Effect of skin tone and activity on the performance of wrist-worn optical beat-to-beat heart rate monitoring

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***Abstract*—Wrist-worn reflective photoplethysmography (PPG) has gained popularity as an unobtrusive method for heart rate monitoring, also known as optical heart rate monitoring (OHR). Recently beat-to-beat heart rate information measured with OHR technology has also started to be utilized in heart rate variability analysis as well as in detection of cardiac arrhythmias. However, as an optical method, the quality of the PPG signal and thus the performance of the technology is affected by the skin tone of the measurement subject. In addition, movement and superficial blood perfusion are other relevant factors affecting to OHR monitoring. We evaluated the performance of optical heart rate monitor manufactured by PulseOn company in controlled trial with 36 subjects of varying skin tones. The results show clear dependence between the skin tone and the coverage percentage of good quality beat-to-beat intervals (BBI) as well as improvement of the coverage and the BBI accuracy after physical activity, especially with people with darker skin tone.**

Keywords— reflective photoplethysmography; wearable optical sensing; beat-to-beat heart rate

I. Introduction

Optical heart rate (OHR) monitoring has become a credible alternative for the heart rate belt in sports monitoring applications due to its comfortability and ease of use. An additional benefit of optical monitoring is that the wrist-worn device can be used throughout the day and it can thus provide data for heart rate variability (HRV) –based applications such as exercise recovery [1] or sleep quality analysis [2]. Another area utilizing information on individual heartbeat intervals and their variation is the detection of cardiac arrhythmias [3]. However, for reliable HRV analysis or arrhythmia detection, accurate beat-to-beat HR information is needed.

OHR measurement is based on reflective mode photoplethysmography (PPG) where the intensity of the light scattered or reflected back from the tissue is varied by the amount of light-absorbing blood in the measurement area. There are several critical factors affecting the reliability of the OHR measurement. These include:

1. Sensor design factors such as sensor geometry: number of LEDs/photodiodes and distance between them, LED color, opto-mechanical design e.g. possible lenses, bulge at the LEDs.

2. Measurement subject factors such as: blood perfusion in the measurement area, presence of non-favorable tissues, skin tone, scars.

3. The measurement context: selection of the measurement location, type of activity (periodic, non-periodic), intensity of the activity.

4. The data analysis approaches: signal processing algorithm, utilization of additional sensor information (movement sensor, multi-wavelength PPG). [4] [5]

Optical measurement is very sensitive to movement due to varying pressure between the sensor and the skin as well as movement of the body fluids caused by the movements of the body itself. Depending on the use case (average heart rate or individual heartbeat intervals), the choices of signal processing approaches are very different. In average heart rate estimation the HR estimation is usually based on frequency domain analysis of spectral components in the signal and utilization of movement information whereas when estimating individual heartbeat intervals, accurate identification and removal of unreliable heartbeats or beat-to-beat intervals is essential. [4]

Fallow et al. studied the signal to noise ratio of four different PPG measurement wavelengths with people having varying skin tones. From the tested LED wavelengths the best normalized (AC/DC) modulation amplitude was obtained with 520 nm green color LED in both sedentary and active conditions with all skin tones [6]. Bent et al. recently studied the heart rate estimation accuracy of six wearable OHR (four commercial and two research phase) devices in five conditions from resting to walking and typing with 56 participants with various skin tones. They did not find statistically significant difference in HR estimation accuracy between skin tones [7]. Spierer et al. however did find clear correlation between the skin tone and the mean absolute error of estimated heart rate in one of the two tested devices [8]. Their study is already from year 2015 and they were testing the devices from an early era of optical heart rate monitoring. In addition, their test protocol consisted of more rigorous activities than Bent et al.'s did.

The aforementioned two studies investigated the estimation of average heart rate. The evaluated devices most likely estimate the average heart rate using frequency domain approaches, which are significantly more tolerant to movement artefacts. They may also be less prone to deterioration of the performance due to lower amplitude and signal-to-noise ratio caused by the darker skin tone. We evaluated the effect of skin tone and improved blood perfusion due to movement on the estimation accuracy and coverage of beat-to-beat intervals.

II. METHODS

A. Study participants

We recruited 36 healthy participants for the study. The participants represented all classes of Fitzpatrick skin tone scale [9]. The distribution to different categories is shown in Table I. The age of the subjects varied between 22 – 40 years (average 30 years). Eight of the subjects were female. The ethicality of the study was reviewed by the institutional ethics review board of Tampere University.

TABLE I. DIVISION OF SUBJECTS ON THE FITZPATRICK SKIN TONE SCALE

2	7	5	7	7	7 (8)[a]

[a] One subject excluded from the analysis

B. Study Devices

Aino optical heart rate monitor manufactured by PulseOn Oy, Finland. The device uses yellowish-green LEDs with peak wavelength at 573 nm and relatively low 25 Hz sampling frequency. Accuracy of the beat-to-beat interval estimation is improved by interpolation. The device determines the reliability of estimated beat-to-beat intervals by analyzing the pulse wave morphology and the level of acceleration. The wrist strap of the device was tightened so that the device stayed firmly at the wrist. One of the test subjects had very thin wrists which prevented tightening the device enough. This subject was thus excluded from the analysis.

Five-lead eMotion Faros 360 Holter monitor manufactured by Bittium Biosignals Oy and Ambu Blue Sensor L-00-S electrodes were used to record the reference ECG with 1 kHz sampling frequency. The reference R-R-intervals were obtained using Kubios software (www.kubios.com).

C. Study Protocol

Our study protocol consisted of six phases with total duration of 35 minutes. The phases were:

1. lying supine for 5 min,
2. walking on a treadmill for 5 min (4 km/h),
3. typing with desktop computer key-board for 5 min,
4. cycling with and ergometer for 5 min,
5. laying supine for 10 min, and
6. laying supine for 5 min with the wrist device turned to the palmar side of the wrist.

The activity phases were introduced to the protocol in order to investigate the effect of increased blood perfusion on the performance of beat-to-beat OHR performance.

The data analysis was performed post-hoc with Python and Matlab. The BBI and RRI tachogram signals were first aligned and stretched by optimizing a cost function combining the timing and length of the intervals so that the corresponding intervals matched. Every good quality BBI was then paired with the closest RRI to calculate the results. We used mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE), root mean square error (RMSE), and the coverage of the good quality BBIs as the figure of merits.

III. RESULTS AND DISCUSSION

Figure 1 illustrates an example beat-to-beat interval tachogram signal for the whole protocol period. The BBIs marked as unreliable by the PulseOn algorithm are shown in yellow color. Different phases of the test protocol are clearly distinguishable. As it is seen in the figure, no BBIs during the walking phase are marked as good quality and it is also seen that the BBIs estimated by the device are random. During the typing and cycling phase there are small portion of the BBIs marked as reliable.

Figure 2 illustrates the effectiveness of the identification of good quality BBIs with the same participant. In this particular case there are only two clear outlier heartbeat intervals during the whole recording. Both these occur during the typing phase. As it is seen, the BBIs follow very well the RRIs during the resting phases. During cycling (Indexes 450 – 750) there are more discrepancy between the BBIs and RRIs. It is worth mentioning that this example is one of the most favorable cases in our study material.

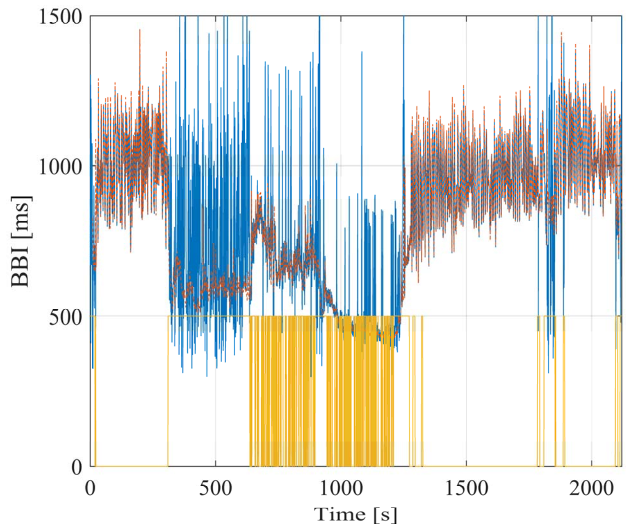

Fig. 1. Example PPG BBIs (blue) and reference RRIs (red) for the whole test protocol. Unreliable BBIs are marked with yellow index marker at 500 level.

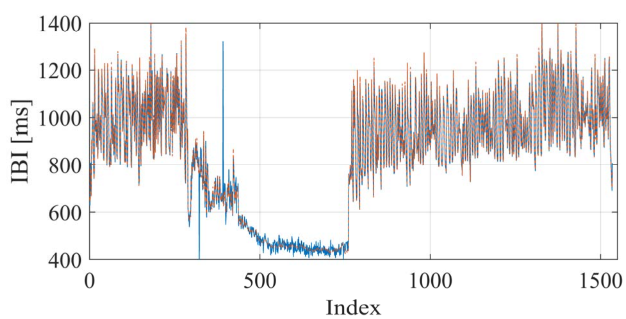

Fig. 2. Good quality BBIs and RRIs of the example measurement.

A. *Effect of Skin Tone*

Figure 3 presents the coverage of the good quality BBIs for the whole duration of the protocol as a function of the skin tone. There is a clear dependency between the BBI coverage and the skin tone. Due to the small overall number of the test subjects we divided them into two groups based on the skin tone and compared the performance between the groups. In Fitzpatrick skin tone scale only the levels V and VI represent clearly darker skin tone and therefore these subjects were set as one group. Table II presents the error metrics for the good quality BBIs for the whole protocol. As can be seen in Table II, there is in practice no difference in the accuracy of the good quality BBIs. In fact, the error is actually higher for the lighter skin tone group. This is affected by the relatively high bias caused mainly by two unfavorable subjects with very high measurement bias. High RMSE in both groups is caused by large sporadic BBI errors mainly during the activity period.

TABLE II. BBI ERROR DURING THE WHOLE STUDY

Skin tone	ME (ms)	MAE (ms)	MAPE (%)	RMSE (ms)
FP 1-4	6,19	12,72	2,00	54,42
FP 5-6	2,00	9,49	1,35	44,58

B. *Effect of Activity and Increased Blood Perfusion*

We also investigated separately the BBI estimation accuracies in the study phases before and after the activity period. Table III presents the accuracy before the activity when the blood perfusion can be estimated to be in the level of normal daily living or e.g. the night sleep. Table IV presents the results after the activity when the overall blood perfusion is escalated. It is seen that especially in the group with darker skin tone the difference in BBI estimation accuracy is clear between these phases.

TABLE III. BBI ERROR DURING THE FIRST RESTING PHASE

Skin tone	ME (ms)	MAE (ms)	MAPE (%)	RMSE (ms)
FP 1-4	0,48	4,62	0,51	8,12
FP 5-6	0,26	8,43	0,96	13,19

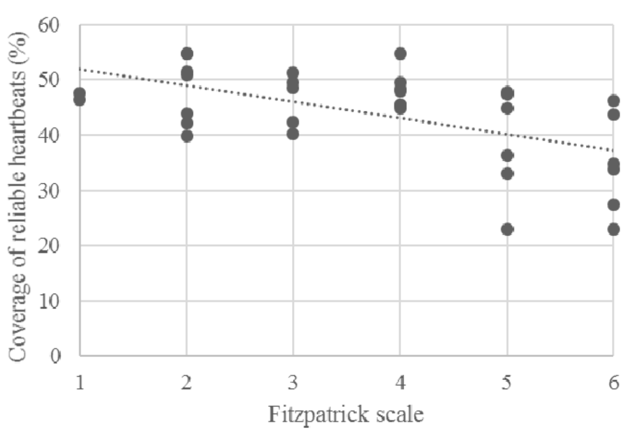

Fig. 3. The coverage of good quality or reliable BBIs of subjects with varying skin tones during the whole protocol period.

TABLE IV. BBI ERROR DURING THE SECOND RESTING PHASE

Skin tone	ME (ms)	MAE (ms)	MAPE (%)	RMSE (ms)
FP 1-4	0,39	3,89	0,46	8,86
FP 5-6	0,68	5,68	0,75	9,90

Table V presents the coverage of good quality BBIs in different phases. Here the difference in the coverage of good quality BBIs before and after the activity is remarkable in the darker skin tone group. Measurement from the palmar side of the wrist was tested as the last phase of the protocol. For the darker skin tone group measurement from this side seems to produce slight benefit but the effect is opposite in the lighter ski tone group. In addition to the difference in blood perfusion between these locations, another factor may be the tendons located on the palmar side. Already small movement of fingers may be enough to cause distortion to the PPG signal and result in loss of the good quality BBIs.

TABLE V. COVERAGE (%) OF RELIABLE BBIS FOR DIFFERENT PHASES OF THE EXPERIMENT

Measurement phase	FP 1-4	FP 5-6
Whole measurement	47,61	36,76
First resting phase	97,42	62,50
Second resting phase	95,93	79,39
Palmar side measurement	93,49	84,98

IV. CONCLUSIONS

We studied the effect of skin tone and increase of blood perfusion due to physical activity on the performance of beat-to-beat heart rate estimation with wrist-worn optical heart rate monitor. It was shown that the skin tone has a clear effect in the proportion of the obtained good quality heartbeat intervals in PulseOn Aino OHR device. However, the effect of skin tone to the accuracy of good quality BBIs was not significant. A clear improvement in both accuracy and coverage of good quality heartbeat intervals was seen as a result of activity (walking on a treadmill and cycling with an ergometer) in the study group with darker skin tone. With lighter skin tone, there was no difference.

This study used OHR devices with 573 nm peak LED wavelength. It should be investigated in the future which wavelength provides the best performance in terms of accuracy and coverage and whether the optimal wavelength varies as a function of skin tone.

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