Characterization of cardiolocomotor coupling in heart rate variability during exercise test

A. Hernando Sanz[1,2] , D. Hernando Jumilla[1,2] , N. Garatachea Vallejo[3] , R. Bailón Luesma[1,2]

[1] Biomedical Signal Interpretation & Computational Simulation (BSICoS) Group, Aragón Institute of Engineering Research (I3A), IIS, University of Zaragoza, Zaragoza, Spain, {610631, dhernand, rbailon}@unizar.es

[2] CIBER – Bioingeniería, Biomateriales y Nanomedicina (CIBER-BNN), Zaragoza, Spain

[3] Faculty of Health and SportScience, University of Zaragoza, Huesca, Spain, nugarata@unizar.es

Abstract

The goal of this work is the characterization of cardiolocomotor coupling which appears in heart rate variability (HRV) during exercise and could mislead the interpretation of HRV related to the Autonomic Nervous System (ANS). 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. Additionally, 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.

1. 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 present 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 [2].

Moreover, components centred at pedalling or stride frequency and their aliases have been observed in HRV during exercise test [3, 4]. These components are thought to reveal cardiolocomotor coupling due to dynamic modulation of veins return across leg's muscular contraction [3] 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.

2. Materials and methods

2.1. 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, O_2 consumption, CO_2 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.

2.2. Heart Rate Variability estimation

HRV is derived from the recorded RR series. Assuming the integral pulse frequency modulation model with time varying threshold (TVIPFM) [2] the instantaneous heart rate is obtained and sampled at 4 Hz, denoted $d_{HR}(n)$. This method is used to model the control of heart rate with a variable cardiac period by the ANS.

A time-varying mean HR 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 modulating signal assumed to carry the information from ANS is estimated as $m(n) = \frac{d_{HRV}(n)}{d_{HRM}(n)}$.

2.3. Definition of spectral components

Smoothed pseudo Wigner-Ville distribution (SPWVD) was applied to $m(n)$, because of HRV lack of stationary, with the same time and frequency resolution as in [3]. Instantaneous power of spectral components of HRV was computed integrating for each time instant the SPWVD in the following bands:

-LF band: Ω_{LF}: [0,04 - 0,15] Hz.

-HF band, centred in respiratory frequency ($F_R(n)$) , Ω_{HF} = [$F_R(n)$ - 0,125, $F_R(n)$ + 0,125] Hz

-Cadence Frequency (CF) band, centred in running stride or pedalling frequency ($F_C(n)$), Ω_{CF} = [$F_C(n)$ - 0,125, $F_C(n)$ + 0,125] Hz

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

$F_C(n)$ in treadmill test is obtained low-pass filtering the running stride frequency recorded with a cut-off frequency of 0,01 Hz. By contrast, in bicycle test this component is fixed to 80rpm since it was not recorded.

Since the intrinsic sampling frequency of HRV is the HR, when $F_C(n)$ exceeds half the 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:

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

Ω_{AF2} = [$F_{A2}(n)$ - 0,125, $F_{A2}(n)$ + 0,125] Hz, $F_{A2}(n) = d_{HRM}(n) - F_C(n)$.

These bands could be represented in the time-frequency map, as it is shown in Figure 1.

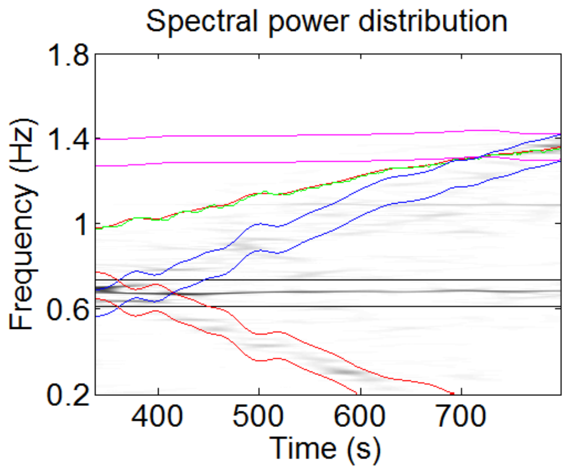

Figure 1 *Time-frequency map showing the components bands. Black represents HF; pink, CF; red, AF1; blue, AF2.*

Instantaneous power of each spectral component is denoted $P_{XF}(n)$ where XF stands for LF, HF, CF, AF1-2.

2.4. Attenuation of cardiolocomotor coupling effect

Sometimes components related to cardiolocomotor coupling overlap with HF band, misleading its interpretation as a measure of respiratory sinus arrhythmia [6]. Depending on the case, sometimes is CF the component that overlap with HF, but could be AF1 or AF2 too, so the general name of $P_{CC}(n)$, (CC: Cardiolomotor Coupling) is used to reflect the power of the component associated to cardilocomotor coupling.

Two main behaviours are observed comparing the power of the HF and aliased band: 1) one of the bands has much more power before or/and after the overlapping zone than the other band; in this case power in the band with the highest power remains the same in the overlapping zone while power in the band with the lowest power is replaced by linear interpolation between its preceding and following values; 2) powers in both bands are similar, so both of them are corrected with a proportional amount that depends on the percentage of overlap between the bands (p_{band}) and the power relationship one minute before the overlap zone ($P_{HF-1MIN}$, $P_{CC-1MIN}$). In case that overlap zone is just at the beginning of the exercise, information on the minute after is used.

The parameter $\alpha = \frac{P_{HF-1MIN}}{P_{HF-1MIN}+P_{CC-1MIN}}$ is used to distinguish between the three possible cases.

Case 1 or $P_{HF-1MIN} > P_{CC-1MIN}$: $\alpha > 0.6$. $P_{HF}(n)$ stays identical, but $P_{CC}(n)$ is corrected in the overlapping zone by linear interpolation between preceding and following values, yielding $P_{CC-C}(n)$.

Case 2 or $P_{HF-1MIN} \approx P_{CC-1MIN}$: $(0.4 < \alpha < 0.6)$. Both powers are corrected keeping in mind the dependence with the two factors explained. In this case, the corrected parameters are:

$$P_{HF-C}(n) = P_{HF}(n) - (1-\alpha) * p_{band} * P_{CC}(n)$$

$$P_{CC-C}(n) = P_{CC}(n) - \alpha * p_{band} * P_{HF}(n)$$

Case 3 or $P_{HF-1MIN} < P_{CC-1MIN}$: $\alpha < 0.4$. $P_{CC}(n)$ stays identical, while $P_{HF}(n)$ is corrected in the overlap zone as in case 1, yielding $P_{HF-C}(n)$.

2.5. Physiological parameters

Studied parameters are defined normalizing instantaneous power of each spectral component by instantaneous total power and averaging the normalized power in four one-minute duration intervals, to study the evolution of the components related [3].

$$P_{TOT}(n) = P_{LF}(n) + P_{HF}(n) + P_{CF}(n) + P_{AF1-2}(n)$$

$$\overline{P_{HF}^{INT}} = \frac{1}{N} \sum_{n=INT_I}^{INT_f} \frac{P_{HF}(n)}{P_{TOT}(n)}$$

$$\overline{P_{CF}^{INT}} = \frac{1}{N} \sum_{n=INT_I}^{INT_f} \frac{P_{CF}(n) + P_{AF1-2}(n)}{P_{TOT}(n)}$$

Where INT shows the temporal interval chosen: **INI**, just the first minute after the test starts; **VT1**, around aerobic threshold; **VT2**, around anaerobic threshold; and **FIN**, just before the maximal effort. INT_i and INT_f represent the initial and final point of the interval and N is the total amount of samples.

These indices are computed from the originally estimated instantaneous powers, $P_{XF}(n)$, as well as for the corrected power $P_{XF-C}(n)$. As this work is centred in HF band, the study of original parameters is denominated $\overline{P_{HF}^{INT}}$. $\overline{P_{HF-C}^{INT}}$ is the name for the corrected parameters.

3. Results and discussion

3.1. Characterization of cardiolocomotor coupling in HRV

Evolution of the power related to cardiolocomotor coupling in the physiological intervals described in Sec. 2.5 is displayed in Figure 2 for both treadmill and cycle ergometer exercise tests. Note that physiological parameters are derived from the corrected instantaneous power $P_{CC-C}(n)$ in order to study only information related to cardiolocomotor coupling.

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 FIN. However, this pattern is observed during treadmill exercise test only in the running stride frequency component.

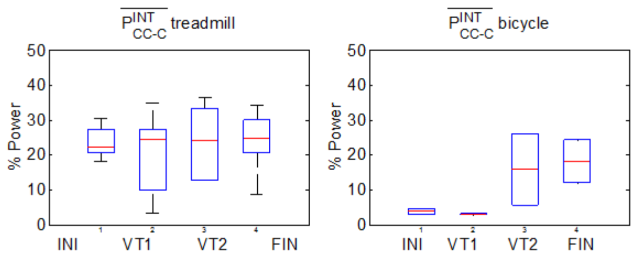

Figure 2 *Representation of $\overline{P^{INT}_{CC-C}}$ (its percentage over total power).In cycle ergometer (right) and treadmill tests (left).*

3.2. Overlap treatment

Figure 3 displays corrected instantaneous powers, $P_{HF-C}(n)$ and $P_{CC-C}(n)$ for each case explained in section 2.4. Lower image represents a case in which from second 450 to 600 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. Something similar happens in the others two images, yielding corrected HF-CF power depending on the case.

The next step is the comparison between the evolution of power in HF band during the exercise test, before and after the correction proposed in this work.

In treadmill test the $\overline{P^{INT}_{HF}}$ representation is meaningfully different with the bicycle's one and the results reported in [5]. As it is shown in Figure 4, its power does not increase, which means that no difference of power between intervals is relevant. When the correction is made, in $\overline{P^{INT}_{HF-C}}$, the results are similar to bicycle test's ones and to the expected results reported in previous works [5]. Furthermore, Wilcoxon analysis denotes that the differences between the intervals INI-FIN, VT1-VT2, VT1-FIN and VT2-FIN are significant as it is shown in Table 1.

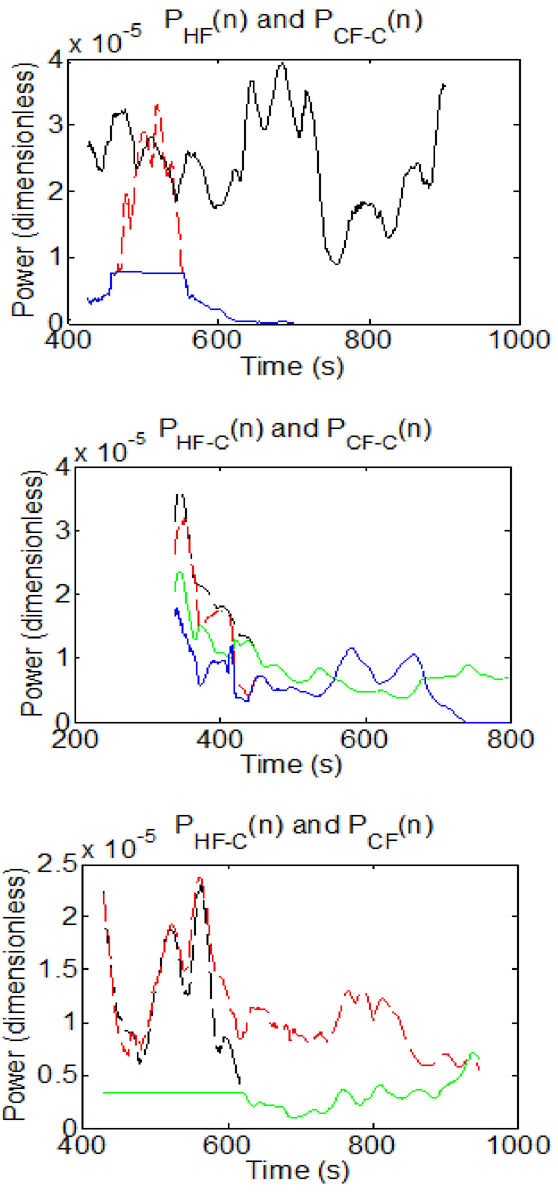

Figure 3 *Representation of $P_{HF}(n)$ (black). $P_{HF-C}(n)$ (green), $P_{CC}(n)$ (red) and $P_{CC-C}(n)$ (blue). Upper image: $P_{HF\text{-}1MIN} >> P_{CC\text{-}1MIN}$; medium image: $P_{HF\text{-}1MIN} \approx P_{CC\text{-}1MIN}$; lower image: $P_{HF\text{-}1MIN} << P_{CC\text{-}1MIN}$.*

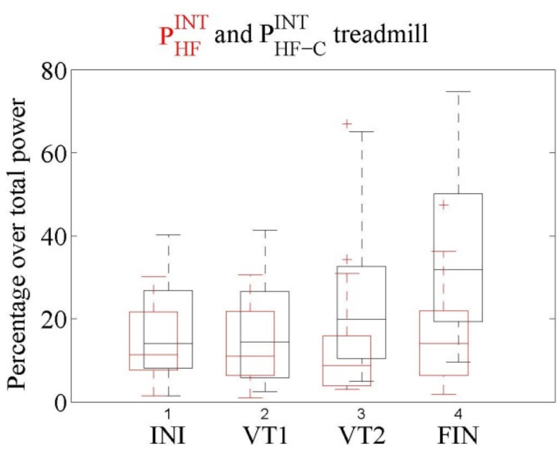

Figure 4 *Evolution of normalized HF power during the treadmill test, in red $\overline{P^{INT}_{HF}}$, and in black $\overline{P^{INT}_{HF-C}}$.*

		INI	VT1	VT2	FIN
Wilcoxon with original param.	INI	1	0.09	0.426	0.542
	VT1	-	1	0.808	0.355
	VT2	-	-	1	0.046
	FIN	-	-	-	1
		INI	VT1	VT2	FIN
Wilcoxon with corrected param.	INI	1	0.426	0.031	9.8E-4
	VT1	-	1	0.02	4.8E-4
	VT2	-	-	1	9E-3
	FIN	-	-	-	1

Table 1 *Results of Wilcoxon Analysis for treadmill test.*

In bicycle exercise tests HF power increases as long as the exercise's intensity increases [5], being the differences higher after the correction as Figure 5 shows. Wilcoxon analysis shows significant differences ($p<0.05$, in green) between intervals in both cases: with original and whit corrected parameters, as it is shown in Table 2.

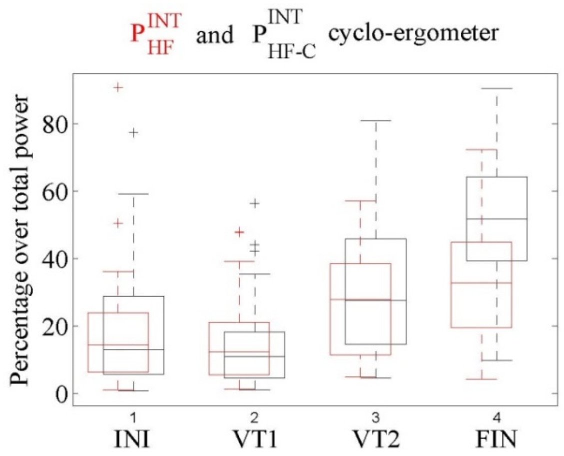

Figure 5 *Evolution of normalized HF power during the cyclo-ergometer test, in red* $\overline{P_{HF}^{INT}}$*, and in black* $\overline{P_{HF-C}^{INT}}$*.*

		INI	VT1	VT2	FIN
Wilcoxon with original param.	INI	1	0.627	0.031	3E-3
	VT1	-	1	0.014	2.3E-4
	VT2	-	-	1	0.144
	FIN	-	-	-	1
		INI	VT1	VT2	FIN
Wilcoxon with corrected param.	INI	1	0.648	0.02	1.8E-4
	VT1	-	1	6E-3	3.1E-5
	VT2	-	-	1	9.2E-4
	FIN	-	-	-	1

Table 2 *Results of Wilcoxon analysis for cyclo-ergometer test.*

The explanation of this two different behaviours lies in the amount of power associated to CF band and its related aliases. For the bicycle exercise test, if overlap happens, HF power is usually higher than cardiolocomotor related power, the latter is corrected, increasing normalized power studied. In contrast to this, treadmill tests have a lot of power in cadence band, which means that no increase of power is registered before the correction. When the proposed method is used power related to cardiolocomotor coupling is corrected, increasing normalized power studied, essentially in the last interval.

4. Conclusions

Cardiolocomotor coupling manifests in HRV during exercise as a component centred at running stride or pedalling frequency. 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 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, HF component displayed more differences related to exercise intensity, presumably better reflecting ANS response to exercise.

Appreciations

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