Evaluation of Wearable Consumer Heart Rate Monitors Based on Photopletysmography

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Abstract— **Wearable monitoring of heart rate (HR) during physical activity and exercising allows real time control of exercise intensity and training effect. Recently, technologies based on pulse plethysmography (PPG) have become available for personal health management for consumers. However, the accuracy of these monitors is poorly known which limits their application. In this study, we evaluated accuracy of two PPG based (wrist i.e. Mio Alpha vs forearm i.e. Schosche Rhythm) commercially available HR monitors during exercise. 21 healthy volunteers (15 male and 6 female) completed an exercise protocol which included sitting, lying, walking, running, cycling, and some daily activities involving hand movements. HR estimation was compared against values from the reference electrocardiogram (ECG) signal. The heart rate estimation reliability scores for <5% accuracy against reference were following: mio Alpha 77,83% and Scosche Rhytm 76,29%. The estimated results indicate that performance of devices depends on various parameters, including specified activity, sensor type and device placement.**

I. Introduction

Heart rate monitoring is useful in wide areas including clinical medical care, pervasive health care, sports and well-being. HR describes an efficiency of cardiovascular system and heart functionality. People have been interested in HR monitoring since ancient Greek [1]. In 1960s Norman Holter invented a portable electrocardiogram (ECG) recorder and a HR analyzer [2]. Another milestone happened in 1982 when Polar Electro produced the first wearable HR monitor designed for sport purposes and based on ECG monitoring [3]. Today, ECG based HR monitors utilize usually chest strap and are widely available for consumers in affordable price. In parallel to chest strap based HR monitors, technologies based on photoplethysmogram (PPG) acquisition from wrist (REF), forearm (REF) or ear (REF) have been introduced. These solutions extend the use cases for HR monitoring by offering better comfort and more unobtrusive monitoring.

However, accuracy of these novel technologies has been little studied which limits their application especially beyond consumer use for recreational purposes. Chest strap based HR monitors, e.g. Polar Vantage XL, Polar Accurex, Cardioschamp and Cateye PL-6000, had a correlation >0.90 and standard error estimate <5 BPM during rest and moderate activity [4]. The best consumer level chest strap HR monitors have been found to provide comparable accuracy with ambulatory ECG in beat-to-beat detection and RR-interval estimation [5, 6]. Correlation coefficient of heart rate variability analysis demonstrated satisfactory correlation between Polar 810s and reference ECG during rest and ercocycling [7]. Another comparison study approves an interchangeability using of the Polar S810, Suunto t6 and ambulatory ECG system [8]. Smarthhealth watches and Polar Vintage XL were successfully validated against ambulatory ECG during four different loads on treadmill [9]. Comparison of the Actiheart and the Reynolds Holter system was performed in normal living conditions during common daily life activities [10]. In comparison, HR monitoring accuracy during treadmill running with finger photoplethymographs was found to be decreased as compared against the ECG reference [11]. A comparability problem of the Photopletysmography devices validation studies are discussed in the comprehensive expertise review [12].

The previous comparison studies are focused mainly on the traditional chest strap devices. Especially PPG based consumer targeted devices have not been objectively validated to date. In this study, we compare the accuracy of two different consumer wearable PPG based HR monitors during exercise against golden standard i.e. ECG based HR. We chose for comparison two different PPG based monitors (wrist and forearm worn devices). Materials and methods

A. Subjects

Twenty-one healthy volunteers (15 males and 6 females; 31,3 ± 10,7 years old) volunteered in the study. All participants were nonsmokers and they perform weekly some kind of physical activity. All subjects gave informed consent while participating the study.

B. Methods

Table 1 contains detailed description of protocol tasks and duration. Total testing time was 50 minutes. Selected protocol tasks focus to simulate intensive exercise, rest positions including sitting, lying on the bed in different positions and standing. Hand movements which can have significant impact of results were simulated in Rubic cube game play.

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978-1-4244-7929-0/14/$26.00 ©2014 IEEE

TABLE I. TESTING PROTOCOL TASKS AND DURATION

Activity	***Duration [min]***
Rest sitting	4:00
Lying on bed on different positions	6:00
Standing	1:00
Walking 3km/h - 0% inclination	3:00
Walking 3km/h - 5% inclination	3:00
Walking 3km/h - 10% inclination	3:00
Walking 5km/h - 0% inclination	3:00
Walking 5km/h - 5% inclination	3:00
Walking 5km/h - 10% inclination	3:00
Running 9km/h - 0% inclination	3:00
Running 11km/h - 0% inclination	3:00
Rest sitting	2:00
Rest sitting and playing with Rubic cube	2:00
Rest sitting	2:00
Cycling 60 rpm	3:00
Cycling 90 rpm	3:00
Rest sitting	4:00

C. Data acquisition

HR was acquired with two PPG based HR monitors: Mio Alpha (Mio Global, Canada) and Schosche myRhyhm (Schosche Industries, CA, USA) (Figure 1).

Mio Alpha is worn on wrist and uses green LEDs and a photodetector for signal acquisition. Data were transmitted from device using the ANT+ technology to Garmin Forerunner device. HR data with timestamps were extracted from Garmin device for further analysis. Scosche Rhythm is worn on forearm and uses infrared LED and a photodetector for PPG acquisition. Data were transmitted by Bluetooth technology to iCardio Smartphone application where it was exported for further analysis. Both of devices were attached on subject body according manufacturers' recommendations.

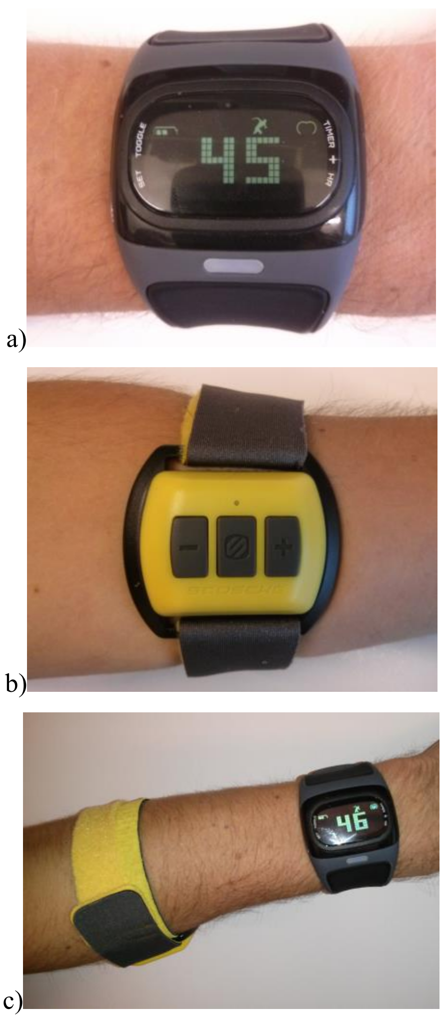
The Embla Titanium multi-parameter wearable recorder was used for measuring the reference ECG signal. This device is designed for acquiring several biosignals including the ECG. Two ECG leads were acquired for reference heart rate estimation. Disposable electrodes were placed according two channels Holter measurement. [13]. Fixing of the disposable electrodes and cables were done by the medical tape for decreasing level of possible motion and other signal artifacts.

C. Statistical analyzes

Analysis of the reference ECG signal was performed with the Kubios HRV tool [14]. The better ECG RAW signal quality channel was selected by visual inspection of both recorded channels. The R-peaks were detected in selected channel by automatic R-peak detection algorithm which is included in HRV tool. In R-peak detection algorithm, QRS complexes are re-sampled at 2048 Hz with sinc-interpolation prior to R-peak detection to reduce the quantization error caused by low ECG sampling rate [15]. The all R-peak detections were verified manually in the reference signal. Heart timing signals algorithm was used for detection of the arrhythmias (ectopic beats) [16]. These beat were excluded from the final statistical evaluation and error estimation.

The evaluated and reference heart rate signals were resampled to 10 Hz sampling frequency. HR acquired from PPG HR monitors and reference HR were synchronized in time by applying cross-correlation function between the reference and the target HR and by maximizing the cross-correlation value at t=0. The signals were smoothed by moving average in 5s second window.

Several HR detection accuracy parameters were evaluated for both of tested device. The successful HR score for < 5% and <10% beats per minutes difference against reference were calculated in 5s average HR window without overlaps. Mean error (ME), mean absolute error (MAE), mean percentage error (MPE), mean absolute percentage error (MAPE) between the mio Alpha, Scosche Rhythm and reference HR were calculated.



a)

b)

c)

Figure 1. a) Mio Alpha. b) Scosche myRhythm c) Test configuration

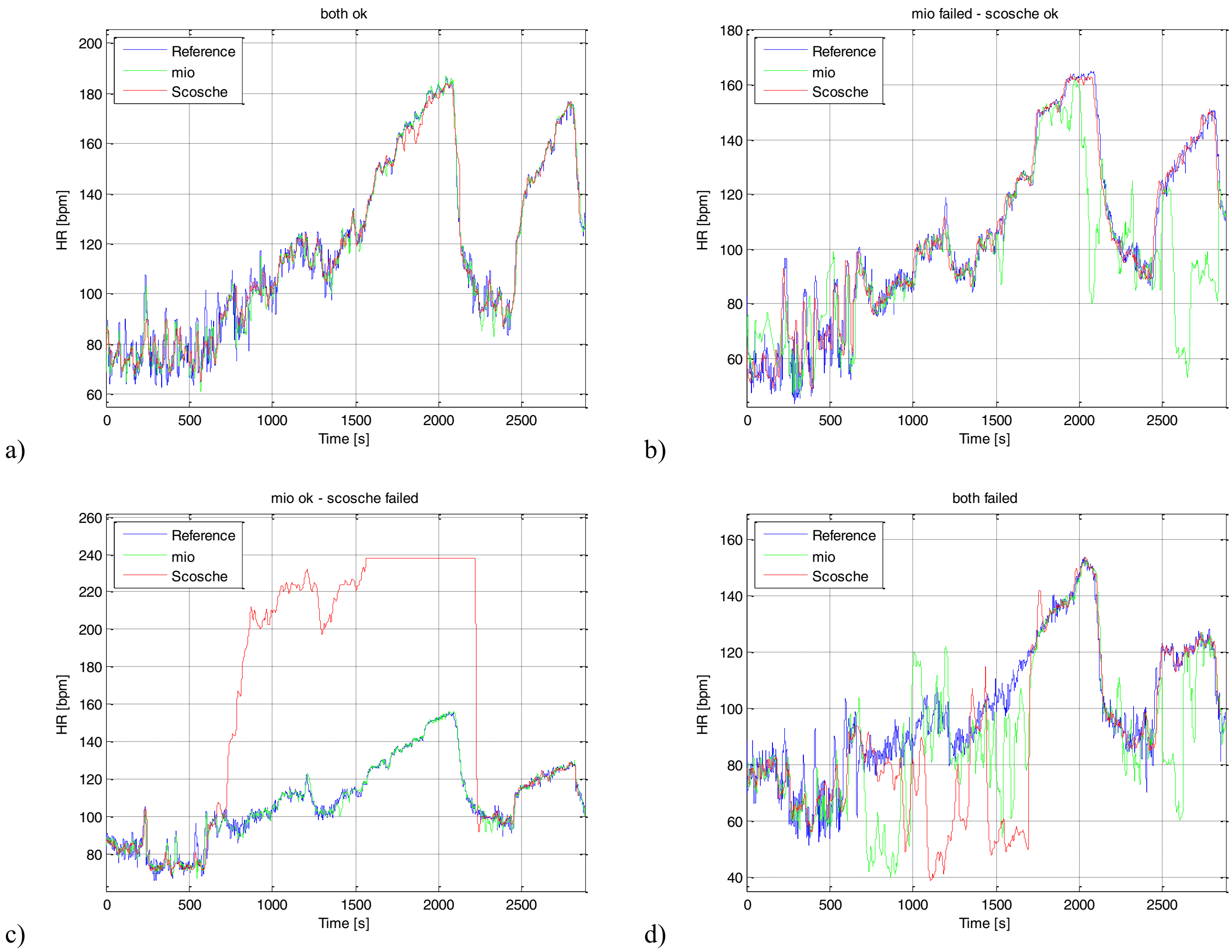


Figure 2. A) HR monitoring successful with both devices. B) Wrist based Mio Alpha fails during ergocycling. C) Forearm based Schosche Rhythm failed during walking and running, likely due to sensor displacement. D) Both devices show poor performance.

TABLE II. MIO ALPHA ERROR STATISTICS AS COMPARED TO REFERENCE ECG BASED HR (N=21)

Activity	***Mean Error* [bpm]**	***Mean Error* [%]**	***Mean Abs Error* [bpm]**	***Mean Abs Error* [%]**
global	-1,21	-1,74	4,43	5,23
rest	-0,20	-0,52	3,92	5,37
walking	-0,89	-1,72	4,98	5,60
running	-2,26	-1,93	2,89	2,37
cycling	-3,76	-4,80	4,64	5,53
rubic	-1,26	-1,83	7,54	8,43

TABLE III. SCOSCHE MYRHYTHM ERROR STATISTICS AS COMPARED TO REFERENCE ECG BASED HR (N=21)

Activity	***Mean Error* [bpm]**	***Mean Error* [%]**	***Mean Abs Error* [bpm]**	***Mean Abs Error* [%]**
global	1,11	-1,62	6,82	6,78
rest	0,07	-1,43	4,83	5,96
walking	1,83	-3,13	10,48	10,49
running	3,28	0,63	6,75	3,81
cycling	-0,89	-0,87	1,84	1,73
rubic	2,59	1,46	4,73	3,94

I. RESULTS

Both PPG HR monitors were able to monitor HR during exercise but not without errors in some cases. Representative examples are presented in Figure 2. HR estimation success rates for different activities are reported on Table II. Average performance was similar in both devices but Mio Alpha performed better during walking and running and Schosche Rhythm during cycling and Rubik's cube. Estimation error for Mio Alpha and Schosche Rhythm are presented in Tables III and IV, correspondingly.

TABLE II. MIO ALPHA AND SCHOSCHE RHYTHM SUCCESS RATES DURING DIFFERENT ACTIVITIES (N=21)

	Mio Alpha		*Scosche myRhythm*	
Activity	*score <5%*	*score <10%*	*score <5%*	*score <10%*
global	77,83	87,49	76,29	86,26
rest	72,53	84,87	69,53	83,88
walking	76,53	87,18	71,64	81,76
running	94,58	96,18	90,97	93,26
cycling	87,71	91,74	92,22	97,43
rubic	51,46	72,29	80,21	91,88

IV. DISCUSSION

We evaluated new PPG based HR monitors against reference (ECG) HR. The results show that the PPG based HR monitors are able to monitor HR during exercise but not without errors. On average, PPG based HR was within 10bpm from true HR 86-87% of the time. This may be considered as satisfactory overall performance. However, sometimes the monitors fail to monitor HR and in such cases grand errors are seen (see Fig 1).

Wrist based monitor (Mio Alpha) performed better during walking and running while forearm based Scosche Rhythm was better during cycling and hand movements (Rubik's cube). It is natural that forearm based sensor is less affected by hand movements which certainly occur in Rubik's cube test but likely also during cycling, related to using hands for balancing and holding the steering while cycling. Poorer performance of the forearm based device during running and walking is, however, slightly surprising as forearm should be objected to lower level of accelerations than wrist also during these activities. The difference may hence be related to different implementation issues, such as algorithms used to extract HR, or sensor arrangements (e.g. use of different wavelengths in PPG acquisition).

The average performance of both devices was satisfactory but momentary grand errors reduce the usefulness of them. Our data does not allow to study the exact reasons for failures. However, poor sensor placement or attachment, or displacement of the sensor during exercising, may explain some of the errors. If optical coupling between the sensor and the tissue is not maintained steady during the monitoring, the loss of signal and hence ability to monitor HR will result.

Our results demonstrate that new PPG based HR monitors are becoming a real option for consumer HR monitoring at least during exercising, when ultimate performance is not required. However, the PPG monitors studied in this paper do not yet reach the level of reliability of the chest strap based HR monitors. The reduced accuracy is partially compensated by better usability and comfort.

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