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Evaluation of Accuracy and Usability of Optical Heart Rate Sensor in Daily Life and Sports

Metropolia University of Applied Sciences

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Health Informatics

Thesis

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Tämän opinnäytetyön aiheena oli PulseOn Oy:n uuden optisen rannesykemittarin prototyypin testaaminen ja arviointi sykemittauksen tarkkuuden sekä rannelaitteen käytettävyyden osalta. Tarkkuutta testattiin kahdella erilaisella testillä; liikuntasuorituksella sekä päivittäisen aktiivisuuden testillä. Käytettävyyttä tutkittiin kyselylomakkeen avulla.

Tavoitteena oli saada mahdollisimman paljon käyttökelpoista tietoa PulseOn Oy:lle. Testien tarkoituksena oli edesauttaa rannesykemittarin kehitystyötä, ja käytettävyyskyselyn tarkoituksena tarkastella rannekkeen käyttömukavuutta.

Menetelminä käytettiin kahta erilaista testiä, joista liikuntasuoritus toteutettiin Töölö Gymillä Helsingissä, ja päivittäisen aktiivisuuden testit koehenkilöiden kodeissa. Referenssilaitteina käytettiin perinteisiä elektrodeihin perustuvia laitteita. Kyselylomakkeeseen vastattiin sähköisesti.

Tulokset näyttivät, että optinen rannesykemittari toimii luotettavasti silloin, kun käsien liike pysyy säännöllisenä tai vähäisenä, kuten juostessa tai pyöräiltäessä. Kuitenkin käsien epäsäännöllisten liikkeiden lisääntymisen myötä rannesykemittarin tarkkuus kärsi. Käytettävyyskyselyn mukaan rannesykemittari on mieluisampi laite käyttää kuin perinteinen sykevyö.

Näytön perusteella voidaan päätellä, että rannesykemittari toimii hyvin normaalin aerobisen liikunnan sekä päivittäisen aktiivisuuden mittaamisessa. Lisäksi se on huomattavasti mukavampi käyttää, kuin sykevyö. Kuitenkin, jotta optinen sykemittari voi tarkkuudellaan kilpailla elektrodeihin perustuvien laitteiden kanssa myös paljon käsien käyttöä sisältävissä harjoituksissa, on kehitystyötä ja hienosäätöä vielä tehtävänä.

Avainsanat	Optinen sykemittari, syke, tarkkuus, käytettävyys

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The subject of this thesis was to test and evaluate the accuracy in heart rate monitoring and the usability of the optical heart rate sensor in PulseOn's new wrist worn device. The accuracy was tested via two different test protocols: Sports and daily life activities. The usability was examined via a questionnaire sent to 12 users.

The goal was to claim valuable data for PulseOn. The purpose of the tests was to contribute to the development of the optical heart rate sensor, and with the usability questionnaire to study the user-friendliness of the device.

The methods for the evaluation were two different tests. The sports tests were performed at Töölö Gym, Helsinki, and the daily life activities were recorded in the volunteers' home. Electrode based devices were used as reference. The data from the devices were processed with Matlab. The usability questionnaire was answered via electronic means.

The results show that the optical heart rate monitor functions reliably when hand movements were regular or minor, as while running or cycling. However, during irregular hand movements and with stress beginning to rise, the accuracy of the wrist monitor suffered. According to the usability questionnaire, the wrist worn monitor is more pleasant to use than a traditional electrode belt.

Based on the findings it can be assumed that the optical heart rate monitor works well while performing normal aerobic exercise and with daily life activities. Moreover, it is notably more user-friendly than an electrode belt. Still, to compete in activities involving a lot of hand movements with the electrode based devices, the optical sensor needs more development and fine adjustments.

Keywords	Optical heart rate monitor, heart rate, accuracy, usability

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Abbreviations

AC *Alternating current.* Current that variables over time.

B2B *Business-to-Business*. Situation where one company makes a commercial transaction with another.

CSV *Comma-separated values.* Stores tabular data, such as numbers and text, in plain text. Each line is a record, and each record consists one or more fields that are separated by commas.

DC *Direct current.* Current that maintains specific value, and does not change.

ECG *Electrocardiography.* Technology that measures the surface potential, which is result of the heart's beating. The measurement during training is usually done by electrode belt.

GPS *Global Positioning System.* Global navigation satellite system that provides location and time information in all weather conditions, when there is an unobstructed line of sight for four or more GPS satellites.

HbO2 *Functional hemoglobin*. Hemoglobin that is fully saturated with oxygen.

HR *Heart Rate*. Count of heart beats per minute.

HRM *Heart Rate Monitor*. Device that measures heart rate.

HRV *Heart Rate Variability*. Variability in the time interval between heart beats.

LED *Light-Emitting Diode.* A semiconductor component, that radiates light when electric current is passed through it. Individual LED's emitting light spectrum is generally very narrow, so the radiation is almost monochromatic. This means that there is only one and specific wavelength.

LED-PD *Combination of a Light-Emitting Diode and a photodetector*. Both components are used in optical sensor.

MAE *Mean Absolute Error.* The mean / absolute of the value of each individual error. The lower the value the better it is.

MAPE *Mean absolute percentage error*. The percentage value for MAE.

ME *Mean error*. The simplest form for error calculation, which gives the average error. The lower the value the better it is.

MPE *Mean percentage error*. The percentage value for ME.

OHR *Optical heart rate*. Technology based on optical measurement of blood flow under skin.

PPG *Photoplethysmography.* Technology that uses optical sensors and different wavelengths to measure light's propagation through the tissue.

RMSE *Root mean square error*. Deviation of sampled values differences to the actual values.

RMSSD *Root mean square of successive differences.* HRV indicator, that correlates the quality of the recovery. Square root from the successive RR intervals differences square sum and the quotient of the sample points.

RR *R-wave peaks*. Usually referred as RR interval, which indicates the time between these two R-wave peaks.

SpO2 *Peripheral oxygen saturation*. The parameter of pulse oximetry and arterial blood's oxygen. Presents the oxyhemoglobin as a percentage of the total functional hemoglobin.

TCX *Training Center XML.* Data exchange format introduced 2007 by Garmin. It provides standards for transferring and storage of heart rate, running cadence, bicycle cadence and calories. It includes GPS tracks as an activity instead of series of GPS points.

USB *Universal Serial Bus.* An industry standard that defines the cables, connectors and communication protocols used in a bus for connection, communication and power supply.

XML *Extensible Markup Language.* Markup language that encodes documents in a format that is both human-readable and machine-readable.

Preface

Thanks to this graduate study, I have learned a lot from heart rate monitoring, test events and product designing. This paper summarizes my interests for body functions, technology to measure it and product development. I cannot wait to see what applications and products will be produced in this industry. Hopefully, I myself will be playing a part in it.

PulseOn had knowledge about this topic more than I could have ever imagined. Company provided all the devices for heart rate monitoring. Töölö Gym gave us permission to use their space and equipment for the sports performance tests. Without the volunteers this Thesis would not exist. Thank you all for your effort.

I also wish to thank Sakari Lukkarinen for his help during the study, as well as Ilkka Korhonen with all employees at PulseOn and all the people at Töölö Gym. Furthermore, I would like to extend my gratitude to my family and friends, who supported and helped me during this study. Thank you all.

1 Introduction

Wearable technology has been increasing its popularity amongst consumers for years. People are curious and want to observe their body functions during their daily life and training. While the heart rate monitoring belt has been a standard for heart rate measurements during exercise, new technologies, applications and approaches are constantly born to challenge it.

The topic of this Thesis is evaluating the accuracy and usability of an optical heart rate sensor during daily life activities and sports. The optical sensor used was PulseOn's new white label product, OHR Tracker. OHR (optical heart rate) is a technology based on optical measurement of blood flow under skin. Accuracy tests were performed in a gym environment (sports) and in home environment (daily life). Both tests had specific protocols were performed by the volunteers. The evaluation of usability was determined via a questionnaire which was sent to the volunteers after they had performed both tests.

PulseOn's new optical heart rate tracker was compared to a traditional electrode based heart rate monitor to evaluate the functionality and user-friendliness. Because of the raising knowledge of fitness and tracking of it amongst the consumers, as well as interest of one's body functions, this kind of comparison is a highly topical theme. People want to know how many steps they took during the day, did they sit too much or move enough and what was their heart rate during these events. With exercising, the demand for credible and fast data is high. The device in use needs to give HR data with minimalist delay. Wearable technology is a constantly growing field and keeping up with the industry requires fluent user interface and user-friendly products.

This paper was made with PulseOn Oy. PulseOn Oy was founded in 2012. The company's headquarters are located in Espoo, Finland, with a subsidiary in Switzerland. The company is privately owned. With over 50 man years of OHR research and development expertise as well as various pending patents for algorithms and device design, the company is a highly respected author in their industry [1: "Company"]. PulseOn provided all the devices for heart rate monitoring.

PulseOn published their first optical heart rate sensor, PulseOn Heart rate wristband, in 2014 via Indiegogo, the largest global crowdfunding and fundraising site online [2]. This first sensor is meant to be used mainly while performing sport activities. The one significant factor of this device is analytics data made with Firstbeat that it gives the user training effect value of the performed activity. The value goes from 1 to 5, 1 being least effective and 5 being most effective [3].

The new prototype of the OHR Tracker, which was used in this Thesis, was under development during writing this paper. This new device is smaller, cheaper and has a better battery lifetime compared to the first OHR device. PulseOn's OHR Tracker enables sport measurements alongside with stress levels, recovery and sleep. PulseOn has developed their sensor technology as a part of Tekes's BioIT-program, which concentrates on biological knowledge [4].

PulseOn provides B2B solutions which enable manufacturers to build top quality optical heart rate devices with minimal research and development effort. PulseOn offers algorithms, optimized power management and software integration, with various levels of customization in mechanical, electrical and software design. Modules, algorithms and software are carefully tested before publish and deployment [1: "B2B Solutions"].

There are a couple of previously done Master's Theses made with PulseOn considering the evaluation of performance of an optical heart rate sensor [5] and the optical sensor's usage when estimating maximum oxygen uptake (VO_{2max}) and energy expenditure [6]. These studies show that optical monitoring is a reliable method for measuring body functions. For example, in his study, Aleksi Haavikko had 20 test subjects, and the results for the optical sensor's reliability (errors being smaller than 10 bpm of the reference reading) varied from 81,75% to 99,40%, with an average of 90,40% [5: 42]. Maria Uuskoski's studies in turn show that the optical sensor can be utilized for VO_{2max} measurements and energy expenditure in the same way the traditional heart rate monitoring belts, although in some cases the optical sensor's evaluation for VO2max and energy expenditure was underestimated compared to the results from respiratory gas measurements [6: 48 – 51].

In short, the main goal was to examine the accuracy and usability of PulseOn's white label optical heart rate tracker in sports performance and in daily life activities, and with this examination to collect useful data for PulseOn as much as possible.

2 Background

Heart is a muscle, which main purpose is to pump oxygenated and deoxygenated blood through the arteries and veins. Oxygenated blood travels from the heart, through the arteries to the tissues. Deoxygenated blood travels to the heart, through the veins from the tissues. Heart, just like the rest of the vital organs, functions by the autonomic nervous system. Autonomic nervous system contains sympathetic and parasympathetic functions. Sympathetic nervous system causes the rise of the heart rate, as the parasympathetic system causes the drop of the heart rate.

Light is examined through reflections, refractions, absorption, interference, polarization and speed via optical components [7: 147]. In OHR monitoring, lights reflection and absorption are significant factors. For this type of monitoring, optical components such as source of the light (LED) and photodetector is needed. The detector's type is a quantum detector, because these detectors operate from the ultraviolet to mid-infrared spectral range, in which the visible light also belongs [7: 461].

After the introduction of portable devices by Dr. Norman Holter, 1957, heart rate monitoring devices were used in clinical practices to diagnose and predict cardiovascular diseases. Since then, HR-monitoring has grown its popularity amongst physiologists and people who are interested their body's performance, when evaluating the level of training and effect of the performance [8: 105].

OHR is a technology developed to measure the heart rate from the blood flow. In this Thesis the data collection and tests were performed with PulseOn's prototype, OHR Tracker, which is under final tests. The used prototype had no display, but three LEDs which indicate different modes and one physical button as Figure 1 presents.

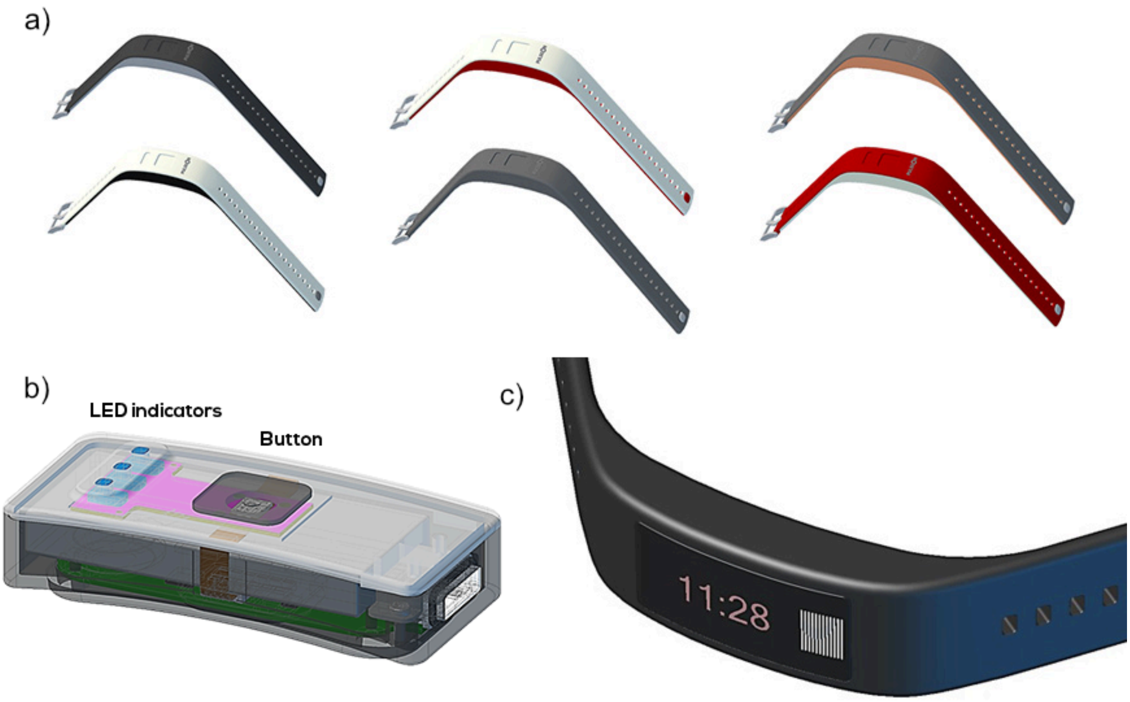

Figure 1. PulseOn's white label OHR Tracker. a) Variable strap designs. b) The body of the device, which is removable from the strap. c) OHR Tracker will be available with a display [1: "B2B Solutions - OHR Tracker"].

When talking about performance and exercising, heart rate tells the efficiency and harshness of the exercise. Heart rate is usually monitored during aerobic exercising. Depending on the target while performing some aerobic activity, it is highly recommended to perform these activities while maintaining a specific heart rate or within specific heart rate limits. The first thing to do is to figure out one's heart rate areas, including aerobic and anaerobic thresholds. It is also recommended to figure out one's resting heart rate and maximum heart rate. Generally, the heart rate gives a very accurate description of the physical condition of the person.

Resting heart rate is a bpm value when the body is doing nothing more than the autonomic body functions. This means that the person is awake, but does nothing more than breathing. Ordinary resting heart rate is from 60-80 bpm, but can be amongst athletes even lower than 30 [9]. Resting heart rate can be measured right after waking up in the morning and before getting out of the bed, or after complete resting (at least 10 minutes staying still). Resting heart rate gets lower as a result of regular exercise [10].

Training with observing the heart rate relies on heart rate zones, aerobic and anaerobic training ranges. These heart rate zones are specific percentage ranges of person's maximum heart rate. By monitoring and controlling heart rate, trainers can optimize their training effect, avoiding too high or too low training levels.

Aerobic training is the training range which causes the production of lactic acid. However, at aerobic training range, the body can still burn it, which prevents the body from getting tired. In other words, oxygen uptake and its consumption are at balance. Aerobic training is in a range of 60-80% of a person's maximum heart rate [10]. This is the training area which is used to improve endurance and weight loss, and is generally recommended for overall cardiovascular fitness.

Anaerobic training in turn is the training range which cannot burn the produced lactic acid anymore, so it starts to accumulate and the muscles start to tire. Anaerobic training is above 90% of a person's maximum heart rate [10]. Anaerobic training is used to improve maximum durability.

Maximum heart rate means the heart's extreme bpm value. This means that the heart rate does not increase even if the stress increases. The maximum heart rate can be sorted out precisely only with maximum fatigue tests. There are multiple ways to approximate maximum heart rate, such as simple calculation formula: (220 – age) [10]. For example, if there is a 25-year- old person, this person's calculated maximum heart rate with this formula would be 195 as Table 1 presents. This, however, is a mere approximation, and does not tell the precise value. The best way to figure out a person's maximum heart rate is the professional and unpleasant test.

Table 1. 25 years old person's aerobic and anaerobic training ranges calculation.

Heart rate value / range	Heart rate value calculation
Maximum heart rate	220 – age = MHR 220 – 25 = 195
Aerobic training	60-80% of maximum heart rate 195 bpm x 0,6 = 117 bpm 195 bpm x 0,8 = 156 bpm Training range: 117-156 bpm
Anaerobic training	90-100% of maximum heart rate 195 bpm x 0,9 = 176 bpm 195 bpm x 1 = 195 bpm Training range: 176-195 bpm

When observing the daily life with heart rate monitors, which usually are long-term measurements, electrode-based devices are not that acceptable, especially when considering the comfort of the user. This is one reason for people's raising interest in activity bracelets.

During daily life activities, the heart rate itself is not perhaps the most important measure, but daily activity in general (step count, energy expenditure, etc.) and the heart rate variability (HRV), which indicates the person's stress levels, nervous system and recovery activity. It tells how ready the person is for exercising or is the person drifting towards overtraining, and it should be measured every now and then, preferably even on a daily basis, every morning. HR indicates the heart's beats per minute, when HRV tells the variability between those heartbeats.

Heart rate variability is the time between the R waves (ECG), or the time between the pulse peaks (PPG, OHR). HRV reading demonstrates how much the heart rate variables in average heart rate. So even if a person is wearing a HR monitor and the value in display is 60, it does not mean that the time between the heart beats is 1 second, but can be something between 0,5 and 2 seconds, as shown in Figure 2. The higher the HRV is, the better the cardiovascular qualities. As the resting heart rate gets lower due the consistent training, the HRV gets higher. HRV is highly sensitive for errors and is affected for example from body's position and age [11; 12].

Figure 2. RR intervals, the time variability between two neighboring heartbeats. Values shown as milliseconds [12].

HRV measurements have raised their popularity amongst both medical and sport sciences. The analysis can be done in variant ways, for example with time-domains. One of these is RMSSD, root mean square of successive differences, which is used to calculate the average variation in the successive heartbeat intervals, as square root from the successive RR intervals differences square sum and the quotient of the sample points [13]. RMSSD is a HRV indicator that correlates the quality of the recovery. RMSSD describes the high frequency heart rate variability in milliseconds [14].

Although there are variable methods to measure heart rate noninvasively, in other words outside the body or from the surfaces of the body, this Thesis concentrates on the differences between electrocardiography (ECG), which is the most used technology when it comes to heart rate monitoring during sports and an application of photoplethysmography (PPG), optical heart rate monitoring (OHR).

2.1 Electrocardiography (ECG)

ECG is a bio-potential technology that measures the electrical activity of the heart. It is at the moment the most commonly used technology to measure heart rate values. The beating of the heart generates electrical depolarizations (increasing the potential) and repolarizations (decreasing the potential). This is called a cardiac cycle. This kind of a cycle causes electrical dipoles, which creates surface potentials [8: 106]. ECG monitors these surface potentials from the specific thorax locations, for example with the heart rate monitoring belt.

The value of the heart rate is presented as beats per minute (bpm). Bpm is a value which is derived from the consecutive heartbeat intervals, to be more specific from the time delay between two R-wave peaks, as RR intervals presented in Figure 3. The values are converted into bpm as follows: (1/RR interval x 60).

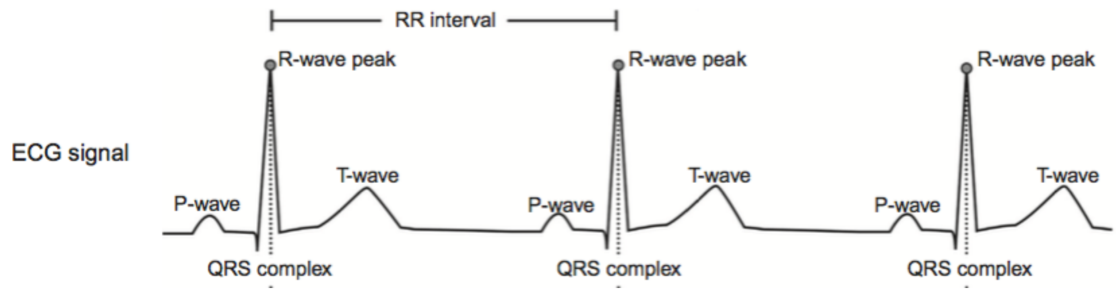

Figure 3. ECG signal includes 5 different waves. Bpm is derived from the RR intervals [8: 106].

ECG signal includes 5 different waves (P, Q, R, S and T) [15]:

- **P wave** corresponds to the right and left heart atrial depolarization;
- **QRS complex** includes Q, R and S waves, and is produced after the depolarization process in the right and left ventricles, produced by ventricular depolarization;
- **T wave** corresponds to ventricular repolarization.

ECG is the most used technology for heart rate measurement during sports. The first wireless ECG heart rate monitor was invented in 1977, for the Finnish National Cross Country ski team by a Finnish trainer Seppo Säynäjäkangas. Retail sales of wireless personal ECG monitors began in 1983 [16].

ECG monitors include the electrode belt and the receiving device, such as a wrist watch or mobile phone. The wrist watch or the phone acts as a display screen giving the user information from the electrode belt. The belt contains two electrodes and a transmitter, as shown in Figure 4. Usually the belt has plastic straps, which need to be wetted with water or another liquid, so that the electrodes will get the most accurate signal. The transmitter is connected to the other side of the belt on top of the electrodes. Some versions of the ECG monitors has these two parts (the belt and the transmitter) combined, so that they cannot be separated.

Figure 4. Electrode based HRM belt from Garmin.

ECG monitors can measure both HR and HRV for short-duration measurements. They usually are very accurate, and ECG is the reference standard when it comes to cardio health and wellness monitoring. The measure’s accuracy is in milliseconds, and because the ECG sensor does not require long settling times, heart rate readings can be obtained very shortly after starting the measurement [17].

The ECG monitor belt can be uncomfortable, especially amongst women when wearing sports bra, because the sport bras may press the monitoring belt. This feels uncomfortable, may change the location of the belt and hamper the measurement. It is quite unpleasant to do activities while being prone, for example while doing back extensions, because the belt presses the solar plexus. It usually needs to be wetted, and it needs to be also fairly tight. If the electrodes are dry, dirty or the belt is poorly adapted, their reliability weakens.

2.2 Photoplethysmography (PPG)

PPG is a technology that uses optical sensors to evaluate the tissue light propagation changes during cardiac cycle. It measures the amount of light that is scattered by blood flow. The most used application for PPG is oxygen saturation measurement, pulse oximetry. For this, two light with different wavelengths are used to estimate the arterial blood absorbance, which is linked to the oxygenation levels of the blood [8: 107].

In the year 1936 two individual group of researches in New Jersey and Stanford examined blood volume changes in a rabbit's ear with a noninvasive optical instrument. A year after this, the first measurement for blood volume changes from human fingers with PPG was made by the team of Alrick Hertzman in St. Louis. The term photoplethysmography was adopted for this new technique that measured changes of volume (plethysmography) with optical application (photo) [8: 108]. The most usual placement for a pulse oximeter is finger or earlobe [18].

After the appearance of light-emitting diode (LED) in 1962, PPG inspired new researches. Now PPG was able to use a simple LED and a photodetector, which enabled its usage in variable environments and applications, outside the laboratories. [8: 108].

To the clinical environment PPG arrived as a result of development of the pulse oximetry, by a team of engineers at Nihon Kohden labs in 1972. Pulse oximetry was noninvasive spectrometric technology that provided a first-ever real-time estimation of blood's gas content with an optical probe around the finger [8: 108]. Conventional pulse oximetry was developed in 1974 by Takuo Ayoagi and has been commercially available since 1981. It has since become a valuable measurement standard frequently used all over the world [19: 976].

The parameter of pulse oximetry and arterial blood oxygen saturation is called SpO_2 (Peripheral oxygen saturation), the functional saturation. It presents the oxyhemoglobin as a percentage of the total functional hemoglobin [19: 976]. This is what Nihon Kohden labs provided as an original dual-wavelength pulse oximeter, an estimation of arterial oxygen saturation.

The conventional pulse oximetry sensor, which is worn around the finger, uses LEDs and photodetector. The light travels from the source (LEDs), through the finger to the detector. Two LEDs transmit red and infrared light through the tissue until they reach the photodetector, as presented in Figure 5. The light undergoes through pulsatile and constant absorption. Arterial blood causes the pulsatile absorption, which is an alternative factor (changes frequently by heartbeat), whereas the tissue, venous blood and non-pulsatile arterial blood causes the constant absorption, which is a stable factor (changes slowly over time).

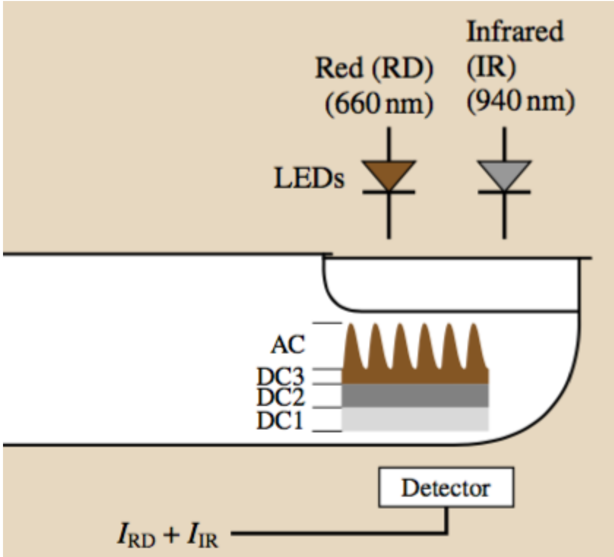

Figure 5. The pulse oximeter's operation. Two wavelengths are transmitted through the finger, red and infrared. The light goes through two kinds of absorption: 1) pulsatile absorption while going through arterial blood (AC) and 2) constant absorption while going through non-pulsatile arterial blood (DC3), venous blood (DC2) and tissue (DC1). The detector measures the intensities I_{RD} (red) and I_{IR} (infrared) of the transmitted light as a function of time [19: 977].

In other words, PPG analyzes the amount of absorption of the transmitted light. Absorbance does not happen only inside the body, but is increased because of the skin's reflection of the light with the multiple scattering effects. The skin structure and shape is variable due to the movement, and this causes changes in the light reflection and absorption. The components that affect the absorption are divided to AC and DC components, as presented in Figure 5, are referred from the levels of voltage, where AC stands for alternating current and DC stand for direct current [8: 109].

PPG monitors can measure both the heart rate (HR) and heart rate variability (HRV). HR is measured from blood pulse rate and HRV is correlated from the time interval from pulse peaks. Basically, both ECG's and PPG's HRV estimation is executed in a very similar way, only with the difference that ECG measures the potential changes from RR interval, and PPG measured the pumped blood pulse time intervals, presented in Figure 6. The PPG's challenge is in signal-to-noise ratio, which causes longer calculation times due to the averaging of pulse values.

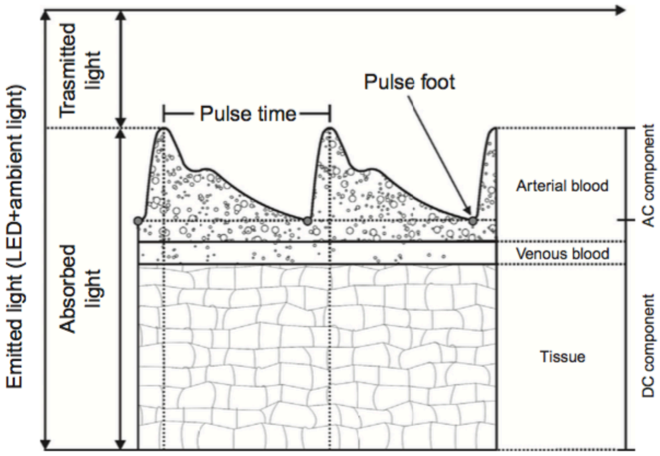

Figure 6. Light's absorption. Light travels through various tissues, in other words AC and DC components, which absorbs the light [8: 109].

When measuring the body with PPG from various locations, some challenges occur. Not all locations of the body are able to pass the light from the other side of the body part to the opposite side of it. These locations are for example the forehead and the ankle. In these kinds of locations, where the tissues are dense, the light is absorbed completely before reaching the photodetector. This is when the reflectance mode of configuration shown in Figure 6 is used. In reflectance, the light source and the photodetector are planted next to each other. This provides the smaller and simpler appearance of the device compared to the traditional PPG monitor.

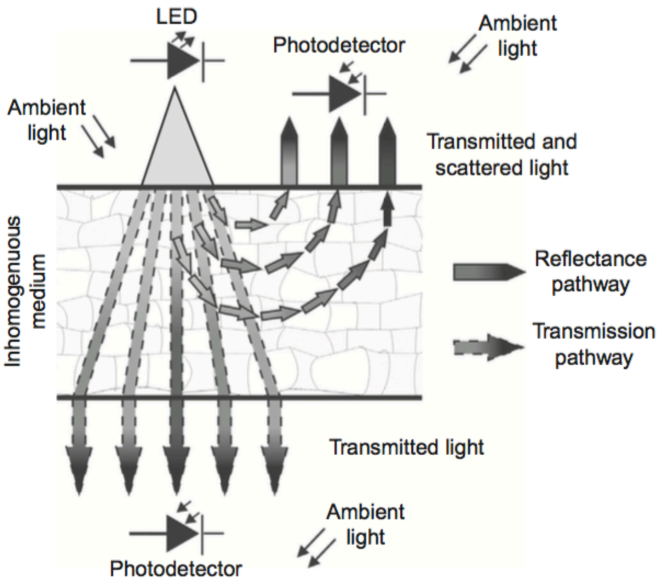

Figure 7. Reflectance light versus light travelling straight through [8: 110].

Human skin is a complex non-homogenous structure. Even a smallest displacement or change in sensor-skin contact may cause changes in the propagation of light. Changes in the temperature of the skin as well as the unique skin types of people affect the measurements done by OHR sensors [20: 430].

The wavelength is determined by the result of studies about the absorbance of light in human tissue. Water (H_2O) is the main molecule in human tissue and allows wavelengths shorter than 950 nm to be transmitted more efficiently. Another constituent of tissue is melanin which skin concentration depends on skin pigmentation. The higher the melanin concentration, the darker the skin.

Hemoglobin (Hb) is the principal constituent of blood. Its light absorbance varies by its chemical binding. Hemoglobin molecules that are not binding reversibly with molecular oxygen (O_2), are called dysfunctional hemoglobin. Hemoglobin that is fully saturated with oxygen is called functional hemoglobin (HbO_2), and if it is not fully saturated it is called reduced hemoglobin. Healthy person’s hemoglobin is mainly functional type [8: 111]. The absorbance and extinction coefficients for these constituents are presented in Figure 8.

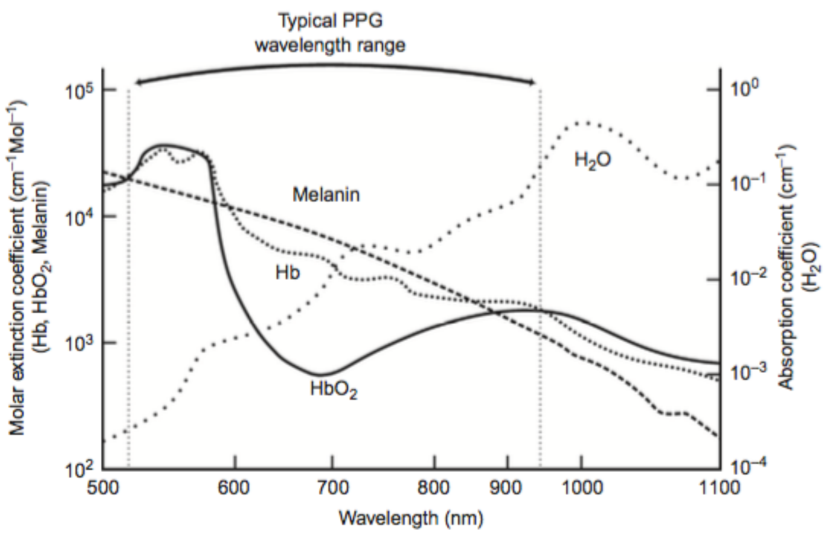

Figure 8. Coefficients of absorption and molar extinction of main biological tissue constituents, wavelengths from 500 nm to 1100 nm [8: 111]. As can be seen, usage of green light is recommendable due the hemoglobin’s and melanin’s higher molar extinction coefficient, while water’s absorption coefficient is yet fairly low.

Measurements done with light skin pigmentation and in normal ambient temperature, approximately 20°C, show that reflected green light has an advantage within AC/DC component ratio over infrared. The longer the wavelength is, the deeper the light penetrates. The scattering effect with infrared in these deeper tissues produces a more complex reflected signal. However, when the ambient temperature gets colder and the microcirculation of blood dramatically decreases, deeper penetration of infrared has the advantage. Also, when skin pigmentation is darker, and absorbs strongly wavelengths shorter than 650 nm, infrared is more desired [8: 112]. This is why they are both used in OHR sensors. It is also stated that with the darker skin, yellow light (590 nm) would be the most effective [21].

3 Optical Heart Rate (OHR) Sensor

Optical heart rate measuring is based on PPG. It uses the exact same basis in terms of technology, but with modifications. As stated in Chapter 2.2 "Photoplethysmography (PPG)", there are locations on the body where light is completely absorbed before reaching the opposite side of the body. This is when the reflectance mode is used to measurement, and this is the method used in OHR monitoring. When the transmitted light hits the tissues and blood vessels, it reflects and scatters. Basically, the light itself stays the same, but the changes of it caused by blood flow tells the sensor the needed information. The faster the heart pumps the blood, the less the green light is reflected to the photodetector [22].

LED-PD distance, which means the traveled distance of light from the light source (LED) to the light sensor (PD, photodetector), and the algorithms that analyze it provide the accurate HR estimation by reducing the movement artefacts, even in intense training. Shortening the LEP-PD distance will reduce the light propagation path, which provides faster process. PulseOn's combination of LED-PD distance, intelligent algorithms and design of the device contribute the accurate HR estimation [20: 431]. The sampling frequency in PulseOn's devices is 25 Hz, which means that 25 samples are taken in every second. The structure of PulseOn's OHR Module is presented in Figure 9.

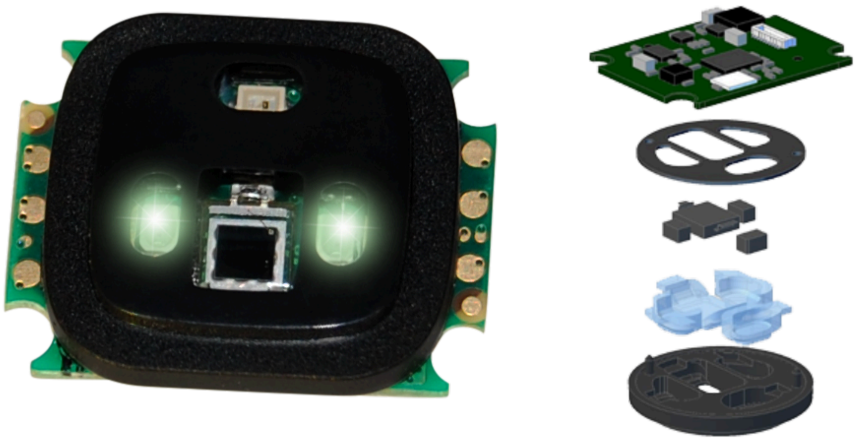

Figure 9. PulseOn's OHR module. Sensor detects blood flow, which varies according to the heart's pumping frequency. The optical signal is translated to accurate heart rate reading via sophisticated algorithms [1: "OHR Module"].

The PulseOn's sensor uses green and infrared lights for the measurement. Green light penetrates through epidermis (two outer layers of the skin) and reaches the end of the papillary dermis (uppermost layer of the dermis). Infrared light in turn penetrates through both of these layers to the end of reticular dermis (lower layer of the dermis). These layers are presented in Figure 10. Papillary and reticular together form the dermis, where the surface blood circulates and where hair follicles and sweat glands are located [23].

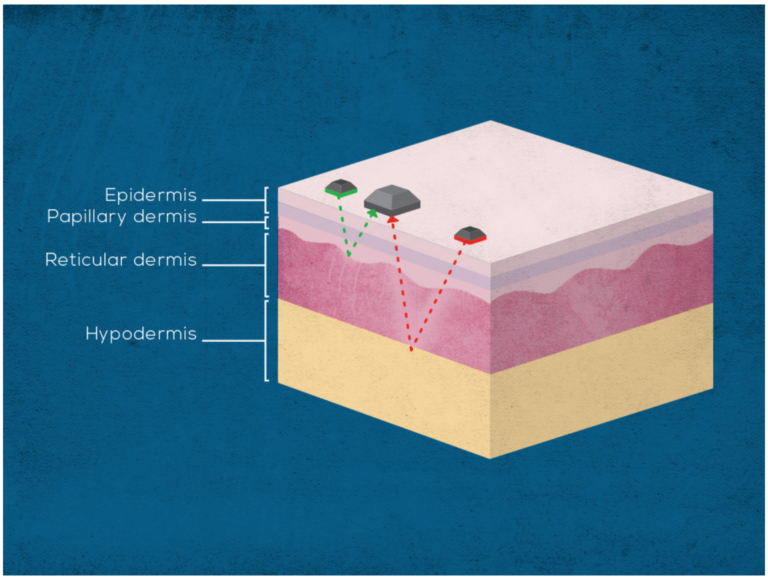

Figure 10. Component placements. When using multi-wavelength, different depths can be reached [1: "Technology - Technology"]. Green light is used to measure the blood flow in epidermis and papillary dermis. Infrared is used to measure the blood flow below these layers, in reticular dermis.

The design and the algorithms have a major role in the measurement. They give variable options to the measurement, as to select the optimal signal in different depths of skin to get the heart rate value in various conditions. The design of the wrist worn device itself is a significant factor, because of the fact that consumers want to wear devices that simply look good, and also because it too affects the measurement. With algorithms, the heart rate evaluation, sampling frequency and power usage can be managed. Algorithms also use the data from acceleration sensor, for example to bypass the values that noise has ruined.

Testing the algorithms is as important as testing the optical components. It is important to test the algorithms with a large scale of different skin colors and tones [21]. The recorded heart rate is basically a combination of the photodetector's light collection and acceleration sensor's data, which are processed with algorithms.

The placement of the device is one of the most important factors. Although OHR tracking can be done from variable body locations, such as ear, forearm and wrist, the last mentioned is an optimal placement due to the easy access and constant line of sight to the display or activity indicators. However, wrist is actually one of the most challenging placements for heart rate measurement.

Hands are one of the most used parts of the body daily, and because of the amount of movement, it makes the measurement quite challenging. This is why the device is advised to be used at least one finger width from the peak of the wrist bone. The higher the device is worn on the arm, the more accurate the readings are, because the device stays more stable. Also, the device's strap needs to be attached tightly, but not too tightly. If the strap is too tight, the device's body presses the blood vessels at the wrist, and the forming pressure exceeds the blood's pressure. This means the blood is not able to flow fluently and as a result, the HR evaluation cannot be done precise due the reduce of lights reflection changes. The width of the device is also one significant factor. When the strap is wider, the pressure is spread over larger area, which eases the pressure.

In a colder environment where the skin temperature is lower and the blood flows deeper, body warms up during the movement and because of that, blood perfusion near the skin increases and green light can be used instead of infrared, and the results are more reliable. This is quite similar behavior compared to electrode belt in its own way. OHR measurement needs blood flow to calculate the HR, and electrode belt needs to be wetted for the accurate results from the surface potential. Both of these happen when the body starts moving, through the warming the blood flow shifts near the surface, and the body starts to sweat, which provides the liquid for the belt's electrodes. So the body itself helps the measurement due warming.

The biggest challenges with OHR monitors are [24];

- **Optical noise** is the major factor in optical heart rate monitoring. When transmitting light in to the skin, only a small fraction of it actually reaches the photodetector, and the total light that is collected may contain very small amount of usable data from the blood flow. The rest of the signals are scattered by human tissues.

- **Skin tone** absorbs light in different amounts with different people. With higher melanin rate, which means darker skin, green light does not penetrate through the skin, and the sensor needs to use infrared instead. This problem occurs also with tattooed users.

- **Sensor's location,** as stated before, is a significant factor when it comes to optical heart rate monitors. Optical noise created in the wrist is much higher than in forearm (higher density of blood vessels near the surface of the skin) or in the ear (mostly cartilage and blood vessels), which is one of the best placements for optical heart rate monitor. However, it would be hard to control the device from this location.

- **Low perfusion** of blood is highly variable across population, and occurs amongst people with obesity, diabetes, heart conditions or arterial diseases. In addition, blood perfusion varies widely as a function of external temperature and body's temperature balance. Low blood perfusion occurs especially in the body's extremities, where most of the optical heart rate monitors are worn. Lower perfusion correlates with lower blood flow signals, which affects the signal-to-noise ratio by reducing it.

The OHR sensor differs from the ECG sensor in many ways. The OHR power consumption is significantly higher than in ECG based methods. This, however, can be lowered due to algorithms. However, the biggest difference is that the OHR sensor does not need an external device, like ECG with the belt and monitor, so an OHR sensor user does not have to wear but only one wearable device. When seeking for more simple and user-friendly solutions, especially in daily life measurements, this makes quite a difference.

3.1 Wearing Wrist Monitor

One of the most important parts of the measurements is that the device is tight enough on the wrist to prevent its movement. In other words, it needs to be tight enough to stay at the same position for the whole measurement. However, wearing the device too tight hampers the measurement and is uncomfortable, so the “sweet spot” needs to be found. Comfortable and flexible strap helps to adjust the position. The instructed placement for the tracker is one finger’s width from the wrist bone’s peak, as Figure 11 presents.

Figure 11. OHR Tracker is worn in the wrist, one finger's width from the wrist bone's peak.

When the optical sensor stays at the same position and in contact with the skin, the measurement gives continuously data from one and the same spot. This is when the data is most reliable. If the sensor moves from that spot, which happens if the device’s wristband is too loose, the data is no longer as reliable, because the measurement comes from another place and the calculation starts from the new spot. A good rule to remember with a rubber band, which the prototype has, is to first tighten the strap so that it is in full contact with the skin, and then tighten it up one step more.

The design and weight of the device are significant factors. A lighter device reduces the forces caused by movement and the skin-sensor pressure changes. This helps the device to maintain the position while measuring. The design provides the comfortable usage, helps to reduce artefacts and improves the measurement reliability [20: 431].

3.2 Measuring with OHR Sensor

The PulseOn's OHR Tracker's prototype starts to measure when the command is sent via mobile phone's Bluetooth. As the measurement starts, the device's LED starts to transmit the light, which scatters and reflects from the body tissues. The photodetector collects all the signals which reaches it, and algorithms start to process the collected PPG signal.

PulseOn's OHR Tracker's intelligent algorithms are able to reject disturbances caused by movements or light scattering. They are based on complex physiological models and statistical optimization [1: "Technology - Algorithms"]. Algorithms calculate the HR value from the detected light and saves the data to the device's memory. In the protocol, which was used during this Thesis and the tests included, the prototype's memory capacity was 90 minutes. This is why the test protocols did not exceed that time.

4 Test Procedures

Test procedures need to be determined keeping the end-user's needs on mind. Some of the manufacturers in this field test the sensors alone, not the complete device, which includes the complete wrist band. This affects the results notably. Also, the tests need to include variable activities, with variable intensities [25].

For every device and application, there needs to be reliable test results and data before the publication. Therefore, every test in every testing field is performed the same way. For this, there needs to be specific protocols. The test event should be as similar as possible with every test, so that the data is comparable. This is why all the sports tests were executed in the same environment with the same devices, as in gym equipment and the wearable devices. The gym environment and equipment were provided by Töölö Gym. All wearable devices, as the tested prototype and the reference devices were provided by PulseOn.

Recruitment of the volunteers was the responsibility of the author. The majority of the test subjects were family and friends. Before testing volunteers, the author executed the tests himself, so that it would be easier to describe the upcoming test for the volunteer. Before every test, volunteers read the informed consent and signed it (see Appendix 1). In the consent, there was a general explanation about the test and the rights of the volunteers. Every tested volunteer was also insured during the test by PulseOn.

The testing protocol for the sports performance was determined by PulseOn. The protocol for the daily life activity test was determined by the author and was then approved by PulseOn. When making this kind of protocols, it must be kept in mind that there are different types of end users. Some like to train easier and at a pleasant level, and some like to train as hard as they can. With optical wrist monitors, it must be remembered that they are sensitive to movement. This is why the protocols need to have various movements and levels, so that the devices accuracy gets tested properly. It is not like all the end users are only going to walk with the device, it also needs to be able to keep up with proper and heavy training.

The main purpose of these tests was to examine the processed heart rate signal of the prototype and compare it with the reference device’s data. During the tests, it was important to take notes of every unusual or noticeable events, for example if the prototype did move from its original placement, or if the volunteer had been ill or was tired before the test. The movement of the device is the number one factor for inaccurate data. This is why the strap of the device needs to be tight enough to prevent the movement.

The following information was collected from the volunteers; Birth date (age), sex, height, weight, wrist circumference, dominant hand, smoking habits, activity class and skin tone. The activity class gave a general course about the volunteer’s training habits, and the skin color tells about the volunteer’s pigmentary, which may affect the measurement results. Darker skin color might distract or prevent the light from penetrating through the skin.

Figure 12 presents Firstbeat’s classification for activity classes. The table for activity class was presented to volunteers, who then told what class indicated their physical activity best.

Your typical physical activity level	Approximate weekly training amount	Activity class
I'm never physically active and I avoid all kind of physical exertion.	-	0
I'm involved in occasional light physical activity approximately once a week.	Less than 15 min	1
	Less than 30 min	2
	~ 30 min	3
I'm involved in physical activity 2-3 x per week.	~ 45 min	4
	~ 2 h	5
	2 – 4 h	6
I'm involved in physical activity 3-7 x per week.	~ 3 – 5 h	7
I'm involved in endurance-type training at least 4 x per week.	~ 5 – 7 h	7.5
I'm involved in goal-oriented endurance-type training almost daily.	~ 7 – 9 h	8
	~ 9 – 11 h	8.5
I'm involved in goal-oriented endurance-type training daily.	~ 11 – 13 h	9
	~ 13 – 15 h	9.5
	More than 15 h	10

Figure 12. Activity class, according to Firstbeat classification. Figure is from PulseOn's form for volunteer's information. The volunteers informed the activity class according to their activity levels.

The skin tone of the volunteers was also documented. Skin's color was compared to the Fitzpatrick Scale, which is presented in Figure 13. Unfortunately, no volunteers with darker skin pigmentation participated in the tests, so the effects of higher melanin concentration could not be evaluated here.

Fitzpatrick Scale for Skin-Type classification

Skin type	Skin color	Hair color (darkest)	Eye color (most common)	Description
I	White or very pale	Blonde	Blue, grey, green	Always burns, never tans
II	Pale white with beige tint	Chestnut or dark blond	blue	Always burns, sometimes tans
III	Beige to light brown (olive)	Dark brown	Dark brown	Sometimes burns, always tans
IV	Light to moderate brown	Black	Brown	Rarely burns, always tans
V	Medium to dark brown	Black	Brownish black	Rarely burns, tans more than average
VI	Dark brown to black	Black	Black	Never burns

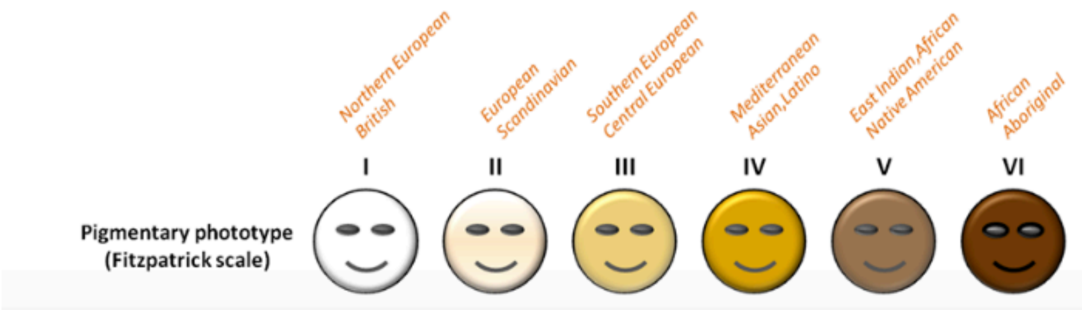

Figure 13. Skin color, according to Fitzpatrick scale. Figure is from PulseOn's form for volunteer's information. The color of the volunteer's skin was compared to this scale and was then documented.

While performing the test protocols, all the unusual and noticeable events were written down, with the time or timing, so that while processing the data the observer could reason why the prototype's heart rate signal had errors, if there were any. For this annotation simply pen and paper were used.

The usability was evaluated with the questionnaire form which was sent to all the volunteers that performed both the sports and daily life tests (see Appendix 4). The questionnaire was done by the method of Likert scale, where there are no questions, but a series of statements with 5 stages of agreement. Option 1 stands for strong agreement and option 5 for strong disagreement [26].

By using this type of scale in a questionnaire, the volunteer does not have to think the shape or structure of the question, but to decide if she or he agrees with the statement. It also reduces the amount of text and supports the user's cognition better than a series of questions. This makes the questionnaire and the results of it more reliable.

4.1 Testing Methods

The tests were performed by specific protocols. These tests gave answers to the question about the accuracy of the optical sensor. The usability was examined with a questionnaire, which was sent to the volunteers after both tests.

4.1.1 Sports

The sports performance test included periods of rest and transition between the tasks. It contained warm up with ergo cycle, walking on a treadmill with two different speeds, both done with three different gradients and running on a treadmill with two different speeds. The overall time spent on a treadmill was 24 minutes. After the treadmill, the subject moved to ergo cycle, and pedaled with two values of resistance and with two targets of rounds per minute. After cycling, the next task was two minutes of rowing. The last two exercises of the normal test were pushups and Jumping Jacks. If the volunteer wanted to, she or he could perform the extended test, which included sit ups, back extensions and squats on top of the normal test.

The prototype of PulseOn's OHR tracker was worn in the non-dominant hand, one finger width from the wrist bone's peak. It had to be fastened tightly enough to prevent the excessive movement, still being comfortable. The skin had to be clean under the device's optical sensor. The used reference device was Garmin Forerunner 620. The reference device's electrode belt goes around the thorax, just below the pectorals. Like the OHR tracker, the electrode belt also had to be tight, so it would not move from its original placement, and it also had to be watered properly, so that the contact surface was optimal. The belt wets during the test because of sweating, but the surface needs to be wetted before taking the test.

The tests were performed in a gym environment, where all the needed equipment were close to each other. All the tests were made in the same gym, so that the tests structure and transitions between the activities remained similar. If anything unusual happened during the test, for example if the device moved or the strap got loose, it was noted. Figure 14 illustrates the sports test event and some of its activities.

Figure 14. Sports test. Test included variable aerobic and muscular strength activities. All of the sports tests were performed in Töölö Gym, Helsinki.

The test group for sports test was formed from N = 16 healthy volunteers, from which 12 were men and 4 women. Their characteristics are presented in Table 2. The volunteers were mainly the same with the daily life test. 2 test events had failure in the reference device (1 with women and 1 with men), which means they are not included in the results due to the lack of comparable data.

Table 2. Sports test's volunteers parameters.

Characteristics	Variability	Range
Age (years)	23 ± 2	21 – 25
Height (cm)	177,25 ± 12,75	164,5 – 190
Weight (kg)	78,8 ± 21,2	57,6 – 100
Wrist circumference (cm)	17,5 ± 2,5	15 – 20
Activity class (Firstbeat)	6,5 ± 1,5	5 – 8

The table above presents the age, height, weight, wrist circumference, activity class of the volunteers and their variabilities. The skin tone was not added to this table because of the lack of the darker pigmentations.

4.1.2 Daily Life

The daily activity test is a test which purpose was to imitate daily life activities. The test contained sitting, working with a computer / display screen, walking outside, basic home-work and resting.

Like the sports test, the daily life test also examined the OHR tracker's accuracy and usability. The prototype was in the non-dominant hand with one finger's width from the wrist bone's peak. As in the sports test, the strap had to be tight and the skin under the device had to be clean. Firstbeat's Bodyguard 2 was used as the reference, and was connected with its two electrodes, one at the right chest upper section below the collarbone, and one at the left side of body, on top of the costal arch.

Daily life tests were performed in home environments and outside (walks). The tests were mainly performed at the volunteers' own homes. Like in the sports test, all unusual events were noted.

The test group for daily life test was formed from N = 17 healthy volunteers, from which 9 were men and 8 were women. Their characteristics are presented in Table 3. The volunteers were mainly the same as in the sports test.

Table 3. Daily life test's volunteer's parameters.

Characteristics	**Variability**	**Range**
Age (years)	25 ± 5	20 – 30
Height (cm)	172 ± 14	158 – 186
Weight (kg)	76,5 ± 25,5	51 – 102
Wrist circumference (cm)	17,25 ± 2,5	15 – 20
Activity class (Firstbeat)	6,5 ± 1,5	5 – 8

Just like Table X in Chapter Y, the table above presents the age, height, weight, wrist circumference, activity class of the volunteers and their variabilities. Again, the skin tone was not added to this table, because of the lack of the darker pigmentations.

4.2 Reference Devices

Devices used for reference data were Garmin Forerunner 620, for sports measurements and Firstbeat Bodyguard 2 for daily life measurements. After the failed test events with Garmin's device, Bodyguard 2 were worn during the sports test, so that if Garmin had failed, the reference data could be changed to Firstbeat's data.

Garmin Forerunner is an HRM device with a wrist monitor, electrode belt and the transmitter connected to the belt. The belt is worn around the thorax, where the electrodes measure the surface potential. The transmitter sends the collected data to the wrist monitor, which displays the variables such as duration, pace, distance and heart rate. The wrist monitor has four physical buttons and a touch screen [27]. Figure 15 shows the Garmin's devices.

Figure 15. Garmin's Forerunner 620 wrist monitor and HRM-Run belt.

The data is uploaded to Garmin’s web based service via USB cable, when it is connected to a computer and Garmin’s software, Garmin Express, reads the data from the device and synchronizes it with the service. The data can be exported from the service as a tcx file.

Firstbeat Bodyguard 2 is generally used for long term measurements to determinate the user’s recovery, stress and sleep quality. The user wears the device for 3 days almost constantly, with one restriction; Bodyguard 2 is not waterproof, so it cannot be used in shower or while swimming. During these events, Bodyguard 2 is taken off, and the electrodes are replaced with new ones before continuing the measurement [28].

Bodyguard 2 starts the measurement automatically when the electrodes are connected to the skin and stops the measurement when the electrodes are disconnected. The correct placement is presented in Figure 16. The electrodes are disposable, and it is recommended to replace them at least once a day, for example after shower or if they for some reason drop off [29]. The data is read from the device via USB port, to the Firstbeat’s web service. From there, the data can be exported in a csv file.

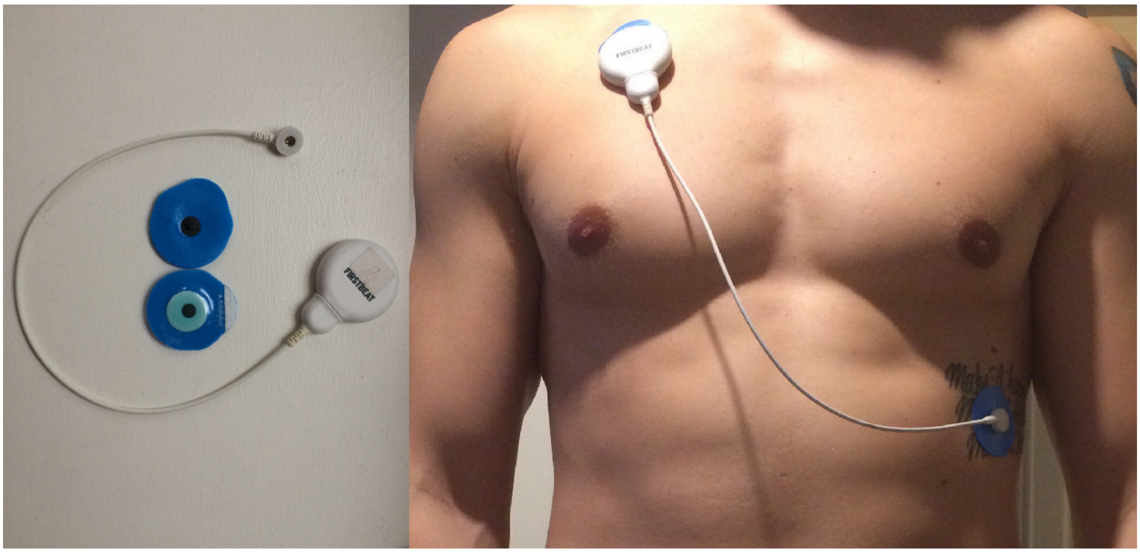

Figure 16. Firstbeat Bogyguard 2 and its usage. The blue parts are electrodes with adhesive surface, so that they stay connected during the measurement [29].

Firstbeat cooperates with PulseOn alongside with many other companies, such as Garmin, Sony and Suunto by offering the analytics service and applications. Firstbeat offers qualities such as lactate threshold, performance condition, VO2max, stress levels and sleep recovery.

4.3 Processing Data

The data from the devices comes in different forms. The data recording and data export of the prototype is managed via a smartphone's Bluetooth. Different digital commands either start the recording, end the recording, export the data out of the device while connected to a computer via USB, or delete the data and clear the device's memory. The software updates are also made via Bluetooth. The raw data will be read with a computer terminal, and after that saved as a text file.

The form of the reference data depends on the used device. With the sports test, the data from Garmin came in as a tcx file. The data from the Firstbeat on the other hand came in as a csv file, which was then converted to a text file.

All the data was processed with Matlab. In Matlab, there needs to be specific script for the data processing. This script allows Matlab to read the tracked data, which is a text file, and open the reference data automatically, but only if the name of the reference file matches the one in Matlab's script.

The script is used for both sports and daily life measurements results. The only difference is the selection of the reference, which are both already written in the script, but the selected reference is uncommented, and the one that will not be used is commented with %-character. First, all the previous commands are cleared. Then, a path for the additional scripts is added. These additional scripts will open both OHR tracker's and reference device's data. Then the sampling rate is determined, which in this case is 25 (25 samples per second). Next the data from the used devices are read. The user selects the wanted OHR trackers text file. These commands will create multiple factors, for example the heart rate and time matrixes. The last steps include the figure for plots, and saving all the data in mat file. The plotting matches the RR intervals from an electrode based device and pulse point intervals from an optical sensor. Script 1 shows the selection of the reference data, by commenting the part of the script with %-character.

```
%% if there is FirstBeat IBI reference:
  FileNameRef = [RootName, '_IBI.txt'];
  [t_ref, hr_ref] = getRef_ibi(PathName, FileNameRef);
  [delayRef] = process_ref_signals(hr_ref, t_ref, hr, t_hr);
  badRefInt = [];

%% if there is Garmin/Polar reference:
% FileNameRef = [RootName, '_ref.tcx'];
% [t_ref, hr_ref] = getRef_garmin(PathName, FileNameRef);
% [delayRef] = process_ref_signals(hr_ref, t_ref, hr, t_hr);
% badRefInt = [];
```

Script 1. Part of the used script, where the Matlab either opens the Firstbeat's or the the Garmin's data. The used reference's commands are uncommented, when the commands for the one which will not be used are commented.

Matlab processes the data and gives the figure of heart rate values as a line, from both the OHR tracker and the reference device, as shown in Figure 15. The Y coordinate presents the HR values as bpm and the X coordinate presents the time in seconds. There will be two different colored lines in that figure, red standing for OHR tracker and black for reference. In Figure 17 it can be seen if there is any variability between these lines. If so, there is something wrong either in the placement of the device or in the algorithm. If not, and all the devices show a similar line, there is no problem.

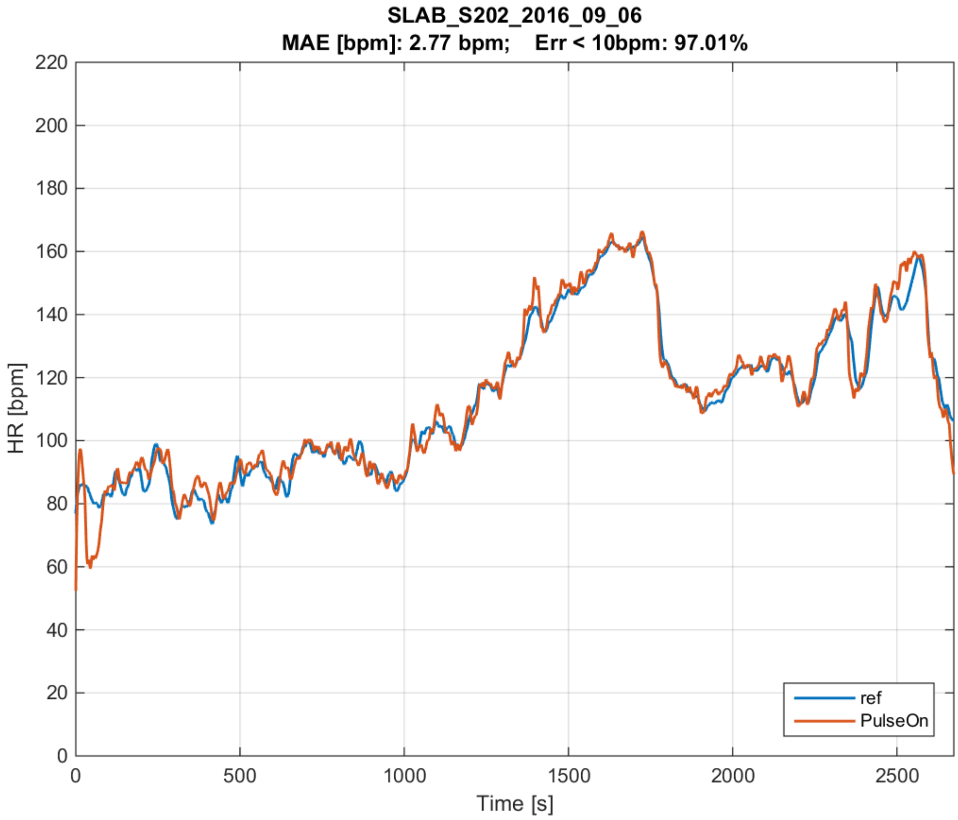

Figure 17. Result figure. Despite the drop in the OHR signal (red line) at the beginning (during warm up cycling), the result seems good. Matlab has calculated error rate between the OHR signal and the reference, which is in this specific case 97,01%. MAE (mean absolute error) value is 2.77.

When examining the result figure (Figure 17), it is important to know what has happened at what time. Specific protocols and annotation are needed, so that the person viewing the figure can combine the error in the line to the events that took place. The sports protocol used had tasks done during specific ranges of seconds, as Table 4 shows.

Table 4. Sports protocol

Task	Time period (min)	Time period (s)
Rest sitting (no motion)	0 – 1	0 – 60
Warm up with ergo cycle	1 – 4	60 – 240
Rest standing / transition	4 – 5	240 – 300
Walking 3 km/h, 0% inclination	5 – 8	300 – 480
Walking 3 km/h, 5% inclination	8 – 11	480 – 660
Walking 3 km/h, 10% inclination	11 – 14	660 – 840
Walking 5 km/h, 0% inclination	14 – 17	840 – 1020
Walking 5 km/h, 5% inclination	17 – 20	1020 – 1200
Walking 5 km/h, 10% inclination	20 – 23	1200 – 1380
Running 9 km/h, 0% inclination	23 – 26	1380 – 1560
Running 11 km/h, 0 % inclination	26 – 29	1560 – 1740
Rest sitting / transition	29 – 30	1740 – 1800
Ergo cycle 50 W, 60 rpm cadence	30 – 33	1800 – 1980
Ergo cycle 90 W, 90 rpm cadence	33 – 36	1980 – 2160
Rest sitting / transition	36 – 37	2160 – 2220
Rowing	37 – 39	2220 – 2340
Rest standing	39 – 40	2340 – 2400
Pushups	40 – 41	2400 – 2460
Rest standing	41 – 42	2460 – 2520
Jumping Jacks	42 – 43	2520 – 2580
Rest sitting	43 – 45	2580 – 2700
Extended protocol includes also	**Time period (min)**	**Time period (s)**
Sit ups	45 – 46	2700 – 2760
Rest sitting	46 – 47	2760 – 2820
Back extensions	47 – 48	2820 – 2980
Rest sitting	48 – 49	2980 – 3040
Squats	49 – 50	3040 – 3100
Rest sitting	50 – 51	3100 – 3160

The table above separates the activities performed and their time periods in sports test. Daily life protocol was performed with the tasks presented in Table 5. Like the table for sports protocol, daily life protocol has a similar separation.

Table 5. Daily life protocol

Task	Time period (min)	Time period (s)
Sitting / watching TV	0 – 10	0 – 600
Working with computer	10 – 25	600 – 1500
Walking outside	25 – 55	1500 – 3300
Housework	55 – 70	3300 – 4200
Rest laying	70 – 80	4200 – 4800

These kind of measurements and their evaluation require different kinds of error calculations, which correlate the accuracy of the tested device. All the functions compare the tested device, which in this case is the PulseOn's OHR tracker prototype, with the electrode based reference devices. These functions are presented below.

Score < 5% indicates the OHR trackers measured heart rate values which differ less than 5% of the reference reading. For example, if the measured heart rate is 179 bpm, and the actual heart rate is 173 bpm, the error is 6 bpm, and the percentage error is 6*100/173 = 3,468 % (less than 5 %).

Score < 10 bpm indicates the OHR trackers measured heart rate values, which are less than 10 bpm of the reference reading, presented in percentage. For example, if the measured heart rate is 184, and the actual heart rate is 176, the error is 8 bpm (less than 10 bpm).

ME stands for mean error, the difference between the prediction and observation as bpm. The closer the ME value is to 0, the better the estimation. It is calculated as follows:

$$\mathrm{ME} = \frac{\Sigma(a-x)}{n}, \tag{1}$$

where n is the number of samples, a is the actual value and x is the predicted value [5: 16].

MPE stands for mean percentage error, which is ME's value in percentage. It is calculated as follows:

$$\mathrm{MPE} = \frac{\Sigma(a-x)\cdot 100\%}{n}, \tag{2}$$

where a is the actual value and x is the predicted value [30].

MAE stands for mean absolute error, average of the absolute errors, which indicates how close the predicted outcome is to the actual outcome as bpm. The closer the MAE value is to 0, the more accurate the prediction. It is calculated as follows:

$$\text{MAE} = \frac{\Sigma|a-x|}{n}, \qquad (3)$$

where a is the actual value and x is the predicted value [5: 16].

MAPE stands for mean absolute percentage error, which is MAE's value in percentage. It is calculated as follows:

$$\text{MAPE} = \frac{\Sigma(\frac{|\mathrm{a}-\mathrm{x}|}{\mathrm{a}} \cdot 100\%)}{n}, \qquad (4)$$

where a is the actual value and x is the predicted value [5: 17].

RMSE (or RMSD) stands for root mean square error, which indicates the difference between the predicted values and the observed values. It is calculated as follows:

$$\text{RMSE} = \sqrt{\frac{\Sigma(a-X)^2}{n}}, \qquad (5)$$

where a is the actual value and X is the value given by estimator model [5: 17-18].

With the test made within the present study, there were no specific target error limits. The main goal was to get the mean absolute error (MAE) as low as possible. Some decent values are ~2 bpm for running and 3 bpm for walking.

5 Results

In this chapter, the results of the tests are introduced. It first discusses the accuracy of the results with the help of numerous graphs and tables, and then their usability in sports and daily life with one comprehensive table.

5.1 Accuracy

Overall the results are clean and comparable. PulseOn's optical sensor measures pulsatile blood flow and gives a HR value as a result of data processing. The HR graph goes together with the reference devices in both sports performance and daily life activity tests, when the movement of the wrist stays minor. In other words, the optical sensor gives the same results as the references when the user is either resting, sitting, walking, running, cycling, doing basic homework or working with the computer. However, when the movement of the hands increases, the optical sensor starts to give deviant HR values, as can be seen in Figure 18, with a drop in the OHR sensor line.

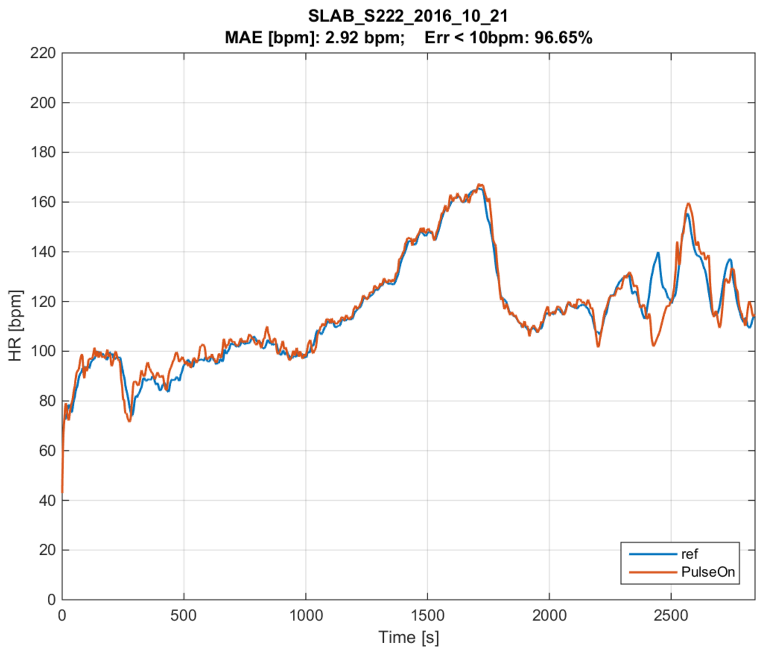

Figure 18. Sports protocol. OHR sensor (red line) does keep up with the reference (black line), when the device is properly worn. Still, when hand movement increases, it may cause false signals, as can be seen at around 2500 seconds, when the subject has just performed pushups.

Figure 18 shows the signal from the optical sensor compared to the electrode based device's signal. These signals are quite similar despite the hand movements. Figure 19, however, shows what can happen to the OHR tracker signal when the hand movements increase.

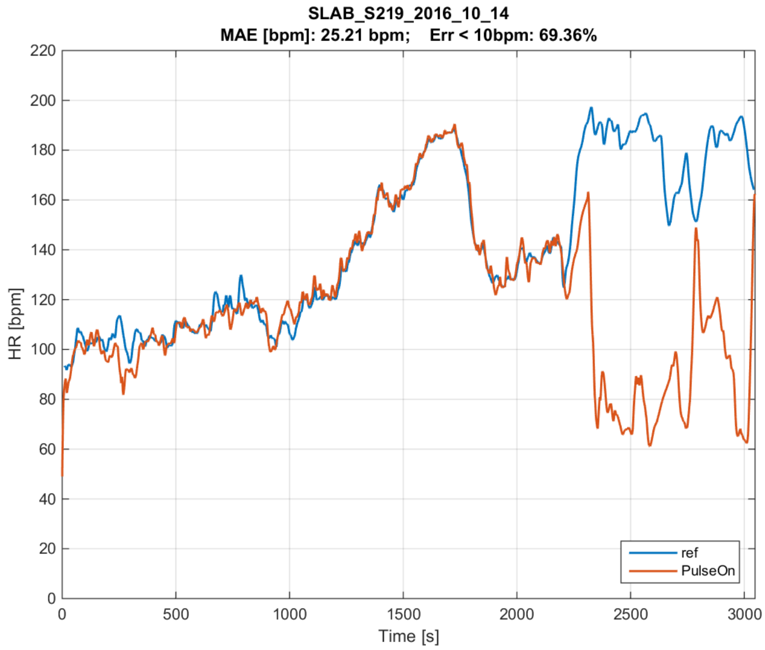

Figure 19. When the movement of the hands increases, it can affect the signal measurement dramatically.

Most of the sports tests results show that during the tasks which does not include major hand movements (walking, running and cycling), the OHR sensor gives closely the same result as the reference device. However, when it comes to the tasks which does include more hand movements (rowing, pushups, jumping jacks, etc.), the OHR sensor gives mixed results (see Appendix 2). Daily life test had much less movements in hands than in sports test, which can be seen in Figure 20, where the errors are quite minor.

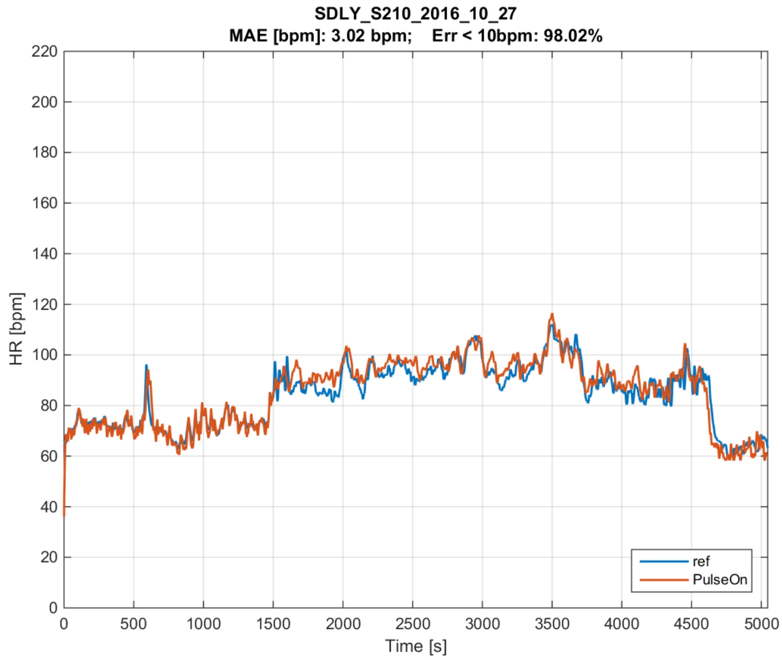

Figure 20. Daily life test. The heart rate values from the OHR tracker and the reference device go well together.

For the most part the results appear great, although there are some errors included. These errors may have occurred due the movement of the device, for example when the subject has put on clothes for outside walking (see Appendix 3).

Table 6 presents the error rates from the sports tests. Challenges during the tests were mainly the placements and movements of the devices. The OHR tracker was worn at the same spot through the whole test, one finger's (index finger) width from the peak of the wrist bone, so that the measurement point stayed the same.

Table 6. The error rates from the sports tests.

ID	score < 5%	score < 10bpm	ME	MPE	MAE	MAPE	RMSE	N Samples
S201	79.7	87.97	-8.26	-5.08	10.71	7.16	28.18	532
S202	83.74	96.26	0.97	0.86	2.86	2.8	4.29	535
S203	77.65	90.09	-1.52	-1.27	5.21	4.18	11.68	434
S204	61.47	75	-6.09	-4.55	10.35	7.88	20.6	532
S207	74.06	87.78	0.26	0.49	4.29	3.64	7.09	532
S208	71.43	83.83	-6.38	-3.63	10.31	7.01	23.6	532
S209	75.71	86.82	-0.59	-0.48	4.74	4.01	8.24	531
S210	84.33	95.52	2.17	2.21	2.85	2.84	4.56	536
S212	65.07	84.35	-1.38	-0.66	6.96	5.78	13.83	607
S213	57	74.63	-6.44	-4.89	9.18	6.98	16.79	607
S214	78.45	88.16	-4.91	-2.79	7.85	5.15	20.84	608
S217	65.07	75.95	1.73	3.50	9.06	9.81	16.38	607
S218	79.93	91.76	0.64	0.41	3.48	2.89	5.57	558
S219	60.79	69.85	-19.89	-11.13	21.62	12.52	41.11	607
S220	64.7	86.21	0.2	0.28	5.47	4.46	8.91	609
S222	83.95	96.47	0.58	0.61	2.85	2.52	5.08	567
average	72.33	85.392	-3.148	-1.669	7.487	5.688	15.002	558.375

The table above presents the volunteer IDs and the errors with the number of samples taken during the measurement (N Samples). It also shows the average of each error. The main goal with these tests was to get the mean average error (MAE) as low as possible. Table 7 shows the average values of the errors as separated activities from sports tests. Other activities are pushups, Jumping Jacks, sit ups, back extensions and squats.

Table 7. Different activities and their average error rates.

Activity	score < 5%	score < 10bpm	ME	MPE	MAE	MAPE	RMSE	N Samples
Rest	76,699	93,205	0,671	0,465	3,436	2,806	4,018	6,438
Walk	80,237	94,439	0,242	0,329	3,306	3,19	4,796	211,25
Run	90,156	98,068	1,186	0,807	2,167	1,43	2,885	67,948
Bike	83,797	91,661	0,575	1,01	4,285	4,166	7,041	92,188
Other	52,705	70,87	-9,74	-5,506	15,406	10,681	24,07	132,813

The table above presents the separated activities from the sports tests, with errors and the number of samples taken during the activity. Table 8 in turn shows the error rates from the daily life tests. Decent MAE value for daily life is 5 bpm. Challenges were the same as in the sports test, the placement and the stability of the devices was critical. Both the prototype and the reference device worked great during daily activity test, and no major issues appeared during the tests.

Table 8. Error rates from daily life tests.

ID	score < 5%	score < 10bpm	ME	MPE	MAE	MAPE	RMSE	N Samples
S201	61.91	87.3	-0.11	0.33	5.26	5.38	7.74	961
S202	73.35	89.55	1.72	2.32	4.12	5.51	5.96	957
S203	42.37	67.5	3.7	4.25	9.63	10.86	14.8	963
S206	64.69	80.76	5.53	6.71	7.57	8.68	15.9	946
S207	73.3	87.76	1	1.38	4.43	5.26	6.95	899
S208	53.39	79.23	0.95	2.28	7.1	8.81	11.21	886
S209	62.31	85.8	1.6	2.1	5.24	6.69	7.48	979
S210	78.22	97.23	1.25	1.34	3.24	3.84	4.27	1010
S211	56.21	81.33	0.31	1.31	5.9	7.39	8.51	1055
S214	55.93	77.96	-2.95	-2.64	7.42	8.07	11.33	962
S215	68.47	85.52	1.98	2.54	4.79	5.85	7.06	1015
S216	73.56	87.84	-1.17	-1.12	4.54	5.09	7.41	798
S218	87.12	96.44	0.51	0.64	2.58	3.15	3.88	955
S220	46.93	67.01	11.52	15.81	14.51	18.96	25.53	961
S221	56.59	75.3	1.75	3.28	6.88	8.63	10.22	903
S223	70.12	87.41	-1	-0.89	4.44	4.75	6.5	810
S224	64.81	84.17	-1.78	-1.36	5.23	5.81	7.94	935
average	63.957	83.4	1.509	2.31	6.068	7.248	9.588	940.882

The table above shows every volunteer’s ID and the errors from the daily life test events. It also presents the samples taken during the tests, and the average of each error. Table 9 shows the activities separately from the daily tests. Other activities are housework and working on a computer.

Table 9. Separated activities and their average errors.

Activity	score < 5%	score < 10bpm	ME	MPE	MAE	MAPE	RMSE	N Samples
Rest	74,993	88,907	3,624	4,947	6,556	9,06	10,092	185,288
Walk	66,895	84,572	0,579	1,012	5,618	5,708	7,806	248,588
Other	58,474	80,81	1,188	1,982	6,113	7,339	8,825	506,706

Table 9 shows the separated activities from the daily life test. Like the tables before, this table also presents the errors and the taken samples.

Wearing the devices as instructed is very important. When the measuring points change during the measurement event, it instantly effected the results. Electrode belt needs to be also watered in addition to tight attachment, otherwise the received HR value will be incorrect. If the user has wide shoulders and narrow waist, it can cause the belt to start to drop lower on the body and hence make the measurement inaccurate.

5.2 Usability

According to the volunteers, the usability of the OHR Tracker or wrist monitor is top quality. Most of the volunteers who answered the usability questionnaire said that simple wrist monitor felt more comfortable than a traditional electrode belt. It also seemed more user-friendly and volunteers would rather wear wrist monitor than a traditional heart rate monitoring belt while daily life measurements and sports. However, a majority of the volunteers said that the wrist monitor does not sound as reliable as a traditional heart rate monitoring belt.

The usability questionnaire was sent to all volunteers who had attended both sports and daily life test. Total N = 12 volunteers answered the questionnaire, from which 7 were men and 5 were women. Table 10 presents the average answers and distribution.

Table 10. Average answers from the usability questionnaire, divided to men and women. 1 = strong agreement, 5 = strong disagreement. In addition, how many agreed (answered either 1 or 2) and how many disagreed (answered either 4 or 5).

Statement	Men	Women	Agrees (M)	Agrees (W)	Disa-grees (M)	Disa-grees (W)	Total agrees	Total disa-grees
The wrist monitor felt more comfortable than the heart rate monitoring belt	2,1	2,4	5/7	3/5	1/7	1/5	8/12	2/12
A wrist monitor sounds more reliable than a traditional heart rate monitoring belt	2,7	4,2	3/7	0/5	3/7	5/5	3/12	8/12
A wrist monitor seems more user-friendly than a traditional heart rate monitoring belt	1,7	1,6	6/7	4/5	1/7	1/5	10/12	2/12
I would prefer a wrist monitor for heart rate measurement during exercise rather than a monitoring belt. Assume that both are equally accurate.	1,7	2,4	6/7	3/5	1/7	2/5	9/12	3/12
I would prefer a wrist monitor for heart rate measurement during daily life rather than a monitoring belt. Assume that both are equally accurate.	1,6	1	6/7	5/5	1/7	0/5	11/12	1/12

In the previous table, the statements which were presented to the volunteers are shown. Columns “Men” and “Women” present the average of the answers from both men and women. Columns “Agree (M)” and “Agree (W)” indicate the agreement from men (7) and women (5) who answered the questionnaire. In turn, columns “Disagree (M)” and “Disagree (W)” indicate the disagreement from men (7) and women (5). Finally, columns “Total agreement” and “Total disagreement” show the total agrees and disagrees from the respondents (12). As can be seen in Table 10, a majority of the volunteers prefer the wrist worn device during both exercise and daily life measurements. However, the wrist monitor does not sound more reliable than a traditional heart rate monitoring belt.

6 Discussion and Conclusions

The wrist worn tracker is not at the same level with ECG based devices just yet when it comes to HR measurements during activities with a lot of hand movements. As the hand movements get more rapid, the measuring gets a lot harder. However, the OHR Tracker does a fluent and accurate job when the hand movements are fairly low, such as while walking, running and cycling. The wrist worn OHR Tracker is a great device for stable movement exercises and daily life measurements.

There are many factors that can disturb the measurement, e.g. the design and weight of the device, how it is worn, does it move from accidental impacts, skin pigmentation, etc. It is impossible to prevent some of these factors, but the development concentrates on all of the factors mentioned above and seeks the best solutions. This technology has had a tremendous progress from its earlier applications, and if it keeps up the pace, it will soon exceed expectations.

The most important thing the user needs to remember is to use and wear the device as instructed, just like with any other device or instrument. With an OHR Tracker, the most important thing to remember is to wear the device at the right place with the correct tension. The strap needs to be tight enough to maintain its position and full contact with skin, but not too tight, so that the blood flows fluently and the strap feels comfortable.

There is still work to do in creating the optimal sensor which gives accurate results even when the hand movements increase, but that is not too far away from today. When this accuracy is reached, with a fair amount of memory and low power consumption, the demand of the devices is going to jump. PulseOn’s OHR Tracker is being tested yet after the study at hand, and with fine adjustments, it is going to be a very tough challenger to the other devices in the same category of personal devices.

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Informed consent

This consent is signed by every volunteer before testing. It has general information about the test and the rights of the volunteer. The base of the consent was same in every test, but the time periods and tasks did change. The sports test had shorter execution time and more tasks than in the consent of the daily activity test.

Optical Sensor Study

INFORMATION LETTER AND INFORMED CONSENT

Contact information

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Valtteri Seraste, Trainee, PulseOn Oy, valtteri.seraste@pulseon.fi

Invitation to participate and target of the study

You are invited to participate in a research study ”Optical sensor’s accuracy and usability”. It is part of PulseOn Oy company research program focused on developing new heart rate monitor. The target of this study is to collect heart rate data for company’s research and development needs.

Research methods

You are asked to wear a set of heart rate devices for approximately 45-60 minutes. The devices monitor your heart rate and activity during various tasks. Test is conducted in the gym and supervised and guided by a PulseOn researcher. The test includes, in particular:

1. **Subject questionnaire**
   a. You are asked to fill a brief questionnaire for study’s set-up and statistical information purposes. Your date of birth, gender, height, weight, general health level, wrist circumference, dominant hand, skin color, smoking and exercise habits will be collected.
   b. You are asked to truly answer if you have any illness or disease which would prevent from physical exercise of approximately 45 minutes.

2. **Protocol tasks**
   a. Protocol contains rest and exercising tasks such as walking, running on treadmill and biking on ergo cycle.

b. Detailed protocol tasks are specified in Appendix with subject questionnaire.

The information collected from each test subject will be studied and the measures from each device under validation will be compared against the validated reference devices. The results will be used for PulseOn research and development needs and scientific reporting purposes.

Potential risks for the test subject

Devices used in the study are targeted to consumer use. They will not cause any health risks to the subjects. Testing protocol includes exercising and will increase your heart rate and involve activities like running. Target level of exercise intensity does not cause any risk for a healthy subject.

Use and archiving of results

All information gathered from the participants and the personal results are handled with full confidentiality. Data is stored anonymously and does not include any person identifying information. All data are stored in electronic form in PulseOn Oy premises. The data will be used exclusively by the PulseOn Oy and its partners for research and development needs.

Participant's rights

Participation to this study is fully voluntary. A participant has the full right to refuse or interrupt the test at any time without a reason without consequences. Organizing and handling of the study results are handled confidentiality at all times. Participant has full rights to ask for additional information from the research scientists at any time of the study.

CONSENT TO PARTICIPATE AS VOLUNTEER

I have been asked to participate in the abovementioned study. I have been given both written and oral information on the study and a possibility to ask questions to the researcher.

I understand that participation in this study is voluntary and I have the right to deny or cancel my participation any time without giving a reason. I also understand that the collected information will be handled confidentially and the information will not be handled together with identifying information (e.g., name, address, etc.).

I agree to participate and give my permission to use the collected data for research and development needs by PulseOn and its partners:

____________________________________ Helsinki _______________ 2016
Volunteer signature

____
Name in capital letters

Researcher:

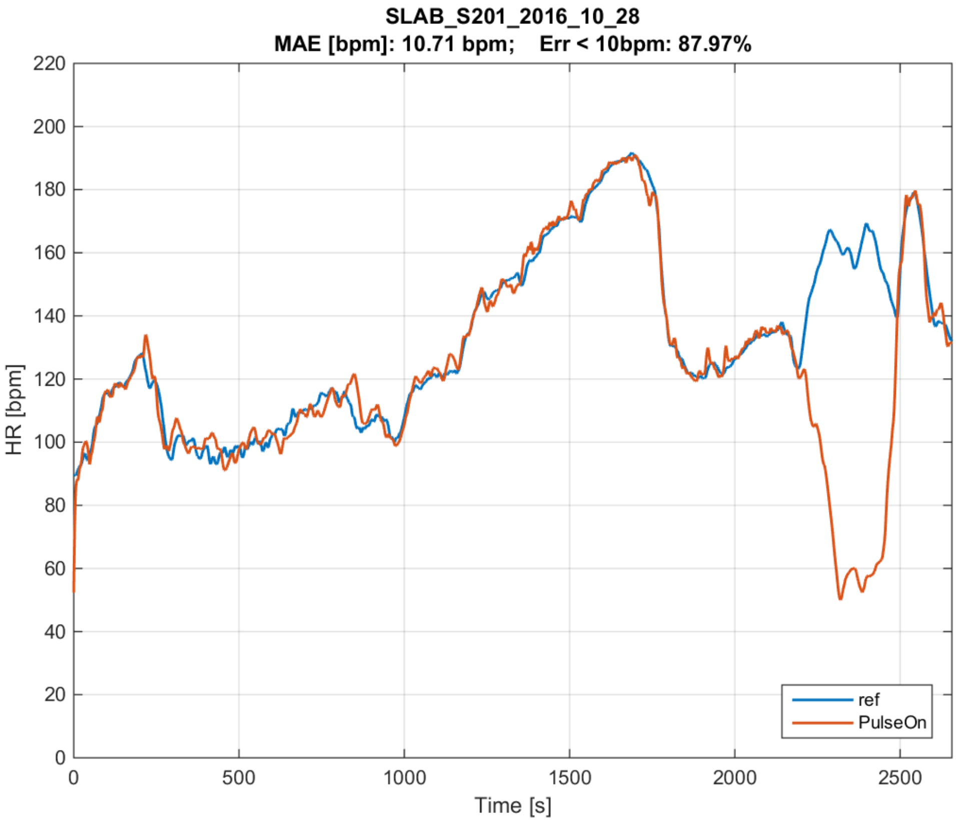
____________________________________ Helsinki _______________ 2016
Researcher signature

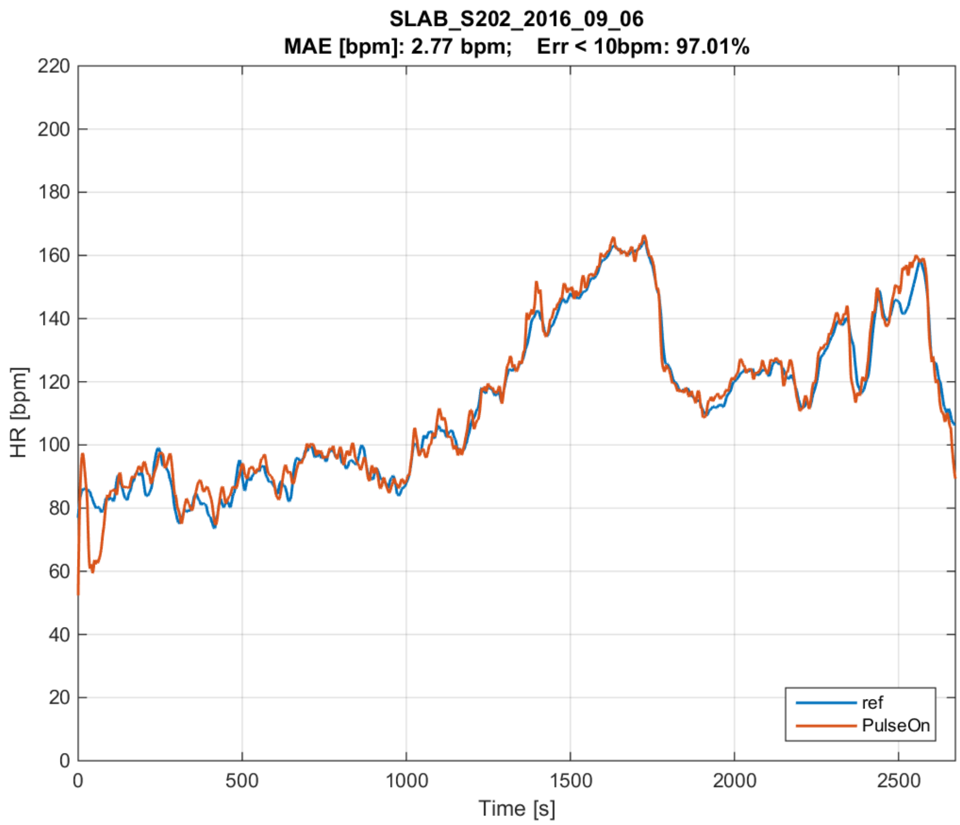
____
Name in capital letters

____
Subject ID number

Measurement figures from the sports tests

The following are the figures from the sports tests, which are processed in Matlab. Results were used to evaluate the accuracy of the PulseOn's prototype.

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MAE [bpm]: 2.77 bpm; Err < 10bpm: 97.01%
HR [bpm]
Time [s]
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PulseOn
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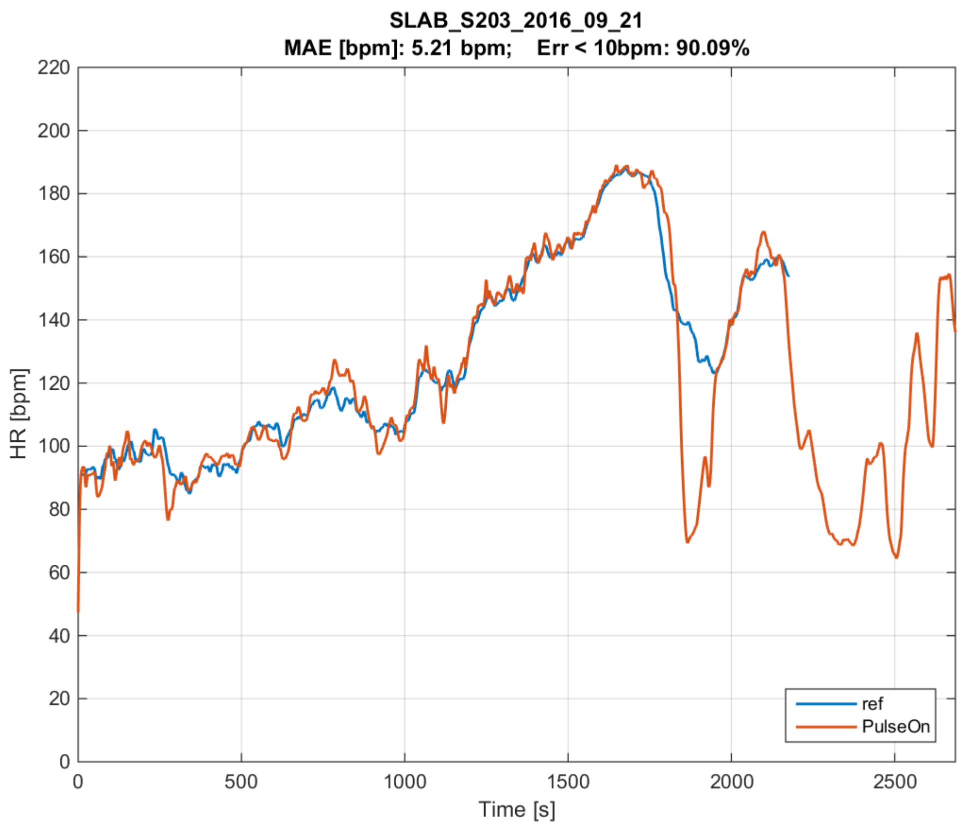
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500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HR [bpm]
Time [s]
ref
PulseOn
0
20
40
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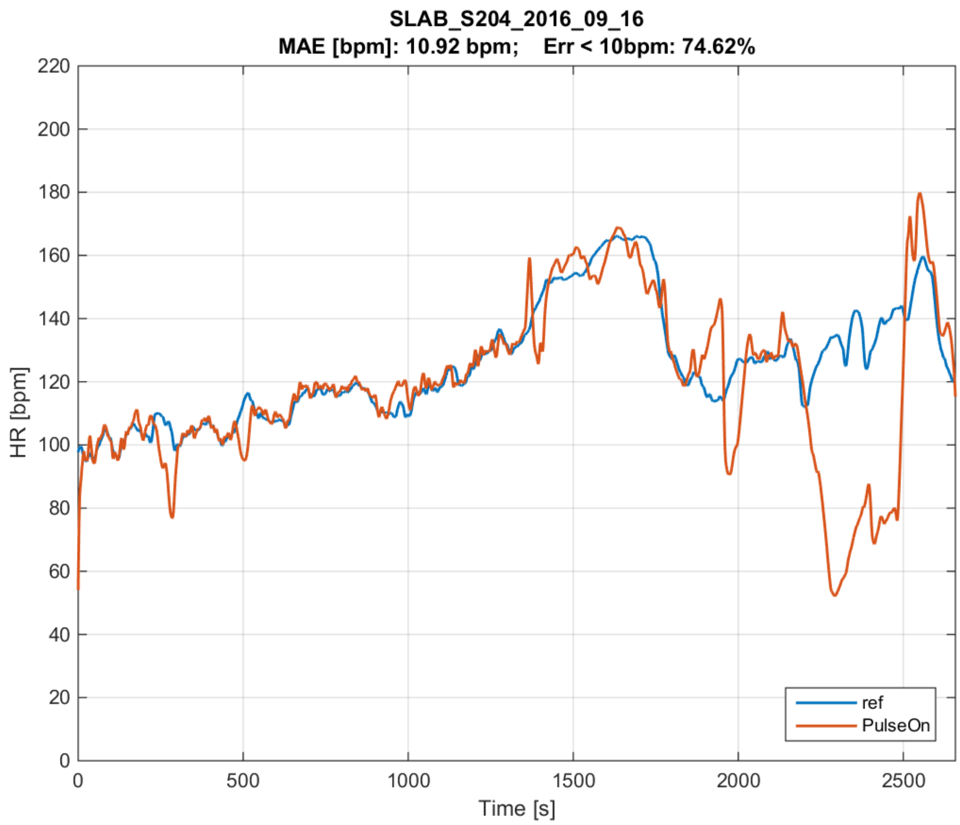
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500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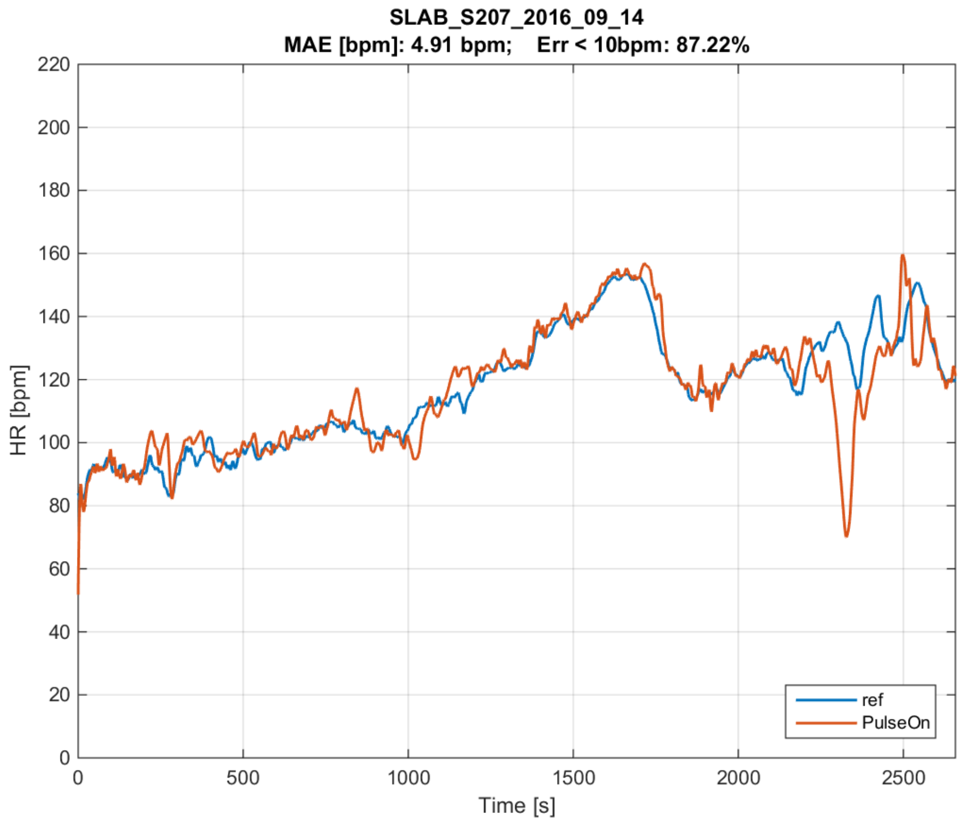
HR [bpm]
Time [s]
ref
PulseOn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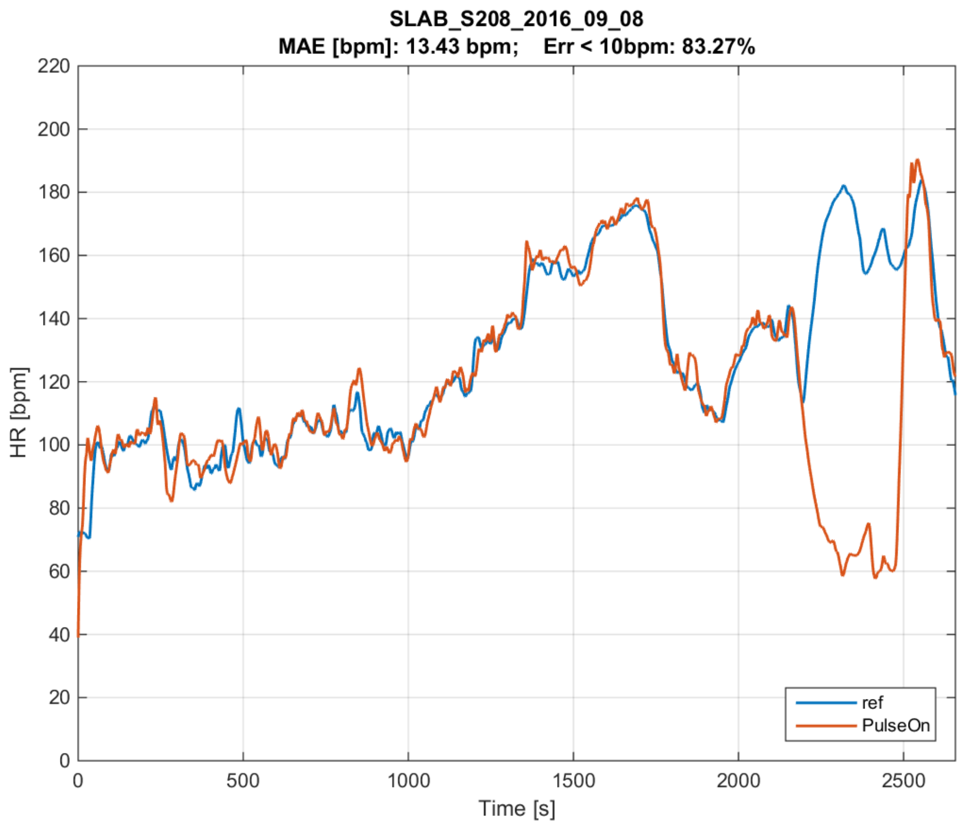
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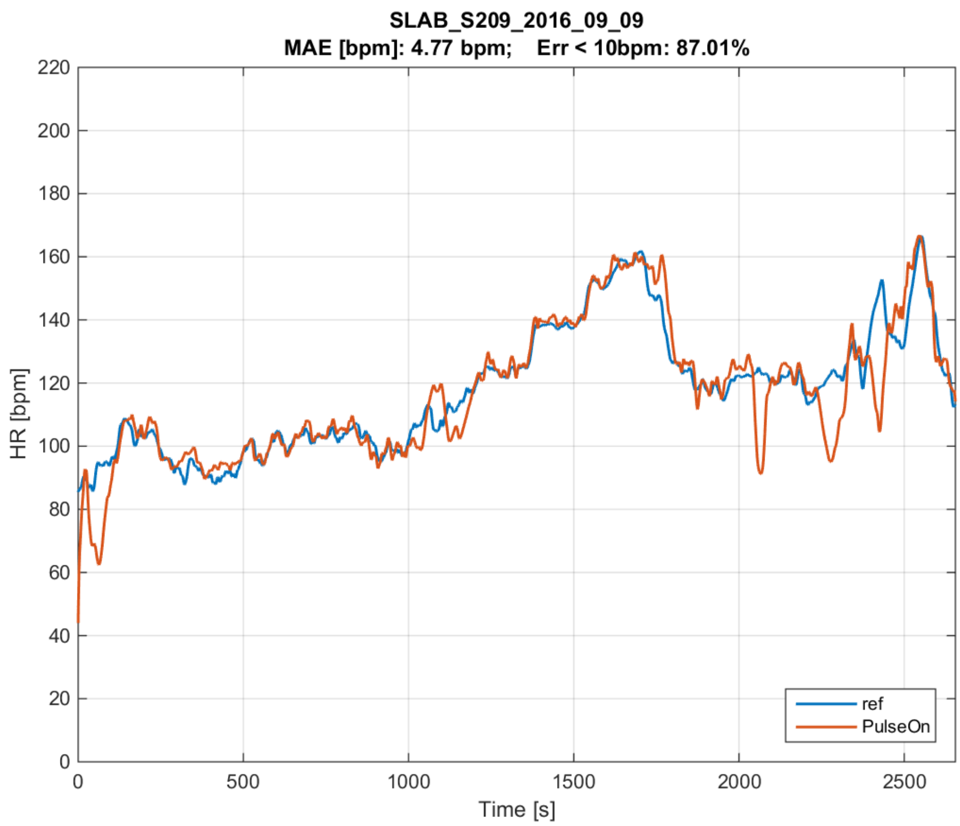
PulseOn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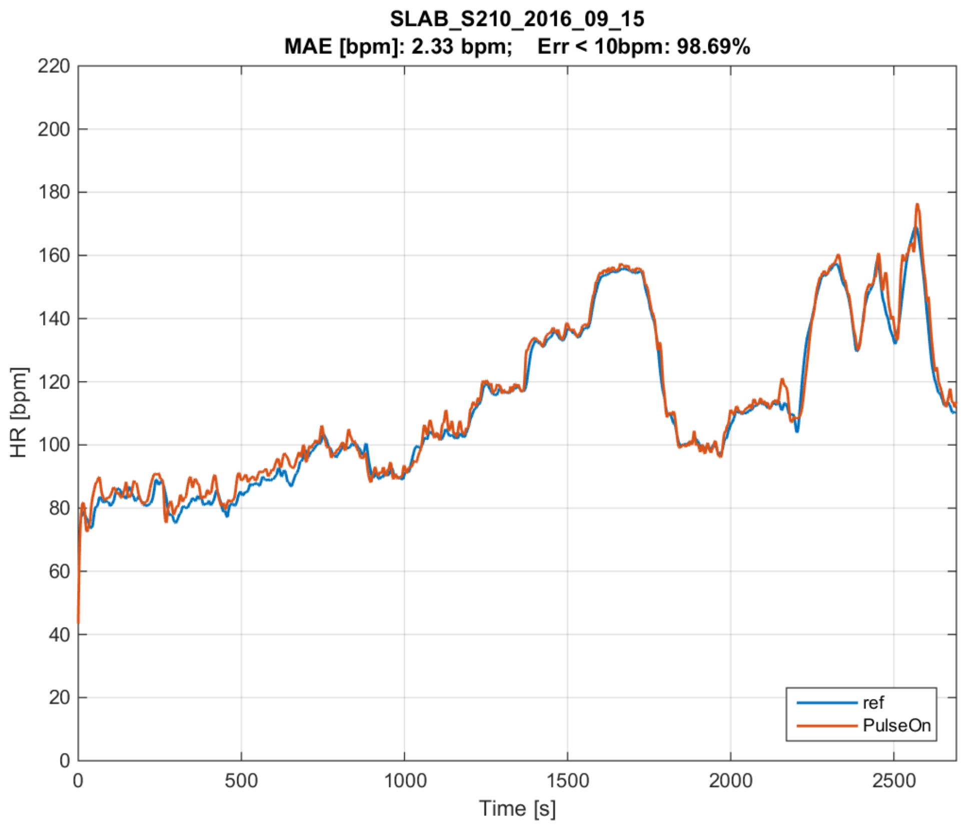
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Time [s]
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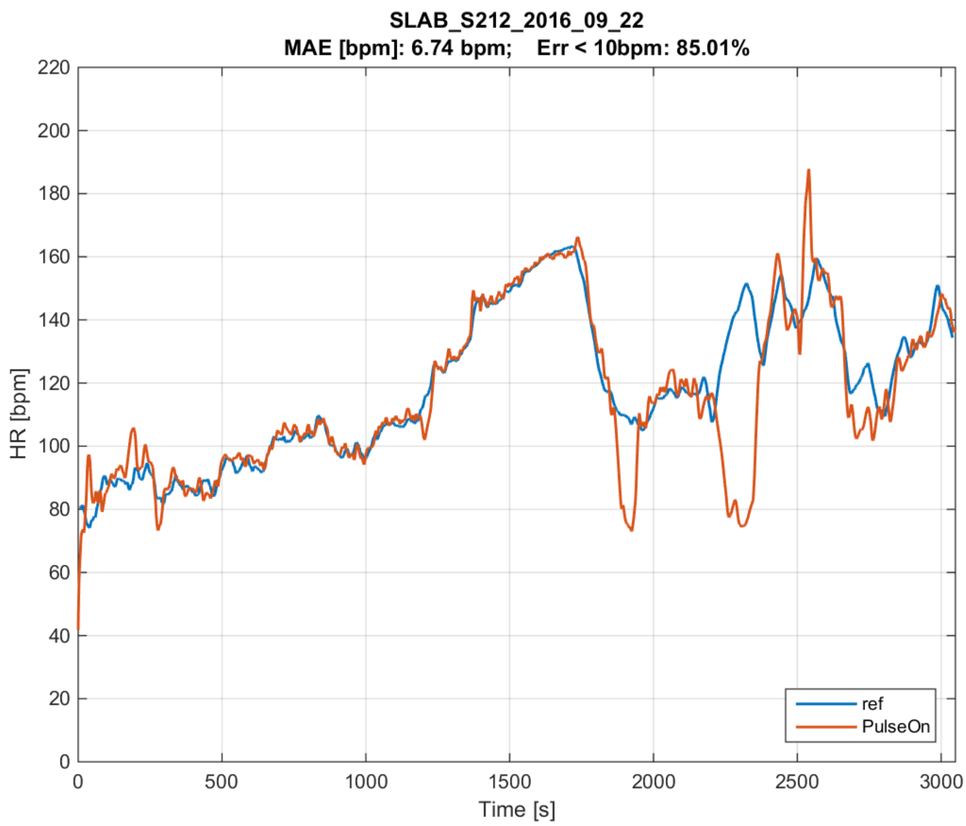
1500
2000
2500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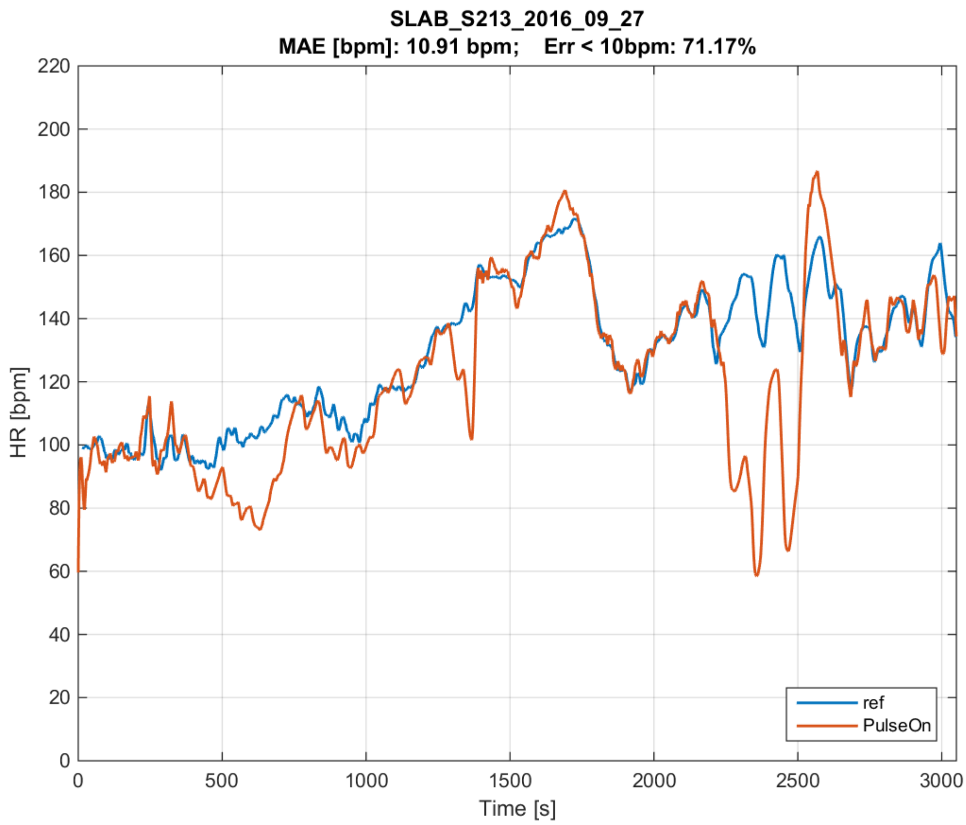
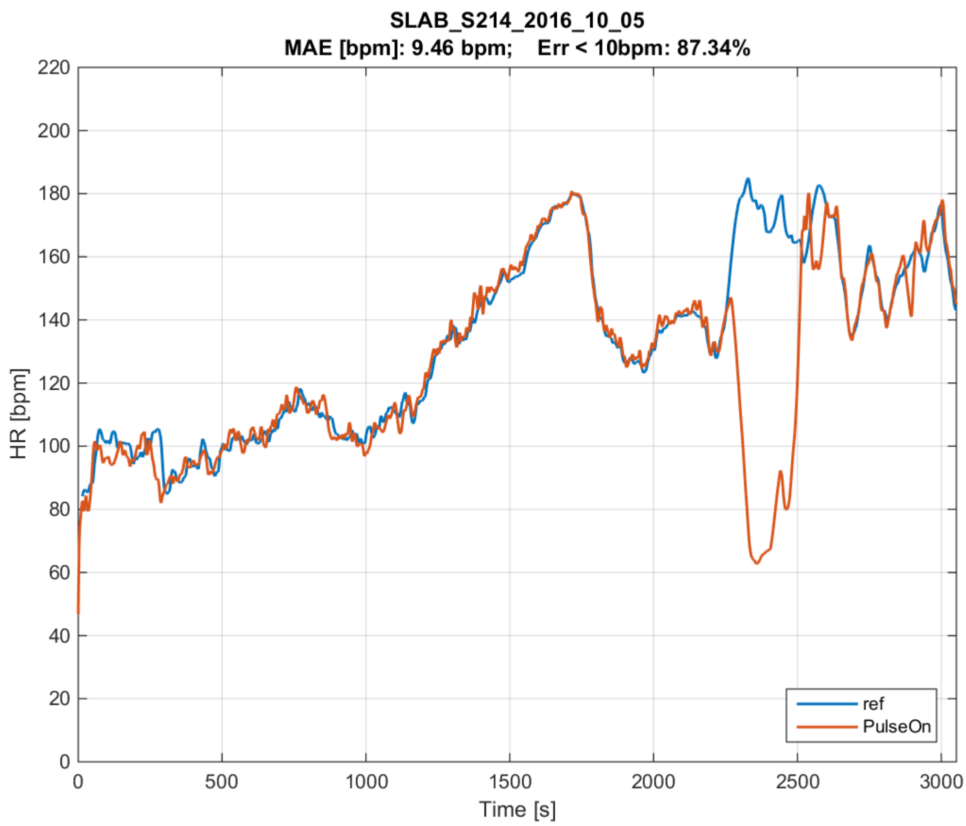
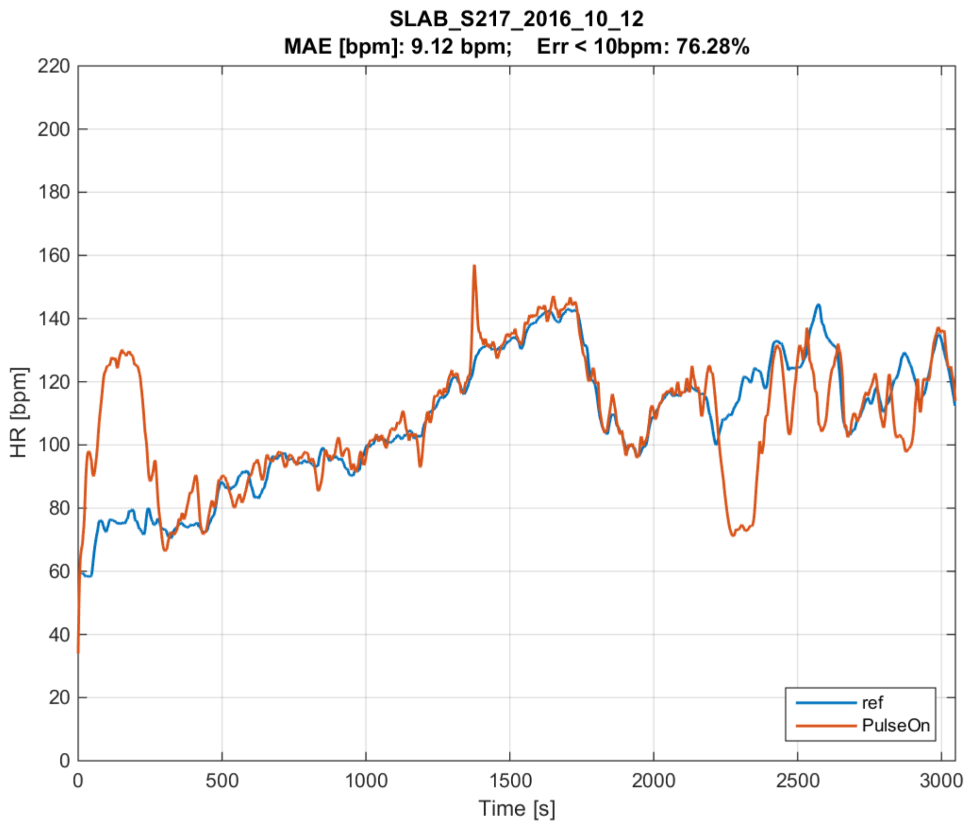
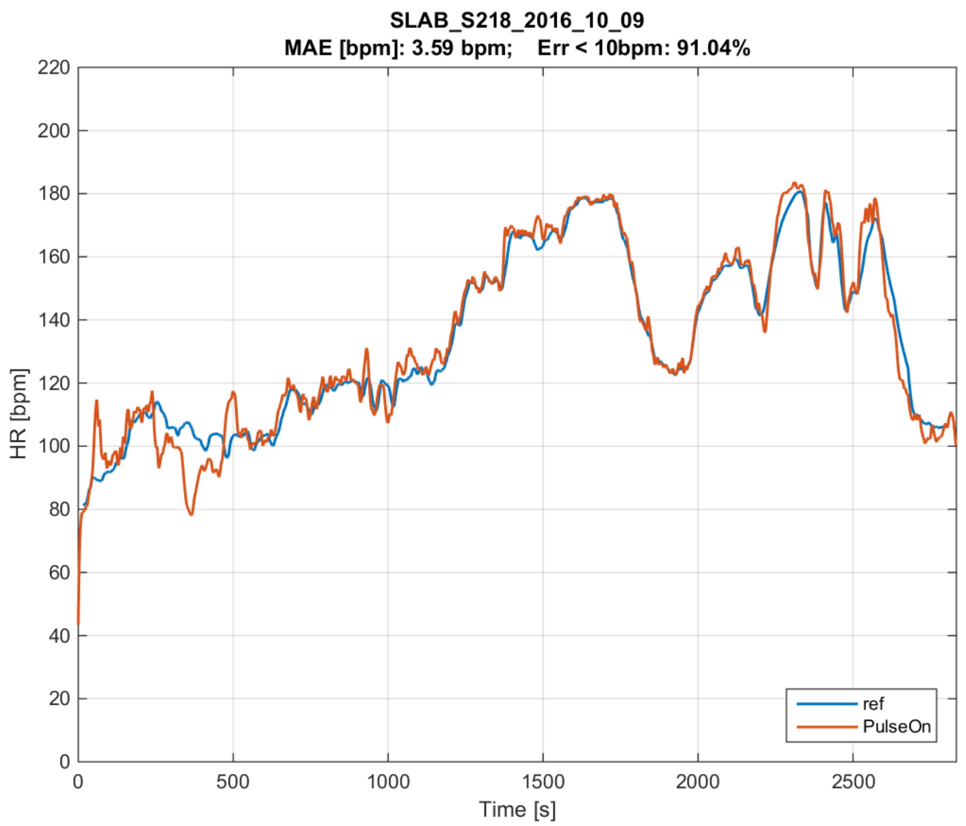
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
0
500
1000
1500
2000
2500
3000

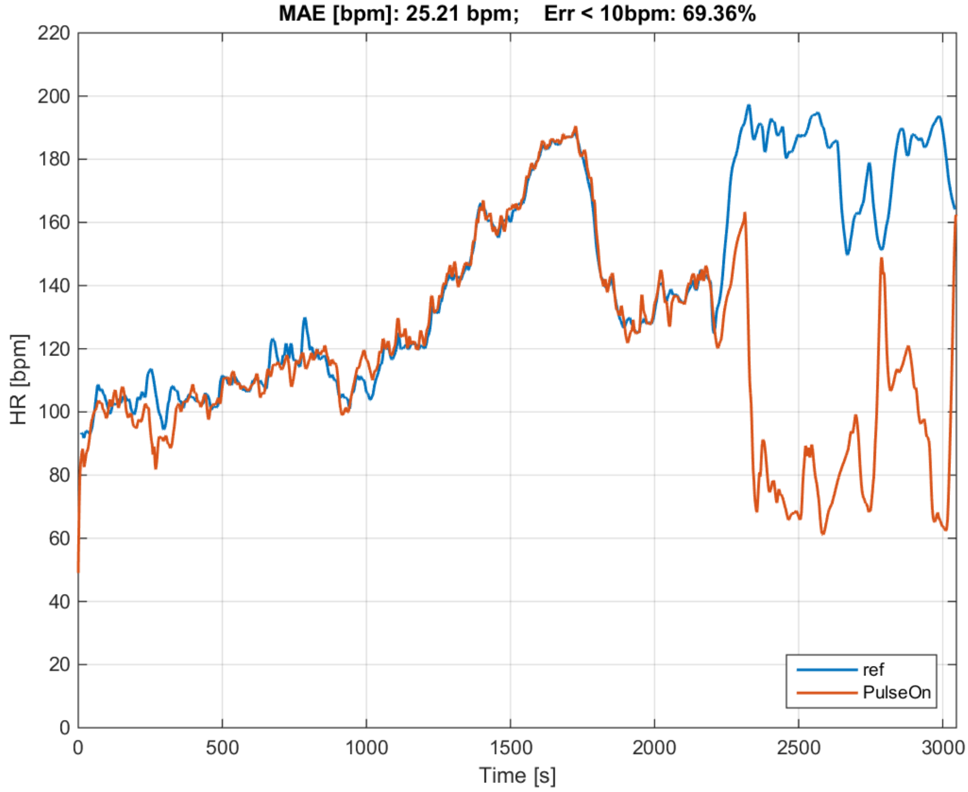

SLAB_S213_2016_09_27
MAE [bpm]: 10.91 bpm;   Err < 10bpm: 71.17%
HR [bpm]
Time [s]
ref
PulseOn
220
200
180
160
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000


SLAB_S214_2016_10_05
MAE [bpm]: 9.46 bpm;   Err < 10bpm: 87.34%
HR [bpm]
Time [s]
ref
PulseOn
220
200
180
160
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000

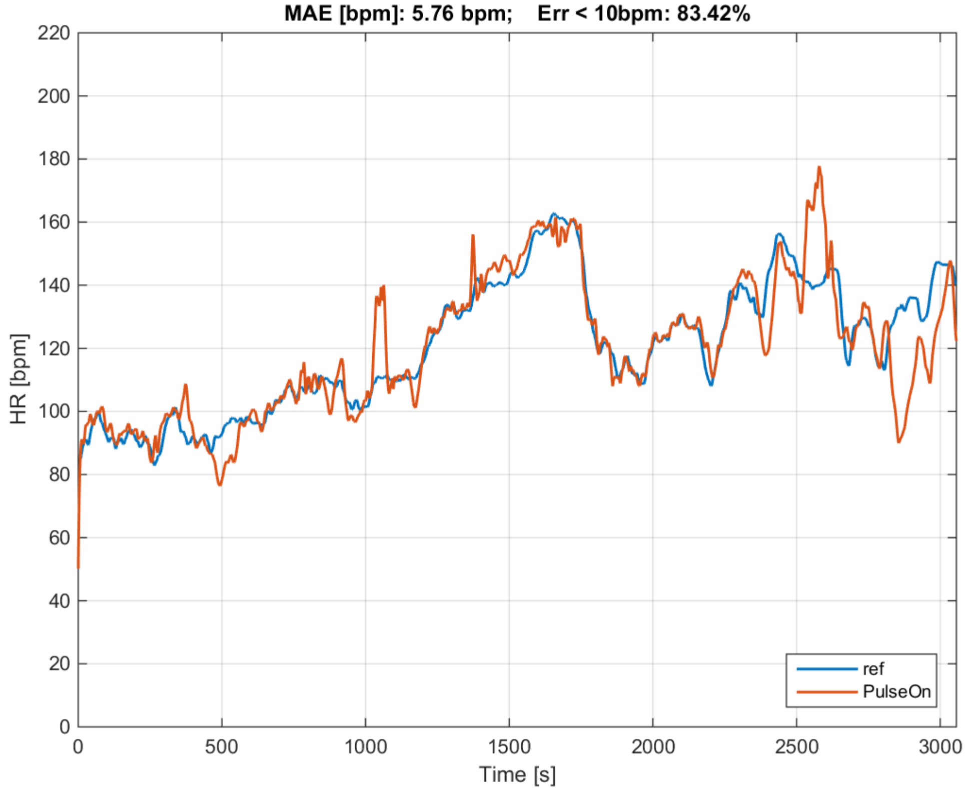

SLAB_S217_2016_10_12
MAE [bpm]: 9.12 bpm;   Err < 10bpm: 76.28%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500
3000

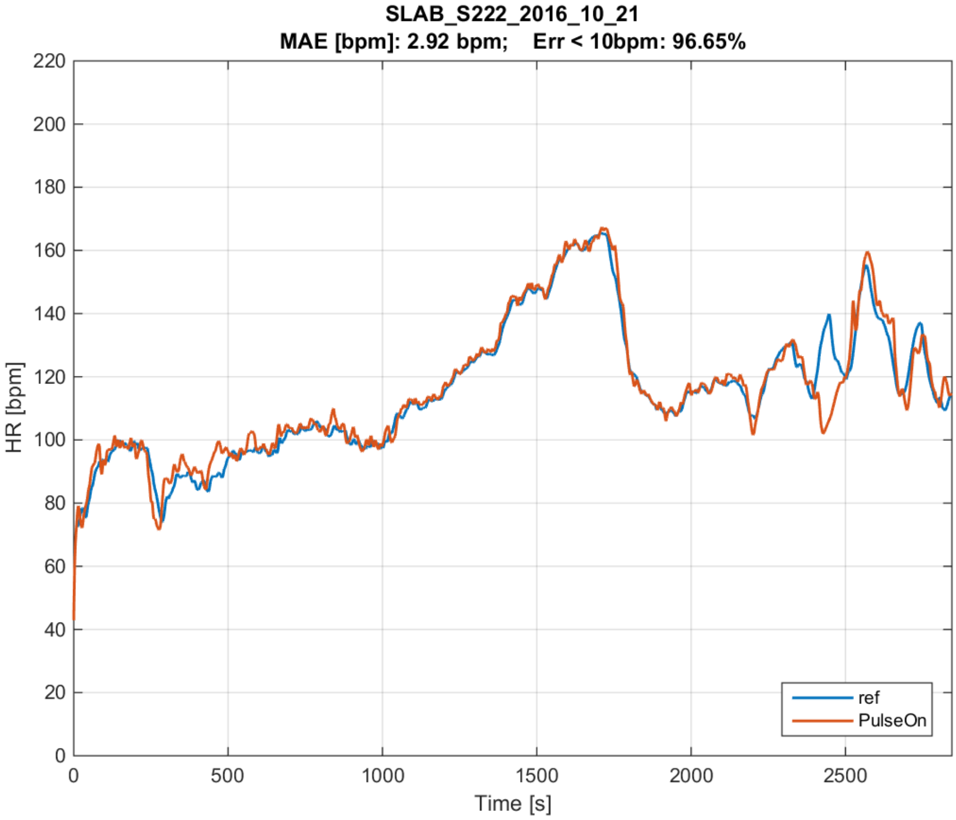

SLAB_S218_2016_10_09
MAE [bpm]: 3.59 bpm;   Err < 10bpm: 91.04%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500

SLAB_S219_2016_10_14
MAE [bpm]: 25.21 bpm; Err < 10bpm: 69.36%



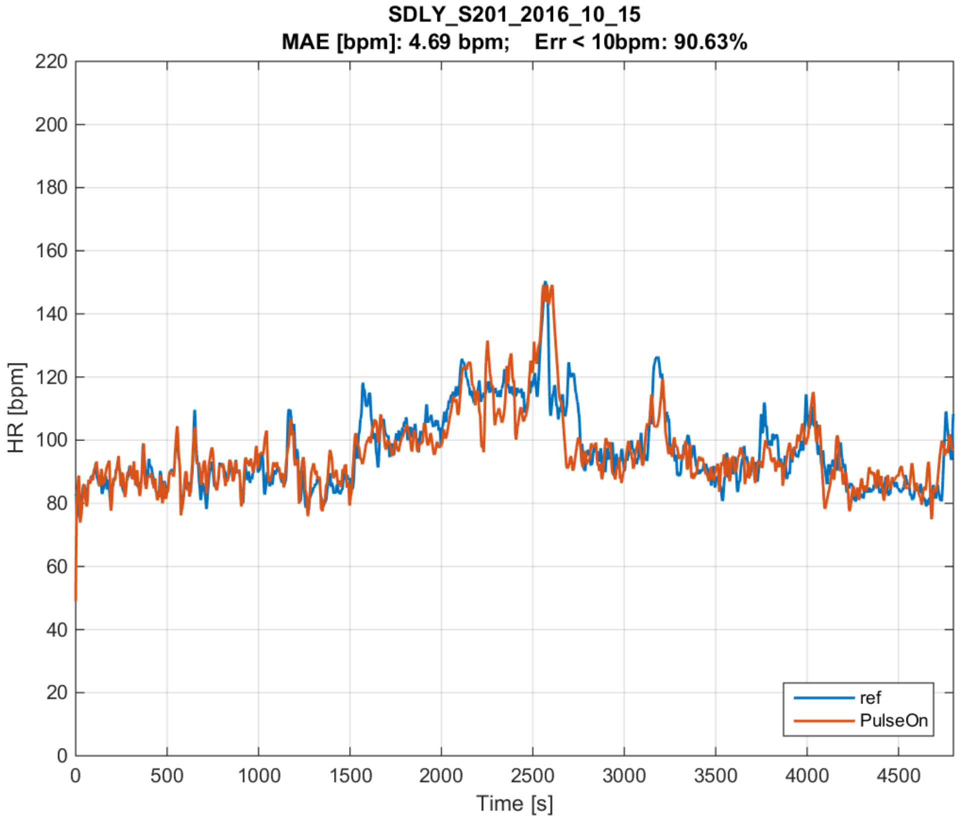
SLAB_S220_2016_10_17
MAE [bpm]: 5.76 bpm; Err < 10bpm: 83.42%

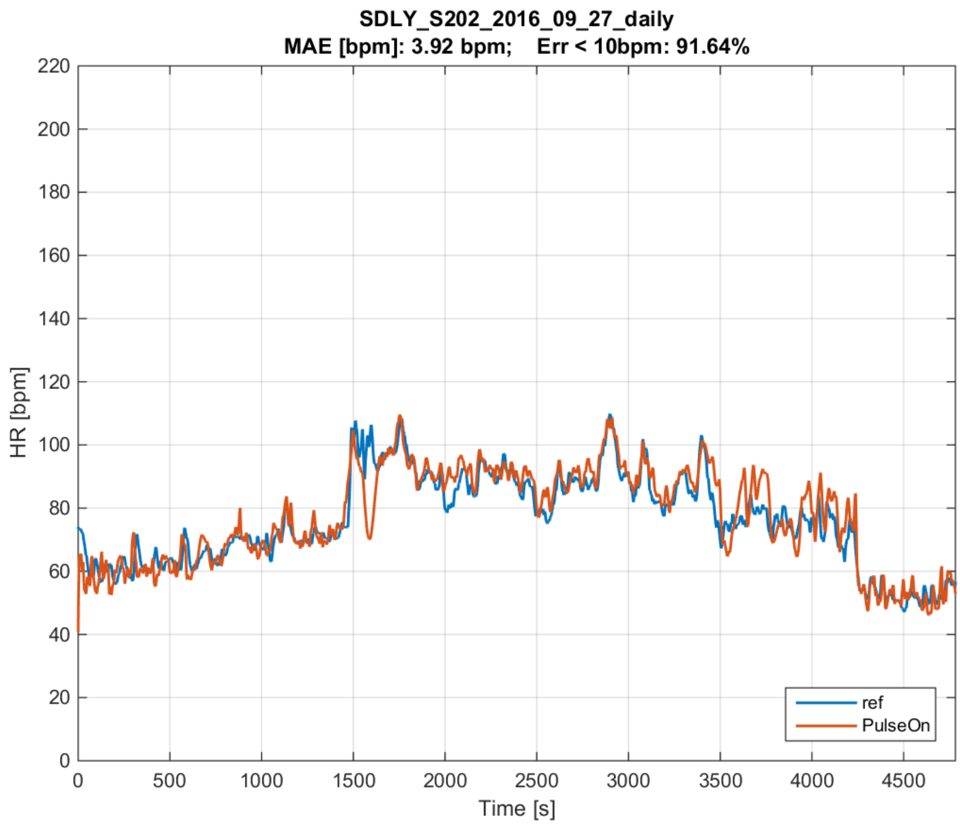


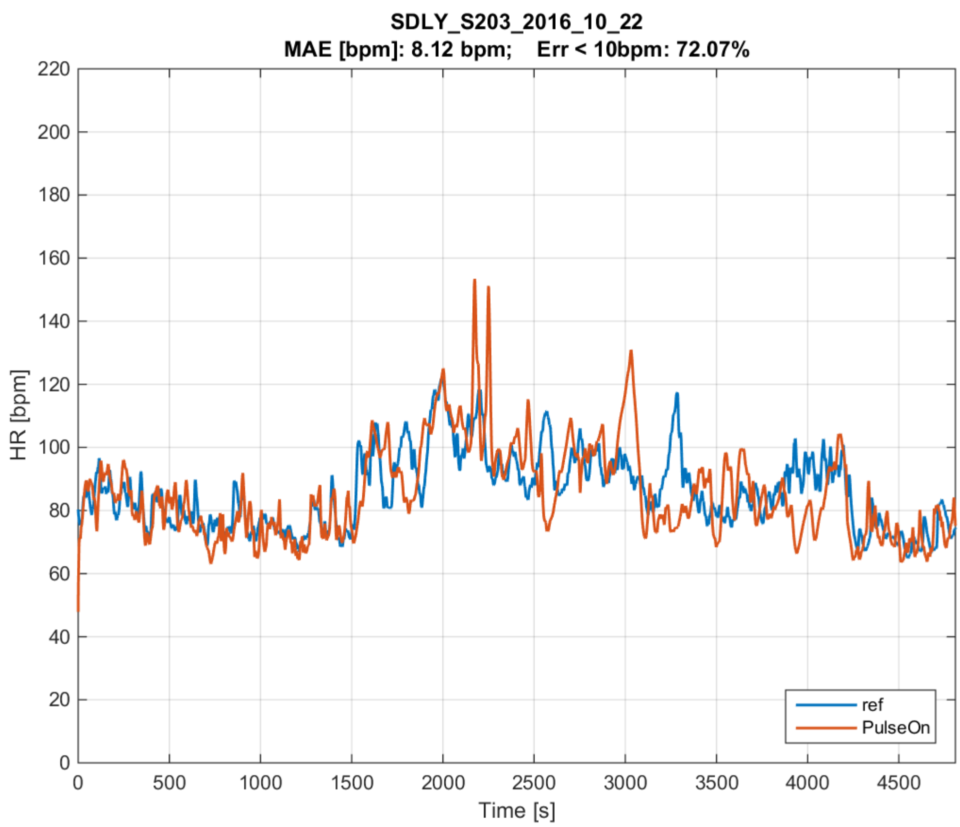

SLAB_S222_2016_10_21
MAE [bpm]: 2.92 bpm; Err < 10bpm: 96.65%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500

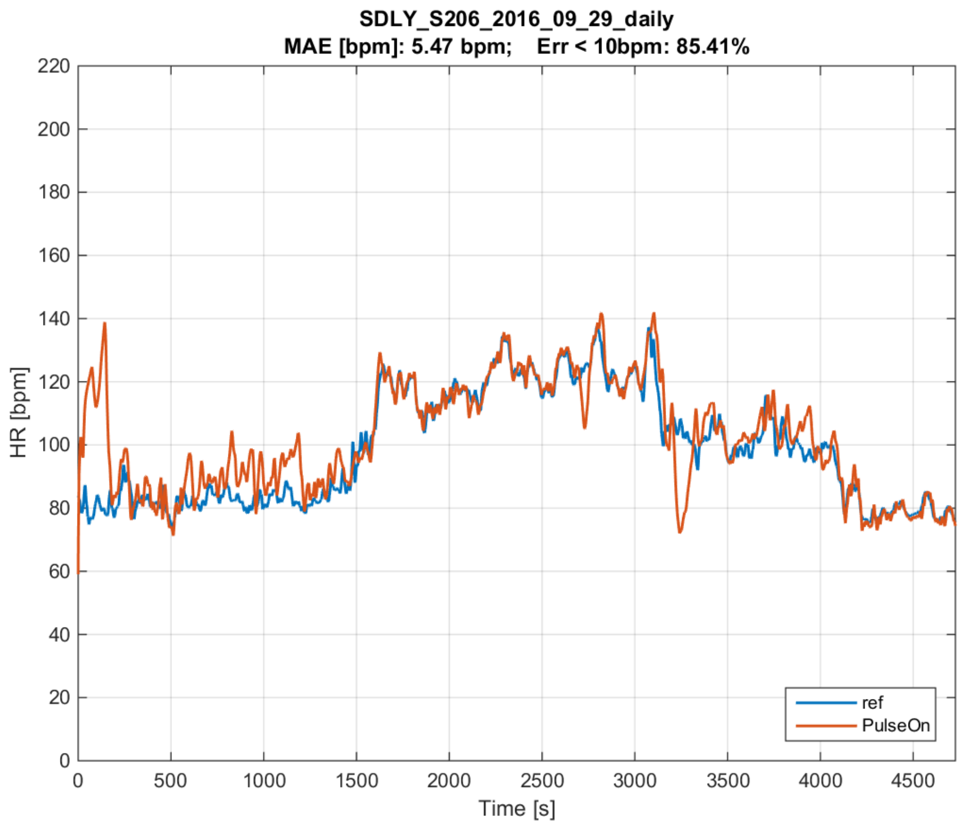
Measurement results from the daily life tests

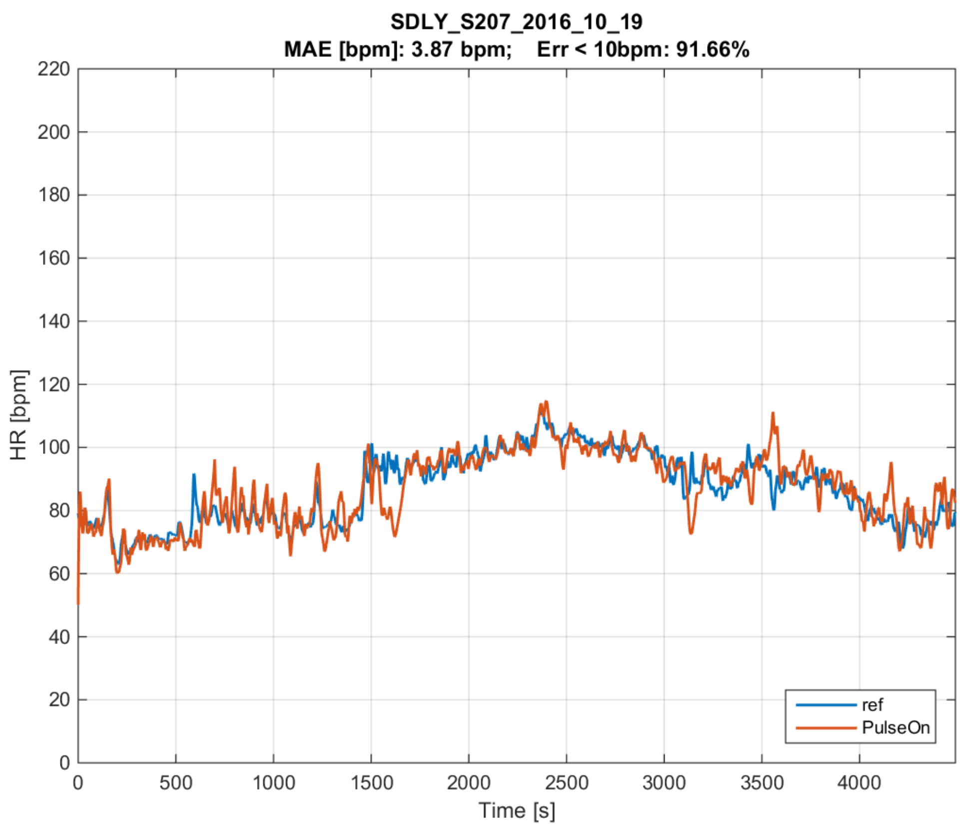
The following are the figures from the daily life tests, which are processed in Matlab. Results were used to evaluate the accuracy of the PulseOn's prototype.

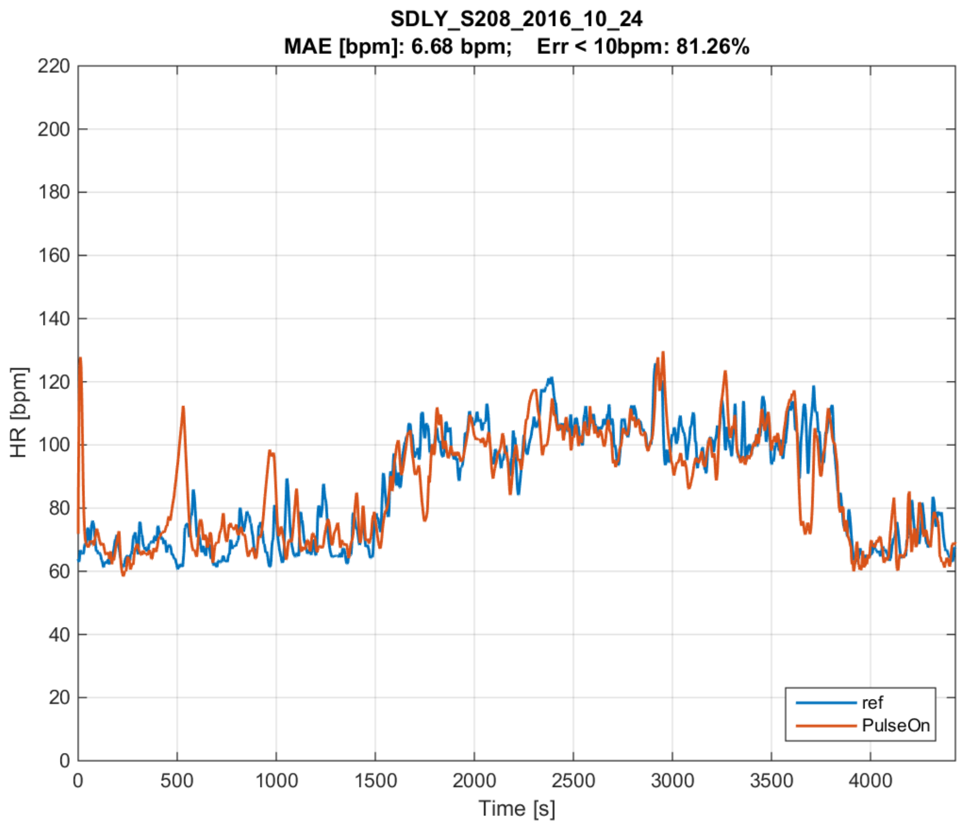


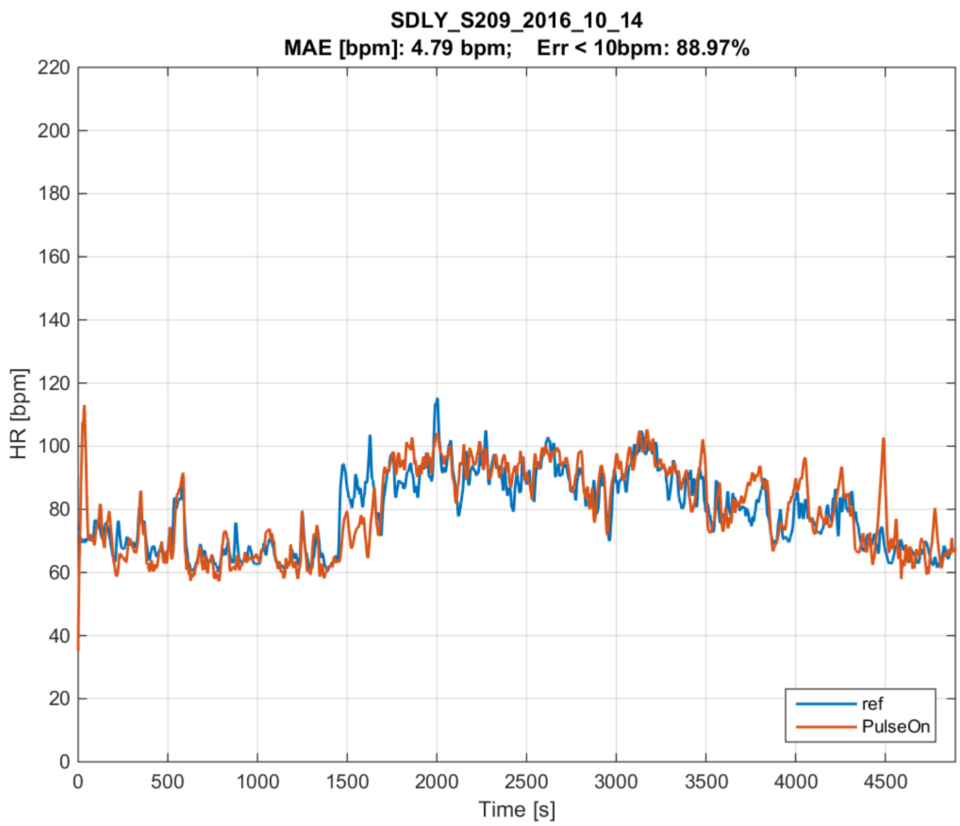

SDLY_S202_2016_09_27_daily
MAE [bpm]: 3.92 bpm; Err < 10bpm: 91.64%
HR [bpm]
Time [s]
ref
PulseOn

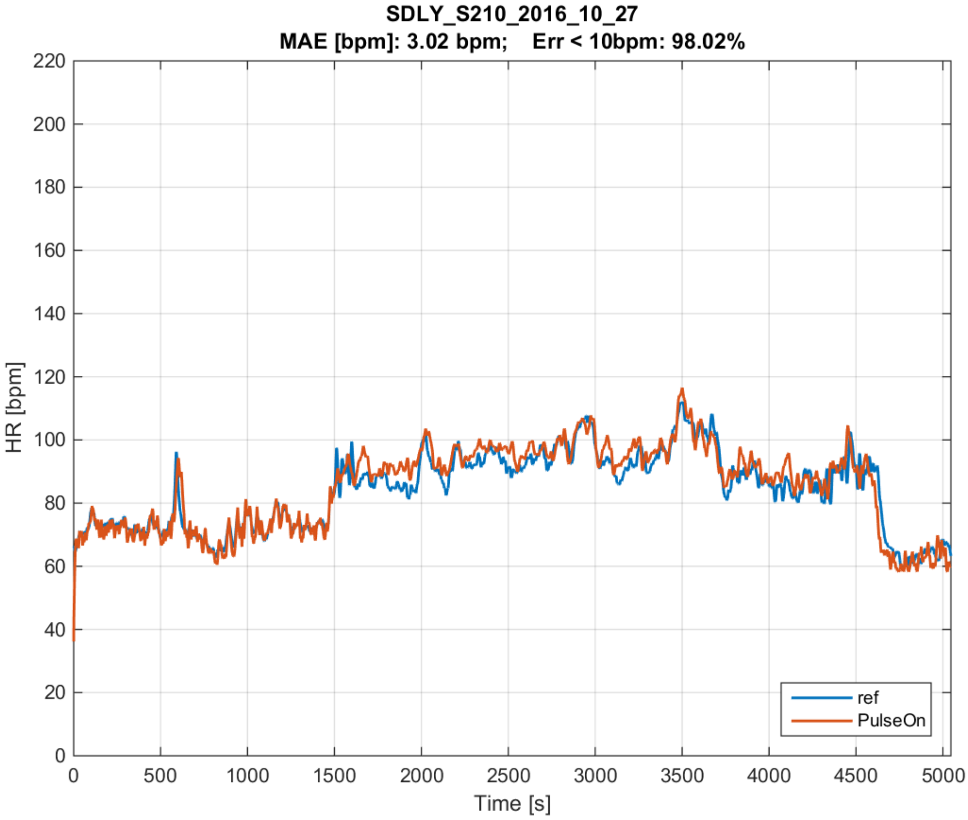

SDLY_S203_2016_10_22
MAE [bpm]: 8.12 bpm; Err < 10bpm: 72.07%
HR [bpm]
Time [s]
ref
PulseOn

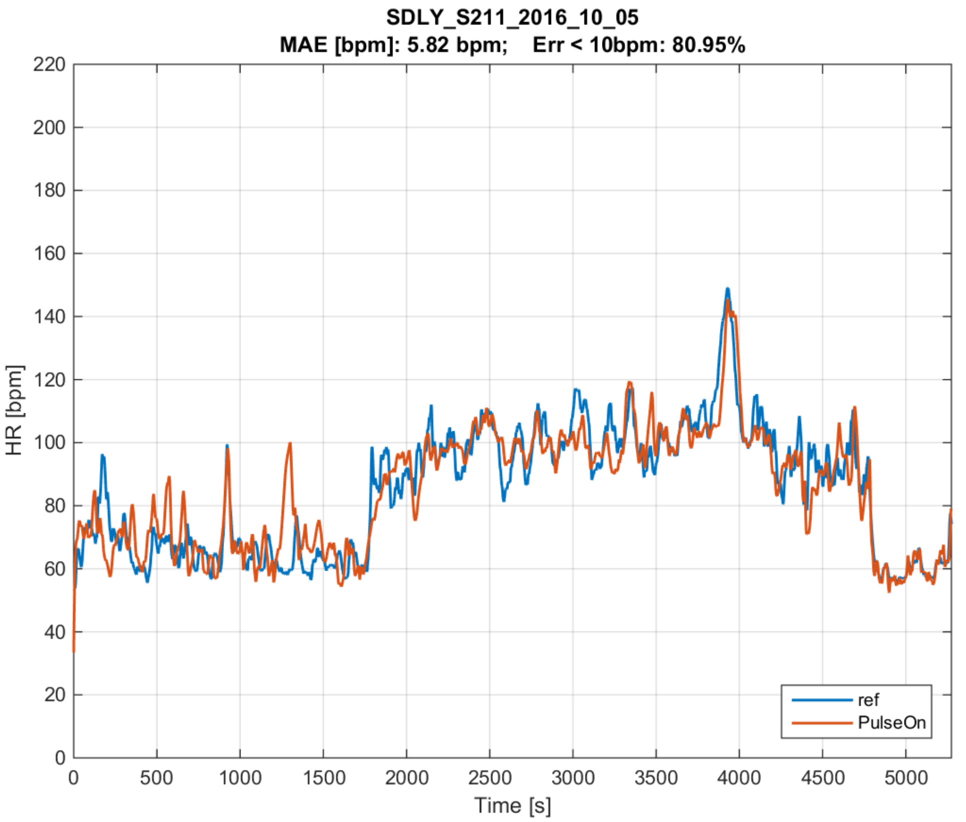

SDLY_S206_2016_09_29_daily
MAE [bpm]: 5.47 bpm; Err < 10bpm: 85.41%
HR [bpm]
Time [s]
ref
PulseOn

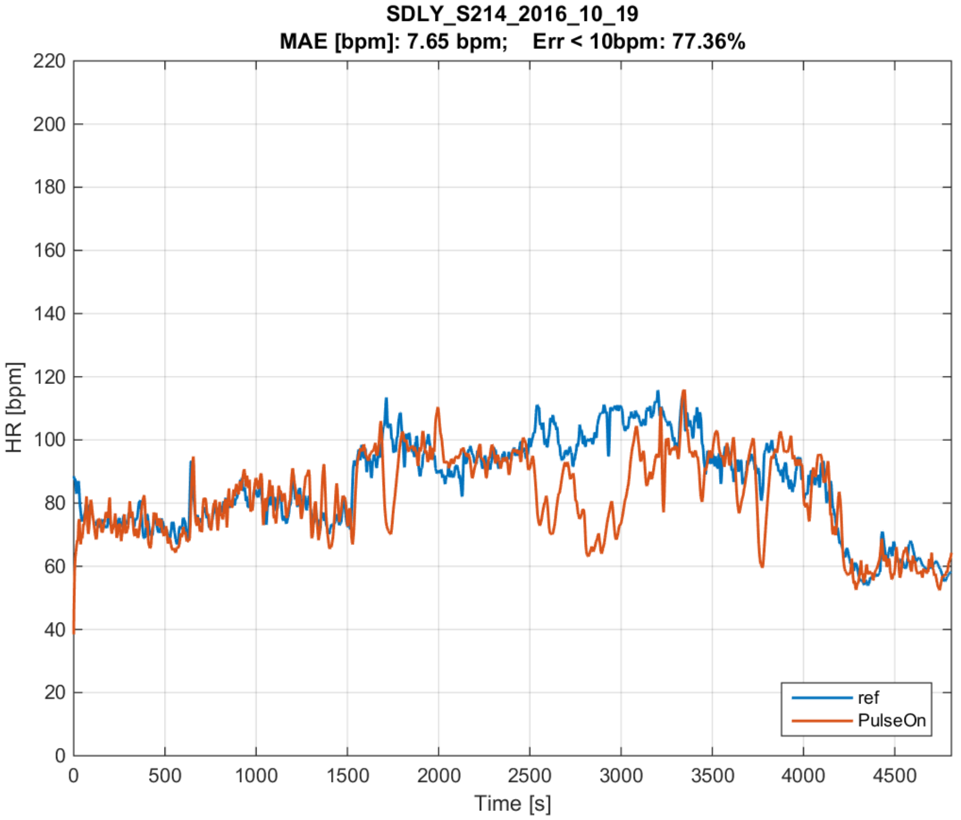

SDLY_S207_2016_10_19
MAE [bpm]: 3.87 bpm; Err < 10bpm: 91.66%
HR [bpm]
Time [s]
ref
PulseOn

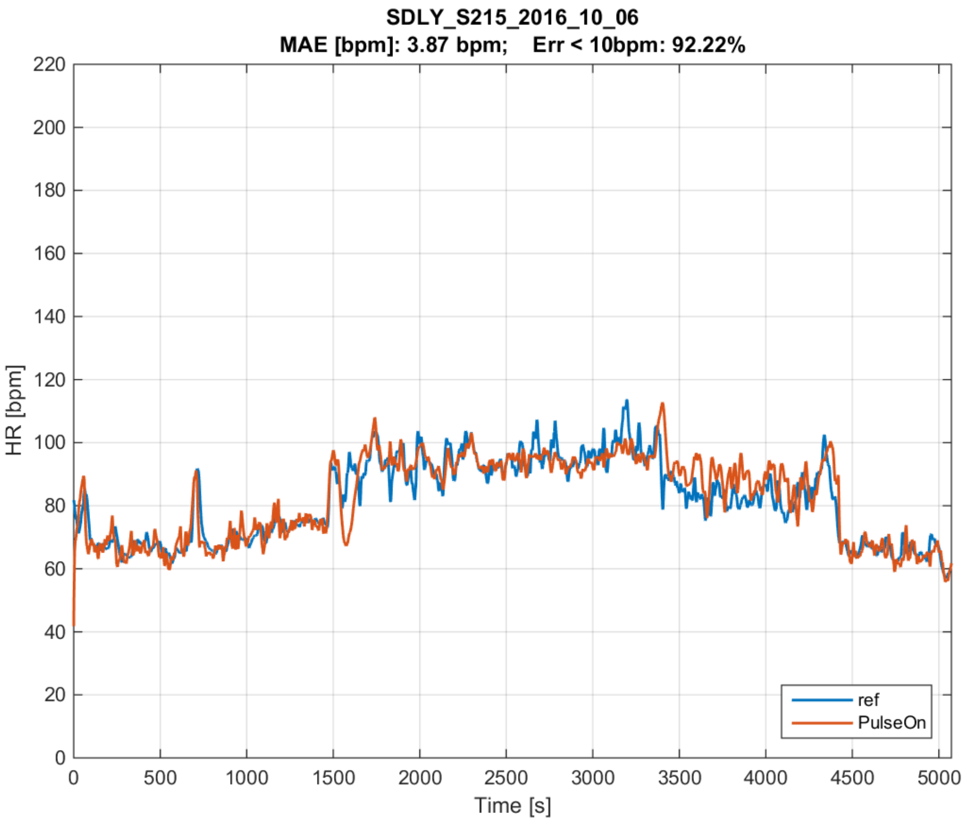

SDLY_S208_2016_10_24
MAE [bpm]: 6.68 bpm; Err < 10bpm: 81.26%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500
3000
3500
4000

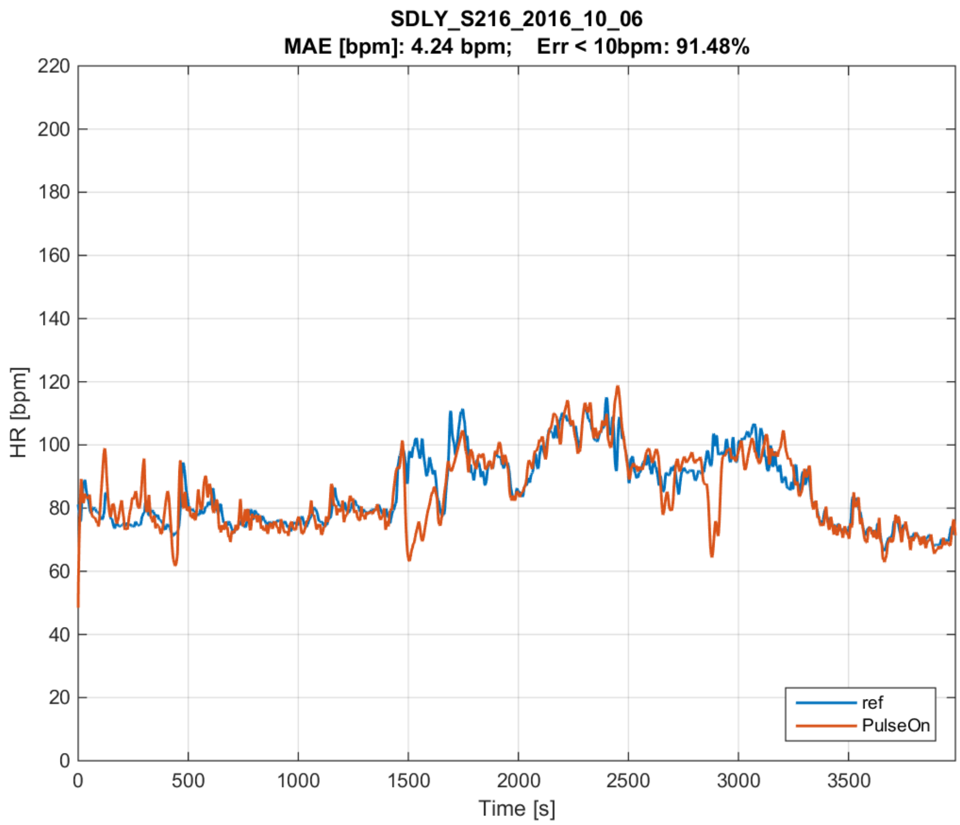

SDLY_S209_2016_10_14
MAE [bpm]: 4.79 bpm; Err < 10bpm: 88.97%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500
3000
3500
4000
4500

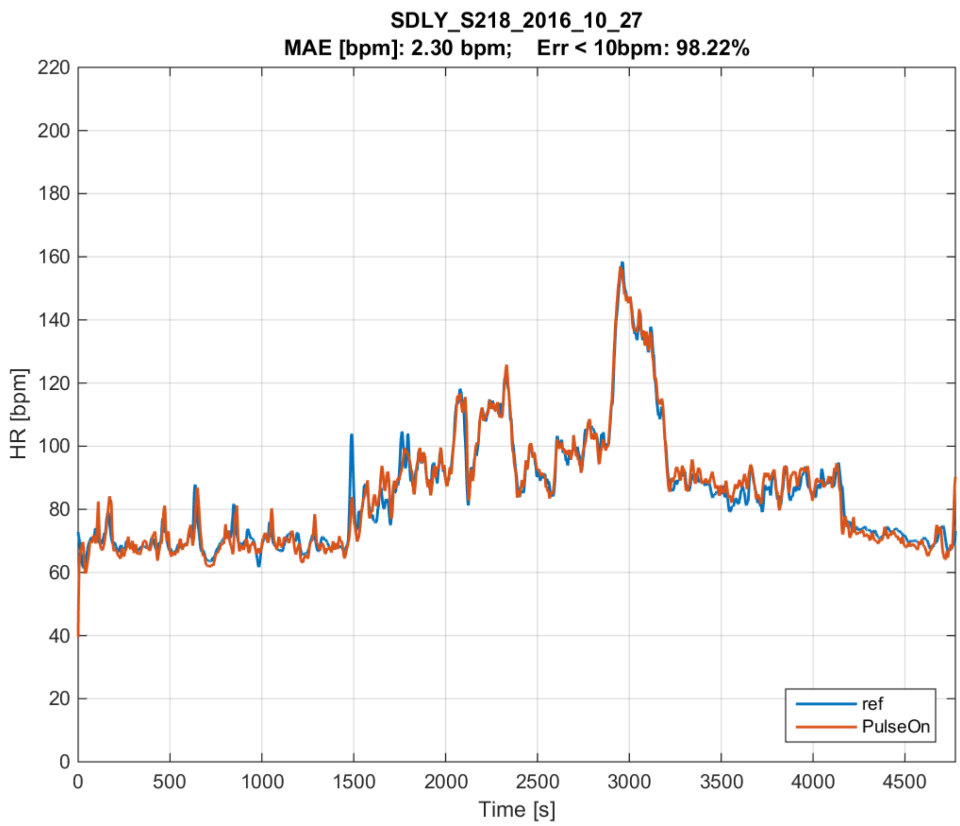

SDLY_S210_2016_10_27
MAE [bpm]: 3.02 bpm; Err < 10bpm: 98.02%
HR [bpm]
Time [s]
ref
PulseOn

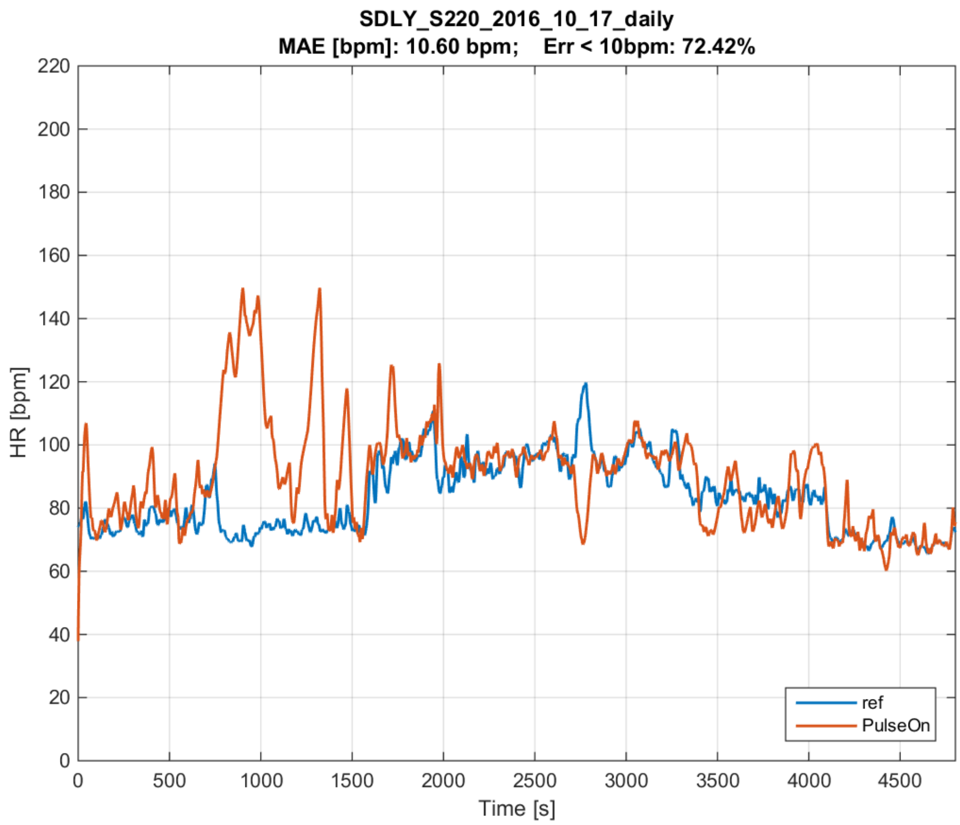

SDLY_S211_2016_10_05
MAE [bpm]: 5.82 bpm; Err < 10bpm: 80.95%
HR [bpm]
Time [s]
ref
PulseOn

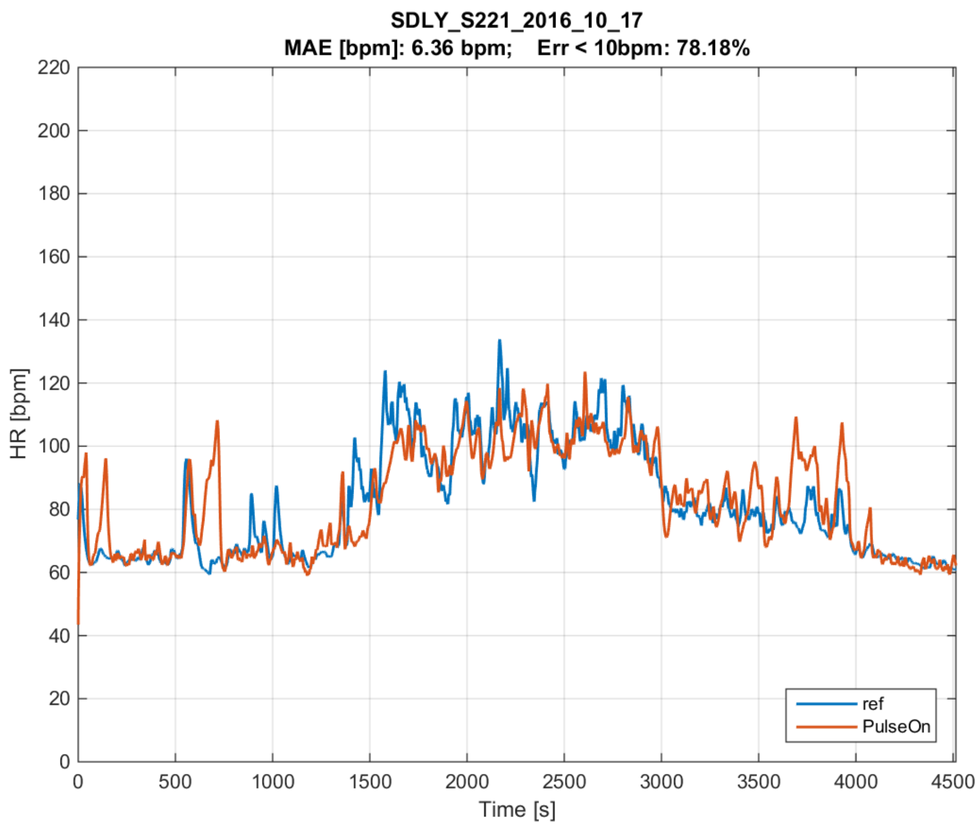

SDLY_S214_2016_10_19
MAE [bpm]: 7.65 bpm; Err < 10bpm: 77.36%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500
3000
3500
4000
4500

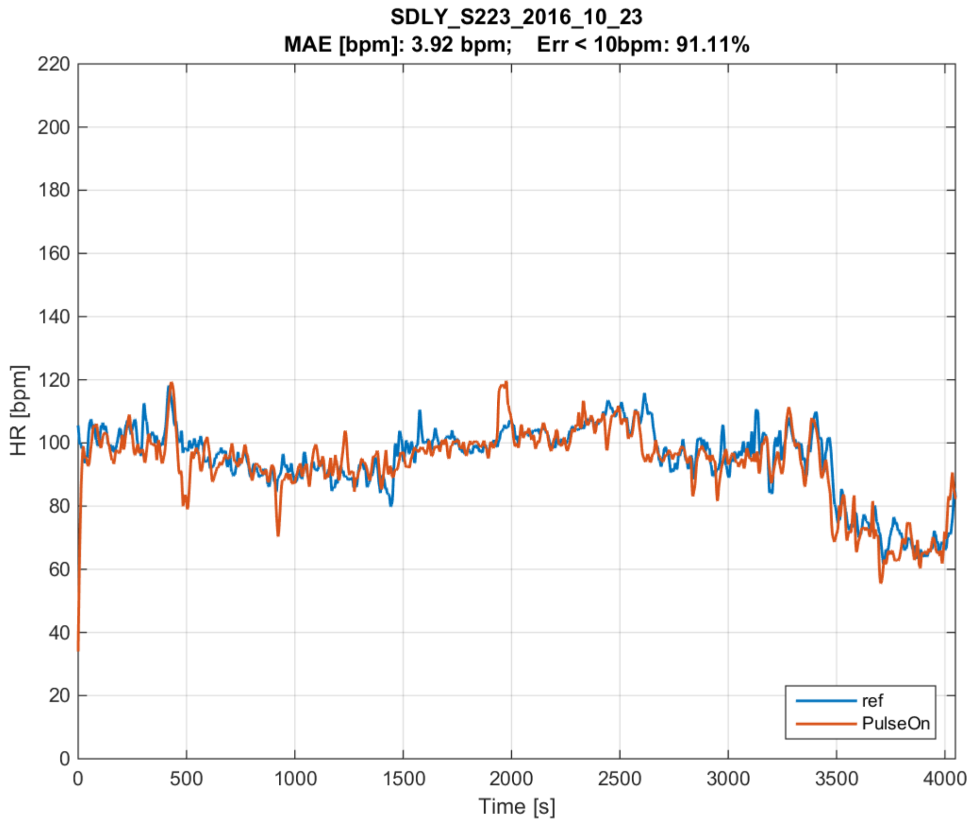

SDLY_S215_2016_10_06
MAE [bpm]: 3.87 bpm; Err < 10bpm: 92.22%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

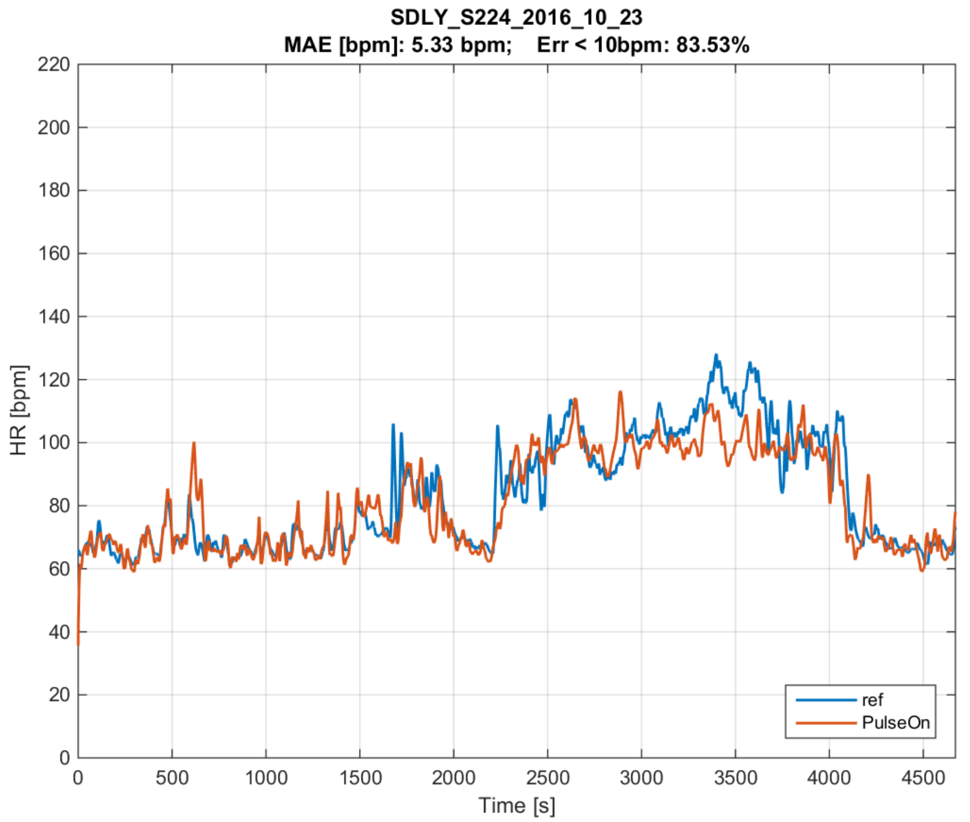

SDLY_S216_2016_10_06
MAE [bpm]: 4.24 bpm; Err < 10bpm: 91.48%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
0
500
1000
1500
2000
2500
3000
3500


SDLY_S218_2016_10_27
MAE [bpm]: 2.30 bpm; Err < 10bpm: 98.22%
HR [bpm]
Time [s]
ref
PulseOn
0
20
40
60
80
100
120
140
160
180
200
220
0
500
1000
1500
2000
2500
3000
3500
4000
4500


SDLY_S220_2016_10_17_daily
MAE [bpm]: 10.60 bpm;   Err < 10bpm: 72.42%
HR [bpm]
Time [s]
ref
PulseOn


SDLY_S221_2016_10_17
MAE [bpm]: 6.36 bpm;   Err < 10bpm: 78.18%
HR [bpm]
Time [s]
ref
PulseOn


SDLY_S223_2016_10_23
MAE [bpm]: 3.92 bpm;   Err < 10bpm: 91.11%
HR [bpm]
Time [s]
ref
PulseOn


SDLY_S224_2016_10_23
MAE [bpm]: 5.33 bpm;   Err < 10bpm: 83.53%
HR [bpm]
Time [s]
ref
PulseOn

Questionnaire for optical heart rate monitor's usability

This questionnaire was send to all of the test volunteers. Answers were used to evaluate the usability and user experiences of the PulseOn's prototype.

Optical heart rate monitor's usability

This form's duty is to determinate user experience from test occasions (performance and daily activity). This form compares the used devices. Please answer on the basis of your own experience about the devices used in the test.

*Pakollinen

Gender *

- Female
- Male

The five following questions are scale type questions

Select one option from the following:
1 - Strongly agree
2 - Agree
3 - Neutral
4 - Disagree
5 - Strongly disagree

The wrist monitor felt more comfortable than the heart rate monitoring belt *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

A wrist monitor sounds more reliable than a traditional heart rate monitoring belt *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

A wrist monitor seems more user-friendly than a traditional heart rate monitoring belt *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

I would prefer a wrist monitor for heart rate measurement during exercise rather than a monitoring belt. Assume that both are equally accurate. *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

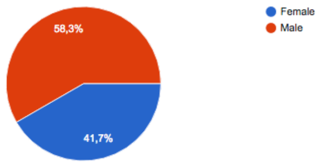
I would prefer a wrist monitor for heart rate measurement during daily life rather than a monitoring belt. Assume that both are equally accurate. *

	1	2	3	4	5	
Strongly agree	○	○	○	○	○	Strongly disagree

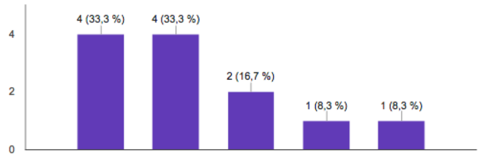
LATAA

Results from the usability questionnaire

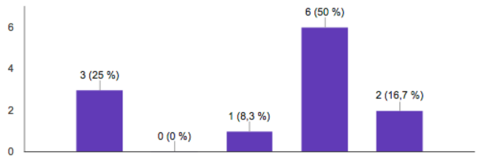
Gender (12 vastausta)



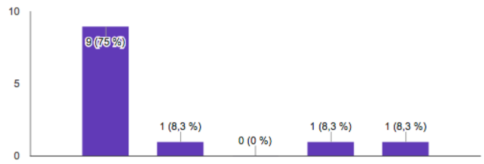
The wrist monitor felt more comfortable than the heart rate monitoring belt
(12 vastausta)



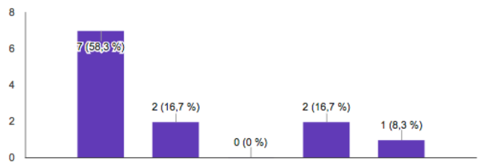
A wrist monitor sounds more reliable than a traditional heart rate monitoring belt
(12 vastausta)



A wrist monitor seems more user-friendly than a traditional heart rate monitoring belt
(12 vastausta)



I would prefer a wrist monitor for heart rate measurement during exercise rather than a monitoring belt. Assume that both are equally accurate.
(12 vastausta)



I would prefer a wrist monitor for heart rate measurement during daily life rather than a monitoring belt. Assume that both are equally accurate.
(12 vastausta)