

Heart Rate Variability in Ultra-Trail Runners

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Abstract

It is not trivial to understand the interactions between heart rate variability (HRV), activity of the autonomic nervous system (ANS) and exercise training. In this way, heart rate (HR) signals were analyzed. HR was recorded during a race of 82 km from two groups of runners performing different training regimes, Active and Elite. Several indexes from time-domain and frequency-domain analysis, time-frequency representation (TFR) and auto-mutual-information function (AMIF) were calculated on RR series in order to describe their dynamicity. TFR and AMIF indexes presented statistical significant differences when comparing the 1st and the 6th hour of the race ($p < 0.002$). LF/HF showed an increasing tendency in Active runners, and a decreasing tendency in Elite runners. Extremely low values of RR standard deviation were found in Elite runners.

1. Introduction

It is known that in ultra-trail races the runner effort intensifies, and the work on the heart speeds up. The study of cardiovascular variability is a potentially powerful method as a basic scientific tool for better understanding the regulation and control of the cardiovascular system. Exercise produces a physiological perturbation that significantly influences autonomic nervous system activity. According to some authors, sustained training alters the variability in heart rate caused by a modification of vagal activity with increased parasympathetic modulations [1-3]. Another study demonstrated that autonomic balance would be one of the first to be affected in case of fatigue-induced homeostatic disturbance [4]. However, cardiovascular variability studies in elite athletes are still an almost unexplored domain.

As it is known, power spectrum of the HRV signal was proposed to be used as a quantitative probe to assess

cardiovascular control mechanisms [5] and methods from non-linear dynamics for HRV analysis may provide a more sensitive way to characterize function or dysfunction of the control mechanism of the cardiovascular system [6,7]. In this way, the aim of this work is to analyze the heart rate variability (HRV) in ultra-trail runners using linear and non-linear signal processing techniques. For this purpose, indexes obtained from RR series in time-domain and frequency-domain analysis, time-frequency representation (TFR) and auto-mutual-information function (AMIF) were defined.

2. Materials and methods

2.1. Analyzed database

Heart rate (HR) was recorded continuously by wireless monitors (POLAR Electro Oy, Oulu, Finland) from two groups of runners performing different training regimes, Active and Elite, during 82 km. A total of 12 runners were involved in this study, with mean age of 38.7 ± 2.8 years. The Active group could run a mean distance of 36.9 ± 14.8 km and the Elite group 59.5 ± 26.2 km. Characteristics of the runners are summarized in Table 1. Sequences of RR intervals were constructed from the recorded HR (bpm). The RR series were filtered by replacing artefacts or ectopic beats if deviate more than a 15% tolerance of the mean value of the previous twenty beats. These unevenly sampled signals were resampled by cubic spline interpolation at 4 Hz. Then, RR series were segmented into sliding windows of 5 minutes using 1 second increments.

2.2. Time-domain and frequency-domain analysis

The mean ($meanRR$) values and standard deviation ($SDRR$) values of RR series were calculated in each window. Frequency-domain analysis was based on the

power spectral density (PSD), calculated using Yule-Walker autoregressive (AR) method in each window. The maximum order of the AR model was fixed to 20. The following spectral indexes were calculated as recommended in [5]: *VLF*, *LF*, *HF*, *LFnorm*, *HFnorm* and *LF/HF* ratio, where $VLF < 0.04$ Hz, $LF = 0.04-0.15$ Hz and $HF = 0.15-0.4$ Hz.

Table 1. Characteristics of the runners.

ID	Tr	Ge	Dist (Km)	Age (Years)	Height (cm)	Weight (Kg)
1	A	M	50	35	180	84
2	A	M	50	41	172	70
3	A	M	25	41	182	91
4	A	F	31	41	NA	NA
5	A	M	50	36	183	75
6	A	F	14	37	NA	NA
7	A	M	25	37	184	74
8	A	M	50	45	171	72
9	E	M	41	37	NA	NA
10	E	M	33	38	178	77
11	E	F	82	38	164	60
12	E	F	82	39	173	67
<i>Active: mean</i>			36.9	39.7	179	77.9
<i>±SD</i>			±14.8	±3.3	±5.7	±8.3
<i>Elite: mean</i>			59.5	38.2	172	68.2
<i>±SD</i>			±26.2	±0.9	±7.1	±8.9

ID: runner; *Tr*: Training class $A \rightarrow$ active, $E \rightarrow$ elite; *Ge*: Gender, $M \rightarrow$ male, $F \rightarrow$ female; *Dist*: Distance from the start of the race where the runner quit; *SD*, standard deviation; *NA*, not available.

2.3. Time-frequency representation

Time-Frequency Representation (TFR) based on Choi-Williams distribution (T_{RR}) (1) was calculated by convoluting (2) and (3),

$$T_{RR}(t, f) = \iint_{-\infty}^{\infty} h(t-t', f-f') W_{RR}(t', f') dt' df' \quad (1)$$

$$W_{RR}(t, f) = \int_{-\infty}^{\infty} RR(t+\tau/2) RR^*(t-\tau/2) e^{-j2\pi f\tau} d\tau \quad (2)$$

$$h(t, f) = \sqrt{\frac{4\pi}{\sigma_c}} e^{-4\pi^2 \frac{(tf)^2}{\sigma_c}} \quad (3)$$

where σ_c was set to 0.005.

Instantaneous power (*IP*) function was calculated as the area under the curve of the $T_{RR}(t, f)$ at each t instant. This value was normalized by the total power in each of the considered bands: VLF, LF, HF and TB (total-frequency band). The normalized powers *LFnorm*, *HFnorm* and the rate *LF/HF* were calculated from *IP*. Instantaneous frequency (*IF*) function was calculated as the mean frequency of the spectrum at each t instant. The mean value (m) was calculated on the *IF* functions with respect to time.

2.4. Auto-mutual information function

Auto-mutual information function (AMIF) is a metric to estimate both linear and nonlinear dependences between two time series, x_t and $x_{t+\tau}$. AMIF is calculated by the distribution of the probability amplitudes of $x_t = RR(t)$ and $x_{t+\tau} = RR(t+\tau)$, and the joint probability of these series, based on Shannon entropy.

$$AMIF(\tau) = \sum_{x_t, x_{t+\tau}} P\{x_t, x_{t+\tau}\} \log_2 \left(\frac{P\{x_t, x_{t+\tau}\}}{P\{x_t\}P\{x_{t+\tau}\}} \right) \quad (4)$$

Probabilities and joint probabilities were computed on the basis of a quantization in 3 bits. This function describes how the information of a signal (AMIF value at $\tau=0$) decreases over prediction time intervals (AMIF values at $\tau>0$). Increasing information loss is related to decreasing predictability, and increasing complexity of the signal. The time-delay considered on the calculus of AMIF was

In this work, AMIF was estimated over a discrete time delay of $0 \leq \tau \leq 100$ samples and normalized by its maximum value that corresponds to $\tau=0$. Different indexes were defined based on AMIF. The first decay (*FD*) of the AMIF was calculated. Also, the AMIF was applied to RR series filtered in *LF* and *HF* bands. Then, the area under the AMIF curve between the τ values corresponding to *LF* or *HF* band was calculated.

2.5. Data analysis

The time evolution of each RR index was analyzed in the two groups of runners: Elite and Active. Then, each RR index was studied as a function of the HR values during different time-intervals of the race. In this way, indexes from the 1st and the 6th hour of the race of each runner were statistically compared using Wilcoxon matched-pairs signed-ranks test. Indexes from Elite and Active runners were statistically compared using the Student t-test.

3. Results and discussion

Figure 1 shows the time evolution of *meanRR*, *SDRR*, *HFnorm* and *LF/HF* (calculated from PSD using Yule-Walker method), *IF* in the *TB* and *AMIF_FD*. It can be noted that the *meanRR* and the *SDRR* of the Active group presented more fluctuations than Elite group at the beginning of the race. This confirms the elite runners to show a better ability to control their own heart rate. Some visual differences are also observed in the central part of the time evolution of *SDRR*, *HFnorm* and *LF/HF* denoting different sympathetic-vagal balance in the two groups during the race. From the visual inspection, it can be noted that *LF/HF* showed increasing tendency in Active runners, while showed decreasing tendency in Elite runners during the race. Similar tendencies are

observed in the scatter plots of the RR indexes with respect to the HR shown in figure 2, in which the color is function of the time from the start of the race.

Table 2 shows the results of the RR indexes when the 1st and the 6th hour are compared. The results of the instantaneous frequency and the AMIF indexes in LF denote an increase of the parasympathetic activity (IF $1^{st} h < 6^{th} h$: p -value<0.05, Wilcoxon test) associated with a loss of modulation of cardiac autonomic outflows by baroreflexes in the LF band ($AMIF_{LF}$ $1^{st} h > 6^{th} h$: p -value<0.05, Wilcoxon test) from the 1st to the 6th hour of the race.

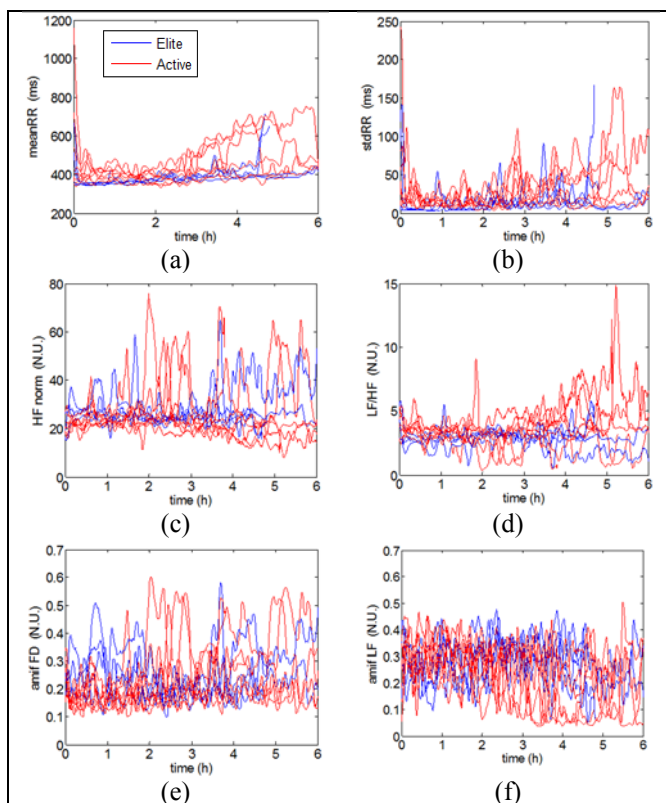


Figure 1. Time evolution of: (a) meanRR; (b) SDRR; (c) HFnorm; (d) LF/HF; (e) AMIF_FD; (f) AMIF_LF from the 1st hour to the 6th hour of the race. Average over 5-minute sliding window.

Table 3 shows the values of the RR indexes calculated separately on each group, Active and Elite. In this case, statistical significant differences were found only when comparing the 1st hour with the 6th hour in Active group, denoting a loss of sympathetic influences in the LF band (Wilcoxon test, p -value<0.05) mainly observed in $AMIF_{LF}$. Comparing the 1st hour of Active with the 1st hour of Elite group, more parasympathetic activity was evidenced in Elite group (Student t-test, p -value<0.05). The results of the Elite group showed lower values of RR standard deviation than in Active group in concordance with the finding of previous studies [6,7] performed in

sedentary and over trained athletes. Also the sympathetic/parasympathetic balance (LF/HF) showed increasing tendency in Active runners, while showed decreasing tendency in Elite runners. In the 1st hour of the race, Elite group showed more parasympathetic activity ($HFnorm$: t-student test, p -value<0.05) than Active group. In a previous study [3], an increase in global HRV, associated with a relative increase in the parasympathetic drive was observed in athletes after 3 weeks of intensive training. However, these data were collected in the recovery period and not during the race.

Table 2. HRV indexes from two periods of the race.

Indexes	1 st hour mean±SD	6 th hour mean±SD	p-value
$meanRR$ (ms)	400 ± 41.7	483 ± 116	0.008
$SDRR$ (ms)	20.1 ± 10.9	40.7 ± 33.2	0.0547 ^{n.s.}
$HFnorm$ (n.u.)	24.4 ± 3.2	28.8 ± 14.5	0.6406 ^{n.s.}
LF/HF (n.u.)	3.27 ± 0.50	3.70 ± 2.25	0.8438 ^{n.s.}
IF (Hz)	0.054 ± 0.013	0.089 ± 0.044	0.023
$AMIF_{FD}$	0.206 ± 0.057	0.293 ± 0.127	0.039
$AMIF_{LF}$	0.283 ± 0.041	0.184 ± 0.079	0.023

SD, standard deviation; *Wilcoxon test*; *n.s.*, non-significant statistical level.

Table 3. HRV indexes from two periods of the race in Active group and Elite group.

Indexes (mean±SD)	Active		Elite	
	1 st hour	6 th hour	1 st hour	6 th hour
$meanRR$ (ms)	418*† ± 40.5	511† ± 124	366* ± 12.6	402 ± 10.4
$SDRR$ (ms)	23.9 ± 11.0	50.4 ± 33.0	12.4 ± 6.5	11.4 ± 3.5
$HFnorm$ (n.u.)	23.1* ± 2.1	27.4 ± 16.3	27.2* ± 3.4	32.8 ± 9.8
LF/HF (n.u.)	3.49* ± 0.36	4.18 ± 2.42	2.83* ± 0.45	2.27 ± 0.92
IF (Hz)	0.047*† ± 0.004	0.092† ± 0.048	0.067* ± 0.016	0.084 ± 0.045
$AMIF_{FD}$	0.177* ± 0.023	0.293 ± 0.145	0.266* ± 0.062	0.294 ± 0.093
$AMIF_{LF}$	0.297† ± 0.037	0.167† ± 0.080	0.2535 ± 0.036	0.2364 ± 0.063

†statistically significant differences (Wilcoxon test, p -value<0.05) when comparing Active 1sth and 6thh; *statistically significant differences (Student t-test, p -value<0.05) when comparing Active 1sth and Elite 1sth; *SD*, standard deviation.

4. Conclusions

Indexes from time-frequency representation and auto-mutual information function calculated on RR series in ultra-trail runners present statistical significant differences when comparing the 1st and the 6th hour of the race. These statistical differences were evidenced in

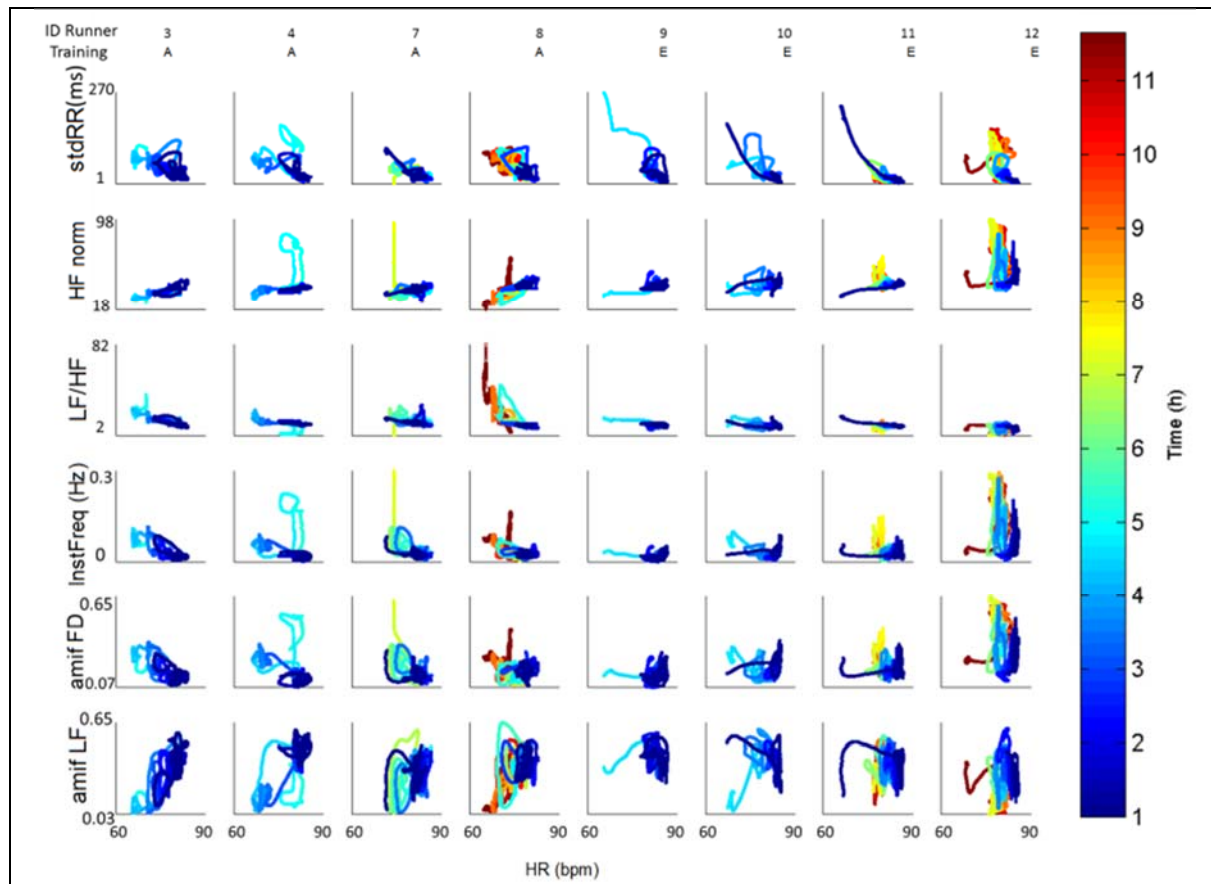


Figure 2. Scatter plot of RR indexes with respect to the heart rate (HR). Color as a function of the time from the start of the race.

Active runners but no in Elite runners. The low values of standard deviation associated with parasympathetic activation in Elite runners may be related to the hard training. However, we need to concern the relatively small numbers of study participants, diminishing the power of statistics.

Acknowledgements

This work was supported within the framework of the CICYT coordinated grant TEC2010-20886-C02, the Research Fellowship Grant FPU AP2009-0858 from the Spanish Government. CIBER of Bioengineering, Biomaterials and Nanomedicine is an initiative of ISCIII. Authors are part of the 2014SGR-1063 consolidated research group of the Generalitat de Catalunya, Spain.

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