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Nonlinear analysis is the most suitable method to detect changes in heart autonomic control after exercise of different durations

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ABSTRACT

This study aimed to compare the heart autonomic control (HAC) response during two time-limited physical workouts using linear and nonlinear methods. A total of 20 healthy volunteers performed two physical workouts lasting 5 (P5) and 10 min (P10). In both workouts, volunteers performed as many repetitions as possible within the time limit of sets of 10 repetitions of four different exercises in the order of pull-ups, push-ups, barbell power clean, and barbell shoulder to overhead press. Barbell exercises were performed using a load of 50% of each volunteer's personal record for the jerk lift. Successive RR intervals were recorded 1 h before, immediately after, and 1 h after each workout. HAC parameters were obtained using linear (e.g., time- and frequency-domain analysis) and nonlinear [e.g., recurrence plot (RP)] methods. The number of repetitions was recorded during each workout, and the cadence (e.g., repetitions per minute) was calculated. All HAC parameters showed a significant main effect with time; however, only some RP parameters (e.g., recurrence rate (REC), maximal length of lines (*L*max), and Shannon entropy) were significantly greater in P5. The number of repetitions was significantly greater in P10, but the cadence was higher in P5. Both workouts induced an acute increase in sympathetic activity and vagal withdrawal; however, P5 exhibited greater REC and *L*max, indicating a greater vagal withdrawal. This could be explained by a more intense performance in P5, as evidenced by the greater cadence. In addition, only the RP parameters (a nonlinear approach) were more suitable to detect acute exercise-induced changes in HAC.

1. Introduction

Exercise-associated health benefits are well known and are most often associated with specific exercise features such as intensity, duration, execution mode, and rest interval. Although standard aerobic and resistance exercise training programs have been widely studied, nonstandard training methods, sometimes referred to as extreme conditioning programs (ECPs), have been increasing in popularity despite having hardly ever been studied. The high-intensity nature of ECPs and their increasing popularity has forced professional associations in the fields of sports science and medicine to take a stance on their possible benefits and risks [1,2].

A wide range of trademarked exercise training programs (e.g., CrossFit, Insanity, Gym Jones, etc.), which are commonly referred to as ECPs, use variable-volume workouts that place emphasis on conditioning and strength training. These workouts often use a time-limited maximal number of repetitions with short or no rest periods between sets to promote general fitness and prepare athletes to compete in events where skills from different sport modalities can be tested (e.g., CrossFit Games and National Pro Grid League [NPGL-GRID]). Ultimately, there is now a new modality of training and sport competition which corresponds to "mixed modality training" (MMT) [3].

The growing demand for MMT seems to be related to the gains in health, physical fitness, and performance [4–6] and to the shorter time spent exercising [7], which improves the potential for higher rates of adherence in the general population [8,9]. Concerns about the safety of MMT is also growing; however, up to now, this seems to be restricted to a risk of musculoskeletal injury [1,10,11].

Monitoring cardiovascular behavior is a common procedure during and immediately after exercise sessions and has been proposed as a predictor of negative cardiovascular outcomes [12,13]. The cardiovascular behavior during and immediately after an exercise session is mainly

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influenced by the autonomous nervous system and may be studied through the analysis of RR interval fluctuations [14,15]. Previous studies investigated this issue but were restricted to traditional aerobic or anaerobic exercise routines [14,15]. Despite the growing demand, to the author's knowledge, there are no studies investigating the heart autonomic control (HAC) before, during, and after MMT workouts. Notwithstanding, temporal and spectral analysis methods are most commonly used to analyze RR interval variability, although nonlinear methods seem to be better at processing complex and nonstationary signals, such as successive RR intervals [16,17].

Therefore the goals of this study were to compare the HAC before and after (immediately and 1 h) two time-limited MMT workouts (lasting 5 and 10 min) and to investigate the sensitivity of different HAC parameters in detecting differences in HAC between the different duration workouts and time instances (i.e., before, immediately after, and 1 h after). A total of 20 athletes performed two protocols (of different durations) consisting of two weightlifting and two bodyweight exercises while having their cardiovascular behavior monitored. RR intervals were extracted, and HAC was estimated using linear and nonlinear methods.

2. Methods

2.1. Subjects

In this cross-sectional study, 20 athletes performed high-intensity physical activity in a gym in São José dos Campos, São Paulo, Brazil. This experimental approach was used to analyze the magnitude of HAC using linear (i.e., time- and frequency-domain parameters) and nonlinear indices, as well as hemodynamic parameters before and 1 h after two time-limited MMT workouts (5 and 10 min).

A total of 20 healthy athletes of both sexes volunteered for this study and were submitted to a clinical examination to determine their current clinical health condition. They had participated in at least one MMT competition (i.e., CrossFit Games Open, Monstar Games, or Arnold Classic MMT Games) in the past 6 months. All volunteers signed an informed consent form. The study was performed in accordance with the Helsinki Declaration and was approved by the local ethics committee. Table 1 presents the subject's characteristics.

2.2. Experimental protocol

Successive RR intervals were recorded for 10 min with participants in a supine position. Recording were taken at three time instances: 1) before the exercise protocols (PRE), 2) immediately after the exercise protocols (POS1), and 3) 1 h after the exercise protocols (POS2) (Fig. 1). Volunteers were asked to warm-up on their own using the same equipment used in the exercise protocol. The RR interval recording was performed using a heart rate monitor (Polar® RS800CX, Finland).

The two time-limited exercise protocols were performed 1 week apart on the same day and time and in the same volunteers. Volunteers performed one 5-min protocol (P5) and one 10-min protocol (P10) in a random design. Despite the different durations, the two exercise protocols were identical. The MMT protocol was designed as a circuit of four exercises prescribed in sets of 10 repetitions in the order of pull-ups (fixed bar), push-ups, power cleans, and shoulder presses to overhead. No fixed amount of rest was prescribed between repetitions, sets, or completion of the circuit, and volunteers were asked to perform as many repetitions as possible within the time limit (5 or 10 min) and rest when needed. After completion of the tenth shoulder press, volunteers carried on from the beginning of the circuit again until the limit time was reached. Power cleans and shoulder presses were performed using either male (20 kg) or female (15 kg) standard Olympic barbells (York Barbell, PA, USA) preloaded (using bumper plates) with 50% of the athletes' one repetition maximum for the jerk lift. To execute the jerk, the athlete stood with feet parallel and with the barbell resting on their shoulders. At the start of the movement, the athlete explosively bent and extended their knees and hips to generate the most momentum in the bar. Following the extension of the knees and hips, the athlete fully extended their arms and pressed the barbell vertically overhead. If the athlete moved their feet out of the frontal plane, they returned them to the same initial line before finishing the lift. Athletes could freely warm-up and attempt the jerk as many times as they wished while increasing the load on the bar as desired. However, the athletes could only try each new weight on the bar for a maximum of three attempts. The maximum weight that the athlete was able to lift in the three attempts was considered as their maximum jerk.

Table 1
Anthropometric data from volunteers.

Variables	Mean ± SE
Age (years)	29.85 ± 1.71
Sex M/F	15/5
Height (cm)	172.0 ± 0.24
Body Weight (Kg)	75.19 ± 3.52
BMI (kg/m^2)	25.2 ± 0.7

M: male; F: female; IMC: body mass index; SE: standard error.

During the execution of the exercise protocol, the volunteers were helped by a stopwatch strategically positioned in the training environment, which indicated the session duration. To compare physical performance in each exercise protocol, the number of repetitions in each exercise bout was recorded and the exercise cadence calculated as the number of repetitions per protocol time (5 or 10 min).

Successive RR interval data were also recorded during each exercise protocol; however, the RR interval variability was not analyzed due to the poor signal quality caused by the trunk and upper limb movements compromising the data.

The RR interval data recorded pre- and postexercise were edited based on visual inspection, and all ectopic beats and artifacts were corrected using a cubic spline interpolation. The successive RR intervals were subsequently analyzed in the time and frequency domains and using a nonlinear analysis method. All analyses were performed using Kubios HRV analysis software 2.1 (Department of Applied Physics, University of Eastern Finland) [11]. To remove disturbing low-frequency baseline trend components, the recorded data were preprocessed using a smoothing procedure with a cut-off frequency of 0.035 Hz, as used and suggested by Ref. [18].

All analyses followed the recommendations of the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [11,19].

Time-domain analysis was performed to obtain the mean of successive RR intervals (MeanRR) and the square root of the mean squared differences between successive RR intervals (RMSSD). Frequency-domain analysis was performed using the fast Fourier transform to obtain the normalized magnitude from the spectrum of low-frequency components (LFnu) (an index of vagal and sympathetic modulation over the heart with sympathetic predominance) and high frequency components (HFnu) (corresponding almost exclusively to vagal modulation of the heart) and the LF/HF ratio (characterizing the sympathovagal balance over the heart). The low- and high-frequency power was divided into bands of 0.04–0.15 and 0.15–0.4 Hz, respectively. The window width was set to 256 s and overlapped to 50%.

The nonlinear analysis was performed using the recurrence plot method [20], which through recurrence quantification analysis (RQA) gave four parameters: maximum line length (*L*max), recurrence rate (REC), determinism (DET), and Shannon entropy of line length distribution (ShEn). Briefly, recurrence plot analysis is a visual representation of the vectored data sequences that show changes in the system as it evolves in time (i.e., to reveal nonstationarity of the series), and RQA quantifies the information contained within the recurrence plots [21]. Previous studies support the notion that RQA parameters are suitable for

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