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Combined heart rate variability and dynamic measures for quantitatively characterizing the cardiac stress status during cycling exercise

Szi-Wen Chen [a,*], Jiunn-Woei Liaw [b], Ya-Ju Chang [c], Li-Ling Chuang [c], Chun-Tse Chien [a]

[a] Department of Electronic Engineering, Chang Gung University, Taoyuan 333, Taiwan
[b] Department of Mechanical Engineering, Chang Gung University, Taoyuan 333, Taiwan
[c] Department of Physical Therapy and the Graduate Institute of Rehabilitation Science, Chang Gung University, Taoyuan 333, Taiwan

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ABSTRACT

In this study, we aimed to seek for different ways of measuring cardiac stress in terms of heart rate variability (HRV) and heart rate (HR) dynamics, and to develop a novel index that can effectively summarize the information reflected by these measures to continuously and quantitatively characterize the cardiac stress status during physical exercise. Standard deviation, spectral measure of HRV as well as a nonlinear detrended fluctuation analysis (DFA) based fractal-like behavior measure of HR dynamics were all evaluated on the RR time series derived from windowed electrocardiogram (ECG) data for the subjects undergoing cycling exercise. We recruited eleven young healthy subjects in our tests. Each subject was asked to maintain a fixed speed under a constant load during the pedaling test. We obtained the running estimates of the standard deviation of the normal-to-normal interval (SDNN), the high-fidelity power spectral density (PSD) of HRV, and the DFA scaling exponent α, respectively. A trend analysis and a multivariate linear regression analysis of these measures were then performed. Numerical experimental results produced by our analyses showed that a decrease in both SDNN and α was seen during the cycling exercise, while there was no significant correlation between the standard lower frequency to higher frequency (LF-to-HF) spectral power ratio of HRV and the exercise intensity. In addition, while the SDNN and α were both negatively correlated with the Borg rating of perceived exertion (RPE) scale value, it seemed that the LF-to-HF power ratio might not have substantial impact on the Borg value, suggesting that the SDNN and α may be further used as features to detect the cardiac stress status during the physical exercise. We further approached this detection problem by applying a linear discriminant analysis (LDA) to both feature candidates for the task of cardiac stress stratification. As a result, a time-varying parameter, referred to as the cardiac stress measure (CSM), is developed for quantitatively on-line measuring and stratifying cardiac stress status.

1. Introduction

It is worth noting that we have developed a cycling based ergometer system for real-time fatigue monitoring and analysis [1]. Although using such a system to perform on-line fatigue progression analysis is of importance to many aspects of applications and has been considered unprecedented, people may feel even more interested in exploring the effects of physical exercise training on the progression of cardiac stress status based on the same ergometer we developed, in such a way that this can be used in sports medicine, and may also be of interest to the cardiologists who carry out stress tests for monitoring the heart condition in patients with heart diseases.

In general, heart rate (HR) usually increases when one is undergoing physical exercise. In this aspect, the Borg rating of perceived exertion (RPE) scale may provide a useful way to reflect how hard one feels about the work while undergoing physical exercise [2]. With ranging from 6 to 20, the Borg RPE scale has been commonly used as a typical and convenient index for monitoring subjective perceived exercise intensity. In fact, the idea of a relationship between HR and exercise in terms of RPE is not original. For example, a previous study in literature reported that the increase in RPE was related to both the cardiovascular status monitored by heart rate (HR), and the local muscle factors monitored by the median frequency of electromyogram (EMG) during fatigue induced by stepping exercise [3]. Another work in literature also indicated that there might exist a linear relationship

* Corresponding author. Tel.: +886 3 211 8800x5792; fax: +886 3 211 8507.
E-mail addresses: chensw@mail.cgu.edu.tw (S.-W. Chen), markliaw@mail.cgu.edu.tw (J.-W. Liaw), yjchang@mail.cgu.edu.tw (Y.-J. Chang), lchuang@mail.cgu.edu.tw (L.-L. Chuang), herkorob@gmail.com (C.-T. Chien).

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between RPE and HR during progressively increasing workloads and submaximal constant load, obtaining correlations ranging from 0.71 to 0.91 [4]. Moreover, Borg also suggested that a high correlation exists between ten times of a person's RPE value and his actual HR during physical activity and this may provide as a good estimate of actual HR during exercise. However, Chang et al. argued that the estimation of HR (i.e., $HR = 10 \times RPE$) might be invalid for exercise at constant workload when exhaustion occurred and suggested that weighting of other factors, such as the factors that influence HR dynamics, should be considered [3].

According to the review of previous works as presented as above, we may see that although the RPE scale has been commonly used for exercise study, exercise itself is a more complex activity which involves cardiovascular factors and hence may not be solely related to a subjective RPE value. Therefore, developing a novel index other than RPE and seeking for its applicability for objectively and quantitatively assessing cardiac stress status during physical exercise are essentially needed. With this in mind, the scientific question of this work is “how can we find an effective way to objectively and quantitatively measure the cardiac stress during the physical exercise?” Seeking for the answers to such a question actually motivated this work. Since greater RPE values resulting from exercise should be related to incremented sympathetic tone and reduced parasympathetic tone, it is nature to speculate that heart rate variability (HRV), rather HR, may provide a more effective and reliable way for figuring out the relationship between cardiac stress and physical exercise. In this aspect, some previous researches in literature, for instance, have also reported that HRV may and does show influence of mental and physical stress [5,6].

However, since variation in HR could be also attributed to a variety of factors, different aspects of HRV analysis may be needed for measuring cardiac stress. Among HRV applications, there are a number of measures derived from the beat-to-beat fluctuations having been widely used as indices of cardiac autonomic control [7–9]. These measures were simply developed using the time- and/or frequency-domain analyses, such as the calculation of the standard deviation and the power spectral density (PSD) of the HR fluctuations. In the time-domain analysis, it has been widely accepted that the standard deviation of the normal-to-normal interval (SDNN) or its related quantities may serve as diagnostically useful HRV indices. As for the frequency-domain analysis, the conventional fast Fourier transform (FFT) is usually applied for PSD calculation. It should be noted that since a uniformly resampling process on the original RR data is required for FFT-based PSD calculation, a low-pass filtering effect due to resampling might undesirably cause a distortion on the PSD of HRV [10]. In order to avoid such a problem, instead of using FFT a compressed sensing (CS) based algorithm for spectral estimation of HRV incorporating the integral pulse frequency modulation (IPFM) model has been developed in previous works [11,12]. Knowing as a novel sensing/sampling paradigm, the theory of CS asserts certain signals that are considered sparse or compressible can be possibly reconstructed from substantially fewer measurements than those required by traditional methods. Using the IPFM model, an ℓ_1-minimization based CS framework was developed for deriving the amplitude spectrum of the modulating signal for HRV assessments in our previous works [11,12]. Since the CS method actually can provide more accurate, robust and high-fidelity spectral estimates of HRV than the conventional approaches, such as the Lomb or FFT methods, in this study we thus used it to estimate the PSD of HRV directly from unevenly sampled RR data.

In addition, HR dynamics were also studied with a nonlinear detrended fluctuation analysis (DFA) based fractal measure. In this aspect, some researchers employed the fractal measures to quantitatively characterize the HR dynamics, and concluded that these measures might be well suited for non-stationary situations, such as incremental exercise, as mentioned previously [13,14]. Moreover, it has been also demonstrated that fractal-like characteristics of HR can be considered as an indication of a normal and healthy heart since fractal measure of HR has manifested itself to change towards uncorrelated randomness for those who were suffering from different heart diseases or in the aging population [14–16]. Therefore, we may speculate that using the fractal scaling exponent, it may be possible to seek a way to effectively quantify the cardiac stress status during exercise.

In this study, we started from examining the effects of physical exercise on HR dynamics and then made a possible link between cardiac stress status and a variety of HRV measures. Time-, frequency-domain measures of HRV and DFA based fractal measure of HR dynamics, as stated above, were all considered as candidates in our investigations. In short, our study aimed to seek for different ways of measuring cardiac stress in terms of HR dynamics first and then to devise a novel index, called the cardiac stress measure (CSM), which can effectively summarize the information reflected by these measures to continuously and quantitatively characterize the cardiac stress status during physical exercise. With CSM, both the cardiac stress status and onset of cardiac stress “overload” can be detected, and thus, designing feasible training programs for patients with heart diseases would become more efficient and easier. Furthermore, since an exercise bicycle can provide a convenient, safe, and effective cardiovascular exercise the patients may need, our CSM index can be incorporated into an exercise bicycle-based ergometer system so the system may have possible applications in many areas. For example, such a system can be used in sports medicine, or applied to stress tests conducted by the cardiologists for monitoring the heart condition in patients with heart diseases, which is considered novel and unprecedented, thus representing a significant benefit and value from our study.

2. Methods and materials

2.1. Subjects and experimental settings

In this research, a stationary bicycle based ergometer system equipped with peripheral components (including an optical encoder and a resistor-based load control device), a set of wireless ECG sensors with the sensor interfacing system, and a personal computer (PC) based control and computational unit was used. Eleven young healthy adults were recruited for undergoing the bipedal cycling test. All the participants were free of heart diseases. The procedures of the experiment and the characteristics of the bicycle ergometer system were clearly explained to them before proceeding. At the beginning, each subject was asked to do one-minute low intensity cycling exercise to warm up body to prevent sports injuries. Then, the experiment started and each subject was asked to sit in an upright position and perform cycling exercise at a constant load and maintain a constant cycling speed of 60 RPM, as best as he could, throughout the entire course of experiment.

When cycling started, the wearable sensors synchronously collected and digitized the ECG data from the subjects and then wirelessly transmitted the digital data into the system PC for the subsequent numerical experimental analysis. In addition, with ranging from 6 to 20, the Borg scale value was also synchronously recorded and updated every minute during the test. For each subject, the experiment was terminated immediately once the Borg scale value reached the maximal value of 20.

2.2. Time- and frequency-domain HRV analysis

A time-domain index of HRV measured by analyzing the standard deviation of the normal to normal RR intervals (SDNN)