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Entropy of Heart Rate on Self-Selected Interval Exercises in Older Women

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ABSTRACT

International Journal of Exercise Science 16(2): 525-537, 2023. Non-linear analyzes such as Approximated Entropy (ApEn) and Sample Entropy (SampEn) could show the adaptability of the autonomic nervous system in relation to the dynamic changes caused by exercise. The aims of the study were: a) Investigate the effects of different Self-Selected based Interval Exercises (SSIE) configurations on Heart Rate (HR) entropy; b) Determine whether the stimuli time promote different entropy responses; c) Observe whether exercises with passive self-selected recovery time (SSRT) promote different HR entropy responses compared to those with imposed time and active recovery; and d) Determine whether post-training entropy responses quickly return to baseline. Fifteen older women were randomized to perform six sessions of SSIE and one session of Self-Selected Continuous Exercise (SSCE), with approximately 24 min duration each. The results showed increases on ApEn during the exercises compared to the moments of rest Pre ($p < 0.001$), Post 6 min ($p = 0.003$) and Post 12 min ($p < 0.001$). Results demonstrated that interval exercises (IE) with SSRT, present lower values of ApEn and SampEn regarding the continuous activity ($p < 0.05$). It was also observed that the entropy values after training returned quickly to levels close to those of pre-exercise rest with a tendency to decrease more pronounced for the continuous. The SSIE were able to promote greater complexity in the HR entropy of older women, allowing greater stabilization of the cardiovascular system, including after training.

KEY WORDS: Interval training, approximated entropy, sample entropy, variability

INTRODUCTION

Autonomic cardiac response during physical exercise must be proportional to the needs for muscle work and blood flow in the skin, maintaining blood pressure and distribution to the organs (34). The analysis of the components of Heart Rate Variability (HRV) could be a useful strategy to assess the increases on sympathetic activation and decreases on parasympathetic activity during exercises (38). In a systematic review by Düking, Zinner, Reed, Holmberg and Sperlich (12) it was demonstrated that exercise prescription based on HRV can promote better physiological and performance adaptations. HRV monitoring can be done using devices for commercial use, which in addition to having good practical applicability, also have proven validity in rest positions (Bias < 0.01) (21) and running (Bias < 0.48) (7). This suggests that monitoring these autonomic variables might play a fundamental role in the physiological effectiveness of different exercise prescription strategies.

The mechanisms responsible for the control of the cardiovascular changes that happen during exercise refer to an influence of the sympathetic (SNS) and parasympathetic (PNS) nervous system on heart rate (HR). Increased parasympathetic activity during rest is mediated through the release of acetylcholine by the vagus nerve (15), keeping low and decreasing HR (18). On other hand, in response to imbalances, SNS stimulates increases in HR, in the conduction of nerve impulses and on myocardial contractility mediated by norepinephrine (18). As according to psychophysiological reactivity theory, these autonomic responses can help identify disease conditions or fitness state (28, 34).

The most common approach to access these autonomic parameters is performed through the analyses of linear components of HRV (48), including on exercise (34). Linear systems typically consist of time and frequency domain analysis, measuring the interval between R-to-R waves on an electrocardiogram (41). The analysis of such components demonstrated the effectiveness of linear methods in identifying changes in blood pressure and recovery after exercise (24, 49). A meta-analysis showed that high week frequency endurance training (>3 $x.wk^{-1}$) was efficient in promoting gains in autonomic function (e.g. measured by linear methods) in older individuals (36). However, the characteristic of not changing as a result of the magnitude of the stimuli (41) could make this method slightly unfeasible to analyze the dynamic characteristics of the cardiovascular system.

A good alternative to assess these dynamic behaviors can be through the analysis of non-linear HR components, including entropy, detrended fluctuation, Lyapunov exponent, fractal dimensions and Poincaré plots (2, 30). In addition, entropy measurements are able to reflect the complexity (e.g. systems involving multiple processes) and regularity (e.g. balanced functioning systems) on time series data (30), which can be useful to understand chaotic systems (i.e. cardiovascular). The most traditional entropy measures in the literature are: 1) Kolmogorov entropy; 2) ApEn; 3) SampEn; 4) Fuzzy entropy; and 5) Shannon entropy (22, 30). These methods are conceptually different and may reflect small changes on dynamic behaviors using different mathematical approaches.

The joint use of ApEn and SampEn measurements can offer a more complete tool in the analysis of the physiology of the cardiovascular system and subtle episodes that may occur in HR (2). ApEn and SampEn measure the regularity and complexity of short time series with possible noise in the signals (42). Its use may have potential with older adults, due to its ability to be less influenced by underlying chaotic systems (i.e. diseases) (22), which is a present characteristic in this population. Although reference values are quite common in other areas of knowledge (i.e. body mass index), in HRV this strategy does not seem to be the most appropriate, since individuals present great inter-individual variability. However, the literature shows that higher entropy values indicate more irregular and unpredictable signals (42), which suggests a greater capacity for physiological adaptation to sudden changes.

Therefore, the use of non-linear methods seems more suitable for analyzing the chaotic nature of the signals during exercise (22). It is known that non-linear components have been used to analyze the biological behaviors of a dynamic nature (48). It is possible that due to the oscillatory and non-periodic number of signals provided by cardiovascular activity (43), non-linear methods may be more efficient in investigating the effects on HR during exercise. In the oldest population, the use of non-linear components is widely used as a form of prognosis and diagnosis of certain diseases that can lead to an increased risk of death (1, 26). To the best of our knowledge, few studies investigated non-linear entropy components during exercise (22, 23, 37), especially on older individuals (5, 33).

It has been demonstrated that High Intensity Interval Training when prescribed with passive recoveries led to increases on heart contractility (4). This results in decreases in the end-systolic volume of older individuals, generating protective effects to cardiovascular fitness through the increase of vagal modulation (4). In order to achieve the best physiological responses, different IE configurations were proposed, to combine the physiological effectiveness of the interval strategy (20) with a self-selected based prescription for recovery period (14). The aims of the study were: a) Investigate the effects of different Self-Selected based Interval Exercises (SSIE) configurations on Heart Rate (HR) entropy; b) Determine whether the stimuli time promote different entropy responses; c) Observe whether exercises with passive self-selected recovery time (SSRT) promote different HR entropy responses compared to those with imposed time and active recovery; and d) Determine whether post-training entropy responses quickly return to baseline. Considering previous results on literature (24), the main hypothesis of the study is that IE with passive recovery and self-selected time will promote less disturbances in the HR entropy as well as allow a quickly return to baseline values.

METHODS

Participants

Study participants were older adult women ($n = 15$) who met the following criteria: 1) age ≥ 60 yrs; and 2) practiced a combination of aerobic and resistance activities in mixed intensities (moderate and vigorous) at least 75 min/week^{-1}, according to American College of Sports Medicine recommendations (3). There were not include those who had: 1) uncontrolled hypertension; 2) type 2 diabetes mellitus; 3) current user of medications or treatments that interfere with HR responses; 4) mobility impairment; and/or 5) other chronic clinical condition which classified as high risk for physical activity. Participants were recruited at the Physical Education and Sport's Center of the Federal University of Pernambuco and performed the interventions individually in the spirometry laboratory with controlled temperature (22° C), usually in the morning.

The sample size was calculated based on *a priori* analysis performed in the *G-Power* 3.0.10 software (Dusseldorf, Germany). The following parameters were used to estimate sample size for an ANOVA test of repeated measures (within-between interaction): A *d* effect size of 0.5 ($f = 0.25$); α error of 0.05; power ($1-\beta$) of 0.80; a correlation between repeated measurements of 0.90 and a non-sphericity correction of 1.0 were used. The sample size suggested by the software was 12 participants. All these values are based on previous research of our group (39). The research follows the statements by the Ethics Committee on Research with Human Beings of the Center for Health Sciences of the Federal University of Pernambuco, under opinion number 2.937.510, and respects all positions of National Health Council resolution, No. 466/2012. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (35).

Protocol

This research was conducted in a randomized crossover design performed in a total of ten visits to the lab. Interventions were carried out in seven visits (i.e. six SSIE and one SSCE), while in the other three, baseline tests were performed (i.e. anthropometrics, familiarizations, incremental submaximal test and a self-selected intensity determination test). The interval between each visit ranged from 48 to 72 h. To avoid any effect on the order of interventions, the seven exercise sessions were individually randomized to each participant through a website (www.randomizer.org). The present study followed the recommendations of Consolidated Standards of Reporting Trials (CONSORT) (13).

During the first visit, an informed consent document was signed, a risk stratification questionnaire was completed, anthropometric data were collected, and participants performed a familiarization on the treadmill. In the second visit, an incremental submaximal test was performed to estimate the oxygen consumption (VO_2) on a treadmill (Inbramed Super ALT, Porto Alegre, Brazil) with continuous monitoring of HRV (V800, Polar, Kempele, Finland). The test started with a 3% slope and speed of 3.0 $km.h^{-1}$. At every minute, 1% in slope was increased until participants reach 55% of reserve HR (47). After that, the demand of activity was maintained for five min and the test was finished. The average values of speed and slope attained on the test were used to estimate maximum VO_2 of the participants (34.1 ± 9.3 $mL.kg.min^{-1}$), according to American College of Sports Medicine equations (3). In the third visit, a test to determine the self-selected intensity (SSI) of each participant was performed based on instructions by Santos, Costa, Costa, Damasceno, Chen, Oliveira, Dames, Pires and Santos (39), which consists of participants self-choose the preferred intensity to perform exercises in an interval activity. The SSI (4.2 ± 0.6 km.h-1 of speed; 6.3 ± 1.7 % of slope) was used to prescribe the SSIE on this research. To more details about the SSI determination test see Santos, Costa, Costa, Damasceno, Chen, Oliveira, Dames, Pires and Santos (39).

The SSIE configurations followed two different types of recovery manipulations: a) active with imposed time (with 35% below of SSI); and b) passive with self-selected time. Both types had stimuli with 35% above the SSI intensity on third visit. The SSCE session was 24 min and participants were able to freely choose and change the intensity (e.g. speed and slope) during the sessions. The sessions with (SSRT) varied the number of repetitions to equalize in 24 min. The number of repetitions, intensity and time of the stimuli and recoveries on SSIE happened according to the following description: a) 12 x (1 min @ +35% SSI / 1 min @ -35% SSI); b) 8 x (1.5 min @ +35% SSI / 1.5 min @ -35% SSI); c) 6 x (2 min @ +35% SSI / 2 min @ -35% SSI); d) ≈12 x (1 min @ +35% SSI / SSRT @ 0%); e) ≈8 x (1.5 min @ +35% SSI / SSRT @ 0%); and f) ≈6 x (2 min @ +35% SSI / SSRT @ 0%). To standardize data collection, the experimental setup of interventions was as follows: 12 min of rest pre-exercise, 4 min of warm-up, ± 24 min of aerobic activity, 4 min of cool-down and 12 min of rest post-exercise. All intervention were conducted by the main researcher (LERS).

HRV was continuously measured for approximately 55 min through a HR cardiac monitor (Polar V800, Polar Electro, Finland), with good practical applicability and accessibility, in all seven exercise sessions. All variables related to HRV were evaluated at six different moments: a) Pre-exercise rest (final six min out of a total of 12); b) During the exercise (three windows corresponding to the moments 33%, 66% and 99% of the activities, with a total of 24 min); c) Post-exercise rest (two moments corresponding to min 6 and 12).

The data was downloaded to the computer using the Polar Flow Sync software and the HRV analysis was performed using the Kubios HRV Standard software (v. 3.1.0, Kubios Ltd., Kuopio, Finland). A correction of the artifacts of the R-R interval series was made using the Kubios artifact correction option, and a 'very strong' correction level was applied. After artifacts correction, no remaining signal noises were identified after visual analysis by principal researcher (LERS) and no data were discarded.

Statistical Analysis

Data normality was verified through the Kolmogorov-Sminorv test. All results are represented by the values of means, standard deviations, and percentages. In the present study, it was decided to analyze the SSIE in two separate ways: a) three sessions of SSIE with active recovery and imposed time; and b) three sessions of SSIE with passive recovery and SSRT. In both analyzes the SSCE was used as an active control condition. Therefore, two different repeated measures ANOVA two way were performed for each variable (ApEn and SampEn) using the exercise conditions vs. the moments. The values of ApEn and SampEn during the SSIE cycle (stimuli and recoveries) were used to perform the analysis. The Mauchly sphericity test was performed and, when necessary, the Greenhouse-Geisser correction was applied. The adjustment factor of Bonferroni was performed when necessary to identify any significant differences. The magnitude of the differences was reported as partial eta squared (η^2_p) and interpreted by the value of effect size (f): small (f = 0.10); medium (f = 0.25); and large (f = 0.40), as suggested by Cohen (9). All analyses are conducted on SPSS 23 (SPSS Statistics, IBM, New York, United States of America), GraphPad Prism 6 software (GraphPad Software, San Diego, United States of America), and Microsoft Office Excel software (Version 365, Microsoft Corporation, Washington, United States of America).

RESULTS

Of the seventeen volunteers initially recruited, fifteen completed all exercise sessions. Two participants were excluded from the analyses for not complete all interventions, one of them for personal withdrawal and the other for not being able to perform the procedures safely on a treadmill. The remaining 15 participants were older women (68.1 ± 3.8 yrs), weekly practitioners of functional activities, with body weight, height, BMI and HR_{Rest} of 64.5 ± 7.5 kg, 1.53 ± 0.1 m, 27.5 ± 3.5 $kg.m^{-2}$ and 70.2 ± 8.7 bpm, respectively. All data presented normality.

The total duration of the IE sessions with imposed recovery time was 24 ± 0 min, with mean HR of 110.5 ± 1.6 bpm (1'/1'), 109.8 ± 1.2 bpm (1.5'/1.5') and 109.6 ± 0.9 bpm (2'/2'). For the IE sessions with SSRT, the total duration was approximately 23.6 ± 0.5 min, with mean HR of 102.8 ± 1.3 bpm (1'/SST), 103.6 ± 1.2 bpm (1.5'/SST) and 104.7 ± 1.3 bpm (2'/SST). In the continuous exercise, the total duration was 24 ± 0 min, and the mean HR was 108.1 ± 4.6 bpm.

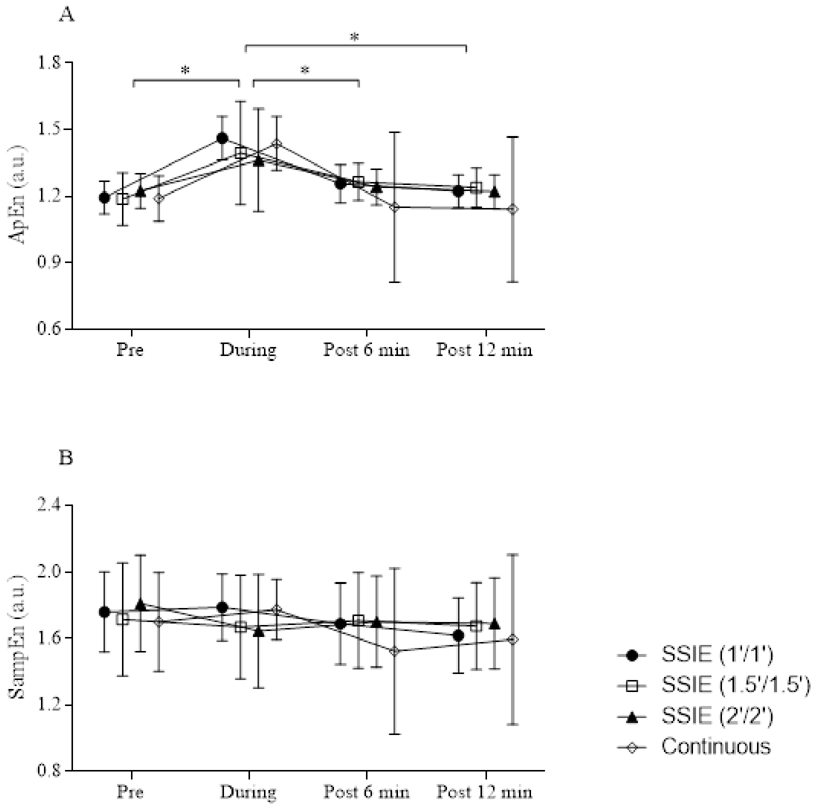

Figure 1: Comparison of interval exercises with imposed recovery time vs. continuous exercise. Panel A – Responses of Approximate Entropy (ApEn); Panel B – Responses of Sample Entropy (SampEn); * - Significant difference between the moments ($p < 0,05$); SSIE – Self-Selected Interval Exercise; a.u. – Arbitrary Units.

The main effect analysis found significant differences in the interaction for the ApEn ($F_{(2.958; 41.407)} = 3.109$; $p = 0.037$; $\eta^2 = 0.182$) and SampEn ($F_{(3.843; 53.795)} = 3.334$; $p = 0.018$; $\eta^2 = 0.192$), when comparing the IE with SSRT vs. the continuous one. The results indicated higher levels of entropy during continuous exercise in relation to interval conditions for ApEn ($p = 0.025$; $p = 0.027$) and SampEn ($p = 0.005$; $p = 0.021$; $p = 0.007$). No significant differences were found in the interaction for the variables of ApEn and SampEn in relation to IE with imposed recovery time.

Significant differences were also found between the moments for the ApEn variable in the comparison between continuous exercise vs. interval with imposed recovery time ($F_{(1,798; 25,173)} = 20.132$; $p < 0.001$; $\eta^2 = 0.590$) and continuous exercise vs. interval with SSRT time ($F_{(1.766; 24.720)} = 8.940$; $p = 0.002$; $\eta^2 = 0.390$). These results indicate higher levels of entropy at the moment during exercise, compared to pre ($p < 0.001$; $p = 0.001$) and post exercise rest ($p = 0.003$; $p = 0.025$; $p < 0.001$; $p = 0.012$). No significant differences were found between the moments for the SampEn.

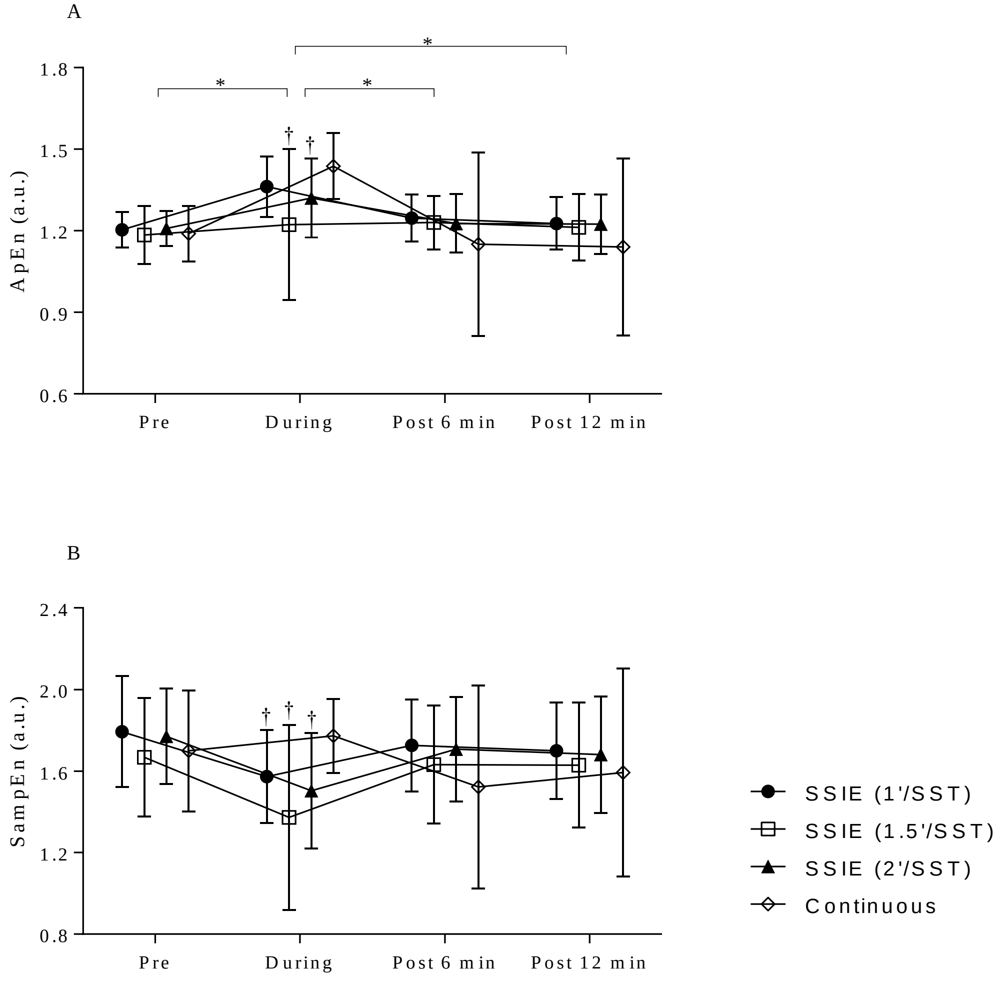

Figure 2: Comparison of interval exercises with self-selected recovery time vs. continuous exercise. Panel A – Responses of Approximate Entropy (ApEn); Panel B – Responses of Sample Entropy (SampEn); * - Significant difference between the moments ($p < 0,05$); † - Significant interaction ($p < 0,05$) SSIE – Self-Selected Interval Exercise; SST – Self-Selected Time; a.u. – Arbitrary Units.

No significant differences were found in the main effect analyzes between the exercises for the variables of ApEn and SampEn. Figures 1 and 2 show the means of entropy founded in each exercise session.

DISCUSSION

Our results showed that the ApEn values increased during the exercises compared to the moments of rest (Pre, Post 6 min and Post 12 min), which indicates higher entropy and lower regularity in the data. Our findings also demonstrated that IE with passive SSRT time present lower values of ApEn and SampEn regarding the continuous activity. Also, the SSCE was able to promote greater entropy compared to the SSIE with passive recovery. With our results, it was possible to observe that the entropy values after training returned quickly to levels close to those of pre-exercise rest, with a tendency to decrease more pronounced for the continuous.

It has been demonstrated that the differences in age and sex cause important autonomic imbalance, which implies an increased risk of mortality and development of certain diseases (27). Although our findings point to an individual homogeneity among the participants, the use of non-linear parameters seems necessary to investigate minimal changes in HR, especially those caused by exercise variations. As shown in previous studies, entropy analysis can be efficient in identifying changes in airflow pattern, temperature and in the assessment of cardiac arrhythmias and depressive disorders (6, 8, 10, 29). In agreement with the study purposes of investigating the effects of different SSIE configurations with variations in recovery intensity and stimuli time, it was possible to observe that the results demonstrate that ApEn indexes can be used to identify disturbances in HR, especially those provided by exercise sessions without considerable decreases or variations in intensity.

As according to another aim of the present study, the characteristics of recovery moments also seem to suggest that the entropy measurements can be used to identify significant reductions in exercise intensity. As our findings show, the dynamic characteristic of IE with passive recovery may have directly impacted the responses of HR. Our SampEn results seem to demonstrate reasonable sensitivity of this component to perceive the elevated number of changes between the moments of stimuli and passive recovery. The literature about passive recoveries points to gains in performance and reduced physiological stress and fatigue across repeated sprints (32, 40). However, future studies should investigate those behaviors in activities with repeated bouts performed at high or supramaximal intensities, since ours, work with moderate intensity based on absolute HR. Therefore, it seems relevant to investigate the effects of several exercise conditions on cardiac entropy in different populations (i.e. healthy and unhealthy) and contexts (i.e. rest, in activity, under emotional or physical stress).

The physiological adaptations behind IE that improve aerobic capacity are related to some peripheral and central factors, as well as the increase in the content of mitochondria in the muscles, capillary density, maximal cardiac output, and blood volume (31). It is possible that these changes, promoted by IE, induce some peripheral modulations that provide superior adaptations and more controlled HR in older women. The autonomic imbalance caused by sympathetic predominance already demonstrated reductions in ejection fraction in patients with heart failure (17). Therefore, the potential activations of SNS, followed by successively PNS withdrawal during the exchanges provided by exercises, could motivate greater responsiveness of the heart and possibly increase the cardiopulmonary efficacy. More precisely, a relevant question to be addressed in future studies it is related to the efficacy of different exercise approaches (i.e. continuous, strength, interval) and intensities (i.e. low, moderate and high) focusing on entropy as the major outcome, as previously initiated by Fiogbé, Ferreira, Sindorf, Tavares, de Souza, de Castro Cesar, Lopes and Moreno (16).

Hypothetically, it is possible that the variables ApEn and SampEn may reflect some physiological states beyond those already demonstrated in the literature. For example, fluctuations in respiratory rate, blood flow and neuromuscular demand can cause dysregulation in the blood ejection system, which in turn will negatively affect the autonomic control of cardiac, pulmonary and muscle functions during exercise. One of the possible causes may be alterations in the neurotransmission process of substances responsible for cardiac muscle contraction (e.g. acetylcholine) or by physiological imbalances in the propagation of the electrical signal through the flow of sodium and potassium channels (25). Previous studies have shown that the HR entropy can be effective to show the loss of complexity in patients with cardiac diseases (50), diabetes (19) and by aging (45).

Considering that one of the aims was to determine the effects of exercises on post-training recovery, results reveal the effectiveness of SSIE strategies to generate positive disturbances on HR entropy during the exercises and quickly return to baseline after the training. Spring, Bourdillon and Barral (46) has showed that some linear measures do not return to baseline values one hour after a constant load cycling perceived as hard. The authors point that increases in afferent neural activity after exercise might be considered as a mediator of autonomic regulation of HR (46). However, as our findings suggest, the entropy measurements seem to demonstrate a tendency to fast return to rest condition after exercise. In a study that analyze a fluctuation component of HR (DFA-alpha1) during active recoveries on exercise, Gronwald, Hoos and Hottenrott (24) has shown that even during moments of active recovery, the fluctuation component returns very quickly to warm up values, without significant changes until the end of the activity. Therefore, it is suggested that decreases in intensity, mainly on passive recoveries, could provide a fast comeback depending on the characteristic of the exercise prescription.

Our study presents some limitations that need be considered on the analysis of the results. First, it was not possible to evaluate the HRV components with more reliable instruments, such as electrocardiographs (ECG) (15). Although the use of portables devices to access HRV present some small measurement errors (11), they can be minimized due to increased applicability provided by this equipment in comparison with ECG (11), ensuring it is more accessible for people in their daily routines. Second, there were not used others physiological parameters measures such as gas exchange and blood pressure that could provide a more consistent analysis of our results. However, in the real-world condition the use of these instruments may generate undesirable effects on the external validity and practical applicability of our study. Future studies should investigate how the performance of exercises with spirometric masks and other equipment impact the analysis of HRV. In addition, external factors, such as, spontaneous speak, previous stress, dysregulated sleep, and others that may impact HRV (44).

The SSIE were able to promote greater complexity in the HR entropy of older women. Furthermore, it was concluded that passive recovery during IE allows greater stabilization of the cardiovascular system, including after training. Finally, the use of ApEn and SampEn variables is suggested to detect whether subtle changes in exercise intensity can generate alterations on HR responses. Therefore, HR entropy components such as ApEn and SampEn can be more representative to monitor cardiovascular reactivity induced by exercise. It is suggested that in stressful situations (e.g. exercise) the randomness of the cardiac system can be more easily identified through entropy measurements.

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