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RESEARCH ARTICLE

Spectral methods of heart rate variability analysis during dynamic exercise

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Abstract
Objectives To apply both autoregressive (AR) and fast Fourier transform (FFT) spectral analysis at rest, during two different dynamic exercise intensities and in recovery from maximal exercise and to compare raw and normalized powers obtained with both methods.
Methods Sixteen participants (age 22.3 ± 4.3 year) performed resting, submaximal and maximal protocols. The submaximal protocol consisted of two 5-min walks at 4 km h^{-1} at treadmill grades of 0 and 7.5%. Beat-to-beat R-R series were recorded. FFT and AR analyses were preformed on the same R-R series.
Results Compared to AR, FFT provided higher total power (TP) and raw high-frequency (HF) power at rest and exercise. Furthermore, FFT LF/HF ratio was lower than with the AR, except under resting conditions. Both methods showed reductions in TP, raw HF and LF powers during exercise and recovery. Only the AR revealed a significant reduction for normalized HF power and increase for normalized LF power in transition from rest to exercise conditions.
Interpretation AR and FFT methods are not interchangeable at rest or during dynamic exercise conditions. The AR method is more sensitive to the effects of exercise on the normalized power spectra of heart rate variability (HRV) than FFT. Finally, as both approaches are equally insensitive to the increase of exercise relative intensity, there is no practical advantage of performing HRV spectral analyses by the AR or FFT at higher workloads.

Keywords Heart rate variability · Spectral analysis · Dynamic exercise · Cardiac autonomic control

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Introduction

Analysis of heart rate variability (HRV) is a valuable non-invasive marker of autonomic nervous system modulation of the sinoatrial (SA) node and is regularly used to study the underlying physiological processes involved in cardiovascular control, both at rest and during exercise [21]. The HRV is frequently analysed in both the time and frequency domains [7] and is most often evaluated at rest. During exercise, an increase in heart rate results from vagal withdrawal at low exercise intensities and from both vagal withdrawal and sympathetic activation at moderate and higher exercise intensities [25, 33]. Heart rate recovery following the cessation of exercise is mainly due to vagal re-activation immediately after exercise termination and further reductions are mediated by both vagal and sympathetic influences [16, 28]. Studies using conventional spectral analysis of HRV have shown that raw total, low-frequency (LF) and high-frequency (HF) powers decrease with exercise [1, 29], but results for LF and HF normalized to total power (TP) have been inconsistent [4, 8, 29, 32, 37, 40]. During recovery, the reduced HRV gradually returns to pre-exercise levels within several minutes or hours depending on exercise intensity [4, 29, 36].

Frequency domain analyses of the HRV signal are usually made using either fast Fourier transform (FFT) or autoregressive (AR) models [3]. There is general agreement that AR and FFT spectral analyses are not interchangeable [3, 31]. Nevertheless, dynamic trends provided by the two approaches are generally equivalent (3), but to date, there are no reports on whether AR and FFT data processing of HRV during submaximal dynamic exercise provide similar results. Indeed, literature still presents conflicting results [19, 22, 26, 32, 37, 42] and a critical dilemma is whether both methods are equally sensitive to the effects of exercise on autonomic function. Thus, it is important to determine whether one methodology is more suitable than the other for HRV assessments during dynamic exercise. The purpose of this study was to apply both AR and FFT spectral analysis at rest, during two different exercise intensities and during recovery from maximal exercise and to compare raw and normalized LF and HF powers obtained with the two methods.

Methods

Participants

A total of 16 participants, 9 male and 7 female physical education students volunteered to take part in the study (22.3 ± 4.3 years old). Participants' characteristics are presented in Table 1. All participants were experienced treadmill walkers and runners and they all were similarly active, accumulating 9-h of physical activity per week as part of their academic work. Medical histories were obtained through direct interviews and exclusion criteria were as follows: (1) history of thyroid or cardiovascular disease, (2) history of diabetes or other metabolic disease that might affect outcome measures, (3) heart rate altering medications, (4) smoking, (5) pulmonary or respiratory disorders, including asthma and (6) orthopaedic injury preventing successful completion of the exercise protocol. After thorough explanation of the study protocol to participants, and after having been shown the equipment, written informed consent was attained. All procedures in this study complied with the Declaration of Helsinki and were approved by the Ethics Committee from the Human Kinetics University at Lisbon-Portugal.

Table 1 Descriptive characteristics of the participants

Variable	Participants (n = 16)
Age (year)	22.3 ± 4.3
Body mass (kg)	65.6 ± 10.3
Height (cm)	171.4 ± 6.7
BMI (kg m^{-2})	22.3 ± 2.5
VO_{2max} (mL min^{-1})	2892.1 ± 695.8
VO_{2max} (mL kg^{-1} min^{-1})	43.9 ± 8.6
HR_{max} (bpm)	191.7 ± 10.1

Values are mean ± SD

BMI body mass index, VO_{2max} maximum oxygen uptake, HR_{max} maximum heart rate

Measurements

All subjects were tested in a postprandial state, approximately 2–4 h after their last meal. Participants refrained from exercise 24 h before testing and caffeine ingestion on testing days. The days of testing consisted of: (1) a standardized body composition assessment, (2) a resting protocol, (3) a continuous submaximal steady-state exercise protocol, and (4) a maximal graded exercise protocol. Testing was carried out in the laboratory with an environmental temperature between 21 and 24°C and a relative humidity between 44 and 56%. In an attempt to control for possible circadian variations in HRV, the measurements were performed between 07.00 and 11.00 h at approximately the same time of day for all individuals.

Body mass was measured at both visits using a calibrated digital scale, and height was measured using a stadiometer (Secca 770, Hamburg, Germany—standing digital scale/height rod attached). Body mass index (BMI) was calculated by dividing the participants' mass in kilograms by the square of their height in meters. Expired gas measurements were made using a computerized on-line breath-by-breath system (Quark b^2, Cosmed® Srl-Italy), which was calibrated before each test with a known volume and with known gas concentrations. HRV data were obtained by means of a Polar RS 800 G3 heart rate monitor (Polar R-R Recorder, Polar Electro, Kempele, Finland).

Testing protocols

Each test was conducted after a 15-min resting period. As previously reported by Perini et al. [27], under free breathing conditions, there are no substantial differences between the power spectra obtained with the subjects in the supine and sitting position. In conformity and to allow comparisons with previous studies [1, 17, 19, 22, 29, 32, 37, 38], resting HRV and VO_2 were obtained during the last 3 min of the resting period in sitting position. Subsequently, participants' HRV and VO_2 data were collected while exercising on a motorised treadmill (h/p/cosmos® mercury med 4.0). The protocol involved continuous walking at a constant speed of 4 km h^{-1} at two different treadmill grades (0 and 7.5%), for 5 min each. According to Sandercock and Brodie, there is some evidence to suggest that the expected augmentation and reduction of normalized HF and LF powers only occurs at low-to-moderate relative intensities [34]. Furthermore, it is also known that 50% of tachograms recorded at intensities above the anaerobic threshold cannot be analysed due to low signal-to-noise ratio [15]. Therefore, in the present study, submaximal treadmill workloads were selected on the basis of previous research conducted in our laboratory with a group of similar characteristics [39]. As reported, both these absolute treadmill workloads are compatible with reliable cardiopulmonary data collection within a seven day period test-retest experimental design; and effective in eliciting different VO_2 fractional utilization (FU) while remaining below 60% of the VO_{2max}.

HRV and on-line VO_2 uptake measurements were obtained during the submaximal protocol. The VO_2 data were displayed as 30-s averages. The last 3 min of each 5-min walk were used for subsequent HRV and cardiorespiratory data analysis [41]. Additionally, the submaximal relative work intensities were determined as percentages of VO_{2max} (fractional utilization).

Maximal protocol

VO_{2max} was determined by means of a continuous incremental test to volitional exhaustion commencing immediately after the second submaximal walk. For this purpose, treadmill grade was increased from 7.5 to 10% while maintaining a speed of 4 km h^{-1} for three minutes and then to 12.5% for a further minute. From this point, grade was held constant whereas speed was increased by 1.6 km h^{-1} every minute until exhaustion. The test was terminated when the subject reached exhaustion and grasped the hand rails of the treadmill. The VO_2 data were displayed in 20-s averages. Data were then examined to determine if VO_{2max} had been attained according to the following criteria [23]: (1) attainment of the age-predicted maximum heart rate, (2) respiratory exchange ratio $\geq$1.15, and (3) a plateau or decrease in VO_2. If one of the first two and the third criteria were not achieved, the subject was required to repeat both the submaximal and maximal protocols after a recovery period ranging from 2 to 7 days. Only one participant required a second test. Recovery from maximal exercise consisted of a 5-min treadmill horizontal walk at 4 km h^{-1} with the last 2 min being used for HRV and cardiorespiratory data analysis.

Measurement and analysis of HRV

The R-R intervals were recorded (Polar R-R Recorder, Polar Electro, Kempele, Finland) at a frequency of 1,000 Hz, providing an accuracy of 1 ms for each R-R interval. Recorded R-R intervals were first transferred to the Polar Precision Performance Software (Kempele, Finland) and visually inspected for undesirable premature beats and noise. An R-R interval was interpreted as premature if it deviated from the previous quantified interval by >30%. No premature beats were observed in the complete set of R-R intervals obtained from each individual; therefore, there was no need for interpolation due to ectopy. The R-R intervals of the last 3 min at rest and each submaximal exercise stage were then chosen for analysis. The same procedure was used for the last 2 min of post-exercise recovery period. AR and FFT calculations were then performed with HRV Analysis Software 1.1 for Windows (The Biomedical Signal Analysis Group, Department of Applied Physics, University of Kuopio, Finland) [24].

Frequency domain

Prior to HRV analysis in the frequency domain, R-R data were detrended [35], and resampled at 2 Hz. The FFT spectrum was then calculated using a Welch periodogram method. In this method, the R-R data were first divided into overlapping segments of 128 R-R intervals. Each segment was then windowed using a Hanning window [18], and FFT spectrum was calculated for each windowed segment with subsequent spectra averaging. The AR spectrum was calculated fitting a 16th-order model [5] to the R-R data. The AR model parameters were solved using a forward–backward least squares method, and finally, the AR spectrum was obtained from the estimated AR parameters. The frequency-domain variables included the TP spectrum (0–1.0 Hz) and the power spectra integrated over the very low frequency (VLF, 0–0.04 Hz), low-frequency (LF, 0.04–0.15 Hz), and high-frequency (HF, 0.15–1.0 Hz) bands. As in previous studies, the higher frequency limit of 1.0 Hz was chosen to include the respiratory frequency during exercise and post-exercise recovery [17, 22].

It is widely accepted that the HF power reflects vagal modulation of heart rate and that both the LF power and the LF/HF ratio reflect a complex interplay between sympathetic and parasympathetic modulation. The physiological meaning of the VLF power assessed from short-term recordings is less defined and its interpretation is not recommended when analysing power spectra density results [7]. Data were expressed as raw and normalized values. The LF/HF ratio (which is independent of normalization) was then calculated. Finally, for the AR modelling, the centered frequency value of each component was also calculated.

Statistical analysis

Standard descriptive statistics were used to summarize the data. Resting, submaximal, maximal and post-exercise

Table 2 Respiratory variables at submaximal walking grades

Variable	Rest	0%	7.5%	Recovery
VO_2 (mL kg^{-1} min^{-1})	3.5 ± 0.7	10.1 ± 1.2*	17.2 ± 1.3$^{\#}$	12.2 ± 2.8†
TV (L)	0.6 ± 0.2	1.1 ± 0.6*	1.4 ± 0.4*	1.6 ± 0.5$^{\#}$
RR (cpm)	15.0 ± 2.8	19.0 ± 5.4*	22.4 ± 6.3$^{\#}$	27.9 ± 4.6†

Values are mean ± SD

VO_2 oxygen uptake, *TV* tidal volume, *RR* respiratory rate

* $p < 0.05$ with respect to rest

$^{\#}$ $p < 0.05$ with respect to rest and 0%

† $p < 0.05$ with respect to rest, 0 and 7.5%

recovery cardiorespiratory data were studied using repeated measures analysis of variance to test for treadmill workload effects. Raw and normalized powers obtained with FFT and AR approaches were compared with the paired Wilcoxon test to determine possible differences between them. Furthermore, the Bonferroni correction for multiple comparisons was used to describe the overall changes in spectral powers, obtained by both methods, following the transition from rest to exercise and post-exercise recovery. We also examined the Pearson correlation coefficients between delta heart rate and delta normalized LF and HF powers in response to the selected workloads (Δ1 WL, from rest to submaximal exercise 1; Δ2 WL, from submaximal exercise 1 to submaximal exercise 2). All statistical calculations were computed using SPSS version 16.0 and a significance level of 0.05 was used.

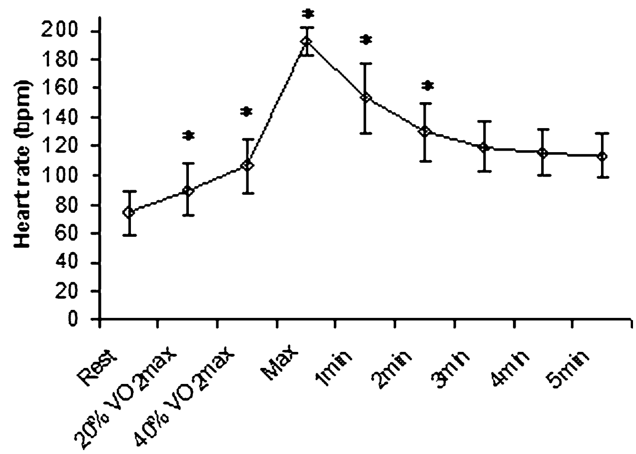

Fig. 1 Heart rate response in transition from resting to exercise and active recovery at a constant speed of 4 km h^{-1}. Values are mean ± SD. *$p < 0.05$ for comparisons of heart rate between adjacent data points

Results

Morphological and cardiopulmonary data

As shown in Table 2, the increase in treadmill grade from 0 to 7.5%, while maintaining a constant speed of 4 km h^{-1}, was effective in eliciting a significant increase in VO_2 from 10.1 ± 1.2 to 17.2 ± 1.3 mL kg^{-1} min^{-1} ($p < 0.05$). Since the participants attained a mean VO_{2max} of 43.9 ± 8.6 mL kg^{-1} min^{-1}, these treadmill grades corresponded to 23.5 ± 4.0% (~20%) and 40.2 ± 7.0% (~40%) of VO_{2max}, respectively ($p < 0.0001$). While the respiratory rate (RR) increased in a continuous fashion from rest to exercise and post-exercise recovery ($p < 0.05$), tidal volume (TV) was not different between treadmill workloads.

Figure 1 shows the between day heart rate dynamics from rest to exercise at different intensities, followed by the 5-min active recovery period. Heart rate increased significantly as a function of treadmill workload from resting conditions to submaximal and maximal exercise ($p < 0.0001$). A significant decrease in the successive heart rate values was only observed for the first 3 min of active recovery after maximal exercise. Thereafter, during the fourth and fifth min of active recovery, heart rate was stabilized ($p > 0.05$).

Power spectra of autoregressive versus fast Fourier transform

Mean values of comparisons between AR and FFT over visits are shown in Table 3. At rest, both TP and HF raw power derived from the FFT calculations were significantly higher than those provided by the AR method ($p < 0.05$). No differences between the methods were obtained for LF raw power ($p > 0.05$). At both relative intensities, FFT TP was also higher than that of AR. Additionally, when compared to AR, FFT provided higher HF raw power at ~20 (284.3 ± 154.6 vs. 156.9 ± 99.5 ms^2, $p < 0.05$) and ~40% VO_{2max} (109.1 ± 66.1 vs. 51.5 ± 33.7 ms^2, $p < 0.05$). Similarly, normalized HF power derived from FFT was higher than that of AR at ~20 (29.0 ± 3.8 vs.

Table 3 Power spectra of heart rate variability derived from autoregressive and fast Fourier transform methods

Variable	AR	FFT
Rest		
TP (ms^2)	2731.9 ± 1186.6	3320.8 ± 1513.1*
VLF (ms^2)	328.7 ± 108.9	744.6 ± 343.4*
LF (ms^2)	1278.9 ± 649.1	1186.3 ± 475.2
HF (ms^2)	1124.2 ± 566.6	1389.9 ± 721.4*
LF (*v*)	61.4 ± 5.1	57.1 ± 5.2
HF (*v*)	38.1 ± 5.0	42.9 ± 5.2
LF/HF	2.4 ± 0.5	1.9 ± 0.4
20% VO_{2max}		
TP (ms^2)	823.1 ± 244.8	1000.3 ± 294.1*
VLF (ms^2)	123.1 ± 39.0	203.5 ± 55.1
LF (ms^2)	543.1 ± 155.0	512.6 ± 122.7
HF (ms^2)	156.9 ± 99.5	284.3 ± 154.6*
LF (*v*)	84.5 ± 2.2	71.0 ± 3.8*
HF (*v*)	15.5 ± 2.2	29.0 ± 3.8*
LF/HF	7.8 ± 1.5	3.6 ± 0.8*
40% VO_{2max}		
TP (ms^2)	260.1 ± 99.4	332.6 ± 113.2*
VLF (ms^2)	40.2 ± 22.2	54.6 ± 13.2*
LF (ms^2)	168.4 ± 47.9	168.8 ± 43.8
HF (ms^2)	51.5 ± 33.7	109.1 ± 66.1*
LF (*v*)	82.6 ± 3.5	68.4 ± 4.5*
HF (*v*)	17.4 ± 3.5	31.6 ± 4.5*
LF/HF	8.6 ± 1.5	3.2 ± 0.6*
Recovery		
TP (ms^2)	46.9 ± 17.9	48.5 ± 14.2
VLF (ms^2)	12.1 ± 4.2	16.5 ± 4.8
LF (ms^2)	25.7 ± 15.7	19.1 ± 7.1
HF (ms^2)	7.0 ± 2.7	12.8 ± 4.1*
LF (*v*)	61.5 ± 7.6	56.8 ± 5.2
HF (*v*)	32.9 ± 7.2	43.2 ± 5.2
LF/HF	6.9 ± 2.8	2.7 ± 1.2*

Values are mean ± SEM

LF low frequency, *HF* high frequency, *TP* total power, *VLF* very low frequency

* $p < 0.05$

15.5 ± 2.2 *v*, $p < 0.05$) and ~40% VO_{2max} (31.6 ± 4.5 vs. 17.4 ± 3.5 *v*, $p < 0.05$). On the contrary, LF normalized power and the LF/HF ratio derived from AR were higher than those obtained with FFT during exercise ($p < 0.05$). Finally, while LF powers did not differ between approaches during recovery, FFT derived raw HF power was higher than that obtained by the AR approach (12.8 ± 4.1 vs. 7.0 ± 2.7 ms^2, $p < 0.05$), with the opposite being reported for the LF/HF ratio.

Comparisons of power spectra between rest, exercise and recovery

As shown in Fig. 2, the comparisons of TP and raw LF power between rest, exercise and recovery provided homogenous results with both approaches. Specifically, TP and raw LF power decreased in a continuous fashion from rest to exercise and recovery. Raw HF powers did decrease with both methods, but significant differences between recovery and exercise at ~40% VO_{2max} were only attained with the FFT ($p < 0.05$). While HF power centered frequency increased progressively from rest (0.25 Hz ± 0.01) to ~20% VO_{2max} (0.31 Hz ± 0.02), ~40% VO_{2max} (0.36 Hz ± 0.03) and recovery (0.48 Hz ± 0.04), LF centered frequency was similar over conditions (~0.1 Hz, $p > 0.05$).

Despite showing a tendency, while the AR calculated normalized LF power and LF/HF ratio both increased significantly from rest to exercise ($p < 0.05$), FFT did not reach significance. Findings for normalized HF power followed those of normalized LF powers, but in the opposite direction. Thus, whereas AR attained a significant decrease for normalized HF power in transition from rest to exercise, FFT only presented such tendency. Nevertheless, both methods were equally insensitive to the effects of an increase in exercise relative intensity. Moreover, the above mentioned differences between approaches for raw HF power during recovery were dissipated after normalization procedures. Finally, the increase in heart rate from rest to exercise at ~20% VO_{2max} (17.9 ± 4.9 bpm, $p < 0.05$) was significantly correlated with changes obtained in normalized powers with the AR (LF, *v*, $r = 0.56$, $p < 0.05$; HF, *v*, $r = -0.55$, $p < 0.05$) and FFT (LF, *v*, $r = 0.54$, $p < 0.05$; HF, *v*, $r = -0.54$, $p < 0.05$).

Discussion

To our knowledge, this is the first study in which FFT and AR methods were applied to the same population over a spectrum that included resting, exercise and post-exercise recovery conditions. The major findings can be summarized as follows:

1. Significant differences between the AR and FFT methods suggest the data generated from these methods are not inter-changeable.
2. Despite the existence of a general common trend between spectral approaches for changes in HRV from rest to exercise and active recovery, the AR method is more sensitive than FFT to the effects of dynamic exercise on the normalized power spectra of HRV.

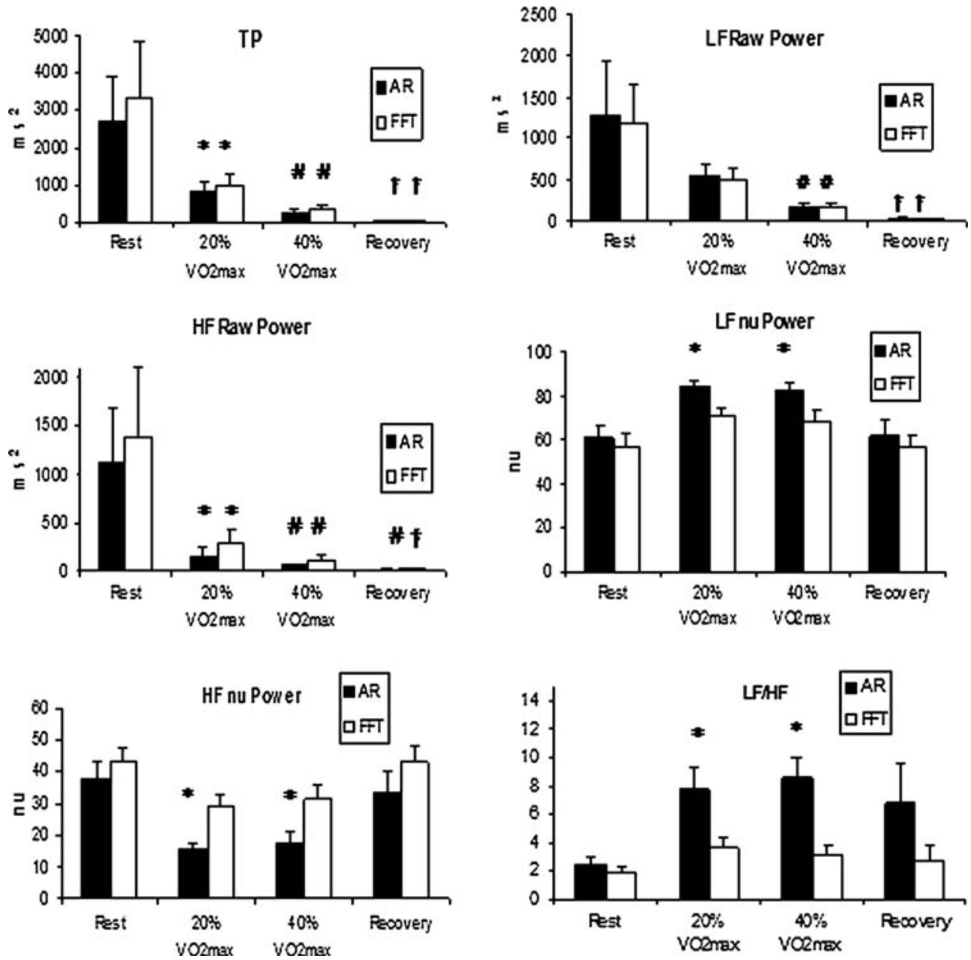

Fig. 2 Absolute and normalized spectral powers at rest, exercise and active recovery. In each panel, *vertical bars* and *vertical lines* indicate means and SEM of the power considered. Spectral parameters are given independently for autoregressive (*AR*) and fast Fourier transform (*FFT*) methods. *TP* total power, *HF* high frequency, *LF* low frequency. * $p < 0.05$ with respect to rest. $^{\#}$ $p < 0.05$ with respect to rest and 20% VO_{2max}. † $p < 0.05$ with respect to rest, 20% VO_{2max} and 40% VO_{2max}

3. Both approaches are equally insensitive to the increase of exercise relative intensity, thus suggesting that there is no practical advantage of performing HRV spectral analyses by the AR or FFT at higher workloads.

The analysis of heart rate variability provides a useful method for studying autonomic function of the cardiovascular system during different physiological and pathophysiological conditions. The development of increasingly sophisticated means of analysing HRV has led to better identification of the role played by the autonomic nervous system under different conditions. Many studies have examined the influence of acute exercise upon raw HF and LF powers of HRV spectrum and there is general agreement that, independently of the HRV spectral approach, they both decrease as a function of exercise intensity [1, 6, 8, 11, 14, 19, 22, 29, 30, 32, 38]. On the other hand, the patterns of change reported for the normalized LF and HF powers or the LF/HF ratio, have been more inconsistent. Inconsistency in findings probably reflect, at least in part, differences in methodology [8], including differences in exercise intensity and duration and completeness of the steady state, the number of heart beats analysed and, additionally, the selected spectral approach for HRV data analysis [19, 22, 26, 32, 37, 42]. Although many spectral methods have been applied, the most popular two are the AR and FFT-based approaches. As shown in Table 3, these two methods give numerically different results at rest, during exercise and at post-exercise recovery and this agrees with previous findings for supine and sitting rest [3, 31], passive tilt test [3], active orthostatism [3, 31], specific circadian periods and pharmacological autonomic modulation [2]. Consequently, the present study corroborates that FFT and AR analyses are not interchangeable at rest and further extend these findings to exercise and active recovery conditions.

According to our results, FFT provided higher TP than AR at rest and during exercise at both relative intensities. These findings are similar to those of Pichon et al. who also reported more TP with FFT than with AR in sitting, but not in standing position [31]. Differences between methods could be due to the Hanning windowing preprocessing before the FFT, which influences, indeed, the overall variability of the signal

[31]. Other authors reported different results from the ones of the present study and those of Pichon et al. [31] at rest in the sitting position [2, 3, 10]. Specifically, Badilini et al. [3] found no differences between FFT and AR for TP obtained from a group of healthy young participants performing supine rest and passive tilt test under metronomic breathing (0.25 Hz). On a different experimental design which included 24-h HRV assessments performed on patients with mild hypertension, Badilini et al. concluded that TP obtained by AR was significantly higher than that of FFT, irrespectively of the circadian period of interest [2]. The authors interpreted these differences as being related to the uncontrolled nature of the experiment in which, a permanently changing environment might have contributed to strong heart rate trends (physical activity, sleep states). In line with Badilini et al. [2], Chemla et al. [10] also reported higher TP with AR than FFT during a 10-min resting period in diabetic patients. Unfortunately, adding to the fact that Chemla et al. [10] included a population subset with high prevalence of autonomic dysfunction [12], authors did not specify the nature of the selected resting period (i.e. supine vs. sitting or free vs. controlled breathing), thus limiting further comparisons. Interestingly, irrespective of discrepancies between studies for TP derived from both approaches under different physiological conditions, there is general agreement that raw HF power is higher with FFT than with AR [2, 3, 13, 31]. Therefore, FFT derives more raw HF power than AR during exercise at different relative intensities; this is in agreement with results obtained from short-term HRV recordings performed at rest in supine, sitting and standing positions [3, 13, 31] and from long-term HRV recordings performed over day and night with or without pharmacological sympathetic blockade [2]. Furthermore, similarly to resting conditions, short-term HRV recordings during exercise, particularly at $\sim$40% VO_{2max}, result in higher VLF spectral power with FFT, compared to AR. This further contributes to the increased TP reported by the former. As the VLF assessed from short-term recordings is a dubious measure [7] that apparently adds significance to an increase in TP from FFT over AR, these differences between methods may not be physiologically relevant.

Generally, whatever the analysis, the decrease in TP and raw HF power in transition from rest to exercise at $\sim$20% VO_{2max}, $\sim$40% VO_{2max} and active recovery were significant. Furthermore, both methods confirmed that exercise raw LF power was not significantly reduced from resting conditions during exercise at $\sim$20% VO_{2max}. On the other hand, only the AR calculations provided significant increases for normalized LF power and significant decreases for normalized HF power during exercise over resting conditions. Similarly, opposing to FFT, AR derived LF/HF ratio also increased from rest to exercise. There was no further change in normalized LF and HF powers or LF/HF ratio with increasing exercise relative intensity and this was transversal to both methods. As it is usually reported by the use of AR analysis during dynamic exercise, both the HRV normalized spectral components and the LF/HF ratio present a biphasic pattern of behaviour in response to increases in relative intensity [34]. In general, while these parameters change in the expected directions at low-exercise intensities, the opposite has been reported for higher relative intensities. This appears to be related to the non-neural genesis of some HF oscillations at higher exercise intensities that further constitute a confounding factor, presently quantified at $\sim$32% of this component [9]. In the present study, as there were no additional modifications of normalized power spectrum or LF/HF ratio despite the significant increase in relative intensity, it seems reasonable to assume that HRV spectral analysis should be restricted to lower exercise intensities for purposes of meaningful physiologic interpretations. In support of this, we only obtained significant correlations between delta heart rate and delta normalized HF and LF powers from rest to exercise at $\sim$20% VO_{2max}. Curiously, HF centered frequency increased linearly with metabolic demand, reflecting the increase in respiratory rate. This corroborates previous findings [4, 9, 26] and is probably related to a direct mechanical effect of enhanced respiratory activity on the heart, occurring not only during low and moderate relative intensities, but also in recovery from maximal exercise. Overall, these results indicate that, both raw and normalized AR powers are sensitive to a reduction in vagal modulation induced by exercise [1, 27, 29, 32, 37, 38]. Additionally, the increase reported by normalized LF power and the LF/HF ratio suggest sympathetic activation with a well-defined shift towards sympathetic dominance during low and moderate intensity dynamic exercise.

The vast majority of studies on autonomic function during exercise have been conducted using cycle ergometry, but findings are contradictory [27, 29, 38, 42, 43]. Some report that the AR normalized LF component decreases linearly and the normalized HF power shows a tendency to increase above resting values at exercise intensities beyond 30% VO_{2max} [27, 29]. On the contrary, for approximately the same exercise intensities, others have demonstrated an increase in the AR normalized LF component above resting values that was accompanied by a decrease in the normalized HF power [38, 42, 43]. Findings from treadmill exercise have been more consistent. In general, LF/HF ratio increases with treadmill exercise and HF decreases [32, 37]. Our results agree with those of previous studies conducted on the assessments of spectral HRV during treadmill exercise at comparable workloads by the AR approach [32, 37]. Moreover, present findings also corroborate those of two recent reports using FFT approach for HRV spectral analysis during low to moderate intensity dynamic exercise [19, 22].

Specifically, the authors reported non-significant changes in FFT normalized LF and HF powers in response to steady state exercise on the cycle ergometer at $\sim 29\%$ VO_{2max} [22] and at ~ 25 and $\sim 40\%$ VO_{2max} on the treadmill [19] ($p > 0.05$). Nevertheless, in accordance with our results, there was a clear tendency towards the increase of normalized LF power paired by a decrease in normalized HF power at the selected relative intensities.

We interpret these findings as related to an overestimation of the HF components with FFT analysis. Of several explanations that could be proposed to explain this overestimation, a relevant one is related to the known wide-band noise that is isolated and suppressed with AR, but constitutes a part of TP spectrum with FFT analysis [13, 20]. A second explanation for the differences between methods might be a consequence of tail effect [3]. In fact, with FFT, the calculation of a component between one frequency band includes the power corresponding to the tail of the neighbouring component, whereas with AR analysis, spectral power corresponds only to a specific oscillatory pattern representing one HRV single component. Finally, in line with the available literature, the systematic overestimation of the HF by the FFT component in our study could be explained by the possibility that the AR extracts only the power corresponding to respiratory sinus arrhythmia and not the associated noise contained within a predefined frequency range [13, 31].

In conclusion, AR and FFT spectral analyses provide different quantitative results at rest, during exercise and at post-exercise recovery period. Specifically, AR methodology is apparently more sensitive to the effects of dynamic exercise on autonomic function when quantified by changes in HRV normalized power. Differences between the two methodologies in normalized units may depend on the intrinsic effects of dynamic exercise itself and may be possibly related to the mode of spectrum integration specific of each approach. Therefore, normalization procedures that do not account for VLF powers are capable of showing significant increases of LF and decreases of HF in transition from rest to whole-body dynamic exercise with AR, but not with FFT. Finally, as both approaches are equally insensitive to the increase of exercise relative intensity, there is no practical advantage of performing HRV spectral analyses by the AR or FFT at higher workloads.

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