HR was considered accurate when it differs less than 10% from the reference (ECG-based) mean HR. Then, coverage on mean HR was estimated as the percentage of accurate mean HR samples with respect to the total samples.

The average coverage (%) for each green PPG channel of each wearable device can be observed in Table 2 for each task of the protocol. Best results in terms of coverage were obtained for *handwriting* task. This result could be explained by the fact that 16 out of 19 subjects were right-handed while all the subjects wore the wearable devices on the left arm. Therefore, during *handwriting* task, the majority of the subjects were writing using the right hand while not moving the left hand, and so sensors were minimally affected by motion artifacts during this stage. On the other hand, *use of archives* task included making photocopies, opening archives and drawers, and walking in the office, involving a considerable amount of motion. This may explain the observation of that lowest coverage was obtained for this stage.

Polar OH1 obtained better results than the Maxim MAXREFDES103 in terms of coverage (70% vs 50% in average across the stages). The reason of this observation may be the different location of the devices. The Polar OH1 was located on the upper side of the arm while the MAXREFDES103 was located on the wrist, being more affected by movement. Another possible reason may be that the location where the Polar OH1 (arm) allows a better contact with the skin than that where the Maxim MAXREFDES103 was located (wrist).

These results are similar to those reported in the literature for other PPG-based wearable devices and protocols [1–4] which, excluding [2] (performed during movement-restricted conditions), ranged from 14.76% to 56%. Also, coverage obtained for the *handwriting* task (from 87.19% to 65.79%), when the movement is minimal for the majority of the subjects, was similar to that reported in [2] (76.34%). However, no strong conclusions should be ex-

Table 2. Coverage results (%).

Task	Polar CH1	Polar CH2	Polar CH3	Maxim CH1	Maxim CH2
Mechanography	70.35	66.32	69.65	44.39	45.96
Use of telephone	78.60	80.00	80.53	72.81	73.51
Handwriting	87.19	82.81	84.39	65.79	67.37
Use of archives	50.53	51.40	52.98	39.12	37.19
Other actions	66.60	67.41	62.15	40.08	44.13
Mean	70.65	69.59	69.94	52.44	53.63

tracted from a comparison between these studies, because the coverage is highly dependent on, among other things, the studied parameter, the criterion to consider that parameter to be accurate, and on the activity that the subject is performing.

With respect to the different channels of the same wearable device, no significant differences were observed for Maxim MAXREFDES103. The channel 2 that have a slightly higher average coverage than channel 1. Similarly, no significant differences were observed between the three green PPG channels of the Polar OH1.

5. Conclusions

The stage involving the most motion, *i.e.*, the *use of archives* task, obtained the worst results in terms of coverage for all the analyzed devices and channels. On the other hand, the stage involving less motion, *i.e.*, the *handwriting* task, obtained the best results in terms of coverage for all the analyzed devices and channels. These results suggest that motion was the main obstacle for the mean HR estimation.

Obtained results show that the best average coverage across stages (70%) was given by the Polar OH1 device, while a 50% was obtained by the MAXREFDES103. These results suggest that the location of Polar OH1 (arm) is more convenient than the location of Maxim MAXREFDES103 (wrist) in this environment, maybe because the motion affects more to the position of the second device. These results should be taken into account when thinking of monitoring mean HR with wearable devices in office environments.

Acknowledgements

This project has been funded by Grants PID2021-126734OB-C21 and PID-2022-138585OA-C32 funded by MCIN/ AEI /10.13039/501100011033/ and by "ERDF A way of making Europe"; Grant PDC2021-120775-I00 funded by MCIN/ AEI /10.13039/501100011033/ and by the "European Union NextGenerationEU/PRTR"; by Gobierno de Aragon (Reference Group BSICoS T39-20R); and by University of Zaragoza under project UZ2022-IAR-06.

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