

Chaotic analysis of heart rate dynamics after an exercise with flexible pole

Ana M. S. Antonio^I, David M. Garner^{II}, Rodrigo D. Raimundo^{III,IV}, Luiz Carlos de Abreu^{III}, Marcelo T. Navega^V, Vitor E. Valenti^I

^I Universidade Estadual Paulista (UNESP), Faculdade de Ciências e Tecnologia, Centro de Estudos do Sistema Nervoso Autônomo (CESNA), Programa de Pós-Graduação em Fisioterapia, Presidente Prudente, SP, Brazil.

^{II} Oxford Brookes University, Faculty of Health and Life Sciences, Department of Biological and Medical Sciences, Cardiorespiratory Research Group, Gipsy Lane, Oxford, United Kingdom.

^{III} Faculdade de Medicina do ABC, Laboratório de Delineamento de Estudos e Escrita Científica, Santo André, SP, Brazil.

^{IV} Universidade de São Paulo (USP), Faculdade de Saúde Pública, São Paulo, SP, Brazil.

^V Universidade Estadual Paulista (UNESP), Faculdade de Filosofia e Ciências, Departamento de Fisioterapia e Terapia Ocupacional, Marília, SP, Brazil.

INTRODUCTION: Exercises with a flexible pole have been applied in clinical practice for upper limb rehabilitation. Nevertheless, its acute effects on cardiac autonomic regulation are unclear.

OBJECTIVE: To evaluate the acute effects of exercise with flexible pole on complex behavior of heart rate variability (HRV).

METHOD: We investigated 32 healthy female volunteers aged between 18 and 25 years who performed a session of exercise with a flexible pole. HRV was analyzed 10 minutes before and 10 minutes immediately after the exercise.

RESULTS: Exercises with a flexible pole did not significantly change time and frequency domain indices of HRV. Non-linear analysis of HRV through the Higuchi Fractal Dimension was not significantly changed during recovery from exercise compared to the control reading at rest.

CONCLUSION: Exercises with the flexible pole were unable to acutely change chaotic behavior of heart rate dynamics. This is advantageous for assessments of levels of rehabilitative treatment required in such patients; and their susceptibility to dynamical diseases.

KEYWORDS: Autonomic Nervous System; Higuchi Fractal Dimension Rehabilitation Medicine.

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E-mail: ninanha25@gmail.com

INTRODUCTION

The physiological response of the Autonomic Nervous System to exercise is characterized by an initial parasympathetic (vagal) withdrawal and a subsequent increase in sympathetic activity. Following exercise, parasympathetic reactivation is involved in the recovery of heart rate to the basal level.^{1,2} Accordingly, heart rate variability (HRV) has been widely used to evaluate heart rate autonomic modulation. This is usually measured through traditional time and frequency domain indices.³

A recently introduced technique of exercise protocol has received attention based on the flexible pole. It is an apparatus with a mass of 0.8 kg and length of approximately 150 cm. The flexible pole provides oscillations induced by movements of the upper limbs. Exercise protocols using the flexible pole have been proved to present positive results in shoulder muscle function training.⁴

Recently, studies assessed HRV responses after a session of exercise with a flexible pole.⁵⁻⁸ They investigated HRV immediately after an exercise with flexible pole through traditional time, frequency domain and geometric analysis. Nevertheless, the nonlinear

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performance of HRV in response to this specific exercise is poorly understood. Furthermore, it has been suggested that linear measurements of HRV provide limited information because nonlinear mechanisms are known to participate in the foundation of heart rate dynamics.⁹

We are assuming that RR intervals behave in a non-linear way analogous to what has been described for Chronic Obstructive Pulmonary Disorder,¹⁰ Attention Deficit Hyperactivity Disorder¹¹ and Epilepsy^{12,13} as dynamical conditions.¹⁴ The benefit of investigating the association with HRV through nonlinear analysis is that it provides an indicator of the risk of “dynamical diseases”.¹⁴ Furthermore, it assesses the level of rehabilitative and physiotherapeutic interventions required for such patients.

The assessment by chaotic global analysis of HRV in response to flexible pole exercise was inconclusive.⁷ An examination of HRV provides qualitative measurement of cardiovascular physiology.⁹ Moreover, it may be expected that a non-linear analysis of heart rate dynamics in response to flexible pole exercise will provide new information regarding physiological performance in this type of exercise. Consequently, this study was undertaken to evaluate the acute effects of flexible pole exercise on nonlinear HRV behavior analyzed by computing the Higuchi Fractal Dimension.¹⁵⁻¹⁶ The current study is part of a general project analyzing HRV in response to different circumstances to determine whether nonlinear dynamic methods have clinical and prognostic applicability and whether dynamic analysis based on chaos theory may complement traditional analysis.¹⁷⁻¹⁸

METHOD

Study Population

To determine the sample size *a priori* an estimation was required, based on Moreno et al.² a sample size of 18 participants was stipulated by a two-tailed test hypothesis, with 5% level of significance and 80% power.

For this study we included 32 healthy female student volunteer subjects, all nonsmokers, aged 19.8 ± 1.6 years height 1.62 ± 0.01 m, mass 58.8 ± 10.0 kg and body mass index (BMI) of 22.2 ± 3.7 m/kg².

All volunteers were informed with regard to the procedures of the study and signed a confidential informed consent letter. Study procedures were approved by the Ethics Committee in Research of UNESP (Case # 0554-2012), and followed the National Health Resolution 466/2012 of October 10, 1996.

We excluded subjects (a) with systolic blood pressure >140 mmHg or diastolic blood pressure >90 mmHg (at rest); body mass index >35 kg/m²; (b) with cardiovascular, respiratory, endocrine, neurological disorders; (c) with any condition that would not allow the subjects to perform the study protocols; (d) under medication with influence upon

the Autonomic Nervous System. Subjects were not evaluated on days 10-15 and 20-25 after the beginning of the menstrual cycle.¹⁹ We also excluded physically active women based on the International Physical Activity Questionnaire (IPAQ).²⁰

Initial Evaluation

The initial evaluation included measurement of height, age, mass and calculation of body mass index. A digital scale (W 200/5, Welmy, Brazil) with a precision of 0.1 kg was used to assess mass. Height was measured by a Stadiometer (ES 2020, Sanny, Brazil) with 220 cm of extension and a precision of 0.1 cm. BMI was calculated as mass/height² (mass in kilograms and height in metres).

Exercise with flexible pole

The flexible pole exercise protocol was performed by the volunteers with shoulders flexed, in a standing position with feet apart (wide base). Exercises were undertaken for 15 seconds with 50 to 60 seconds of rest between each exercise. Three repetitions were executed for each exercise.

Exercises were performed in the following positions:

Shoulders at approximately 180° of flexion; flexible pole parallel to the ground in the frontal plane;

Shoulders at approximately 90° of flexion; flexible pole in the transverse plane;

One shoulder at approximately 90° of flexion; flexible pole perpendicular to the ground on the sagittal plane.^{5,6}

HRV analysis

The RR intervals were recorded with a mobile HR monitor at a sampling rate of 1 kHz. RR intervals were downloaded through the Polar Precision Performance program (v.3.0, Polar Electro, Finland): this software enabled the extraction of RR interval file in “txt” format. For data analysis we used 500 RR intervals; initial digital filtering was complemented with manual filtering for the elimination of artefacts and intrusions. We only included series with more than 95% of the cardiac cycles in sinus rhythm. HRV was analysed in the 10-minute period before the performance of the exercise (control protocol) and in the 10-minute period immediately after the performance of the exercise with flexible pole (experimental protocol).

Linear analysis of HRV

The spectral components of low frequency (LF: 0.04 - 0.15 Hz) and high frequency (HF: 0.15 - 0.40 Hz) in absolute (ms²) and normalized units were applied for HRV analysis in the frequency domain. The Fast Fourier Transform (FFT) algorithm was necessary to perform the spectral analysis of HRV.²¹

The pNN50 (percentage of adjacent RR intervals with durations differing by more than 50ms), SDNN (average standard deviation of normal RR intervals) and RMSSD

(square root of the average square differences between normal adjacent RR intervals) indices were used for time domain HRV analysis. For analysis of linear indices (time and frequency domains) we used the Kubios HRV[®] analysis software.²²

Protocol

The exercise protocol was performed in the same room for all volunteers. The recorded temperature ranged from 21°C to 25°C and the humidity from 50% to 60%. Volunteers were instructed not to drink caffeinated beverages, alcohol or other substances that influence the autonomic nervous system for 24 hours before the study protocols. Data was always collected between 18:00 and 21:00 to standardize circadian influences.²³ All procedures were explained to each subject separately and the subjects were instructed not to talk during the entire protocol.

Statistical Analysis of HRV Linear Indices

To define the sample size, as previously noted, we performed a sample calculation based on the study of Moreno et al² considering the RMSSD index. We aimed at a significant difference for 11 msec, assuming a standard deviation of 16.2 msec, with an alpha risk of 5% and beta risk of 80%. We obtained a minimum number of 18 subjects per group.

Normal Gaussian distribution of the variables was verified by the Shapiro-Wilk goodness-of-fit test (z value >1.0). We applied the paired Student t-test for parametric distributions, or the Wilcoxon test for non-parametric distributions. We considered differences significant when the probability of a Type I error was lower than 5% (p < 0.05). To undertake the mathematical analysis, we used the Biostat[®] 2009 Professional 5.8.4 software.

Higuchi’s Fractal Dimension

As previously noted Higuchi developed an algorithm for measuring the fractal dimension of discrete time sequences.¹⁶ It is based on a measure of the length, L(k), of the curve that represents the considered time series while using a segment of k samples as a unit. In this study we used sequences of 500 RR intervals.

If L(k) scales are such that

$L(k) \sim k^{-D_f}$, this defines a curve that will express fractal dimension D_f . A simple curve has dimension equal to 1, but a plane has a dimension equal to 2. D_f is always between 1 and 2 and quantifies the complexity of the curve. The time series of this curve can be represented on a graph.

From a given time series, X(1), X(2), ... , X(N), the algorithm builds k new time series:

$$X_{km}: X(m), x(m+k), X(m+2k), \dots, \dots,$$

$$X\left(m + \text{int}\left(\frac{(N-m)}{k}\right) \cdot k\right) \text{ for } m = 1, 2, \dots, K,$$

where, m is the initial moment, k is the time interval and int(r) is the integer part of a real number r.

For example, for an interval k=4 and a sample of N=1000 items, the algorithm produces 4 time-series:

$$\begin{aligned} X_{41}: & X(1), X(5), X(9), \dots, X(997), \\ X_{42}: & X(2), X(6), X(10), \dots, X(998), \\ X_{43}: & X(3), X(7), X(11), \dots, X(999), \\ X_{44}: & X(4), X(8), X(12), \dots, X(1000), \end{aligned}$$

The “length” $L_m(k)$ of each curve X_{km} is then calculated as:

$$L_m = \frac{1}{k} \left[\left(\sum_{i=1}^{\text{int}((N-m)/k)} |X(m+i \cdot k) - X(m+(i-1) \cdot k)| \right) \right] \times \frac{N-1}{\text{int}\left(\frac{(N-m)}{k}\right) \cdot k}$$

Where, N is total number of samples:

$L_m(k)$ is not “length” in the Euclidean sense; in fact, it represents the normalized sum of absolute values of difference in ordinates of pair of points distant k (with initial point m). The “length” of curve for the time interval k, L(k), is calculated as the mean of the k values $L_m(k)$ for $m= 1, 2, \dots, k$:

$$L(k) = \frac{1}{k} \sum_{m=1}^k L_m(k)$$

The value of fractal dimension, D_f is calculated by a least-squares linear best-fitting procedure as the angular coefficient of the linear regression of the log-log graph.

So, when L(k) is plotted against 1/k on a double logarithmic scale, with $k = 1, 2, \dots, k_{max}$, the data should reside on a straight line, with a slope equal to the Fractal Dimension of X. Thus, Higuchi Fractal Dimension is defined as the slope of the line that fits the pairs $\{\ln[L(k)], \ln(1/k)\}$ in a least-squares sense. In order to choose an appropriate value for the parameter k_{max} , Higuchi Fractal Dimension values were plotted against a range of k_{max} . The point at which the Fractal Dimension reaches a plateau is considered as a saturation point and that represents the k_{max} value which should be selected. At this point the appropriate level of statistical significance should be maximal.

With $a = D_f$ according to the following formulae: $y = ax + b$

$$D_f = \frac{n \sum (x_k \cdot y_k) - \sum x_k \sum y_k}{n \sum x_k^2 - (\sum x_k)^2}$$

where, $y_k = \ln L(k)$, $x(k) = \ln(1/k)$.

$k = k_p, \dots, k_{max}$ and n denotes the number of k values for which the linear regression is calculated ($2 \leq n \leq k_{max}$).

RESULTS

Linear Indices of HRV

Figure 1 indicates time domain behavior of HRV before and after exercise with flexible pole. We achieved no significant change in RMSSD, pNN50 and SDNN indices.

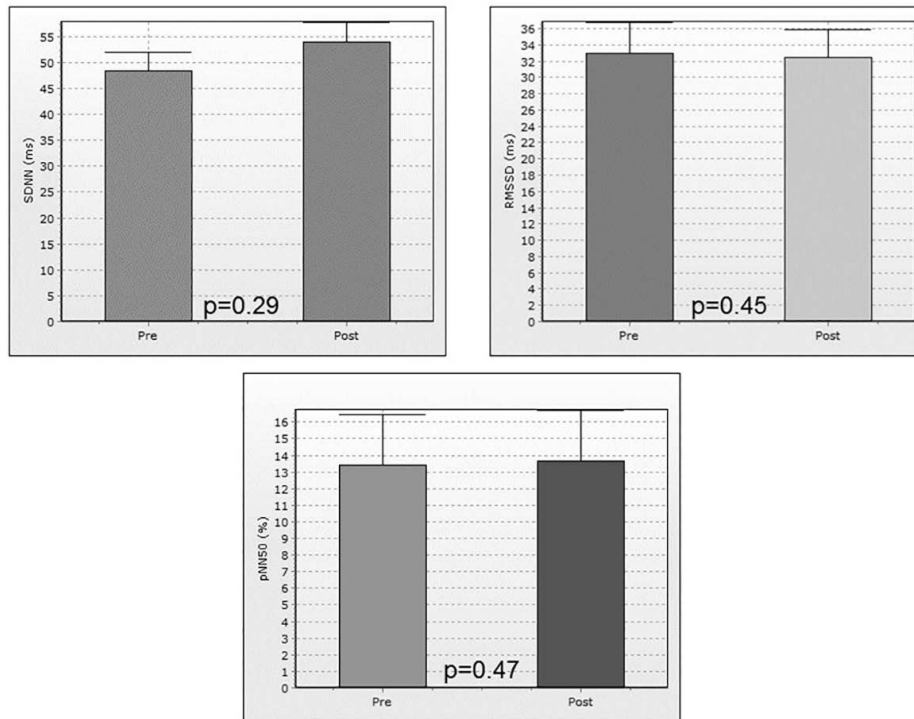


Figure 1 - Time domain indices of HRV before (pre) and immediately after exercise (post) with flexible flexible pole. RMSSD: root-mean square of differences between adjacent normal RR intervals in a time interval; pNN50: percentage of adjacent RR intervals with a difference of duration greater than 50ms; SDNN: standard deviation of normal-to-normal RR intervals; ms: milliseconds.

Spectral analysis of HRV indicated no significant difference for HF, LF and LF/HF ratio between before and immediately after the standardized exercise, as shown in Figure 2.

K_{max} & Higuchi Fractal Dimension

The box-and-whiskers plot for Higuchi Fractal Dimension of RR intervals. The line in the centre of the box is the median; the whiskers of the outer points are the 10th and 90th percentiles, with the outer edge of the boxes representing the 25th and 75th percentiles. The difference between the outer box edges is the inter-quartile range (Figure 3). All points computed for the Higuchi Fractal Dimension are between 1 and 2.

Normalization tests

Normalization of the data is essential to comprehend the relevant statistical test of significance to apply. Here we applied the Anderson-Darling²¹ and Lilliefors tests.²² The Anderson-Darling test for normality applies an empirical cumulative distribution function. The Lilliefors test is most suitable when the number of subjects is low. Here, there are 32 subjects in each cohort. The results from both tests were inconclusive.

Therefore the parametric one-way analysis of variance; (ANOVA1) and the non-parametric Kruskal-Wallis²³ tests of significance must be applied, as shown in Figure 4, left. We considered dissimilarities significant when the probability

of a type I error was lower than 5% ($p < 0.05$). The Kruskal-Wallis test of significance provided a p-value of 0.1433. The aforesaid optimum value was obtained at a value of K_{max} of 80. Observing non-parametric statistics for this optimum value $p < 0.05$ we can recognize that the median value for Higuchi Fractal Dimension increases from 1.9556 to 1.9830 in this cohort - see Figure 4, right.

DISCUSSION

Previous studies have reported the acute effects of flexible pole exercise performance on cardiovascular and HRV responses. The effects of flexible pole exercise on HRV through time and frequency domain and geometric indices analysis was considered.^{5,6} In this project, we investigated HRV through the Higuchi Fractal Dimension analysis and reported an absence of chaotic behavior of HRV before and immediately after a 10 minute session of exercise with the flexible pole.

As ascertained by our statistical analysis, the time and frequency domain indices of HRV did not significantly vary after the exercise protocol. The Higuchi Fractal Dimension established lower p-values compared to those calculated from traditional linear indices. Thus, it revealed that HRV analysis by the Higuchi Fractal Dimension may be more sensitive at detecting heart rate changes compared to standard linear techniques.

Ogata et al⁶ recognized that a period of exercise with flexible pole immediately reduced HRV in males.

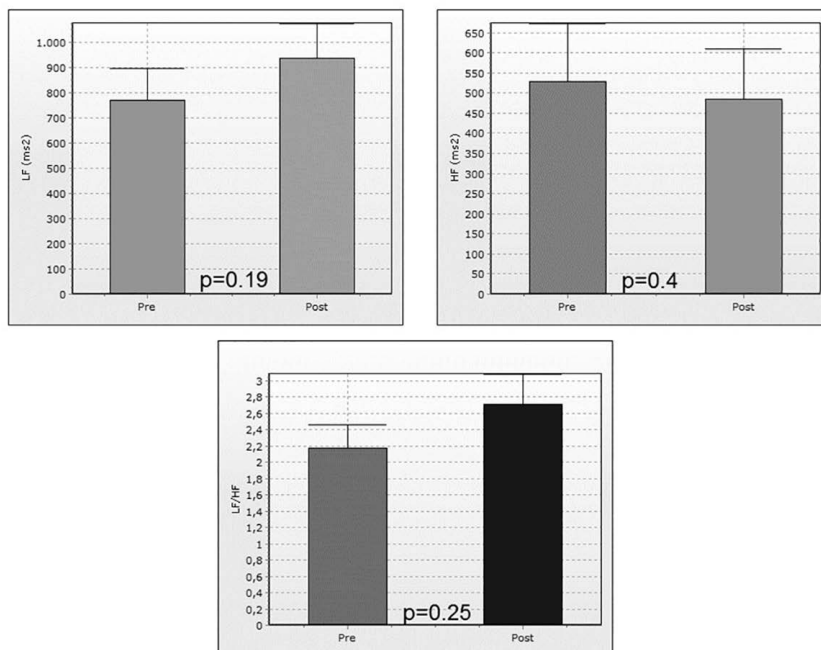


Figure 2 - Frequency domain analysis of HRV before (pre) and immediately after exercise (post) with flexible pole. HF: high frequency; LF: low frequency; LF/HF: low frequency/high frequency ratio. nu: normalized units; msec: milliseconds.

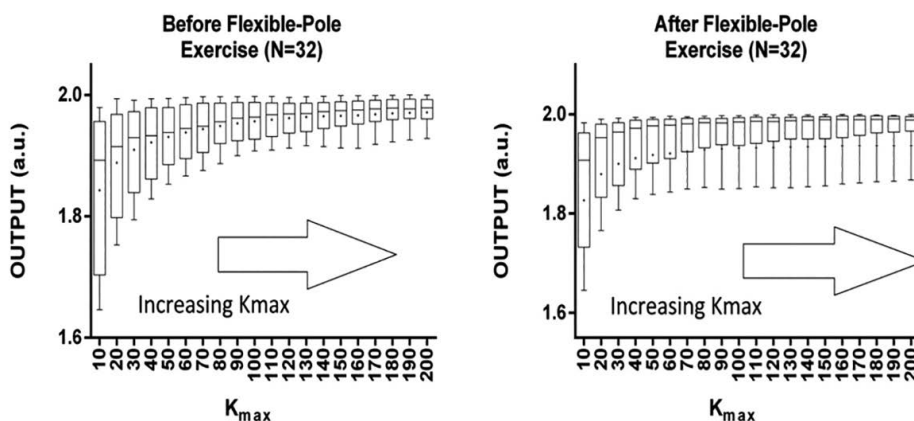


Figure 3 - The mean value in both categories is given by (+). For the Higuchi Fractal Dimension of the RR intervals before flexible pole exercise (left) and after flexible pole exercise (right) subjects calculated multiple times between 10 and 200; equidistantly for different levels of K_{max} . The number of RR-intervals was 500 and number of female subjects was 32.

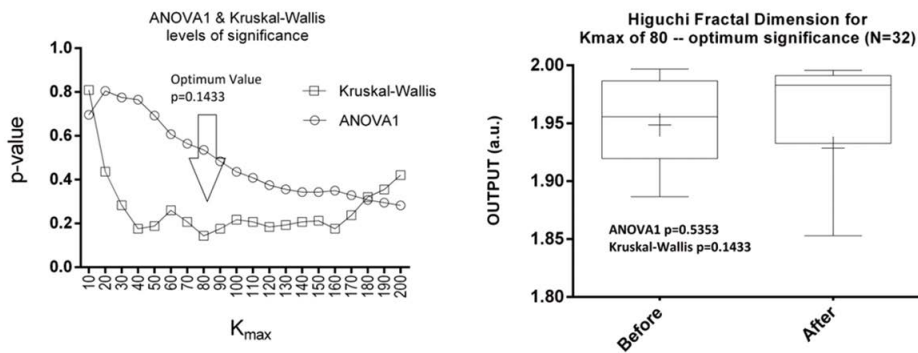


Figure 4 - The levels of significance (left) - parametric (ANOVA1) and non-parametric (Kruskal-Wallis) for values of the Higuchi Fractal Dimension at specific levels of K_{max} between 10 and 200 at equidistant intervals of 10. The groups compared here are the Higuchi Fractal Dimensions calculated for the 32 female subjects before and after flexible pole exercises. Then for this sole optimum value of K_{max} of 80 the Higuchi Fractal Dimension (right) before and after flexible pole exercises. Where the line in the central of the box is the median, the whiskers of the outer points are the 10th and 90th percentiles, with the outer edge of the boxes representing the 25th and 75th percentiles. The difference between the outer box edges is the inter-quartile range. The mean value in both categories is symbolized by (+). The number of RR-intervals was 500 and number of female subjects was 32.

Furthermore, parasympathetic recovery was noted approximately 30 minutes after the protocol. The authors analyzed the linear, time and frequency domain indices of HRV. However, they did not report significant HRV responses in the first 10 minutes after exercise. Likewise, we did not detect significant non-linear HRV responses in the initial 10 minutes during recovery from the exercise protocol. This indicates that chaotic behavior of HRV analysed through the Higuchi Fractal Dimension was unaltered during this period.

Equally, a previous study⁵ by our group indicated an absence of HRV responses after a protocol of exercise with flexible pole. The project successfully analyzed HRV through time, frequency domain and geometric indices.

Generally, our conclusions support the Higuchi Fractal Dimension as a method of greater sensitivity for analysis and to identify HRV changes.

HRV analysis and its independence provide an improved application of these assessments in order to advance the investigation of new techniques and the physiological rationale.³ It is important to understand that Higuchi Fractal Dimension analysis of HRV does not discriminate the parasympathetic or sympathetic components of cardiac autonomic regulation. It indicates the complexity of HRV. The greater the complexity, the more physiologically adapted the organism.²²

It would be advantageous to have larger sets of subjects – there were only 32 here. Superior statistical significance would have been achieved if the time-series were longer exceeding, for example 1000 RR intervals, as is typical as is typical in such studies. Further significance could be achieved by substituting the Higuchi Fractal Dimension algorithm with Approximate Entropy,²⁴⁻²⁶ Sample Entropy,²⁷⁻²⁹ Correlation Dimension algorithms or combinations thereof.³⁰

The present study presents additional findings compared to previous studies published.⁵⁻⁸ Dos Santos et al⁸ evaluated the acute effects of flexible pole exercise on heart rate dynamics through time and frequency domain HRV indices. The authors did not report significant differences on SDNN, RMSSD, pNN50, LF (nu), LF (ms²), HF (nu), HF (ms²) and LF/HF ratio. Those indices represent the linear behavior of HRV. Our results provide further information indicating the complex behavior of heart rate autonomic control during recovery from exercise with flexible pole. The mathematical method of Higuchi Fractal Dimension applied on RR interval is completely different from the classical mathematical methods used on time and frequency domain analysis.

We also evaluated HRV in different post-exercise periods compared to the references cited.⁵⁻⁸ While we investigated HRV in the initial five minutes post-exercise, previous studies evaluated it during the initial 60 minutes after exercise. In this context, we did not find significant change in complex behavior of HRV after an acute session of flexible pole exercise.

Application of flexible pole exercises has been widely used in rehabilitation and physiotherapy clinics. Even so,

there are few scientific studies supporting its effectiveness. Knowledge of the feasibility of its use can bring greater safety to patients with neurological, cardiac and/or metabolic disorders. The application of the protocol to young adults and the lack of research in this area could be a criterion addressed in this study. However, here we evaluated only females in order to avoid gender related effects.

■ CONCLUSION

An acute session of flexible pole exercise did not significantly modify the chaotic behavior of heart rate dynamics through Higuchi Fractal Dimension. We suggest this protocol as a procedure to moderate exercise intensity.

■ ACKNOWLEDGEMENTS

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■ CONFLICT OF INTERESTS

Authors declare no conflict of interest concerning this project.

■ AUTHOR PARTICIPATIONS

All authors participated in the acquisition of data and revision of the manuscript, Antonio, Garner and Raimundo performed statistical analysis and drafted the manuscript. Antonio, Navega, Abreu and Valenti designed the project, interpreted the data and drafted the manuscript. All authors read and gave final approval for the version submitted for publication.

ANÁLISE CAÓTICA DA DINÂMICA DA FREQUÊNCIA CARDÍACA APÓS EXERCÍCIO COM BARRA FLEXÍVEL

INTRODUÇÃO: Exercícios com uma barra flexível têm sido usados na prática clínica para a reabilitação do membro superior. No entanto, os seus efeitos agudos sobre a regulação autonômica cardíaca não estão bem esclarecidos.

OBJETIVO: Avaliar os efeitos agudos do exercício com barra flexível sobre o comportamento complexo da variabilidade da frequência cardíaca (VFC).

MÉTODO: Foram investigadas 32 voluntárias saudáveis com idades entre 18 e 25 anos que realizaram uma sessão de exercício com barra flexível. A VFC foi analisada 10 minutos antes e 10 minutos imediatamente depois do exercício.

RESULTADOS: Os exercícios com a barra flexível não alteraram significativamente os domínios de tempo e frequência de VFC. Análise não-linear da VFC através

da Dimensão Fractal Higuchi mostra que a mesma não foi significativamente alterada durante a recuperação do exercício em relação ao controle pré-exercício.

CONCLUSÃO: O exercício com a barra flexível não alterou profundamente o comportamento caótico da dinâmica da frequência cardíaca. Isto é vantajoso para a avaliação de níveis de tratamento de reabilitação necessário em tais pacientes; e sua suscetibilidade a doenças dinâmicas.

PALAVRAS-CHAVE: Sistema Nervoso Autônomo; Dimensão Fractal Higuchi; Medicina de Reabilitação.

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