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Wavelet Transforms in Sport: Application to Biological Time Series

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1. Introduction

In sports, biological signals are often used to control and design the sports activity. One of the most common used signals is heart rate (HR). Heart rate variability (HRV) refers to natural fluctuations in the interval between normal heartbeats that occurs while individuals rest or exercise. HRV results from the dynamic interplay between the multiple physiologic mechanisms that regulate HR, and it mainly reflects an expression of the interplay between the sympathetic and parasympathetic nervous systems (Task Force, 1996). Two main oscillatory processes interact with the heart as feedback and forward mechanisms, via autonomic pathways: the modulation of the heart rate by breathing, known as respiratory sinus arrhythmia (RSA), and the short-term blood pressure control, known as baroreflex. These main rhythms usually appear in the high and low frequency ranges of HRV, respectively; however, the dynamic interactions in the cardiovascular system may change this typical spectrum. However, the intrinsic properties of the complex autonomic regulation of cardiovascular function are difficult to measure since, even at rest, emotions and mental loading may affect it.

Usually, HRV is used as a non-invasive method to measure the cardiac autonomous input and it is analyzed from different viewpoints: time domains, frequency analysis and non-linear dynamics. According to the Task Force (1996), the power spectrum for time series, at rest, can be classified as follows: (i) power in the very low frequency range (VLF), *0.003–0.04 Hz*, (ii) power in the low frequency range (LF), *0.04 – 0.15 Hz*, and (iii) power in the high frequency range (HF), *0.15 – 0.4 Hz*. The HF normally reflects respiratory-related activity and appears to be mediated by vagal tone. LF is linked to the baroreceptor reflex and can be mediated by the vagus and cardiac sympathetic nerves. (Houle and Billman,1999) suggested that the LF component results from an interaction of the sympathetic and parasympathetic nervous systems and, as such, doesn't accurately reflect changes in the sympathetic activity. VLF zone is related, especially, by thermoregulation fluctuations and vasomotor tone (Task Force, 1996). With exercise, the very high frequency (VHF) should be taken into account (> *0.4 Hz*).

A difficulty in determining the value of these frequency bands during exercise is given by the lack of stationary in data series. When these time series are not stationary in frequency the problem is even more serious. The so-called "time-frequency analysis" provides the observer with a tool to detect changes both in time domain and in frequency domain,

simultaneously. Several models have been proposed: The Short-Time Fourier Transform (STFT), the Gabor Transform (Windowed Fourier Transform), the Wigner-Ville Distribution (WVD) and its refinements, and finally the Wavelet Transform (see Daubechies, 1992; Chui, 1992; Cohen, 1992; Abry and Flandrin, 1996; Teich et al. 1996). In this paper, we used the Wavelet Transform as this method has proven a powerful tool suited for the analysis of the time–frequency localization and non-stationary behaviour of time series as for the previous treatment of the signal**:** detrending, smooth, filters, etc.

The Wavelet Transform (WT) decomposes a series into time-scale or time-frequency domains, which allows identification of temporal changes of dominant modes of variability, while the Fourier transform solely gives the spectral contents of the whole series. In this chapter, we will see some applications of this method to nonstationary data series very different among them, but obtained from the same system (cardiorespiratory system). Therefore, in this chapter we show the usefulness of methods based on the Wavelet Transform (WT) from two completely different viewpoints: during a cycloergometer test to exhaustation (elite cyclists) and when a subject is at rest in a mindfulness meditation state (MM) (Zen meditation or Zazen).

The Physical Education Department and the Physic Department of the University of Las Palmas (ULPGC) have been working jointly on this projects. All individuals tested to the present date were volunteers who signed their consent once informed on the aims of the experiments. The study was conducted according to the guidelines of the Helsinki Declaration adopted by Worldwide Medical Association on Research on Humans.

2. Practical aplications

2.1 Data analysis

The time-scale or scalogram of a signal is the squared modulus of its Continuous Wavelet Transform (CWT): $|W(a,b)|^2$, and is an average power spectrum for all the scales or frequencies, similar to a smoothed Fourier for each time. The scale parameter a and the localization parameter b assume continuous values, and the scalogram of a time series can be visually represented by an image or a field of isolines. In the present work, the Wavelet basic function as known as Morlet wavelet, was employed to analyse the temporal variation of the HRV. The Morlet wavelet is a modulated Gaussian function, which is well localised in time and frequency:

$$\psi_0(t) = \pi^{-1/4} e^{iw_0 t} e^{\frac{-1}{2}t^2} \tag{1}$$

Where ω_0 is the non-dimensional frequency which defines number of cycles of Morlet wavelet (Torrence and Compo, 1998). For large ω_0 the frequency resolution improves, though at the expense of decreased time resolution. For this reason, we chose various values for the parameter and found that $\omega_0 = 20$, is well suited for our purposes.

Integrating $|WT(a,b)|^2$ over a specific scale or frequency band provides the time dependent power of the signal in that frequency band:

$$S(t) = \int_{f_1}^{f_2} |WT(a,b)|^2 df \tag{2}$$

In the Discrete Wavelet Transform (DWT) scheme, the signal *f* of length *N* is decomposed into both approximation (*cAj*), and detail (*cDj*) coefficients by the use of two quadrature mirror filters (quadrature mirror filter bank). At each decomposition or reference level *J*, the approximation coefficients cA_J and detail coefficients cD_1, cD_2,...,cD_J are obtained, and we can reconstruct the approximation signal $A_J(t)$ and the details signal $D_j(t)$, $j=1\ldots J$. Therefore, the signal $f(t)$ may be expressed as the sum of a smooth part plus details as follows:

$$f(t) = A_J(t) + \sum_{j=1}^{J} D_j(t) \tag{3}$$

A discrete wavelet transform (DWT), with a Daubechies (Db8) type base function was initially used to obtain the mean HR signal and to eliminate the trend of the signal over time. Further mathematical details on this procedure can be found in Percival and Walden (2000).

First at all and in all cases analyzed, the measurement errors (artefacts and spurious data) and ectopic heart beats were manually checked and eliminated from the RR interval data. It has also been taken into account that the HRV time series produces an irregularly time-sampled signal. To recover an evenly sampled signal, a linear interpolation was applied to each time series.

3. Case 1

***HRV analysis during exercise*:** All individuals performed an incremental ramp test cycloergometer exercise on a Monark-816, including breathing gas analyses and HR measurements. They performed a gradual effort starting at *100 W*, increasing *5 W* every *12* sec., until exhaustion. RR interval data (the time-interval between each heart beat) were collected by using the heart rate monitor *Polar S810i* (Polar Electro Oy, Kempele, Finland).

The HR interval time series is non-stationary during physical exercise, and therefore the time series include a low frequency baseline trend component. The lowest frequency components are useful for studies on long-term modulation, but they may affect the power spectra of the HRV signal used by us. Detrending is usually used to remove the effects of non-periodic low-frequency changes in the time series before doing further analysis, and in practice, linear or polynomial trend removal and high-pass filtering are the most commonly applied algorithms to do it. Nevertheless, here we propose the DWT method to remove extremely slowly oscillating components from HRV data, considering that it provides greater control of the content in low frequency to be removed, and it is important to understand the effect of detrending on the spectral properties of the time series. DWT was used to decompose the HRV signal into *J* wavelet scales, with Daubechies (Db8) wavelet filters (García-Manso et al., 2007). Then, the detrended signal is reconstructed using the wavelet coefficients at the first *J-1* scales.

In the Figure 1 we can observe that the values of HR (in milliseconds) increase as a response to the stress originated by an increase of the load. The Figure 1 also shows the results of applying the DWT to the signal.

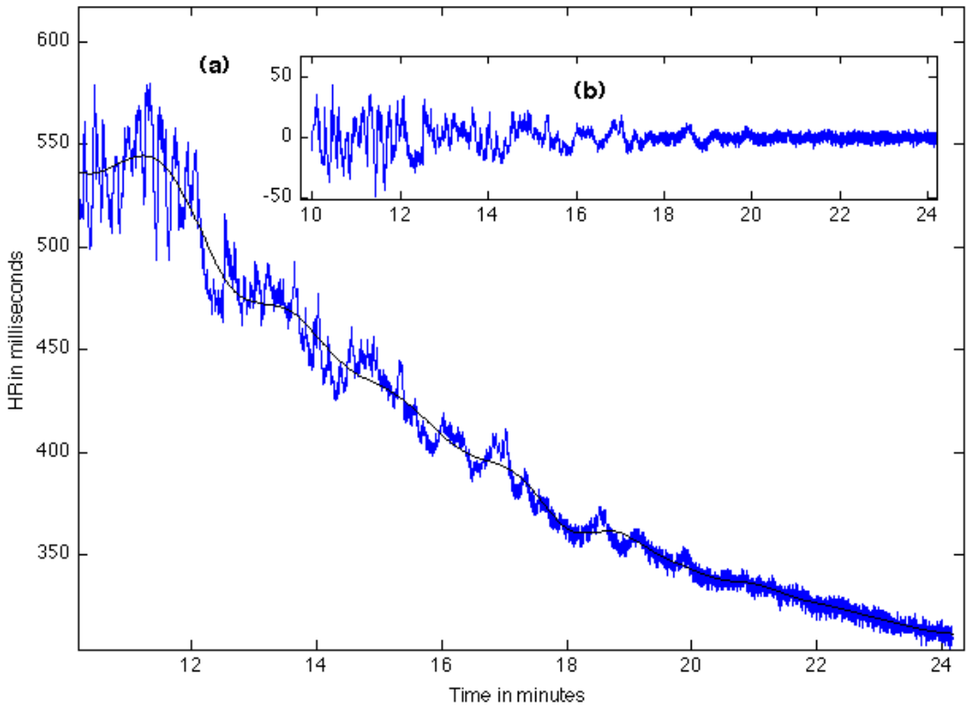


Fig. 1. a) The incremental exercise signal of subject 1 (HR in milliseconds). Also, the trend according to the DWT is shown (Daubechies 8, $J = 7$). b) The detrended incremental exercise signal.

Figure 2 shows the results of applying the CWT to the detrended signal. The method highlights three zones during the incremental test: *the activation*, *transitional* and *crisis or alarm zones*. It seems to represent three different functional mechanisms, which may be associated to characteristic metabolic processes (area of aerobic prevalence, transition aerobic-anaerobic and area of anaerobic prevalence). The *Transitional Zone* is characterized to be a phase of certain stabilization of HF and LF within the range of minimum values, which may be observed during the test (see Figure 2). Another relevant aspect of the transitional zone it is that the peaks of LF show a linear and positive increment as the load intensity increases.

In a *crisis or alarm zone*, in most of the analysed cases, if the effort is maintained despite the high fatigue caused by the exercise, the signal tends to concentrate on the high or very high frequency bands, indicating clearly that the subjects exert themselves at their highest potential limits. Some subjects give up executing their maximum effort, due to motivation reasons, local fatigue or low resistance to fatigue, instead of using their functional system to the utmost. For this reason, the use of traditional indicators as the stability of VO_2 max, RC over *1.2* or others, may not suffice for the detection of the entering in the crisis zone, while Continuous Wavelet Transform (CWT) proves to be a highly sensitive and useful technique to explain in detail the heart behaviour during incremental exercise.

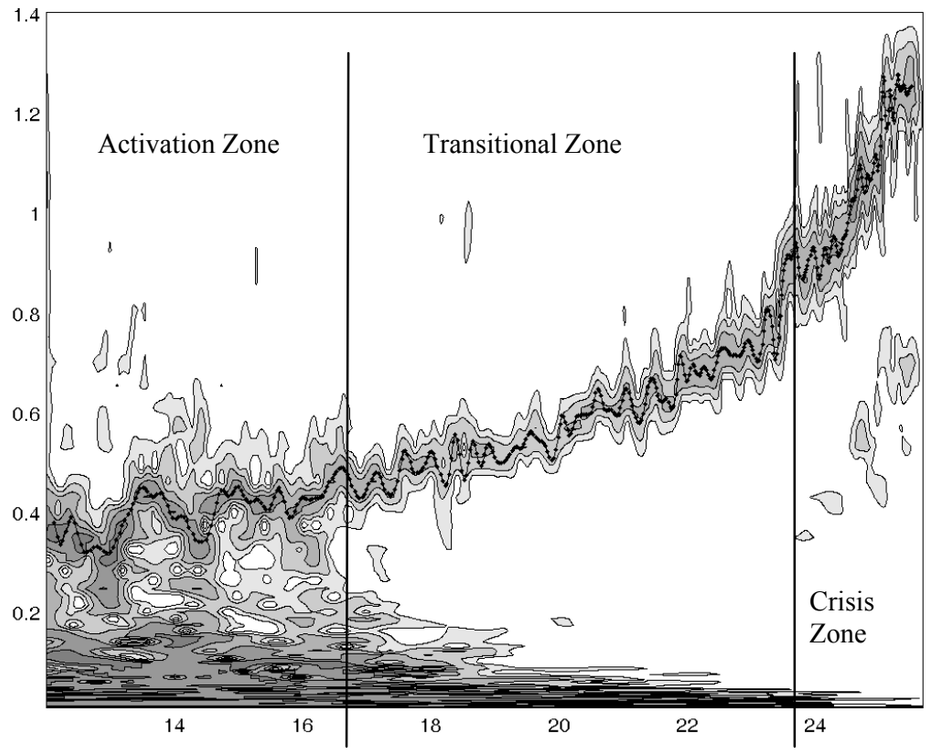


Fig. 2. Contour map of the wavelet coefficients of the heart rate variability shows the changes in the frequency components with time, obtained using a Morlet base function where $\omega_0 = 20$. The x-axis represents time in minutes, and the y-axis the frequency in Hz. Coefficients below a certain value have been eliminated in order to improve the readability of the spectrogram. The dotted lines show respiratory frequency values in Hz.

One of the most interesting applications is identifying the anaerobic threshold (level of exertion where your body must switch from aerobic metabolism to anaerobic metabolism). Some studies used WT for this purpose (Cottin et al., 2006; Cottin et al., 2007; García-Manso et al., 2008) with the following methodology:

- The evolution of frequency peaks (f_p) of the HRV HF-VHF band. The aerobic and anaerobic thresholds were determined on the basis of the changes in the values of f_p in the test. The aerobic threshold was taken as the first inflection point of the kinetics of the f_p slope, and the anaerobic threshold as the second inflection.
- The evolution of the product of the HF-VHF spectral energy value ($PS\ f_p$) by (f_p). This variable decreased with load until reaching a minimum value; the first inflection point representing the aerobic threshold; it then remained stable until it started to show a moderate increase, the second inflection point representing the anaerobic threshold.

4. Case 2

***HRV analysis during Zen meditation*:** Zen Buddhist meditation was chosen because this practice does not involve voluntary efforts to concentrate in a single object; it has a mindfulness approach, which means that it includes the reflexive observation of the whole

perceptual field and does not use any external method to reach a meditative state. The absence of voluntary efforts and the inexistence of any rule determining how the breathing pattern should be, makes this "technique" especially suitable to investigate the intrinsic properties of the autonomic nervous system (Lehrer et al., 1999; Phongsuphap et al., 2008). Differently than simple rest or sleeping, during mindfulness meditation the mental contents are observed with detachment, creating a delicate state of consciousness that involves both sustained attention and deep relaxation. Lutz et al. (2008) call this state "*open monitoring meditation*" and explain that it "involves nonreactive monitoring of the content of experience from moment to moment, primarily as a mean to recognize the nature of emotional and cognitive patterns".

Sample selection and data collection: A total of *19* subjects (*7* females and *13* males, mean age *43.65* ± *7.60* years, mean meditation experience *9.81* ± *8.82* years), with a consistent practice (at least three times a week) of Zen meditation, participated in this study. Exclusion criteria included the presence of cardiovascular disease or any disease that affects the autonomic balance and the use of any medication that could influence the results. The RR interval data were collected by using Polar S810i, which seems to be an adequate instrument to minimize the possible disturbance that data collection may cause in a meditation process. In any specific case we took simultaneous measures of breathing and HRV, using the multi-function monitoring equipment I-330-C2+. The subjects were instructed to sit quietly for *10* minutes before the beginning of the meditation, already in the position they customarily take during Zazen practice. They sat upright in a cross-legged position on a cushion (*zafu*), with the hands held together in front of the navel. The eyes are kept semi-open and the back upright to avoid drowsiness. After the baseline recording, a bell rings and the subjects start meditating, as they always do, for *40* minutes. After that, the bell rings again and an additional 5-minute recording was taken during quiet sitting. All data were collected in the meditation rooms of *Luz Serena* Temple (Valencia, Spain) and of the *Dojo Zanmai San* (Tenerife, Spain), which follow the same tradition and are systemically integrated.

In this study we found evidences that the evolution in Zen meditation can be characterized for specific patterns of cardiac variability and we found a tendency towards a shift in RSA to the LF range (Peresutti et al., 2010). So, for long-term practitioners the power in the HF ranges significantly decreases and it seems that there is a tendency towards a frequency coupling as regards the years the subject have meditated. In long-term practitioners the attention is opened to the diverse experience content; in the case of instructors with over *10* years of experience, the RSA frequency decreases and couples with LF oscillations, but there is no resonance. We found that even when the breathing frequency is higher than *0.15 Hz*, the RSA and the LF oscillations may coincide, but do not produce a resonant effect.

The Figure 3 represents the WCT of RR interval for a Zen instructor (ZI) with over 11 years of experience. The box *(a)* is the time series; *(b)* the scalogram and *(d)* is the power spectrum (FFT) of HRV signal. In box *(c)* shows the sum of wavelet coefficients (power) in the LF band for each time, obtained using equation (2). The LF band in the box (d) appears as a broad band. However, the wavelet analysis reveals that in reality is a narrow band that varies in time. We can see (horizontal arrow in Figure) how, at the beginning of the meditation, frequency drops to *0.065 Hz* and the power increases significantly. This time interval, about *5* minutes, is responsible for the presence of a sharp peak in the Fourier Spectrum around *0.065 Hz*.

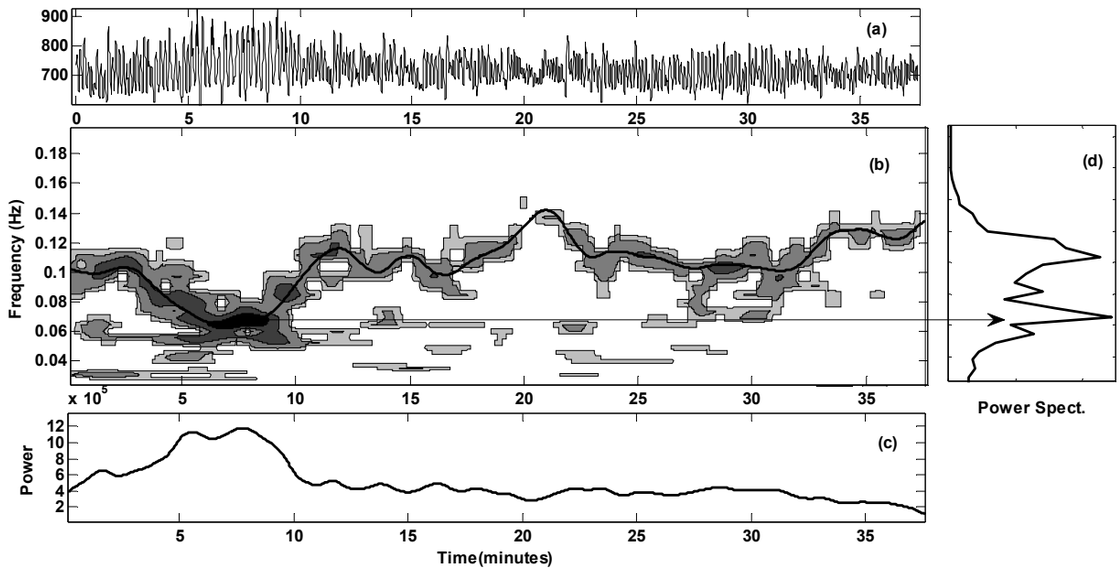


Fig. 3. Wavelet analysis of HRV. It shows the temporal evolution of the low frequency band LF (*0.04-0.15 Hz*) for Zen instructor (ZI), during mindfulness meditation. (*a*) RR interval time series. (*b*) Scalogram. The higher coefficient values are shown in greyscale (contour lines) and lower values were excluded. Darker areas represent higher values. The solid line corresponds to the highest values coefficients (peaks). (*c*) Sum of wavelet coefficients (power) in the LF band for each time. (*d*) FFT of the time series, where the axes have been invested, coinciding the axis *y* with the frequency (LF band only) and the axis *x* with the power. The axis *y* of (*b*) and (*d*) are the same.

In the case of more advanced meditators (Zen Masters with over *20* years of practice) breathing oscillates within the LF range, coupled with the other cardiovascular rhythms and producing resonance, although there may be variations in frequency, especially in the second half of meditation.

The WCT-based analysis also allows us to analyze the simultaneous action, but independent, of HRV and breathing during meditation in two different subjects: Zen instructor and the Zen Master. The Figures 3 and 4 show the wavelet analysis of both HRV and respiratory data, for the Zen instructor and the Zen Master (ZM), respectively.

It should be noted that in the first half of meditation there is less variation in the LF range. Nevertheless, in the second half there is much more variation of the LF probably due to the appearance of a breathing frequency higher than *0.15 Hz* although the RSA and the LF oscillations still coincides, which means that, although the frequencies vary, their relation remains stable, or in other words, the ratio remains almost constant. In long-term practitioners, the attention is opened to the diverse experience content; for the ZI the RSA frequency decreases and couples with LF oscillations, but there is no resonance. The resonance phenomenon described here occurs when the breathing oscillates within the LF range, coupled with the other cardiovascular rhythms. We found that even when the breathing frequency is higher than *0.15 Hz*, the RSA and the LF oscillations may coincide, but do not produce a resonant effect, note the presence of VLF oscillations (Figure 4). Further discussion on this point can be found in: Vaschillo et al. (2006), Cysarz et al. (2005), Peng et al. (1999).

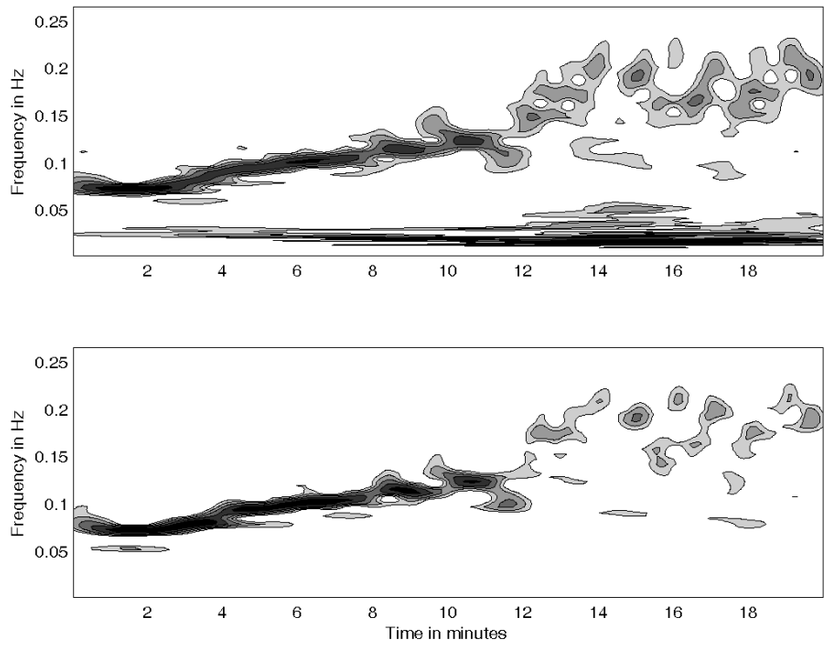


Fig. 4. Wavelet analysis of HRV (top) and respiration (bottom) showing the temporal evolution of the frequencies for ZI during mindfulness meditation. The higher coefficient values (power) are shown in greyscale (contour lines) and lower values were excluded. The darker areas represent more power.

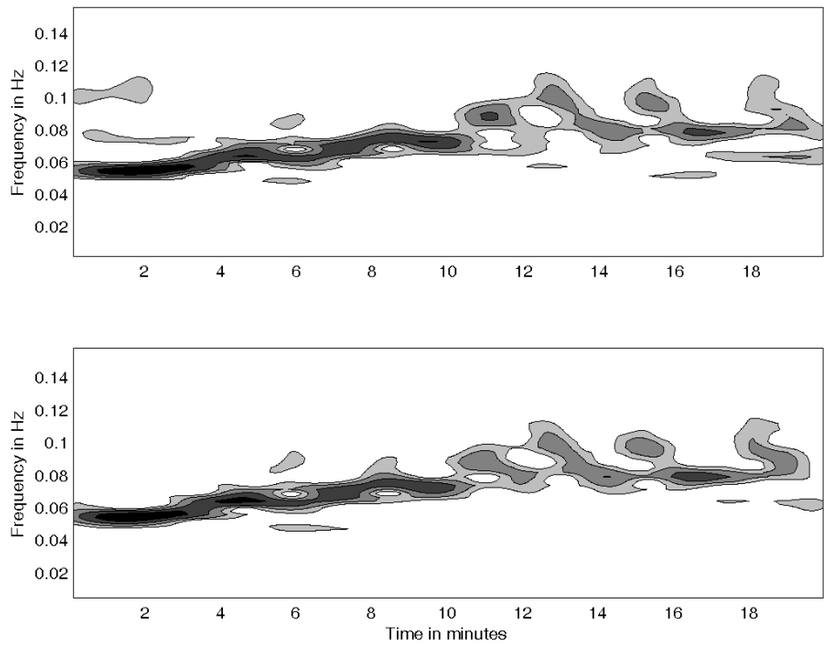


Fig. 5. Wavelet analysis of HRV (top) and respiration (bottom) showing the temporal evolution of the frequencies for ZM during mindfulness meditation. The higher coefficient values (power) are shown in greyscale (contour lines) and lower values were excluded. The darker areas represent more power.

For the Zen Master (Figure 5), the same pattern as shown for ZI is observed, with two different phases in the meditation; however, for ZM, even in the second half, the breathing oscillates exclusively in the LF range and the resonant effect never disappears. We believe that this more irregular pattern in the second half of Zazen, typical among long-term practitioners, could be related to an even less controlled state, when attention stability is well established and a greater depth in the meditation can emerge. If we consider that there is a tendency towards a coupling between HRV characteristic frequencies regarding the years of meditation practice, and also the previous works and the present results from the Zen Master, it is possible that the appearance of a resonant effect between long-term practitioners characterizes the pure state of mindfulness.

5. Conclusion

From the analysis of the experimental data obtained, it may be stated that the wavelet analysis proves as a subtle and precise tool for the detailed study of the cardiac response to physical exercise or coupling of biological rhythms in the absence of physical movement and mental processes dominated. The application of this method allows, on one hand, a global analysis of the behaviour and, on the other, a detailed study of concrete phases or zones and precise responses occurring during exercise.

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Wavelet Transforms and Their Recent Applications in Biology and Geoscience

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This book reports on recent applications in biology and geoscience. Among them we mention the application of wavelet transforms in the treatment of EEG signals, the dimensionality reduction of the gait recognition framework, the biometric identification and verification. The book also contains applications of the wavelet transforms in the analysis of data collected from sport and breast cancer. The denoting procedure is analyzed within wavelet transform and applied on data coming from real world applications. The book ends with two important applications of the wavelet transforms in geoscience.

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