Heart Rate Variability During Physical Exercise

Heike Leutheuser, Bjoern Eskofier

Digital Sports Group, Pattern Recognition Lab, University of Erlangen-Nuremberg, Germany

Introduction

Heart rate variability (HRV) is the present oscillation of the heart rate. The interest in HRV as a parameter of the parasympathetic and sympathetic influence of the autonomic nervous system on the heart has increased in the last few decades (Kaikkonen et al., 2007). It is known that its influence changes under different conditions such as rest, exercise or mental stress and different body postures (supine, sitting, standing). Results how its influence changes during exercise have been inconsistent (Boettger, 2010, Tulppo et al., 1996). HRV parameters are used as indicators for fatigue or overtraining (Aubert et al., 2003).

HRV parameters can be calculated in the time or frequency domain. Standard parameters that are derived from the HRV signal in the time domain are the mean RR interval, the mean heart rate or the square root of the mean squared differences of successive RR intervals (RMSSD) (Task Force, 1996). In the frequency domain, features determined by the power spectral density (PSD) like the power within the low frequency (LF) band (0.04 - 0.15 Hz) or the high frequency (HF) band (0.15 - 0.4 Hz) are common (Task Force, 1996).

We investigated the influence of physical activity on HRV in a large-scale study. Running, the chosen physical activity for this manuscript, is a task that has increased its interest in the last few years when looking at the number of recreational athletes participating in Marathons. Running does not require much equipment, can be done almost everywhere and is inexpensive. Here, we examine if and how HRV parameters of the time or frequency domain are changing during one hour of running.

Methods

Hardware The Polar RS800 Running Computer was used to obtain kinematic data (running speed, stride frequency) and physiological data. The recorded biosignals were the heart rate and the time between two consecutive heart beats (RR intervals) with a resolution of 1 ms (Eskofier et al., 2008, Eskofier et al., 2012). The running speed was measured with a sampling frequency of 0.2 Hz.

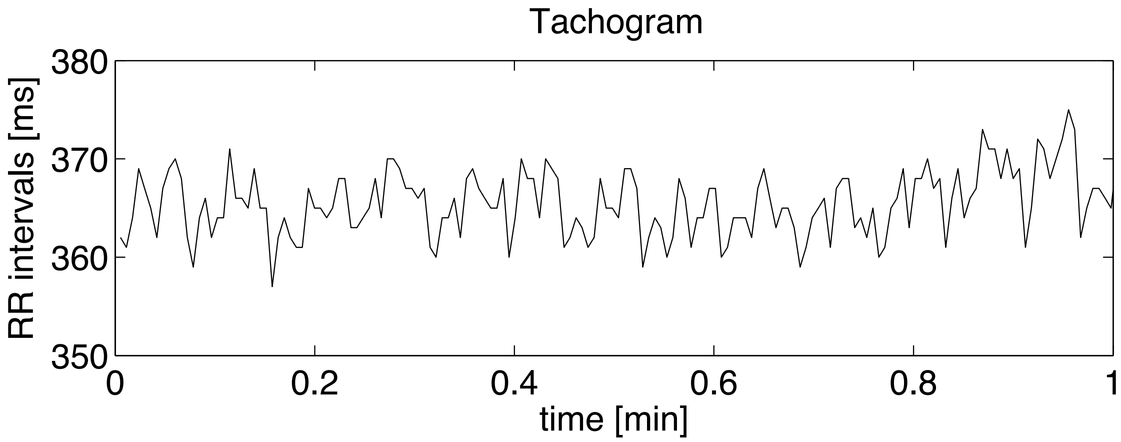

Fig. 1 Tachogram of RR intervals in ms over time

Data The study consisted of 431 runners whose running experience varied within the volunteers. More details on the study can be found in the original publications (Eskofier et al., 2008, Eskofier et al., 2012). A subset of 295 subjects (98 female and 176 male*, age 43 ± 11 years*, BMI: 23.1 ± 2.4 kg/m²*, mean ± SD (standard deviation)) was used as for these the entire data sets were available. The subjects got the task to complete a run in one hour in a self-determined fashion, without distance or speed requirements.

Analysis Several parameters were calculated to obtain different HRV measures. All physiological parameters for HRV analysis were calculated from the tachogram (Fig. 1), in which consecutive RR intervals are plotted (Task Force, 1996). The RR intervals were divided in segments of five minutes each. In the time domain, the average heart rate and the square root of the mean squared differences of successive RR intervals (RMSSD) were calculated (Task Force, 1996):

$$RMSSD = \sqrt{\frac{\sum_{i=1}^{N-1}(RR_{i+1} - RR_i)^2}{N-1}}.$$

In the frequency domain, the power spectral density (PSD) of RR intervals was determined. After eliminating the DC component by subtracting the mean of the five minute segment, the Fourier transform (FT) of the signal was obtained. Then, the squared magnitude values of the FT were calculated. This PSD was normalized with the total power minus the power of the very low frequencies (≤ 0.04 Hz) (Task Force, 1996). The low frequency component (LF) of this PSD reached from 0.04 to 0.15 Hz, and the high frequency component (HF) from 0.15 to 0.40 Hz. The results in the frequency domain are based on the LF/HF ratio. The calculation of the FT required equidistant values of RR intervals. Therefore the RR intervals were linearly interpolated with a sampling frequency of 8 Hz (Singh et al., 2004).

The kinematic parameter running speed was divided in segments of five minutes each likewise the tachogram. The average running speed within each segment was calculated as fourth parameter.

* 27 subjects did not answer the questionnaire with respect to gender, age and BMI

Statistics All parameters were evaluated using a univariate analysis of variance (ANOVA) with repeated measures and a multivariate ANOVA with repeated measures (Stevens 1996). In an ANOVA model, it is tested if the null hypothesis is accepted at the significance level α. The null hypothesis is that there is no difference in the means of all segments. The alternative hypothesis is that at least two means differ significantly. If the null hypothesis was rejected, multiple dependent t tests with the Bonferroni correction as post-hoc procedure were used. The Bonferroni correction was necessary to keep the overall α under control.

The basic requirements in applying one of these ANOVA models were independence of observations and multivariate normality. The independency was given due to the problem. The Lilliefors test (Lilliefors 1967), which is a specialized version of the Kolmogorow-Smirnow test for testing normal distribution, was used at the significance level α. When parameters after visualization in a histogram did not resemble a normal distribution, the natural logarithm of these parameters over the data set was used. The method of univariate ANOVA with repeated measures assumes the sphericity or circularity assumption. If the sphericity assumption is violated, the Greenhouse & Geisser correction (Stevens 1996) was applied to decrease the degrees of freedom.

Each analysis was performed using the Matlab package (MathWorks Inc., USA).

Results

The results section has been divided into two parts. The first part deals with the experiments described in the methods above. Due to the interesting results, a further experiment with only the last three segments was performed. The results of this experiment are described in the second part.

Tab. 1 states the results of the experiments over the complete data set. The three physiological parameters heart rate, ln(RMSSD) and ln(LF/HF) and the kinematic parameter speed were tested for the requirements of both ANOVA models. Although the Lilliefors test was not satisfied for every segment, both ANOVA models with repeated measures were applied to the parameters (McDonald, 2009) except for ln(RMSSD). Here no single segment fulfilled the requirement of multivariate normality. The sphericity assumption, necessary for the univariate ANOVA model, was rejected for the three remaining parameters. Hence, the degrees of freedom for the univariate ANOVA were decreased with the Greenhouse & Geisser correction in these cases. In our case, both degrees of freedom were divided by the factor 12. Both ANOVA models revealed the same result. The null hypothesis of equal means within these 13 segments was rejected for every parameter.

Hence, the post-hoc procedure of multiple dependent t tests with the Bonferroni correction was applied. The post-hoc procedure, presented in Fig. 2, revealed that each parameter had adjacent segments with no significant differences parameter speed.

*Table 1: Results of the Lilliefors test and for both ANOVA models. Abbr.: seg. = segment; uni. = univariate; multi. = multivariate; *The numbers in the brackets indicate segments, in which the Lilliefors test was rejected.*

	Lilliefors test (α = 0.10)	**uni. ANOVA (α = 0.05)**	**multi. ANOVA (α = 0.05)**
Heart rate	accepted (2)*	F(1,294) = 1334.8, p < 0.001	F(12,283) = 480.2, p < 0.001
ln(RMSSD)	rejected	n.a.	n.a.
ln(LF/HF)	accepted (1,13)*	F(1,294) = 294.7, p < 0.001	F(12,283) = 126.5, p < 0.001
Speed	accepted (1,9,11)*	F(1,294) = 2194.3, p < 0.001	F(12,283) = 338.3, p < 0.001

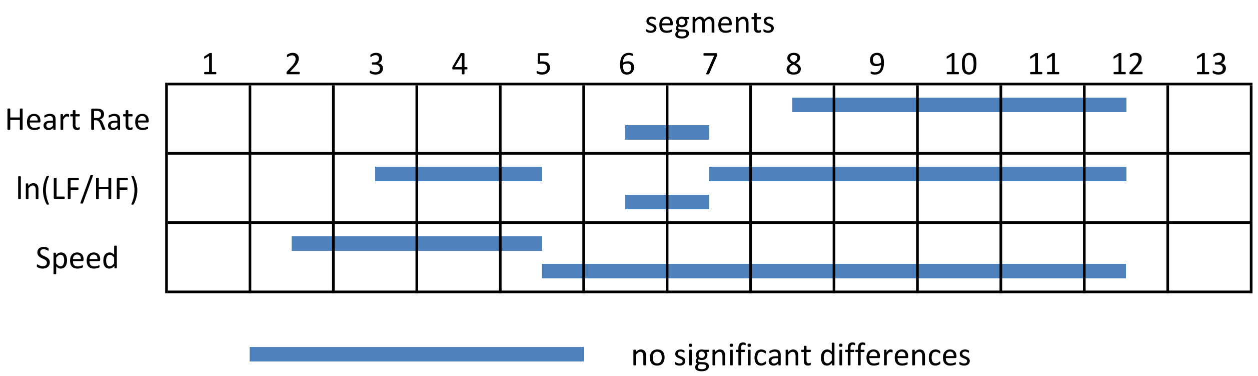

Fig.2: Results of the post-hoc procedure (multiple dependent t test with the Bonferroni correction) for all three parameters. The blue bar indicates adjacent segments with no significant differences.

Because of the interesting results, further investigations were done with the last three segments (segments 11 to 13). As each segment consisted of 5 minutes, the segments were divided in minutes. This resulted in a considered time of 15 minutes in total. Tab. 2 shows the results of the Lilliefors test and both ANOVA models. The parameter ln(RMSSD) was again tested for the requirements of the ANOVA models and, as neither the multivariate normality nor the sphericity assumption was fulfilled, not considered in further analysis. The three remaining parameters accepted mostly the normality assumption. The sphericity assumption was rejected for the three parameters, wherefore the Greenhouse & Geisser correction was used in the univariate case, too. Both ANOVA models revealed the result that the means of each parameter considering these 15 minutes were not equal. The post-hoc procedure is shown in Fig. 3.

*Table 2: Results of the Lilliefors test and for both ANOVA models for the last three segments (last 15 minutes). Abbr.: seg. = segment; uni. = univariate; multi. = multivariate; *The numbers in the brackets indicate segments, in which the Lilliefors test was rejected.*

	Lilliefors test (α = 0.10)	**uni. ANOVA (α = 0.05)**	**multi. ANOVA (α = 0.05)**
Heart rate	accepted (5)	F(1,294) = 213.4, p < 0.001	F(14,281) = 75.6, p < 0.001
ln(RMSSD)	rejected	n.a.	n.a.
ln(LF/HF)	accepted (4,6,12,13)	F(1,294) = 70.1, p < 0.001	F(14,281) = 26.7, p < 0.001
Speed	accepted (1,2,8,12)	F(1,294) = 450.7, p < 0.001	F(14,281) = 65.4, p < 0.001

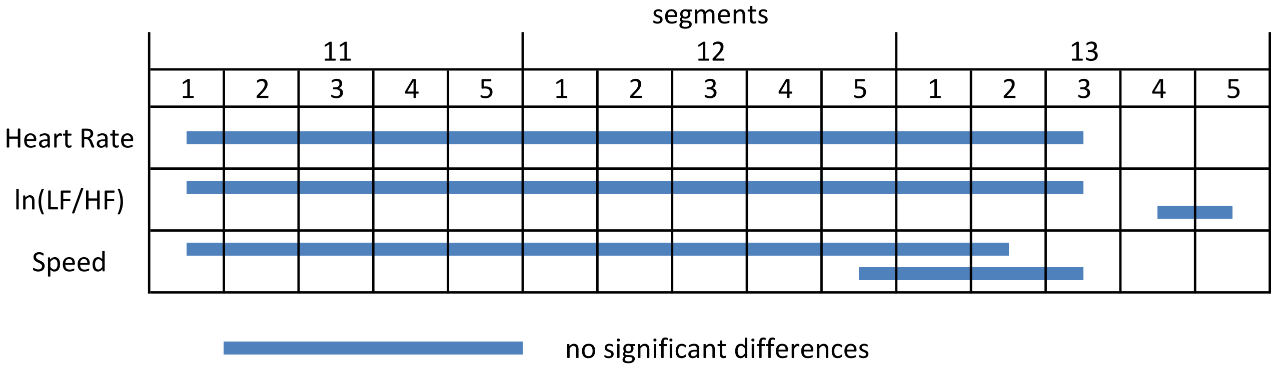

Fig.3: Results of the post-hoc procedure (multiple dependent t test with the Bonferroni correction) for the last three segments (last 15 minutes) for three parameters. The blue bar indicates adjacent segments resp. minutes with no significant differences.

Discussion

The post-hoc procedure of multiple dependent t tests demonstrated that no different means for the segments 8 to 12 were present in all four parameters. As each of the three parameters changed from the 12th to the 13th segment, these segments were further investigated. The 13th segment is the last segment in which data was recorded and all volunteers were free to run or to rest, just as they preferred.

Partitioning the last three segments into five sub-segments of length one minute allowed a closer investigation of the end of the training session. Considering the three longest bars in Fig. 3, the speed changed between the second and the third minute of the 13th segment. The heart rate and the ln(LF/HF) changed one minute later: between the third and the forth minute of the last segment. Here a delay of one minute was obvious.

The cardiovascular system has to deal with an increased demand during physical exercise. As soon as the physical activity is finished, the cardiovascular system adapts to the current physiological demand. We found a delay of one minute between the physiological parameters and the kinematic parameter after decreasing the running speed. One minute is the time that our running population needed to adapt the circulatory system to a change in running speed.

Looking at the start of the training, the speed did not change between the 2nd to the 5th segment and then between the 5th to the 12th segment. The parameter ln(LF/HF) did not change between the 3rd to the 5th segment and between the 6th and the 7th segment. If a connection between these two parameters was existent, is uncertain.

The heart rate did not change between the 6th and the 7th segment. As the heart rate changed from the start of the exercise until the 6th segment, this is another evidence that the circulatory system needs time to adapt to physiological changes.

One drawback of this study is that neither a resting phase at the beginning nor the end had been included. Therefore, it is not possible to compare running and rest data. Another disadvantage is that the data sets were divided in segments of five minutes. Whether this length of the segments reflects well on the autonomous nervous system has to be further evaluated.

Summary and outlook

We presented an analysis of the variation of heart rate and the ln(LF/HF) as well as the kinematic parameter running speed over time during a free one hour outdoor run. Our analysis was based on two different ANOVA models with repeated measures. The used post-hoc procedure consisted of multiple dependent t tests with the Bonferroni correction. The ln(RMSSD) as a parameter for the chosen ANOVA models had to be excluded as the requirements for the ANOVA models were not fulfilled.

During this one hour of running, all three parameters reached a process where the means did not alter significantly. We detected a delay of one minute between varying running speed and measured heart rate.

In further analysis, subgroups of athletes, like female and male runners or experienced and unexperienced runners will be examined. With these further investigations more information regarding HRV and fatigue could be gained.

Acknowledgments

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