# Evaluation of Accuracy and Reliability of PulseOn Optical Heart Rate Monitoring Device

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***Abstract*— PulseOn is a wrist-worn optical heart rate (HR) monitor based on photoplethysmography. It utilizes multi-wavelength technology and optimized sensor geometry to monitor blood flow at different depths of skin tissue, and it dynamically adapts to an optimal measurement depth in different conditions. Movement artefacts are reduced by adaptive movement-cancellation algorithms and optimized mechanics, which stabilize the sensor-to-skin contact. In this paper, we evaluated the accuracy and reliability of PulseOn technology against ECG-derived HR in laboratory conditions during a wide range of physical activities and also during outdoor sports. In addition, we compared the performance to another on-the-shelf wrist-worn consumer product Mio LINK®. The results showed PulseOn reliability (% of time with error <10bpm) of 94.5% with accuracy (100% - mean absolute percentage error) 96.6% as compared to ECG (vs 86.6% and 94.4% for Mio LINK®, correspondingly) during laboratory protocol. Similar or better reliability and accuracy was seen during normal outdoor sports activities. The results show that PulseOn provides reliability and accuracy similar to traditional chest strap ECG HR monitors during cardiovascular exercise.**

## I. INTRODUCTION

Wearable monitoring of heart rate (HR) during physical activity and exercising allows real-time control of exercise intensity and training effect. Chest strap HR monitors based on electrocardiography (ECG) have been the standard for sports HR monitoring for 20 years. Chest strap based HR monitors typically have a correlation of >0.90 and a standard error estimate <5 BPM during rest and moderate activity, which is considered sufficient for consumer sports use [1]. The best chest strap HR monitors have been found to provide comparable accuracy with ambulatory ECG HR monitoring [2, 3, 4]. However, discomfort and complication of use has limited their popularity among consumers. Optical HR monitoring allows an unobtrusive and comfortable alternative for HR monitoring during exercise. However, most products up to today have suffered from poor reliability and accuracy [5]. In this paper, we evaluate a PulseOn optical HR monitor and evaluate it against ECG-based HR monitoring as well as against another on-the-shelf wrist-worn consumer optical HR monitor Mio LINK® in laboratory conditions. We also show that the system is robust to real-life outdoor conditions.

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## II. PHOTOPLETHYSMOGRAPHY AND WEARABLE HR MONITORING

### A. *Physiological Principles*

PulseOn is based on photoplethysmography where skin tissue is illuminated with a light source (typically LED) and the intensity of light that has propagated through the tissue is measured with a photodetector (PD) [6]. The blood volume in the small peripheral vessels close to the skin (see Figure 1) is varying with the pumping action of the heart and causes variations in the propagated light intensity. By analyzing these variations it is possible to derive HR. However, there are several factors which affect the light propagation and hence make reliable optical HR monitoring highly challenging.

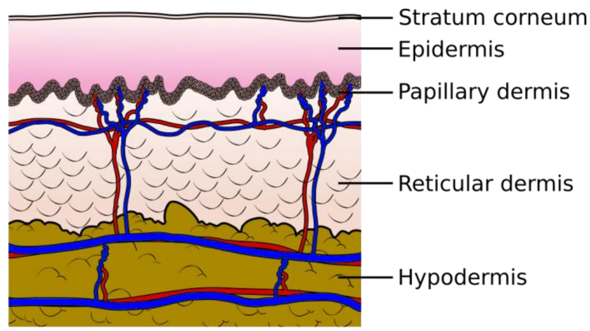


***Figure 1. Structure of human skin. The thickness of papillary dermis and reticular dermis, where blood flow mainly occurs, vary between 0.6 and 3mm. When the skin is cold, perfusion in papillary dermis is minimal and is reduced also in reticular dermis.***

First, the human skin is a complex non-homogeneous structure (Figure 1). Thus, even a small displacement of the sensor or a change in the sensor-skin contact may cause significant changes in the light propagation path [6]. This makes the technology very prone to movement artefacts. Furthermore, human physiology, especially temperature control, causes peripheral vascular dilatation and constriction depending on multiple factors (*e.g.*, environmental temperature, intra-body heat production), and hence both the volume of blood close to skin and the depth of main perfusion varies greatly between conditions and individuals. Finally, there are inter-individual differences in the skin and tissue structures and thickness of the layers as well as the amount of melanin. As a result, the optimal measurement depth as well as the strength of the signal varies greatly between situations and individuals. Measurement depth may be optimized by the selection of the light color (wavelength) and design of the sensor layout [6]. The depth of penetration of the light into the tissue depends on light wavelength and distance between the LED and the PD [6]. Due to optical properties of the different components of the tissue, longer wavelengths, such as infra-red light (IR), will penetrate deeper into the tissue than short wavelengths (*e.g.*, green light). In addition, shortening the PD-LED distance will reduce the average light propagation path, and vice versa. Green light with short PD-LED distance is able to illuminate blood flow only very close to skin while IR light and longer PD-LED distance provide deeper measurement. However, the larger the measurement area is, more prone to movement artefacts the measurement is [6]. As a result, green light and short PD-LED distance are less sensitive to movement artefacts [7] but more sensitive to poor perfusion (*e.g.*, during cold skin). Typical optical HR solutions compromise between these demands and provide measurement on a single wavelength and single PD-LED distance, resulting in a single average measurement depth in all conditions and individuals, making it sensitive to variations in blood perfusion (*e.g.*, cold skin), individual differences, and/or movements.

Optomechanical design of the sensing device affects the signal quality significantly [6]. Reducing the weight of the sensing device, reduces forces caused by the movement and thereafter the skin-sensor pressure changes during exercise

### B. *PulseOn Technology*

PulseOn sensor solution[1] takes advantage of multiple light wavelengths and optimally matched LED-PD distances to allow the measurement of blood flow on the wrist in different tissue depths (see Figure 2). It dynamically chooses the optimal combination for reliable and accurate HR monitoring. The use of green light and short PD-LED distance allows for a robust HR monitoring, even during intense movements, while the use of IR and longer PD-LED distance allows for HR acquisition even during low blood perfusion (*e.g.*, cold skin).


***Figure 2. PulseOn sensor solution combines green and IR light with optimally matched LED-PD distances.***

The mechanical design[2] of the housing and the strap provides PulseOn with a stable skin-sensor contact in a wide range of conditions without compromising the comfortable use. The design also reduces artefacts and improves HR reliability. The light weight (29g, including strap) further reduces artefacts and improves usage comfort. Intelligent algorithms analyze PD signals and decide the optimal measurement combination in each situation. HR detection algorithm applies integrated accelerometer data to reduce movement artefacts and provides accurate HR estimation even during very intensive training, spanning up to full running speeds and maximum HR levels.

## III. EXPERIMENTAL VALIDATION

### A. *Controlled Laboratory Protocol*

The test group consisted on N=19 healthy volunteers, from which 9 are men and 10 women (see Table I). All participants were nonsmokers and physically active[3].

**TABLE I. SUBJECTS' ANTHROPOMETRIC PARAMETERS**

| Characteristic | $\mu \pm \sigma$ | Range |
|---|---|---|
| Age (years) | 28.30 ± 5.69 | 23 – 47 |
| Height (m) | 1.74 ± 0.11 | 1.55 – 1.90 |
| Weight (kg) | 72.30 ± 12.59 | 52 – 99 |

The subjects followed a standardized protocol that included a wide set of activities, ranging from sedentary to vigorous and causing rapid and wide variations in HR, recorded in laboratory settings (see Table II). The treadmill and ergocycle used in the execution of the protocol were Daum Ergo Run Premium Alpha 24 and the Tunturi Alpha 300 respectively.

**TABLE II. TESTING LABORATORY PROTOCOL AND DURATIONS**

| Activity | Duration |
|---|---|
| Standing | 1min |
| Walking on a treadmill at 3km/h, 0% inclination | 3min |
| Walking on a treadmill at 3km/h, 5% inclination | 3min |
| Walking on a treadmill at 3km/h, 10% inclination | 3min |
| Walking on a treadmill at 5km/h, 0% inclination | 3min |
| Walking on a treadmill at 5km/h, 5% inclination | 3min |
| Walking on a treadmill at 5km/h, 10% inclination | 3min |
| Running on a treadmill at 9km/h, 0% inclination | 3min |
| Running on a treadmill at 11km/h, 0% inclination | 3min |
| Rest sitting | 4min |
| Cycling 60rpm* | 3min |
| Cycling 90rpm* | 3min |
| Rest sitting | 4min |

*Unconditioned males (activity class <5): 50 Watts
*Unconditioned females (activity class <5): 50Watts
*Conditioned males (activity class 5 or above): 100Watts
*Conditioned females (activity class 5 or above): 75Watts

HR signals were acquired with the wrist-worn device Mio LINK® through a Garmin Forerunner 610 (ANT device) and the PulseOn's HR monitor. Both devices were located on different wrists as indicated on their respective user manuals. The chest-strap ECG Polar Electro RS800CX HR monitor was used as the reference. This chest strap provides an ECG-level accuracy of the HR during sports [4]. PulseOn, Mio LINK®, and reference HR signals were synchronized in time by maximizing the cross-correlation among the signals. This process resulted in comparable and time-synced HR signals among all devices. Then, all data was linearly interpolated to the match PulseOn's HR monitor operation frequency and averaged over 5s windows. PulseOn HR performance was estimated by the following parameters:

[1] Patent pending.
[2] Patent pending.

[3] The experimental procedures described in this paper complied with the principles of Helsinki Declaration of 1975, as revised in 2000. All subjects gave informed consent to participate and they had a right to withdraw from the study at any time. Their information was anonymized prior the analysis.

- *Reliability:* % of time that the absolute error is smaller than 10bpm.
- *Accuracy:* complement of the relative error (*i.e.*, 100% - mean absolute percentage error).

The reliability provides a sense of the amount of time the system is working within an acceptable confidence interval. The 10bpm error threshold was chosen to represent a level which is adequate for consumer sports device for typical recreational use. and the accuracy provides a sense of the error committed by the system at any point in time.

We show in Table III the mean performance indicators for specific activities (resting, walking, running, and biking) as well as global values for the whole protocol. PulseOn had significantly better global performance than Mio LINK® during the protocol (reliability 94.5% vs 86.6% and accuracy 96.6% vs 94.3% for PulseOn and Mio LINK®, correspondingly). The difference was mainly caused by the walking activity, where PulseOn reaches an average reliability of 90.8% and an average accuracy of 95.8% whereas Mio LINK® obtains the values of 73.7% and 90.2% respectively.

TABLE III. MEAN PERFORMANCE INDICATORS OF PULSEON AND MIO LINK® DURING THE LABORATORY PROTOCOL

| Activity | PulseOn | | Mio LINK® | |
|---|---|---|---|---|
| | Reliability (%) | Accuracy (%) | Reliability (%) | Accuracy (%) |
| Rest | 97.9 | 97.1 | 97.4 | 97.3 |
| Walking | 90.8 | 95.8 | 73.7 | 90.2 |
| Running | 99.4 | 98.0 | 99.8 | 98.8 |
| Cycling | 96.0 | 96.8 | 97.0 | 97.7 |
| Protocol | 94.5 | 96.6 | 86.6 | 94.3 |

In Figure 3, we show the Bland-Altman plots comparing the error distributions of PulseOn and Mio LINK®. As expected from Table III, the error distributions for rest, running, and cycling are very similar for both devices. Walking is the activity that has greater dispersion on both devices. However, we can observe a larger dispersion for Mio LINK® around the interval [80,140] bpm. This has a clear impact on the global performance for the complete protocol.

## B. Outdoors Testing

Subjects from Section III.A were randomly assigned to perform physical exercises outdoors. We recorded a total of 24 events that included track-running, trail-running, urban-running, walking, track-cycling, and road-cycling. Then, we grouped the recordings by their dominant activity in one of the following classes: Walking, Running, or Cycling.

We used the chest-strap ECG Polar Electro RS800CX HR monitor to obtain a reference heart rate. The data obtained from PulseOn's HR monitor was averaged over 5s windows and resampled using linear interpolation in order to match the same sampling rate as the reference signal.

In Table IV, we show mean performance indicators of the PulseOn's HR monitor for each activity category. We can see that the values obtained, in terms of reliability and accuracy, are equivalent to those found in the controlled laboratory protocol of Section III.A. These values validate the PulseOn's HR monitor technology and show that the system is robust to real-life outdoor conditions (*e.g.*, changes in temperature, wind, and non-uniform pace).

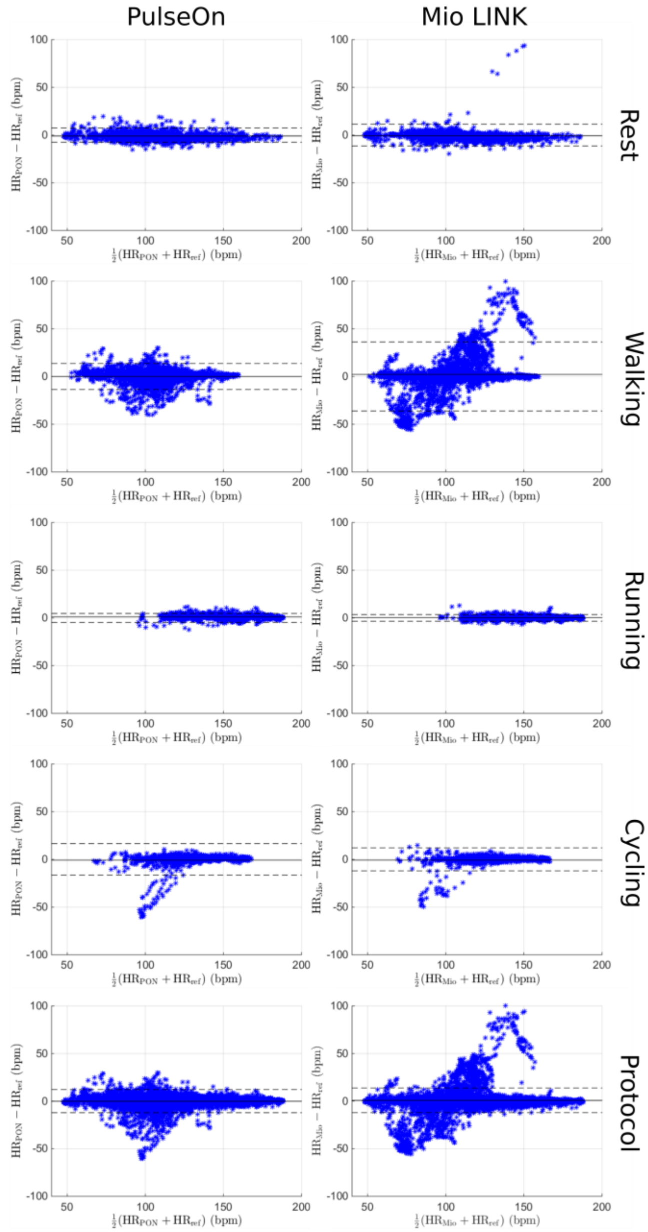


***Figure 3. Bland-Altman plots comparing the reference ECG-derived HR to the HR derived from the wrist-devices. The left column compares the PulseOn monitor to the reference, and the right column compares the Mio LINK® to the reference. The rows from, top to bottom, correspond to the following activities: rest, walking, running, biking, and full protocol. $HR_{PON}$, $HR_{Mio}$, and $HR_{ref}$ refer to the heart rate estimated with the PulseOn monitor, Mio LINK®, and the reference respectively.***

TABLE IV. MEAN PERFORMANCE INDICATORS OF PULSEON IN OUTDOOR ACTIVITIES

| Main activity | PulseOn | |
|---|---|---|
| | Reliability (%) | Accuracy (%) |
| Walking (N=3) | 94.1 | 96.6 |
| Running (N=17) | 99.1 | 97.9 |
| Cycling (N=4) | 95.2 | 97.3 |
| Mean (N=24) | 97.8 | 97.6 |

In Figure 4, we compare the performance of the PulseOn monitor against the ECG-based reference for several outdoor activities. The PulseOn's HR monitor is capable of following the reference in stationary situation (*e.g.*, Figure 4B, C, G), as well as in fast changing heart rates (*e.g.*, Figure 4E, H). These differences are activity-dependent and reflect intrinsic characteristics from the type of exercise. For instance, Figure 4H shows the heart rate while driving a road bike in the city. The steep variations of the heart-rate values are linked to periods of time where the subject was steady in traffic lights.

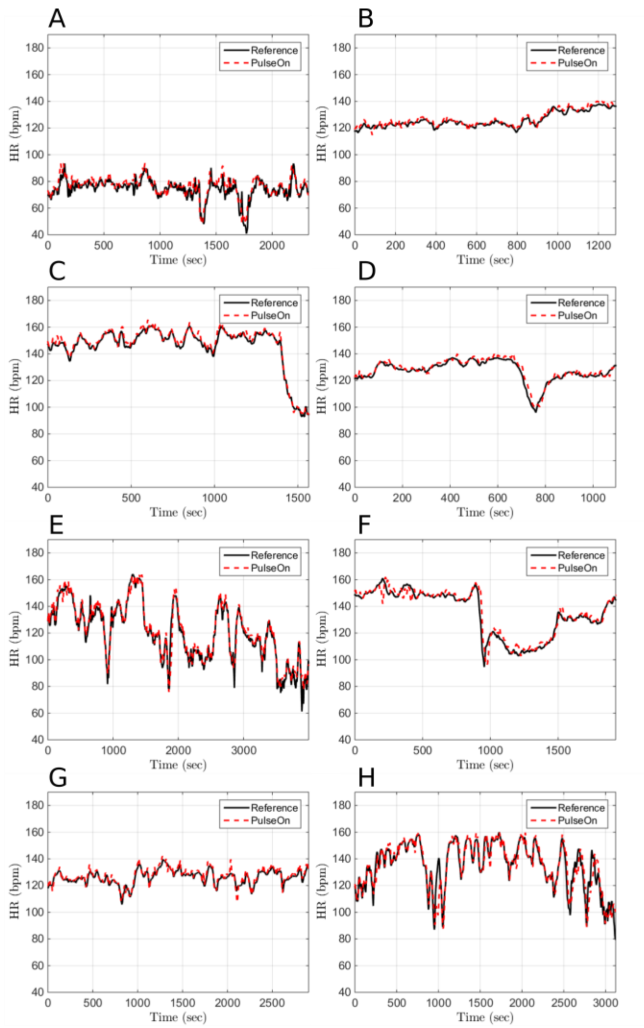


***Figure 4. Comparison of the performance of the PulseOn monitor against the ECG-based reference, for several outdoor activities. A) Walking with two stops. B) Outdoor running. C) Outdoor running for 22 minutes and walking for 3 minutes. D) Outdoor running. E) Trail running in Lapland. F) Trail running in Lapland to Kiilopää. G) Outdoor cycling. H) Road-biking in traffic.***

## IV. Conclusion

PulseOn HR monitor measures blood flow in different depths of skin tissue and adapts to different situations and individual differences. PulseOn mechanical and sensor optimization provide reliability and accuracy comparable to ECG based chest belt HR monitors [1, 3, 2, 4] during typical cardiovascular exercises.

The results showed that PulseOn's mean reliability is 94.5% with an accuracy of 96.6%, opposed to 86.6% and 94.3% of Mio LINK®.

We also provided evidence of the robustness of the system in outdoor activities such as trail-running, urban-running, walking, track-cycling, and road-cycling. Under these conditions, PulseOn's HR monitor obtained an accuracy of 97.8% and a reliability of 97.6%.

## V. References


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