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Full Length Article

Non-linear dynamics of cardiac autonomic activity during cycling exercise with varied cadence

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ABSTRACT

In recent years, complex models of cardiac regulation have integrated heart rate variability (HRV) as a measure of the cardiac autonomic activity during exercise. Using detrended fluctuation analysis (DFA) technique, the present study examines the influence of cycling cadence and exercise duration on non-linear dynamics of HRV.

Sixteen trained cyclists performed a 60-minute exercise bout at 90% of the individual anaerobic threshold on a bicycle ergometer. Cadence was changed every 10 min (90–120–60–120–60–90 rpm). Heart rate (HR) and RR-intervals were recorded continuously during exercise. HRV time domain measures (meanRR, SDNN) and correlation properties were analyzed using short-term scaling exponent alpha1 of DFA. Moreover, blood lactate (La) and rating of perceived exertion (RPE) were recorded at regular intervals at the end of condition.

HR, La and RPE increased significantly at 120 rpm compared to 60 rpm. In contrast, all analyzed HRV parameters (meanRR, SDNN, DFA-alpha1) showed a significant decrease during cycling at 120 rpm compared to 60 rpm. The comparison of the first and last 10 min with the same cadence indicates a significant increase in HR and RPE, but also a significant decrease in all analyzed HRV measures.

The decrease of HRV values over time and in relation to the increase in cadence indicates a decrease in the overall variability as well as a reduction in complexity of the RR-interval-fluctuations due to the increased organismic demands. Therefore, the decrease of DFA-alpha1 might be associated with a withdrawal of the organismic system aiming at the maintenance of the homeostasis under the control of the central nervous system. In this context, non-linear HRV analyses provide a more systemic view of cardiac regulation during exercise.

1. Introduction

In recent years, different concepts of cardiac regulation and exercise fatigue have integrated heart rate variability (HRV) as a measure of the cardiac autonomic activity during endurance exercise (Hottenrott & Hoos, 2017; Michael, Graham, & Davis, 2017). With regard to time and frequency domain of the HRV parameters, physical demands have shown to induce a decrease in the total variability due to 1) drastic reduction in vagal activity and 2) increases in sympathetic activity, regardless of exercise intensity

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(Robinson et al., 1966, Yamamoto, Hughson, & Nakamura, 1992, Nakamura, Yamamoto, & Muraoka, 1993, Tulppo, Makikallio, Takala, Seppanen, & Huikuri, 1996, 2001). Furthermore, it has been reported that these linear parameters lead to inconsistent results during different modes of exercise (Hottenrott, Hoos, & Esperer, 2006; Sandercock & Brodie, 2006). The present state of research suggests that under physiological conditions, the HRV signal is mainly composed of quasi-periodic oscillations, while also showing random fluctuations and so-called fractal structures (Goldberger et al., 2002) which cannot be analyzed with linear parameters. Consequently, additional to time and frequency domain measures some studies have examined non-linear HRV parameters to analyze time series during different exercise modes (Tulppo et al., 2001; Hautala, Makikallio, Seppanen, Huikuri, & Tulppo, 2003; Casties, Mottet, & Le Gallais, 2006; Lewis & Short, 2007; Platisa, Mazic, Nestorovic, & Gal, 2008; Hottenrott & Hoos, 2017). Futhermore, these parameters may allow a more systemic view of the cardiac regulation and autonomic control during different exercise modes. In this respect, methods of non-linear dynamics in HRV analysis do not describe the amplitude of the variability, but rather qualitative characteristics of the structure and dynamics of the signal. For example, the detrended fluctuation analysis (DFA) allows the separation of the random variability in the time series from the variability resulting from physiological processes (Goldberger et al., 2002; Hoos, 2010; Hottenrott & Hoos, 2017). DFA attempts to quantify the presence or absence of long range scale-invariant or fractal correlation (Seely & Macklem, 2004). Thus, the DFA is a non-linear method to quantify the fractal scale and the degree of correlation of an HRV signal in form of a dimensionless measure. This method has already been applied for cardiovascular risk assessment as well as prognosis in clinical settings (Peng, Havlin, Stanley, & Goldberger, 1995; Stein, Domitrovich, Huikuri, & Kleiger, 2005; Platisa & Gal, 2008; Huikuri, Perkiömäki, Maestri, & Pinna, 2009; Perkiömäki, 2011). As DFA provides robustness against artefacts and has a low dependence on heart rate (Peng et al., 1995; Tapanainen, Seppanen, Laukkanen, Loimaala, & Huikuri, 1999; Sandercock & Brodie, 2006), this method seems suitable for the analysis of the complexity of cardiac regulation regarding the autonomic nervous system activity during various exercise modalities and intensities.

Investigating the isolated influence of different exercise modes on HRV, previous studies have shown a decrease of i.a. time domain and non-linear HRV measures with increasing exercise intensity in incremental exercise test settings (Hautala et al., 2003; Casties et al., 2006). Further studies are necessary to quantify the influence of other exercise variables, such as movement frequency and duration to be able to use the additional value of DFA analysis for exercise control in the future. In this respect, previous studies reported that cycling cadence influences performance (Faria, Parker, & Faria, 2005), although there is no consensus on the basic criteria for the choice of cadence. Ettema and Lorås (2009) conclude that increasing cycling cadence leads to a small reduction in efficiency. However, no firm conclusions on the energetically optimal cadence for cycling can be drawn due to the multiple factors that affect energy expenditure. Gotshall, Bauer, and Fahmer (1996) indicated that higher pedal cadences result in a more effective muscle pump, which in turn increases the blood flow and the venous return. Furthermore, few studies investigated the influence of cycling cadence and exercise duration on cortical activity using electroencephalography (EEG) during and after cycling exercise and reported an increased activation at higher cadences and a decreased activation over time (Ludyga et al., 2016).

In this context, the aim of the present study was to analyze the influence of cycling cadence and exercise duration on time domain HRV measures, as well as its non-linear dynamics in a laboratory setting, in order to investigate the influence on complex organismic demands and the additional value of DFA analysis for the understanding of movement control. We postulated that at higher cadence and in the course of exercise duration, a loss of variability and complexity of cardiac regulation is to be expected.

2. Materials and methods

2.1. Subjects

Sixteen endurance trained cyclists (age: 25.9 ± 3.8 years; height: 180.7 ± 6.1 cm; body mass: 77.4 ± 8.2 kg; body fat: 12.3 ± 3.4%; VO_2peak: 54.1 ± 6.1 ml/min/kg) were recruited from local sports clubs. We included male, non-smoking adults, which performed cycling training sessions for at least 8 h per week within the last 6 months. A preliminary medical check-up following the S1 guidelines of the German Association for Sports Medicine and Prevention (DGSP, 2007) was performed to make sure subjects were free of cardiovascular, neurologic, pulmonary or orthopedic issues. The check-up also included an ECG at rest and a personal anamnesis. Following the explanation of any risks and benefits associated with the study, the participants provided written informed consent. All procedures were in line with the declaration of Helsinki and the study protocol had been approved by the local ethics committee.

2.2. Procedure

First, body mass and body fat were measured (BC-545 Innerscan, Tanita, Netherlands). Afterwards, aerobic fitness was assessed using spiroergometry (Metamax 3b, Cortex, Germany) during an incremental test until voluntary exhaustion (start: 100 W, increment: 20 W, length: 3 min, cadence: 80–90 rpm) on a high-performance bicycle ergometer (E 2000s, FES, Germany). Blood lactate concentration was assessed at the end of each stage. Based on Dickhuth et al. (1991), the individual anaerobic threshold (IAT) was assessed based on lactate-power curves. One week after the first laboratory visit, participants completed a 60-minute exercise bout at 90% of the IAT (Power in Watt [W] was defined as external workload, (Fig. 1)) on the same bicycle ergometer. This load was chosen to ensure that the session has a submaximal intensity, which can be endured for 60 min. Prior to the exercise bout, there was a warm up at 100 W for 10 min followed by 150 W for 5 min (cadence: 80–90 rpm). While the external load was held constant during the subsequent 60-minute bout, cadence was changed every 10 min (90–120-60–120–60–90 rpm). In order to maintain the cadence during the test, cyclists received visual feedback from the RadErgoII software (Fig. 2). After the exercise bout there was a cool-down