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HRV (Heart Rate Variability) as a non-invasive measurement method for performance diagnostics and training control

Abstract: The aim of this study was to determine whether non-invasive heart rate variability (HRV) recordings can be used to monitor training exercises and to estimate athletic performance. Thus far, condition and performance have been evaluated with lactate test procedures and spirometry. Several tests were conducted to determine the relationship of data from lactate test samplings, spirometry and HRV recordings. Four groups of professional athletes in different disciplines such as ball sports ($n=15$), martial arts ($n=17$), endurance sports ($n=8$) and hobby athletes ($n=6$) underwent a standardized treadmill or bicycle ergometer step test while increasing load rates, e.g. 2 km/h or 20-50 Watt every 3.5 minutes, synchronized with standardized series of lactate test sampling, spirometry and ECG recording. An inclusion criterion for all athlete groups was a minimum training frequency of an hour, five days a week focusing on continuous performance improvement. Evidence shows that offline analysis of ECG data allows conclusions on actual individual athletic performance without the need for complex instrumentation and laboratory environment. The total power parameter of the HRV reaches a plateau phase in all tested subjects and this plateau phase reaches zero near the 2 mmol threshold of lactate concentration in all subjects recorded on a bicycle ergometer. Nine out of ten subjects measured on the bicycle ergometer had negatively correlating data of lactate concentration and total power of HRV ($\alpha < 0.05$). Lactate measurements using treadmills require resting periods for blood sampling. As the HRV increases instantly in these resting periods, the use of bicycle ergometers, where no testing breaks are needed, is recommended for further research.

Keywords: Heart rate variability, HRV, performance diagnostics, training control, athletes, lactate

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1 Introduction

Measuring lactate concentration in capillary blood and calculating the aerobic and anaerobic threshold is an established method for assessing and monitoring athletic performance [1]. These thresholds are estimated when blood lactate levels reach 2 and 4 mmol in step tests [2]. In treadmill tests the increment typically lies between 0.5 and 2 km/h and between 20 and 50 W in bicycle or rowing ergometer tests. This testing procedure requires blood sampling, an invasive method that needs skilled personnel and a laboratory environment as well as time consuming offline analysis. An alternative method to estimate the athletic performance is spirometry. Spirometry variables include oxygen uptake (VO_2) and carbon dioxide output (VCO_2) [3]. Using VO_2 , the ventilatory threshold (VT) can be calculated, which exhibits a close relationship with lactate thresholds [4]. The VT is defined as the point where pulmonary ventilation increases disproportionately compared to the oxygen consumption during exercise [5]. This measurement method also requires skilled personnel and expensive metabolic gas analysis instrumentation.

According to Shaffer et al. [6] all healthy biological systems exhibit complex patterns of variability which can be described as mathematical chaos. The electrocardiogram (ECG) as a biological signal from the heart is non-periodic. The ECG appears as a so-called quasi-periodic signal which means that the signal pattern (P wave, QRS complex and T wave) is always similar, but not under periodic condition. The time between one R peak and the next R peak of an ECG changes continuously. This change is described as the heart rate variability (HRV). Therefore it can be concluded that the HRV is the variation in the time interval between successive heartbeats [7], [8].

During dynamic exercise, heart rate increases due to both parasympathetic withdrawal and augmenting sympathetic activity [9]. It is proposed that the relationship of these autonomic pathways is an indicator for performance. HRV, as the variation in the time interval between successive heartbeats, reflects the activity of the autonomous nervous

system [10]. HRV parameters are calculated from ECG recordings. Consecutive beat-to-beat intervals on the ECG are displayed in the so-called tachogram which can be analyzed in the time domain and in the frequency domain. Two important time domain analysis parameters are: the SDNN (standard deviation of the normal to normal interval) that is used as an indicator for general variability of the heart rate as well as the RMSSD (root mean square of successive differences), correlating with parasympathetic activities [11]. It is expected that both parameters decrease during incremental performance tests. The frequency domain of the tachogram is divided into four bands: high frequency (HF; 0.15 - 0.4 Hz), low frequency (LF; 0.04 - 0.15 Hz), very low frequency (VLF; 0.0033 - 0.04 Hz) and ultra low frequency (ULF; < 0.0033 Hz). The sum of these frequency bands is the total power (TP; < 0.4 Hz) [11]. The HF component corresponds to the parasympathetic pathway and reflects sleep, regeneration and fatigue. VLF and LF components relate to the sympathetic pathway and to physical stress, such as exercise and correlates with noradrenalin in plasma [11]–[13].

This study investigates the behavior of HRV time and frequency parameters during incremental athletic testing procedures and describes the relation between data of common performance tests and HRV in athletes.

2 Material and Methods

An overview of the measurement setup with professional athletes is given in figure 1. A minimum age of 18 years and the condition of a hobby or professional athlete, meaning a minimum training frequency for an hour per day, five days a week, with a focus on continuous performance improvement and regular competitions were prerequisites for participating.

Figure 1: Measurement setup for sport specific step tests (left: bicycle ergometer, right: treadmill); recording of heart rate variability, lactate sampling from the ear lobe and spirometry.

The subjects were divided into four categories depending on their practiced sport: martial arts, ball sports as well as

endurance and hobby athletes. Overall 46 subjects were included in the study (average age: 25 years).

The subjects underwent a standardized step test, including three simultaneous recordings: spirometry, lactate concentration and HRV. Lactate was sampled using different sport specific protocols on a bicycle ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany) or a treadmill (Quasar med, h/p/cosmos sports & medical gmbh, Nußdorf, Germany).

Spirometry was recorded using the Vyntus CPX Metabolic Cart (CareFusion, CareFusion GmbH, Höchberg, Germany) system. Lactate concentration in the blood was sampled after each step and several times after completion of the test. To this end, a 25µl capillary blood sample was taken from the ear lobe and analyzed using an enzymatic-amperometric measuring instrument (Biosen C-Line GP+, EKF Diagnostics GmbH, Barleben, Germany). The HRV of the subjects was recorded using the “RR measurement”-function of a pulse monitor wristwatch (Polar V800, Polar Electro, Kempele, Finland) in combination with the H10 sensor (Polar H10, Polar Electro) and a pulse monitor belt size M (Polar Pro belt, Polar Electro). In order to gather blood samples from the subjects using the treadmill for the testing procedure, the run had to be interrupted. These time periods were not considered in the HRV analysis.

3 Results

The data gathered confirmed that the HRV decreases under physical load, but no reproducible markers were found that

Figure 2: Lactate concentration and the heart rate variability parameter RMMSD (square root of the mean squared differences of successive RR intervals) of a step test on a treadmill (data of subject number 010). Dashed lines show the 2 and 4 mmol thresholds.

showed relations between time domain parameters of HRV (SDNN and RMSSD) and lactate or spirometry data. Exemplarily the RMSSD and lactate data of subject number 010 is shown in figure 2 with a spearman's correlation rho of -0.4286 ($\alpha = 0.3536$).

Figure 3: Lactate concentration and total power of heart rate variability of a step test on a treadmill (data of subject number 010). Dashed lines show the 2 and 4 mmol thresholds.

Nine out of ten data sets, recorded on the bicycle ergometer, showed a significant negative correlation between lactate concentration and the TP parameter of the HRV, seven out of ten subjects even had a very strong negative correlation with $\alpha < 0.01$ (table 1).

Table 1: Spearman's rank correlation coefficients between the total power of heart rate variability and lactate sampling of subjects recorded during a step test on a bicycle ergometer. * indicates a $\alpha < 0.01$.

Subject No.	rho	α
019	-0.9286	0.0067*
021	-0.8929	0.0123
022	-0.9643	0.0028*
023	-0.9643	0.0028*
024	-0.9762	3.97E-04*
025	-1	0.0167
026	-0.8833	0.0031*
027	-0.8286	0.0583
042	-0.955	0.004*
044	-0.9421	5.09E-06*
Mean:	-0.9121	0.0188

Figure 4 serves as an example to show the course of lactate concentration and the TP parameter of HRV during an incremental test on a bicycle ergometer. The dashed lines show the corresponding power at the 2 (310 Watt) and 4 mmol (356 Watt) thresholds. The TP frequency parameter of the HRV reaches a zero plateau in the same power step as the aerobic threshold. This behavior was shown in all subjects using the bicycle ergometer.

A subgroup analysis in an attempt to demonstrate the differences in the sport groups showed no clear findings. Furthermore, a spearman correlation was calculated between spirometry and HRV parameters and showed no significant relation.

4 Discussion

The data confirmed the findings of Perini et al. [14] that the TP of HRV decreases under physical exercise. A plateau phase of this parameter was shown in all subjects. This plateau phase reached zero in all subjects measured on the bicycle ergometer near the 2 mmol blood lactate threshold which can be used to evaluate physical performance. This behavior is exemplarily shown in subject nr. 026 (figure 4). The subjects recorded on the treadmill had to interrupt running for the blood sampling procedure. In these short periods the HRV increased again and gave new baseline values for the next step which influenced further data analysis. The TP parameter of HRV recorded using the treadmill also showed a plateau in all subjects, but the point where the plateau reached zero had a time shift to the 2 mmol lactate threshold, exemplarily shown with data of subject nr. 010 in figure 3. This time shift could be due to the influence of the lactate sampling in the resting periods where HRV increases instantaneously.

Table 1 showed that lactate concentration and TP of HRV negatively correlates significantly ($\alpha < 0.05$) under increasing physical load in a bicycle ergometer step test in nine out of ten subjects. Furthermore, there was a very strong negative correlation ($\alpha < 0.01$) in seven out of ten subjects. No relation was found between the 4 mmol threshold and markers of HRV. Additionally, a subgroup analysis showed no sport specific HRV behavior. No reproducible markers were found comparing spirometry data and HRV time and frequency parameters.

A manual identification of HRV thresholds, as in Karapetian et al. [5] and Simões et al. [15], as well as a nonlinear analysis, like examined by Flöter et al. [16], is planned in the further course of this study.

Figure 4: Lactate concentration and total power of heart rate variability of a step test on a bicycle ergometer (data of subject number 026). Dashed lines show the 2 and 4 mmol thresholds.

To conclude, the study showed that there is evidence that the TP frequency parameter of HRV recordings correlates with lactate concentration, and that the curvature reaches zero near the 2 mmol lactate threshold, in blood levels during step tests on bicycle ergometers. Important is a constant physical load with no resting periods.

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