ORIGINAL RESEARCH PAPER

WEARABLE PHOTOPLETHYSMOGRAPHY DEVICE FOR TELEMETRIC MONITORING OF PULSE WAVE PARAMETERS

Zbignevs Marcinkevics[1], Viktorija Mecnika[2], Edgars Kviesis[3], Uldis Rubins[3], Ivars Krievins[2]

[1]Latvia University
Faculty of Biology, Department of Human and Animal Physiology
Address: 4 Kronvalda blvd., Riga, LV1586, Latvia
E-mail: zbigis@latnet.v

[2]Riga Technical university
Institute of Textile Technology and Design
Address: 14/24 Āzenes Street, Riga, LV 1048, Latvia
Phone: +371 67089821
E-mail: Ivars.Krievins@rtu.lv, viktorija.mecnika@gmail.com

[3]Latvia University
Institute of Atomic Physics and Spectroscopy
Address: 4 Šķūņu Street, Riga, LV1050, Latvia
Phone: + 371 67225493

Abstract

At present efficient training requires a complex approach incorporating the control of the exercise intensity and observation of athlete physiological variables. The heart rate monitoring during training session has become a common procedure, while more extensive investigation requires expensive technology and experienced personnel. Photoplethysmography (PPG) may be one of the potentially promising, simple and inexpensive techniques for acquisition of physiological parameters related to cardiac and arterial-hemodynamic activity. The aim of the current study is development end evaluation of a digital, multi-sensing photo diode technology based PPG device for telemetric monitoring of pulse wave parameters. Six young and healthy volunteers (21-23 y.o.) participated in this study. PPG signal has been recorded from the skin over the temporal artery in rest conditions, during veloergometry test and recovery period. The data has been processed and statistically analyzed with custom developed PPG waveform analyses software, providing information on PPG waveform related parameters, such as systolic peak time, relative amplitude, pulse duration, time to maximal ejection velocity, *etc. A reliable, low noise PPG signal has been obtained from all the subjects. Computed PPG signal waveform parameter changes reflected different physiological conditions (rest period, exercise, post-exercise recovery period) and were consistent with the values reported in the literature. We concluded that digital multi-sensing photo diode PPG device demonstrated high accuracy and convenient use, which suggests potential application in exercise physiology and training*.

Key words: *photoplethysmography, pulse wave, hemodynamic parameters, wearable sensor, biomedical garment.*

Introduction

At present efficient training requires a complex approach incorporating the control of the exercise intensity and observation of athlete physiological variables. On one hand, inefficient intensity may oppress the athlete performance; on the other hand, overtraining might cause exhaustion and other health related problems. Modern technologies are offering advantageous opportunities to improve athlete performance including telemetric monitoring and further analysis of physiological and kinematic parameters and high-performance sportswear and equipment (Shishoo et al., 2005). At the moment there are a wide range of commercially available products (Polar®, Zephyr® heart rate monitors etc.), however despite of technological achievements the most commonly assessed cardiovascular parameter during the training session still remains the heart rate (HR).

A more advanced modification of HR assessment method is heart rate variability (HRV) analysis, which may provide information on sympathetic and parasympathetic balance during the rest and recovery, and may serve as an indirect indicator of overtraining (Mourot et al., 2004). Hence, HRV analysis requires application of more advanced heart rate monitors with accurate beat-per-beat RR interval registration and special software incorporating real time spectral analyses.

Another significant parameter measured during exercise is arterial pressure (AP). However, continuous, beat-per-beat registration of such parameter requires expensive laboratory equipment (Finameter midi, FMS Inc.) and measurement precision can be affected by body movement during an exercise. Currently there are no commercially available technologies for assessment of hemodynamic variables during training affordable to a wider consumer range. Still, a potentially promising method, which may provide physiological information on cardiac and arterial-hemodynamic function, is photoplethysmography (PPG). Photoplethysmography is a non-invasive measuring technique based on optical detection of arterial pulse. The signal consists of a slow component (DC) and alternating component (AC). AC component mainly reflects cardiac activity while DC tissue blood perfusion and slow vasomotions of the blood vessels (Allen, 2007). Quantitative analysis of PPG signal provides physiological information on cardiac and hemodynamic function. It comprises evaluation of parametric values of the pulse wave amplitude, its temporal features, e.g. of foot-to-foot interval time, time of pulse wave reflection etc. (Dupre et al., 2004). However, in order to get more detailed information on physiological processes, quantitative analysis of the pulse wave may be supplemented with qualitative evaluation of the signal waveform, which represents individual properties of blood circulation (Schmidt & Kurjak, 2005). Major clinical applications of PPG technology utilized in biomedical equipment are monitoring of blood oxygen saturation level, continuous measuring of beat-to-beat blood pressure and vascular diagnostics (Allen, 2007). Although there have been a few studies attempting to identify and quantify exercise related PPG waveform parameters (Poon et al., 2003; Sandberg et al., 2005; Zhang et al., 2001; Chellappan et al., 2008). It is well known that efficient post-exercise recovery requires simultaneous adjustment of both cardiac parameters and peripheral arterial stiffness (MacDonald, 2002; Hogan, 2009; Dimpka, 2009). Therefore on-line observation of hemodynamic processes during training might be of great interest to sport physicians and coaches. The aim of the current multi-disciplinary study is development and laboratory testing of a wireless wearable multiple-photo detector device integrated into textiles (head-bandage).

Materials and Methods

Design of wearable PPG system

The developed electronic setup consists of wire-connected PPG probe, electronic circuit and 240 mAh Li-ion accumulator (Fig.1, Fig.2). The multiple-PD probe contains one infrared LED in the centre of the probe and nine photodiodes, located around the LED (Fig.3). The device operates in the reflection mode, while most of the commercially available biomedical PPG devices operate in the transmission mode. In our design the preference is given to reflection mode, because it allows recording of PPG signal from various body sites, regardless of tissue thickness. Unlike transmission mode reflection mode is more appropriate in the research field and might expand applications of PPG devices in hemodynamic parameter assessment, e.g. telemetric monitoring of peripheral blood pressure during recovery period, non-invasive express method for artery stiffness evaluation for elderly and hypertensive patients etc.(Kaibe et al., 2002; Mackenzie et al., 2002). The operation types of the device- power mode, Bluetooth connection and discharge levels of the Li-ion accumulator, - are indicated by two colour LEDs. Registered PPG signal is acquired with 1 ms resolution by a high speed microcontroller NXP LPC2148 ARM7, which operates at 48MHz clock frequency.

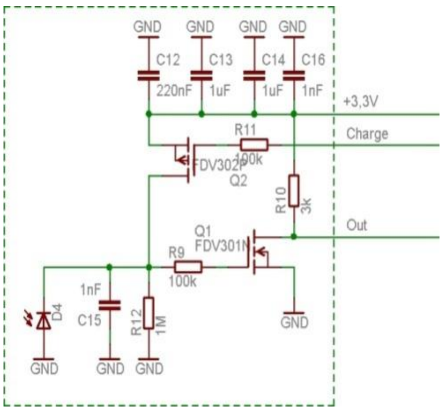

Figure1. Electronic circuit of the sensor probe (d=21 mm)

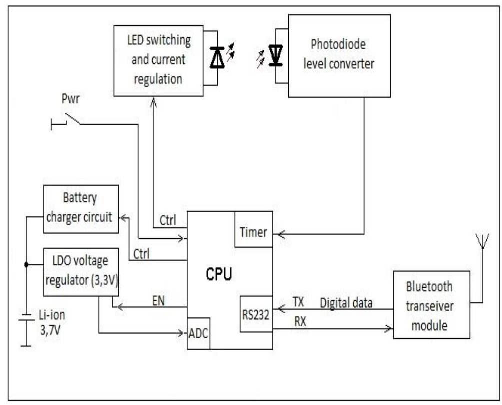

Figure 2. Block-diagram of the device (21x38x5 mm), see details in text

The substantial innovation of this device is digital acquisition of PPG signal based on photo diode (PD) discharge time detection. The capacitor discharge time is measured by a built-in 32-bit timer capture module (Fig.2). This method of PPG signal acquisition does not require application of analogue operation amplifiers and filters insuring less signal noise and reduced power consumption. Data transmission up to 10 meters distance is provided by Bluetooth module, which connects to a personal computer (PC) or Personal digital assistant (PDA) via a standard serial port (SSP).

Figure 3. The prototype of the head bandage with embedded PPG device; probe contains 1 emitter and 8 detectors

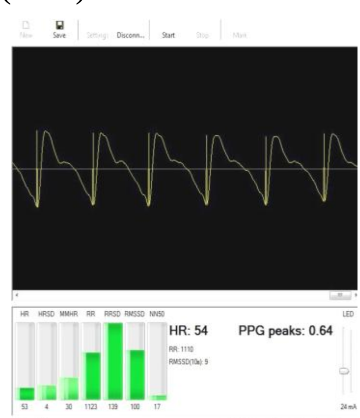

Figure 4. Software screenshot DataScope for PPG signal real-time monitoring, see details in text

The device and the probe have been designed to provide integration of the electronic system into different textile types (Fig.3). The technical parameters of PPG system have been previously evaluated in pilot study and described elsewhere (Grēve et al., 2011; Mečņika et al., 2012).

Recording of the physiological data obtained by the garment integrated PPG device has been accomplished by the custom developed software DataScope (LU ASI) for PPG signal acquisition and device operation in real time (Fig.4). This software is necessary for device setting changes, such as LED intensity, signal filtering and others. DataScope incorporates Pulse rate variability analyses module (PVR) which computes parameters from PPG signal: HR, foot-to-foot interval, systolic and diastolic peak ratio pulse rate variability parameters (PRSD – Pulse Rate Standard Deviation (n/min), MMPR – Max - Min Pulse rate Rate (n/min), FF– Pulse Width (ms), RRSD – Pulse Width Standard Deviation (ms), RMSSD – RMS Standard Deviation (ms), NN50 – Interval percentage, where Δ interval > 50 ms) however we excluded this analyses from current research (Fig.4).

Experiment procedure

To test PPG system operation during exercise and demonstrate potential of this innovation in sports physiology a pilot study has been performed. A PPG measurement has been taken from six sedentary normotensive female volunteers 19-27 year old, in rest condition, during cycling exercise and recovery period, that lasted 180s, 180s and 360 s. respectively. The subject inclusion criteria were absence of apparent arterial disease, physical abnormalities and medication. This study was approved by local ethics committee (LU EKMI). All experimental procedures were explained to the volunteers and informed consent obtained to participate in this study. The entire procedure has been carried out in laboratory settings in a well ventilated, temperature controlled room (23±1.5 ^{o}C). The physical load has been induced by veloergometer (Monark Ergomedic 894E Bike) at 120 W. During entire experiment PPG signal was acquired from the skin over the temporal artery *(a.temporalis)* by wireless PPG device integrated into a head bandage (see Fig.3). PPG device has been controlled by custom developed software DataScope (LU ASI), the off-line data analyses were performed by custom developed PPG waveform analyses software: *PPG_waveform analyses* (LU ASI) see fig. 7. The potentially important PPG waveform parameters were extracted from signal waveform and included in further analyses see figures 5 and 6. Figure 6 demonstrates the hemodynamic parameters obtained from the superficial temporal artery *(a.temporalis)*. Pulse duration (PP) is a time of interval between two successive feet (F_i, F_{i+1}), systolic peak amplitude (P_1) results from the direct pressure wave travelling from the left ventricle to the recording site, and a diastolic peak (P_2) derives from reflections of the pressure wave by arterie (Qawqzeh et al., 2011). The time to dA/dt_MAX characterizes cardiac function (ref). The 2nd derivative of PPG consists of four peaks - e a, b, c and d waves see figure 5. (Kaibe et al., 2002; Hashimoto et al., 2005; Šimek et al., 2005)

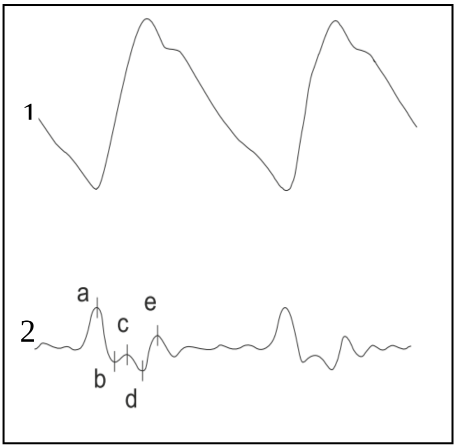

Figure 5. Initial PPG signal (1.) and second derivative of PPG signal: SDPPG (2.); signal deflection points are denoted: a - e

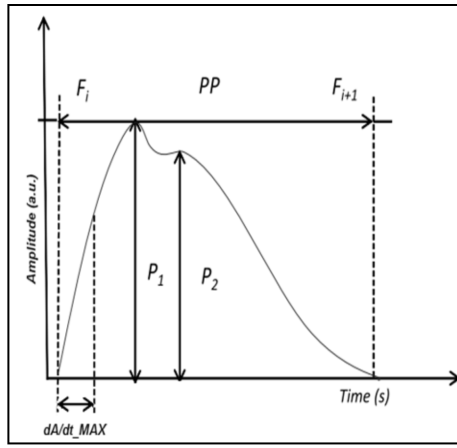

Figure 6. PPG waveform parameters computed by the PPG_waveform analyses software

The ratio between b and a peaks (b/a) is determined from the SDPPG signal and is related to distensibility of large conduit arteries. The average parameter values from aforementioned parameters were computed for all subjects in rest conditions (1 min before exercise) and during exercise (last minute of exercise), parameter changes during recovery were visually inspected by experienced expert.

Results

It was possible to obtain high quality, low noise PPG signal during rest, 120 W veloergometric exercise and recovery period from all six subjects. The subject movement during cycling produced minor artefacts which were successfully eliminated by DataScope real-time processing software. The larger sensor movement artefacts during cycling were reduced by “smart” bondage design preventing sensor floating on the skin and in the same time providing enough comfort for the subject.

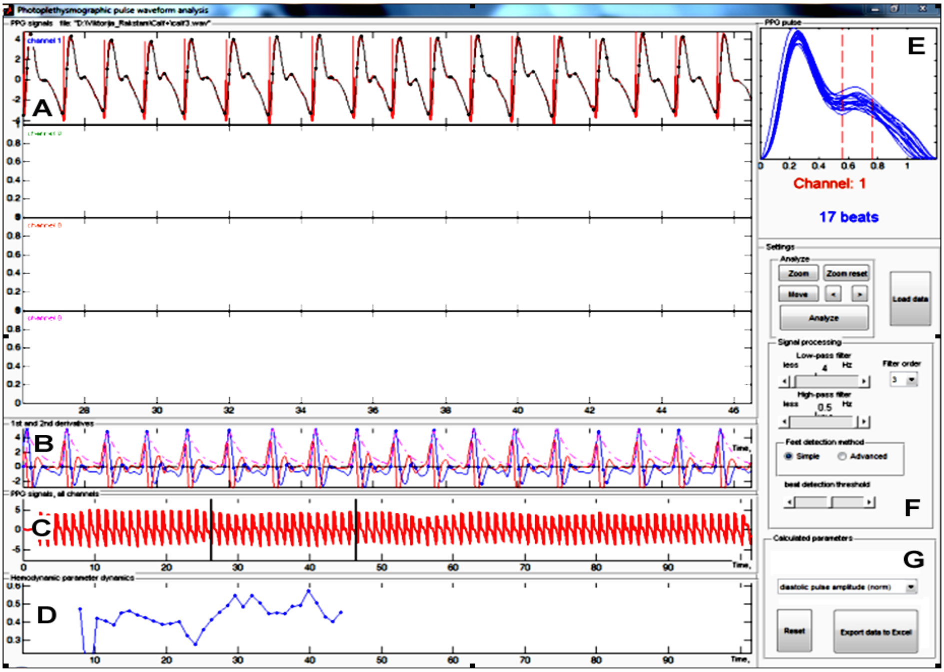

Figure 7. Software screenshot for PPG signal hemodynamic parameters analysis: A- PPG signal channel window; B- 1st derivative (blue line) and 2nd derivative (red line) of PPG signal; C- Signal window; D- Computed parameter window; E- Diastolic peak amplitude selector window; F- low-pass and high-pass filters settings; G- Selector for visualised PPG parameter (signal displays on D)

The incorporated multi diode PPG probe collected reflected light even in conditions when absorbance of the light has relatively high (dark skin colour, diverse tissue optical properties, low blood perfusion), thus insuring low noise, high amplitude signal. During resting conditions (baseline) all PPG signal components were relatively stable insuring accurate detection of waveform hemodynamic parameters. Although hemodynamic parameters vary across individuals it was feasible to calculate average values for the group: resting pulse duration was 0.74±0.14 sec., systolic peak amplitude 5.65±1.14 a.u., diastolic peak amplitude 4.11±0.9 a.u., time to dA/dt_MAX 0.056±0.005 sec., b/a ratio 0.69±0.09. In contrast to the rest conditions the onset of cycling exhibited abrupt changes of parameters. The general characteristics of the subjects and the summary of obtained PPG hemodynamic parameters during the last minute of veloergometric exercise are represented in table 1. The typical values of hemodynamic parameters during entire test protocol: rest, exercise and recovery period are shown in Figure 8. Changes during recovery period were exponential, containing two or more phases; therefore application of descriptive statistic for post-exercise recovery data has been avoided. The inspection of data trend by experienced physicians revealed close relationship to the physiological conditions: as seen in the figure 8. the beat-per-beat dynamics reflect different phases of protocol.

Table 1

Individual characteristics and PPG hemodynamic parameters of the subjects during exercise

CODE	*BMI (KG/M^2)*	*PULSE DURATION (S)*	*TIME TO DA/DT_MAX (S)*	*SYSTOLIC PEAK AMPLITUDE (A.U.)*	*DIASTOLIC PEAK AMPLITUDE (A.U.)*	*B/A*
I.A.	22.5	0.433±0.013	0.049±0.006	3.337±0.297	2.097±0.223	0.518±0.089
J.M.	21.5	0.411±0.012	0.050±0.005	14.167±1.002	5.400±0.529	0.581±0.093
R.K.	19.1	0.345±0.005	0.056±0.003	12.633±1.079	4.210±0.872	0.431±0.097
C.I.	20.5	0.353±0.003	0.058±0.028	7.633±1.380	3.163±0.607	0.463±0.105
H.T.	21.0	0.368±0.009	0.053±0.013	2.036±0.192	0.964±0.085	0.528±0.114
O.R.	22.1	0.410±0.006	0.059±0.007	5.957±0.352	3.107±0.687	0.526±0.070

Table 1.Individual characteristics and hemodynamic parameters of the subjects (mean ± SD). Table indicate subject code, body mass index (BMI) and five PPG waveform derived hemodynamic parameters computed for the last minute of cycling test: pulse duration, time to dA/dt_MAX, systolic and diastolic pulse amplitudes and second derivative parameter- b/a.

Discussion

Recently an attractive though challenging approach is optical non-intrusive acquisition of hemodynamic parameters characterizing progress of training, such as peak parameter values during an exercise or dynamics of post-exercise recovery period. During past five years there have been many attempts to develop photoplethysmography methods for assessment of cardiovascular system of athletes. The main questions addressed in these papers were: development of multispectral PPG probes (Asare et al., 2011), improvement of signal processing algorithms, to suppress noise and artifacts during body movement (Yong-Sheng et al. 2005), and seeking for a new waveform derived indexes (Huotari et al., 2011).

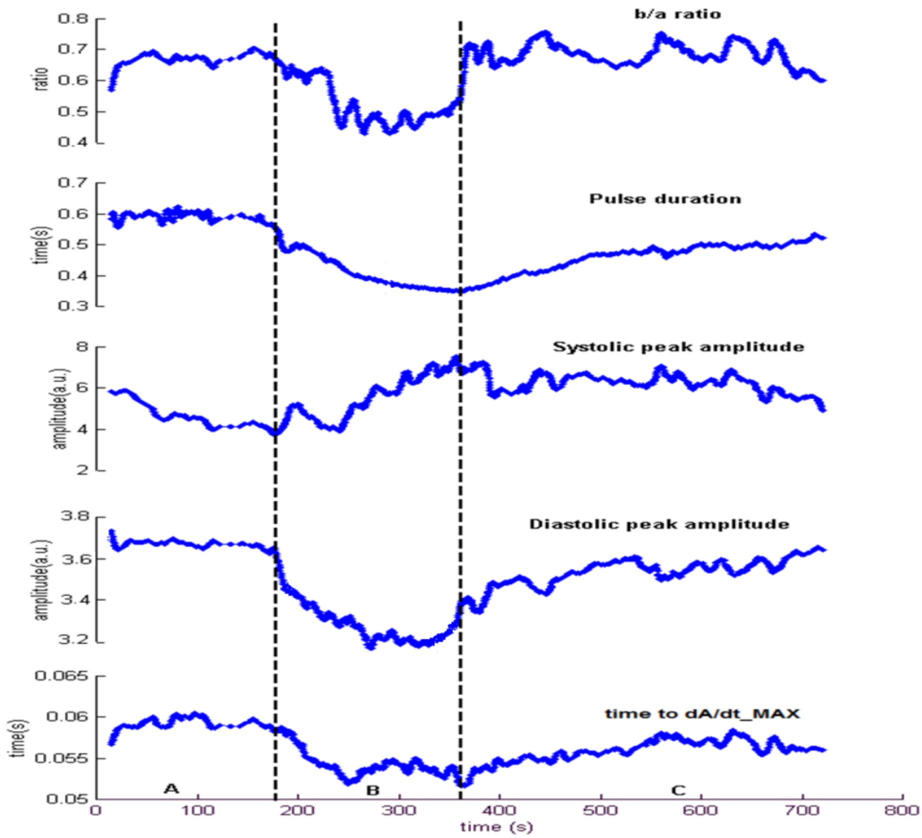

Figure 8. Representative example from one subject, showing typical beat-per-beat PPG waveform derived hemodynamic parameter changes during test procedure; A- hemodynamic parameters during rest conditions, B- cycling induced changes of hemodynamic parameters, C-oscillations of hemodynamic parameters during post exercise recovery period

Several studies described application of PPG in tissue blood flow assessment during an exercise incorporating multispectral approach in combination with unique geometry and position of photosensitive elements: the well-known paper published by Zhang and colleagues demonstrated potential of PPG in assessment of human anterior tibial muscle blood flow during arterial occlusion and isometric and concentric contractions (Zhang et al., 2001; Zhang et al., 2004). Later same group with Saundberg continued to develop this technique, and substantially improved muscle blood perfusion measurement technique. In his study the muscle perfusion was measured during exercise with a near-infrared light penetrated down to the vascular depth inside the muscle (Saundberg et al., 2005). One year later

Näslund and colleagues introduced and evaluated PPG technique to assess blood flow in bone tissue: measuring blood flow changes in human patellar bone (Näslund et al., 2006). The relatively few papers have been published that describe exercise induced PPG waveform parameter changes (Chellappan et al., 2008; Linder et al., 2008; Qureshi et al., 2002) and to the best of our knowledge there is almost no papers describing application of conduit artery PPG during an cycling exercise. Our technical design is based on utilization of special geometry and arrangement of light emitting and detecting elements in the probe, thus increasing sensitivity and reducing noise. Similarly study by Sandberg and colleagues confirmed the importance of distance and arrangement of detector and emitter elements for PPG signal recording from selected depth. Specially designed flexible Velcro straps compensated for the major movement artifacts during the exercise, while smaller signal distortions were eliminated by intelligent adaptive filtering. In the same way in the study by Lee B author emphasizes filtering procedure as a powerful tool to reduce artifacts in PPG signal (Lee et al., 2011). Application of novel -"digital" PPG registration principle yield device more robust against noise, reduced number of electronic components and substantially decreasing the size of device which was crucially important for successful integration in to textile. Our previous studies confirmed precision of similar digital PPG device in heart rate detection and heart rate variability studies in rest conditions: PPG signal was simultaneously recorded with a reference ECG signal from the group of healthy subjects. The reference devices were Polar® RS100 heart rate monitor and Contec Medical Systems TLC5000 12 Channel Holter (Grēve et al., 2011; Mečņika et al., 2012). In both case the prototype demonstrated high correlation with reference devices. The obtained PPG waveform derived hemodynamic parameters differ between the subjects although gender, body mass indexes (BMI) and age were similar. Such a difference was expected and could be partly explained by different fitness level (Rabbia et al., 2002) and psychological stress during recording procedure. Some subjects exhibit decreased pulse duration (0.6 sec), hence group average was slightly lower then normal, corresponding to approx. 81(beat per minute) bpm. Considering the fact that subjects were sedentary but healthy and normotensive this value is acceptable. PPG amplitude values were different because of distinctive tissue optical properties, however in all cases systolic peak amplitude was higher then diastolic. Similar findings regarding PPG amplitudes were reported by others(Allen, 2007; Korpas et al., 2009). Due to the limited calibration of PPG amplitude, more reliable and precise are PPG signal time based parameters, such as first, second or third derivative or preferably their ratios. However is some cases detection of time changes in the inflection phases might be sophisticated due to artefacts and signal noise (Sukor et al., 2011). In our study in the resting conditions time to dA/dt_MAX was approximately 0.056 which is acceptable for such situation (Adler et al., 1996; Morimont, 2012). The average b/a ratio was 0.7 and confirming normal distensibility of large conduit arteries (Takazawa et al., 1998). In general resting data is acceptable and previous investigators have reported similar results. As expected the most prominent changes of parameters occurred during exercise and recovery period. The cycling produced well known adaptation of cardiovascular system to an exercise induced stress, as reported elsewhere (MacDonald, 2006; Rozanski et al., 2001; Wilkins et al., 2004; Ho et al., 1997). In respect to baseline (rest conditions) pulse duration decreased, indicating elevated heart rate, systolic amplitude raised pointing to an elevated arterial blood pressure, b/a ratio and diastolic amplitude diminished indicating decreased arterial stiffness and lowered peripheral resistance (Takazawa et al., 1998; Otsuka et al., 2007; Hashimoto et al., 2005). Time to dA/dt_MAX decreased indicating increased ventricular contractility during an exercise (Adler et al., 1996; Morimont, 2012). Caution should be used when interpreting alterations of PPG waveform derived parameters because the pulse waveform is determined by the complex interactions of different factors such as systemic circulatory parameters and properties of blood vessels, including pressure wave reflection and pulse wave propagation in the aorta and arteries and waveform may depend on recording site (Allen, 2007). Summarizing our results we can conclude that the main advantages of the wearable PPG device for application in sport are: 1)Stable signal recording- headband is situated on the most stable segment of human body. 2)Miniature and waterproof device hardware- can be easily embedded in another type of sport garment, such as swimming cap. 3) Hemodynamic parameters are recorded from conduit artery (temporal artery), site which is relatively least affected by the *swelling of the tissue during exercise. 4)Provided parameters are related to systemic hemodynamics, such as cardiac contractility, peripheral resistance and arterial pressure which can be used for evaluation of training.*

Conclusion

The custom developed wearable telemetric PPG system demonstrated potential in monitoring of hemodynamic parameters during exercise, thus providing non-intrusive on-line control of important physiological parameters during training.

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