Evaluation of the Beat-to-Beat Detection Accuracy of PulseOn Wearable Optical Heart Rate Monitor

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***Abstract*— Heart rate variability (HRV) provides significant information about the health status of an individual. Optical heart rate monitoring is a comfortable alternative to ECG based heart rate monitoring. However, most available optical heart rate monitoring devices do not supply beat-to-beat detection accuracy required by proper HRV analysis. We evaluate the beat-to-beat detection accuracy of a recent wrist-worn optical heart rate monitoring device, PulseOn (PO). Ten subjects (8 male and 2 female; 35.9±10.3y) participated in the study. HRV was recorded with PO and Firstbeat Bodyguard 2 (BG2) device, which was used as an ECG based reference. HRV was recorded during sleep. As compared to BG2, PO detected on average 99.57% of the heartbeats (0.43% of beats missed) and had 0.72% extra beat detection rate, with 5.94 ms mean absolute error (MAE) in RRI as compared to the ECG based RRI (BG2. Mean RMSSD difference between PO and BG2 derived HRV was 3.1 ms. Therefore, PO provides an accurate method for long term HRV monitoring during sleep.**

I. Introduction

New wearable sensing technologies provide unobtrusive, comfortable and affordable methods for long-term real life monitoring of health and physiological status of the users. Multiple commercial devices have been recently released allowing measurement of e.g. physical activity, heart rate and sleep. However, there is an increasing need to evaluate the accuracy of these new technologies and compare them to established gold standards.

Heart rate variability (HRV) provides significant information about the health status of an individual. HRV may be used in a wide spectrum of applications, such as clinical practice [1], sleep quality measurement [2], and stress and recovery analysis [3]. Accurate detection of beat-to-beat heart rate is necessary for the analysis of the HRV [4, 5]

Several studies have been evaluated chest strap (ECG) based wearable heart rate monitors for HRV detection accuracy [6, 7, 8, 9]. These devices were usually compared against ambulatory ECG recorders in controlled laboratory conditions. Published results present high accuracy for the estimation of RR intervals using chest strap devices, with limits of agreements for group differences of less than ±10ms. On the other hand, wearing chest straps is uncomfortable in long term heart rate monitoring applications, especially during sleep. In addition, dry skin and poor skin contact often disturb chest strap based HRV monitoring during sleep.

Photoplethysmography (PPG) provides an alternative method to monitor HRV [10, 11,12]. In [13, 14] the accuracy of HRV extraction from PPG during sleep was compared against ECG based RR Holter recordings. All of the mentioned studies used wearable devices based on infrared and red LED reflective PPG sensing technology, with encouraging results. However, it has been suggested that pulse rate variability (PRV) from PPG is sufficiently accurate only for healthy (and mostly younger) subjects at rest, HRV estimated from PRV tends to be overestimated against ECG based values, and motion artifacts lead to inaccurate PPG-based beat detection [15].

The aim of this study is to evaluate the accuracy of the beat-to-beat detection of the PulseOn (PO) consumer wearable optical heart rate monitor. The comparison is performed against the Firstbeat Bodyguard 2 (BG2) wearable RR interval recorder. The application of Firstbeat beat–to–beat data artifact correction algorithm, estimation of HRV parameters and energy expenditure are also presented in this paper.

II. Methods

A. Subjects

Ten healthy volunteers (8 male and 2 female; 35.9±10.3 years old) participated in this study. Two male participants were ex-smokers. All subjects perform moderate physical training weekly. A total of 13 recordings were obtained for this study.

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B. *Data recording conditions*

Subjects performed the recordings at their homes in normal bedroom sleeping conditions. The average non-stop recorded sleep time of all subjects was 5.1±1.2 hours. The recordings did not span the whole nights due to battery limitations. The subjects were instructed to start the recordings as soon as they went to bed.

C. *Data acquisition*

PO (PulseOn Technologies Ltd, Espoo, Finland, www.pulseon.fi , [accessed 31.03.2015]) is a wearable wristband consumer optical heart rate monitor with double wavelength technology (green and infrared) and optimized optical sensors for high accuracy signal measurements (see Figure 1) [14]. The device was worn as instructed by the manufacturer on non-dominant hand, about one finger width from the wrist bone, and tightened by the subjects so that the skin contact was firm but still comfortable for the whole night recording. Beat-to-beat HR was detected automatically by the device. Data was logged to PO mobile phone application and uploaded for further processing offline.

Figure 1. PulseOn consumer wearable optical based heart rate monitor with double wavelenght optical sesing technology

The reference RR intervals were acquired with BG2 (Firstbeat Technologies Ltd, Jyväskyla, Finland, www.firstbeat.fi , [accessed 31.03.2015]) long term ECG based recorder with two disposable electrodes (see Figure 2). This device provides standard RR interval precision in milliseconds. The beat-to-beat detection accuracy and artifact correction algorithm of the selected reference device was evaluated in a laboratory protocol study [16].

Figure 2. Firstbeat Bodyguard wearable RR intervals recorded based on ECG signal aquistion with disposable electrodes

D. *Signal processing*

Firstly, both the data from the PO wrist device and the data from the BG2 reference device were processed with the Firstbeat artifact correction method [17]. Ectopic beats were detected using the algorithm presented by Mateo et al. in [18] and excluded from the evaluation.

Since both devices were not turned on at the same exact moment, the streams of data were synchronized with each other by minimizing their mean absolute difference.

Afterwards, to compensate for eventual time drifts between PO and BG2 clocks, we split the data in intervals of five minutes and performed a new synchronization for each interval.

Using the synchronized PO and BG2 data from each interval, we determined the percentage of correctly detected beats (true positive), extra beats (false positive), and missed beats (false negative). For every PO detected beat, we check how many reference beats were detected in the interval $[t-0.5l, t+0.5l]$, where t is the time when the beat was detected and l is the length of the corresponding RR interval. If there is only one reference beat within the interval, then it is considered detected correctly. If there are more than one reference beats, then PO was considered to have missed a beat detection. And if there is no corresponding reference beat, then PO detected a wrong beat. We present an example of this method in Figure 3. For the beat at position $t = 3050$ ms, there are two corresponding reference beats, so we assume that in this case we miss a beat. For the beat at position $t = 5500$ ms, there is no corresponding reference beat, so we consider this an extra beat. This is not a 100% accurate method for beat identification, but, to our knowledge, there is no other better automatic way of doing this.

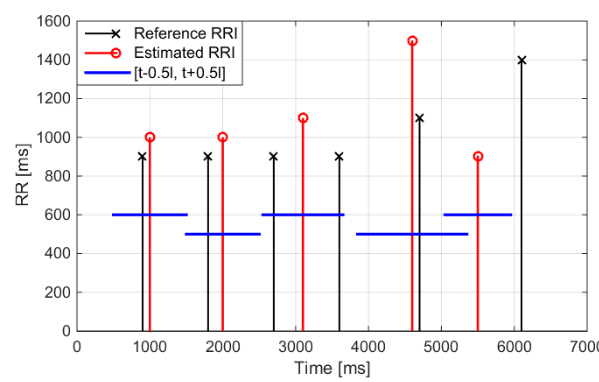

Figure 3. Illustartive example of detecting extra and missing beats

Besides the extra detected and missed beats, we determined the mean absolute error (MAE), the mean absolute percentage error (MAPE), and the root mean square of successive differences (RMSSD).

Finally, we put together the results from all five-minute intervals to obtain the statistics for the whole measurement. Because the five-minute intervals which contain extra or missed beats also contain more artifacts, in order to reduce the effect of outliers on the analysis, we did not consider them when computing the MAE, MAPE, and RMSSD.

III. Results

The size of the used dataset was 223524 heart beats. The statistics for both uncorrected and corrected data are presented in Table I.

TABLE I. USED DATASET

Error type	Dataset statistics	
	Before artifact correction	*After artifact correction*
Heart beats	223524	221390
Mean [ms]	1071	1062
Std [ms]	244.16	257.93
Min. value [ms]	270	399
Max. value [ms]	2977	2335

Table II provides the summary of the beat detection accuracy, for the cases before and after artifact correction.

TABLE II. BEAT DETECTION ANALYSIS

Error type	Beat–to–beat detection	
	Before artifact correction	*After artifact correction*
Correct beats [%]	99.42	99.57
Extra beats [%]	1.93	0.72
Missing beats [%]	0.58	0.43

The results show that PO detects correctly 99.42% of the heart beats, relative to the BG2 reference, but also adds some extra beats due to movement artefacts. After artifact correction, the amount of false positive beats is reduced from 1.93% to 0.72% (a relative decrease of 62.7%) and the amount of false negative beats is reduced from 0.58% to 0.43% (a relative decrease of 28.3%). This leads to a final detection rate of 99.57%.

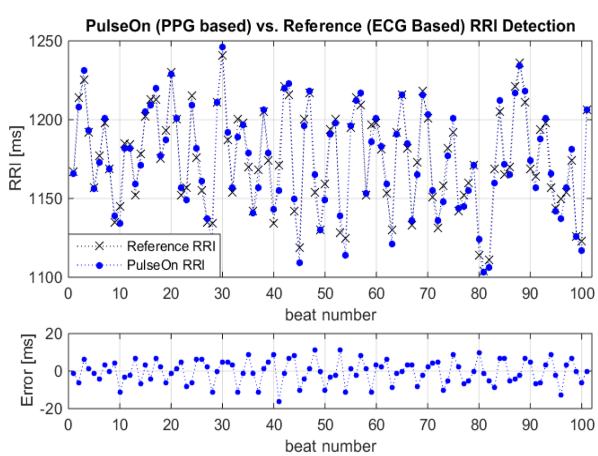

Figure 4. Example showing the RR intervals for 100 heart beats, for POn and BG2. The lower graphs shows the instantenuous error between synchronous intervals

B. *Beat–to–beat interval measurement*

After identifying the correctly detected heart beats, we used them to analyze the accuracy of the beat-to-beat interval estimation. In Figure 4, we show 100 consecutive heart beats, estimated using the PO device and BG2 reference. The top part of the figure shows the duration of the RR-intervals, and the bottom part shows the difference between synchronous PPG-ECG pairs.

The comparison between synchronous beat-to-beat intervals (for all PO detected beats that have only one corresponding reference beat) is performed by evaluating the mean absolute error and the mean absolute percentage error, and the results are given in Table III.

TABLE III. INTERVAL DETECTION STATISTICS

Error type	Beat–to–beat interval estimation	
	Before artifact correction	*After artifact correction*
ME [ms]	-0.32	-0.33
Error std [ms]	14.40	11.74
MAE [ms]	6.68	5.94
MPE [%]	-0.03	-0.03
MAPE [%]	0.62	0.56

The overall mean error is -0.32±14.40 ms before artifact correction and -0.33±11.74 ms after artifact correction. This information is also presented in the Bland-Altman plot from Figure 5. In addition, this figure shows the error distribution and the distribution of the RR interval duration. (Because of the high similarity of the Bland Altman plots for uncorrected and corrected data, we only show the figure for the corrected data.)

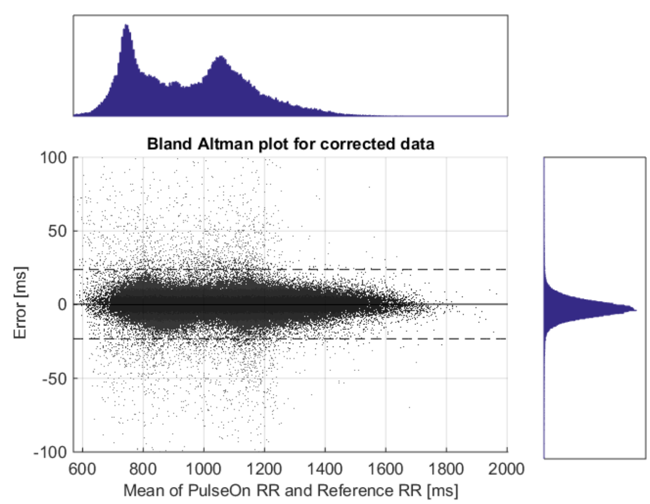

Figure 5. Bland - Altman plot comparing the reference ECG-obtained RR intervals to the PPG-obtained RR intervals, for artifact corrected data. The confidence interval ($\mu \pm 2\sigma$, depicted by the dashed lines) is $[-23.15, 23.83]$ ms.

C. Heart rate variability parameters comparison

The mean error and the mean percentage error provide us with information about how accurately we determine the duration of inter-beat intervals. However, by themselves, they do not provide information about the heart rate variability or about biased measurements.

One measure which describes HRV is the root mean square of successive differences (RMSSD) [4]. We computed it for both PO and BG2 measurements[Table IV]. The RMSSD difference between the PO measurements and the BG2 reference was 4.2 ms (7.00%) for the uncorrected data, and 3.1 ms (4.74%) for the corrected data.

TABLE IV. RMSSD STATISTICS

PulseOn (PPG) RMSSD [ms]	64.18	68.48
Reference (ECG) RMSSD [ms]	59.98	65.38
RMSSD difference [ms]	4.2	3.1

In Table V, we provide several examples of parameters deduced using the RR intervals from this study. The values were determined using the Firstbeat Sports software and represent the average for all the subjects. As the recordings were done during the night, the relaxation time is considerably higher than the stress time, the heart rate is low, the training effect is minimal, and the recovery index is high.

TABLE V. HEART RATE VARIABILITY PARAMETERS

	PulseOn	*Reference*
Relaxation time (min)	195.38	196.31
Stress time (min)	74.53	82.53
Average HR (bpm)	55.84	55.61
Training effect (1->5)	1.03	1.02
Scaled Firstbeat Recovery index (%)	100	100

IV. CONCLUSION

This study explores the accuracy of RR interval detection using PPG based wrist worn device, PO. PO correctly detected 99.57% of the heart beats, and had 0.72% extra beat detections due to movement artefacts during sleep. The MAE was 5.94 ms, and the RMSSD difference against ECG based BG2 reference 3.1 ms. As expected, correcting the artifacts with the Firstbeat Sports software based artefact correction algorithm led to more precise estimation of the beat-to-beat intervals, a very noticeable improvement being visible in the reduction of extra-detected beats.

The results demonstrate that new PPG based HR monitors are becoming a real option for consumer use, not only for HR monitoring while exercising, but also for HRV analysis. PPG provides a more comfortable solution, as they do not require electrodes to be placed on the body. PO device evaluated in this study provides HRV accuracy comparable to ECG based devices and is sufficient for reliable HRV monitoring during sleep.

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