Attenuation of the Influence of Cardiolocomotor Coupling in Heart Rate Variability Interpretation During Exercise Test

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Abstract— **During exercise test, cardiolocomotor coupling related components appear in heart rate variability (HRV), blurring its interpretation as autonomic nervous system (ANS) marker. These cardiolocomotor coupling related components are centered at the pedalling and running stride frequency, as well as at their aliases, and may overlap with the low frequency (LF) and high frequency (HF) components of HRV. In this work cardiolocomotor-related HRV components are studied during maximal exercise test on treadmill and cycle ergometer. Power in the bands related to cardiolocomotor coupling increases with exercise intensity in cycle ergometer but not in treadmill exercise test, where it displays higher values for all exercise intensities. A method is proposed to reduce the effect of this coupling in the interpretation of HRV. Evolution of the power in the low frequency (LF) and high frequency (HF) bands are studied after the proposed reduction of cardiolocomotor coupling, showing more significant changes with exercise intensity than before the method is applied.**

I. INTRODUCTION

Heart Rate Variability (HRV) is considered a non-invasive method to assess the regulation of the Autonomic Nervous System (ANS) over the heart (rate), which could be altered in a wide variety of pathological and physiological situations [1]. Spectral analysis of HRV at rest reveals the presence of two main components: a high frequency (HF) component synchronous with respiration and mainly mediated by parasympathetic system, and a low frequency (LF) component with sympathetic and parasympathetic influence [1].

The study of HRV during exercise testing is appealing to sports physiologists to understand how ANS respond to exercise, and to physicians to reveal ANS alterations which may not be visible at rest. However, HRV spectral analysis and interpretation during exercise presents some peculiarities. It requires the use of time-frequency methods, since HRV is highly non-stationary in these recordings; a dynamic HF band centred at respiratory frequency, which varies with exercise intensity; and the correction of HRV by the time-varying mean heart rate, which increases with exercise [3].

Moreover, components centred at pedalling or stride frequency and their aliases have been observed in HRV during exercise test [4], [5]. These components are thought to reveal cardiolocomotor coupling due to the dynamic modulation of the venous return due to leg muscle contraction [4] and may overlap with LF and HF bands, misleading their interpretation in terms of sympathetic or parasympathetic activation.

In this work we analyse these components related to cardiolocomotor coupling as function of exercise type (running, pedalling) and intensity. Then, we propose a method to reduce their influence in the interpretation of HF band when overlapping exists.

II. MATERIALS AND METHODS

A. Study population

Recordings of 25 healthy athletes have been analysed during two different maximal exercise tests, one on treadmill and the other on cycle ergometer, with fixed running stride or pedalling rate at 80 rpm. Recordings include 5 minutes resting seated and 3 to 5 minutes of active recovery. Exercise intensity was gradually increased up to reaching 90% of the maximal heart rate, where exercise intensity was kept 2 more minutes.

Instantaneous RR series were recorded using RS800CX from Polar Electro Oy. Ventilatory and exchange gases (ventilation, respiratory frequency, O2 consumption, CO2 expenditure) were measured breath by breath by OxyconPro from Jaeger Viasys Healthcare. In treadmill test, the running stride frequency was recorded using stride sensor S3 from Polar Electro Oy.

B. Heart Rate Variability estimation

HRV is derived from the recorded RR series. From the beat occurrence time series, t_k, an instantaneous heart rate (HR) signal is obtained based on the the integral pulse frequency modulation model (IPFM) [2], which accounts for the presence of ectopic beats. The instantaneous HR signal is sampled at 4 Hz and denoted $d_{HR}(n)$. Then, a time-varying mean HR (called $d_{HRM}(n)$) is obtained low-pass filtering $d_{HR}(n)$, with a cut off frequency of 0,03 Hz. HRV is obtained as $d_{HRV}(n) = d_{HR}(n) - d_{HRM}(n)$. Finally, the influence on HRV of changes in mean HR induced by exercise is attenuated with the correction proposed in [3], $m(n) = d_{HRV}(n)/d_{HRM}(n)$, where $m(n)$ represents the modulating signal which carries the information from ANS.

C. Definition of spectral components

Time-frequency analysis was applied to $m(n)$ by means of the Smoothed pseudo Wigner-Ville distribution (SPWVD),

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with the same time and frequency resolution as in [4]. This method is chosen because it follows faster variations than Short-Time Fourier Transform (STFT) and with their adaptative filters can attenuate cross-terms.

Instantaneous power of HRV components was computed integrating the SPWVD for each time instant in these bands:

- LF band: $\Omega_{LF} : [0,04-0,15]Hz$.
- HF band, centred at respiratory frequency $(F_R(n))$, $\Omega_{HF} = [F_R(n)-0,125/2, F_R(n)+0,125/2]Hz$.
- Cadence Frequency (CF) band, centred at running stride or pedalling frequency $(F_C(n))$, $\Omega_{CF} = [F_C(n)-0,125/2, F_C(n)+0,125/2]Hz$.

$F_R(n)$ is obtained low-pass filtering the recorded respiratory frequency with a cut-off frequency of 0,01 Hz.

$F_C(n)$ in treadmill test is obtained low-pass filtering the recorded running stride frequency with a cut-off frequency of 0,01 Hz. In cycloergometer test this component is fixed to 4/3 Hz (80rpm) since pedalling frequency was not recorded.

Since the intrinsic sampling frequency of HRV is the HR, when $F_C(n)$ exceeds half the mean HR, aliasing occurs and aliased components appear in the visible part of the spectrum [3]. There are two main aliased components (denoted AF1 and AF2) which appear in these recordings, whose instantaneous power is estimated integrating the SPWVD in the following bands:

- $\Omega_{AF1} = [F_{A1}(n)-0,125/2, F_{A1}(n)+0,125/2]Hz$, $F_{A1}(n) = -d_{HRM}(n)+2\cdot F_C(n)$.
- $\Omega_{AF2} = [F_{A2}(n)-0,125/2, F_{A2}(n)+0,125/2]Hz$, $F_{A2}(n) = d_{HRM}(n)-F_C(n)$.

Figure 1 displays the SPWVD of $m(n)$ for a volunteer during the exercise phase of a treadmill exercise test. The spectral bands of interest are represented on it.

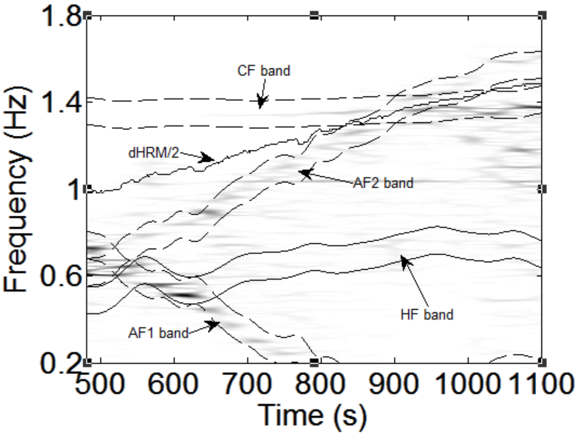

Fig. 1. Time-frequency map showing the components bands. Continuous represents HF; striped , CF (constant in 1.3 Hz); AF1 (dissapear in 700 s); AF2 (increase from 0.6 to 1.4 Hz).

Instantaneous power of each spectral component is denoted $P_{XF}(n)$ where XF stands for LF, HF, CF, AF1, AF2.

D. Attenuation of cardiolocomotor coupling effect

Components related to cardiolocomotor coupling overlap sometimes with HF band, misleading its interpretation as a measure of respiratory sinus arrhythmia [7]. In this section, we propose a method to attenuate the effect of this overlapping in the interpretation of HF power.

Sometimes it is CF the component which overlaps with HF, but other times it is AF1 or AF2, so, in the following, we use the general name of $P_{CC}(n)$, (CC: Cardiolomotor Coupling) to denote the power of the component associated to cardilocomotor coupling. To attenuate the effect of the overlapping between CC and HF components, we propose to subtract from the estimated powers in CC and HF bands an amount that depends on the percentage of overlap between the bands, and on the power relationship one minute before the overlapping zone. The largest the overlap between the bands, the largest the amount to be subtracted. This amount also depends on the relationship between the powers in CC and HF bands prior to the overlapping, under the assumption that powers won't change significantly during the overlapping zone. If HF power is larger than CC power, most of the power in the overlapping zone is assumed to be contributed by the HF component, so a larger amount will be subtracted from CC power than from HF power.

The corrected powers in HF and CC bands are:

$$P_{HFc}(n) = P_{HF}(n) - (1-\alpha)\kappa P_{CC}(n)$$
$$P_{CCc}(n) = P_{CC}(n) - \alpha\kappa P_{HF}(n)$$

where $\alpha = P^1_{HF}/(P^1_{HF}+P^1_{CC})$, and P^1_{HF} and P^1_{CC} represent the mean power in HF and CC bands, respectively, one minute before the overlapping zone. In the case that overlapping zone is just at the beginning of the exercise, information on the minute after the overlapping zone is used. The parameter κ represents the percentage of overlap between the CC and HF bands and it is computed as the ratio between the frequency range of overlapping and the width of the band (0,125 Hz).

E. Physiological indices

Instantaneous power of each spectral band is normalized by instantaneous total power, defined as $P_{Tc}(n) = P_{LF}(n) + P_{HFc}(n) + P_{CFc}(n) + P_{AF1c}(n) + P_{AF2c}(n)$. The average of these normalized powers in one-minute duration intervals constitute the studied parameters, and are denoted as

$$\overline{P^I_{XFc}} = \frac{1}{I_e - I_b + 1} \sum_{n=I_b}^{I_e} \frac{P_{XFc}(n)}{P_{Tc}(n)}, \qquad (1)$$

where XF stands for LF, HF and CC. Superscript I denotes each of the four temporal intervals considered, beginning at $n = I_b$ and ending at $n = I_e$:

- BEG: the first minute after the test starts
- VT1: around aerobic threshold
- VT2: around anaerobic threshold
- MAX: just before the maximum HR

These indices are computed from the powers $P_{XFc}(n)$, in which the effect of cardiolocomotor coupling has been attenuated, in order to characterize cardiolocomotor coupling and to study the evolution of LF and HF components during the exercise test. For comparison purposes, indices computed from the powers $P_{LF}(n)$ and $P_{HF}(n)$, which do not account for the overlapping with cardiolocomotor coupling components, are also considered.

III. RESULTS AND DISCUSSION

A. Characterization of cardiolocomotor coupling in HRV

In Figure 2 it is displayed the evolution of the power related to cardiolocomotor coupling in the physiological intervals described in II-E for both treadmill and cycle ergometer exercise tests. Note that physiological parameters are derived from the corrected instantaneous power $P_{CCc}(n)$ in order to study only information related to cardiolocomotor coupling.

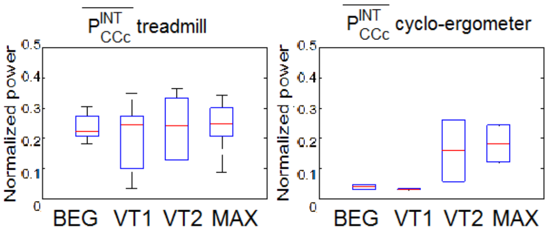

Fig. 2. $\overline{P^{I}_{CCc}}$ in treadmill (left) and cyclo-ergometer tests (right).

An increase in the power of cardiolocomotor-related components with exercise intensity is observed in cycle ergometer but not in treadmill exercise tests. It has been observed that pedalling frequency component and their aliases follow this trend during bicycle exercise test, with notably increased values in VT2 and MAX. However, this pattern is observed during treadmill exercise test only in the running stride frequency component. The aliased components had comparable (and not negligible) power for all intensities.

B. Attenuation of the effect of cardiolocomotor coupling

Figure 3 displays corrected instantaneous powers, $P_{HFc}(n)$ and $P_{CCc}(n)$ as it is explained in II-D. Upper image represents a case in which from second 520 to 640 there is an increase in $P_{HF}(n)$, which could be erroneously interpreted as reflecting parasympathetic activation. However, it seems reasonable that this increase is due to the overlapping with a cardiolocomotor related component. After the correction, no parasympathetic activation could be interpreted. On the other hand, lower image shows a case with an increase of $P_{CC}(n)$, which does not correspond with its power after and before. It seems to be due to the overlapping with HF band.

C. Physiological indices

It is observed that $P_{LF}(n)$ decreases as exercise intensity increases both in bicycle and treadmill test, as reported in [6]. Results are similar with and without the proposed attenuation, although $\overline{P^{I}_{LFc}}$ shows higher values than $\overline{P^{I}_{LF}}$. The studied parameter is normalized, so it is dependent on $P_{Tc}(n)$, which includes $P_{HFc}(n)$ and $P_{CCc}(n)$, that are lower than $P_{HF}(n)$ and $P_{CC}(n)$, justifying $\overline{P^{I}_{LFc}}$ increase. Friedman

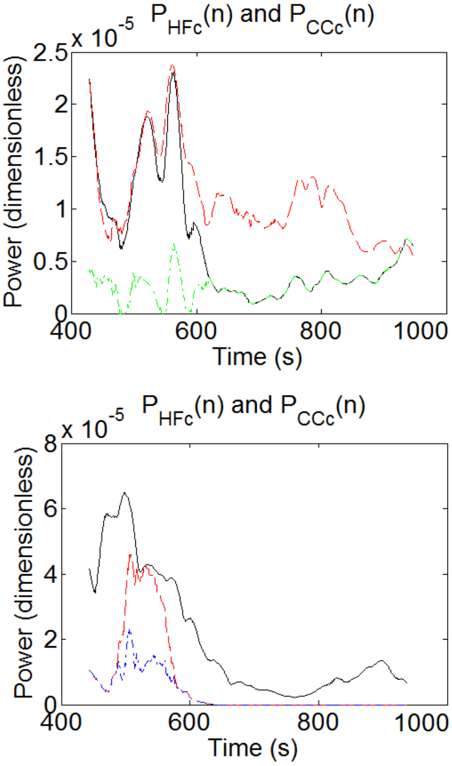

Fig. 3. Representation of $P_{HF}(n)$ (continuous black line) and $P_{CC}(n)$ (striped red line). Upper image, correction of HF power: $P_{HFc}(n)$ (dotted and striped green line in the upper image). Lower image, correction of CC power: $P_{CCc}(n)$ (dotted and striped blue line in the lower image).

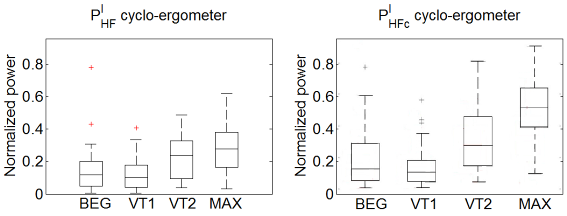

Fig. 4. Evolution of normalized HF power during the cyclo-ergometer test: left original parameters ($\overline{P^{I}_{HF}}$); right corrected parameters ($\overline{P^{I}_{HFc}}$).

TABLE I

RESULTS OF FRIEDMAN ANALYSIS COMPARING EACH INTERVAL WITH ALL THE OTHERS FOR CYCLO-ERGOMETER TEST.

$\overline{P^{INT}_{HF}}$				
-	BEG	VT1	VT2	MAX
BEG	1	0.835	**7 E-3**	**7 E-3**
VT1	-	1	**0.022**	**4 E-4**
VT2	-	-	1	0.061
MAX	-	-	-	1
$\overline{P^{INT}_{HFc}}$				
-	BEG	VT1	VT2	MAX
BEG	1	0.835	**7 E-3**	**1 E-4**
VT1	-	1	**7 E-3**	**1 E-5**
VT2	-	-	1	**2.4 E-3**
MAX	-	-	-	1

analysis does not show significant differences ($p < 0.05$) between $\overline{P^{I}_{LFc}}$ and $\overline{P^{I}_{LF}}$.

Regarding HF power, results depend on the type of exercise as Figures 4 and 5 show. In bicycle exercise tests HF power increases as long as the exercise's intensity increases, as reported in [6], being the differences higher after the attenuation of the effect of cardiolocomotor coupling on HRV indices. Friedman analysis shows significant differences ($p < 0.05$) between original and corrected parameters in the values related to the last interval, because of its increase with the proposed method. Parameter $\overline{P^{I}_{HF}}$ only shows significant differences between the two first intervals and the two last ones (BEG-VT2, BEG-MAX, VT1-VT2 and VT1-MAX). Parameter $\overline{P^{I}_{HFc}}$ displays also these significant differences, and the difference VT2-MAX increases, becomes significant.

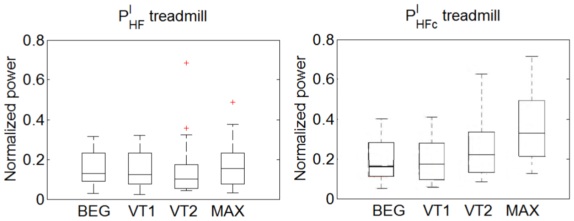

Fig. 5. Evolution of normalized HF power during the treadmill test: left original parameters ($\overline{P^{I}_{HF}}$); right corrected parameters ($\overline{P^{I}_{HFc}}$).

TABLE II

RESULTS OF FRIEDMAN ANALYSIS COMPARING EACH INTERVAL WITH ALL THE OTHERS FOR TREADMILL TEST.

		$\overline{P^{I}_{HF}}$		
-	BEG	VT1	VT2	MAX
BEG	1	0.088	1	1
VT1	-	1	0.394	0.67
VT2	-	-	1	**0.033**
MAX	-	-	-	1
		$\overline{P^{I}_{HFc}}$		
-	BEG	VT1	VT2	MAX
BEG	1	0.2	**0.033**	**6 E-4**
VT1	-	1	**0.033**	**0.01**
VT2	-	-	1	**0.01**
MAX	-	-	-	1

In treadmill test the evolution of $\overline{P^{I}_{HF}}$ is meaningfully different with respect to the bicycle's one and the results reported in [6]. As it is shown in Figure 5, its power does not increase, which means that no difference of power between intervals is relevant. When the effect of the overlapping is attenuated, $\overline{P^{I}_{HFc}}$ evolution is similar to bicycle test's one and to results reported in previous works [6]. Furthermore, Friedman analysis shows that the differences between the intervals BEG-MAX, VT1-VT2, VT1-MAX and VT2-MAX are significant.

The explanation of these two different behaviours lies in the amount of power associated to CF band and its related aliases. For the bicycle exercise test, when overlap happens, HF power is usually much higher than cardiolocomotor related power, and the effect of the overlapping in HF power is not so relevant. Only in the last interval both powers are similar and the correction applied is relevant. In contrast to this, in treadmill tests there is more power associated to cardiolocomotor coupling in all the intervals when overlap happens (essentially in VT2 and MAX), and the method proposed for the attenuation of the overlapping effect changes significantly the values of HF power.

IV. CONCLUSIONS

Cardiolocomotor coupling manifests in HRV during exercise as a component centred at running stride or pedalling frequency, as well as at their aliases when HR is not high enough. It has been characterized for different types of exercise and intensities, showing that during cycle ergometer exercise test, cardiolocomotor coupling is small for low exercise intensity but increases considerably with exercise intensity. However, during treadmill exercise, cardiolocomotor related power exhibits similar values for all exercise intensity. The main complication with cardiolocomotor coupling is that its components may overlap with LF and HF band, misleading their interpretation. In this work, we propose a method to attenuate the effect of cardiolocomotor coupling in HRV interpretation. After the attenuation, LF and HF components displayed more differences related to exercise intensity, presumably better reflecting ANS response to exercise.

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