Changes in fractal properties of motor control during fatigue

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Abstract.

Fatigue affects the performance in all athletics specialties. From a physiological point of view it has been understood as a linear phenomenon produced by the impairment and failure of a specific "site" or mechanism. Some recent evidences have revealed its non linear nature proposing to study it as a dynamic complex phenomenon (Hristovski & Balagué, 2010). Our aim is to investigate the type of variability of two different order parameters obtained during static and dynamic exercises, respectively, performed until the fatigue-induced spontaneous termination point (FISTP). 12 participants performed a static elbow flexion exercise (80% of 1-RM) and a continuous cycle ergometer exercise (80% of max. load, keeping the pace at 70 rpm) until the FISTP. The changes in the elbow angle during the effort were recorded through an electrogoniometer and its software (Biometrics, Ebiom). The oscillations of the cycling rpm were recorded continuously through the cycle ergometer system (Sport Excalibur 925900). The time series of both parameters were analyzed by time and frequency domain methods (autocorrelation and spectral analysis). The spectral indexes were calculated estimating the linear fit slope of the power spectrum with respect to frequency in logarithmic coordinates. A scale invariant relation was found between the spectral power of the rpm variability and the frequency in both exercises. The values of the spectral indexes oscillate between -1 and -2 pointing to the presence of a fractal dynamics in the spectrum (from anti-persistent to persistent Brownian motion as fatigue develops) and towards a self-organized process in both cases. The fractality observed in these data series inform about the non linear nature of the exercise-induced fatigue and question the linear orientation of the available research. New practical applications related with the control of training should be developed in athletics according to it.

Keywords: fatigue, fractality, nonlinear dynamics. Self-organization, static exercise, dynamic exercise.

Introduction

Fatigue affects negatively performance in all sports activities and has a particular detrimental effect in endurance specialities. The research of exercise-induced fatigue has evolved notably during the last years. The unclear and sometimes controversial results obtained by the pioneer and also recent studies trying to find a unifying theory through a reductionistic approach (Hargreaves, 2008; McKenna & Hargreaves, 2008) has promoted the development of alternative approaches to study it. Some scientists have assumed that the involved mechanisms in the fatigue process depend and are specific on the task being performed changing the classical question of *what causes muscular fatigue?* by the question of *what causes task failure?* (Maluf & Enoka, 2005; Enoka & Duchateau, 2008). Others have tried to introduce integrative approaches to cope with the complexity of the phenomenon (Lambert, St. Clair Gibson & Noakes, 2005; Noakes, St. Clair Gibson & Lambert, 2005). They propose the existence of a special kind of central programmer exerting an integrative homeostatic control over the physiological systems. With or without central controller the extant models to explain the exercise-induced fatigue can be consider as being linear (Balagué & Hristovski, 2010). This means that the response of the system to a change in some of the independent variables is always proportional to that change. Anyway some recent results have revealed the non linear dynamic complex nature of the FISTP (Hristovski & Balagué, 2010). In any case the type of integration of the multiple components intervening in the fatigue process seems to be a still unsolved but very important point to proceed with the research of the subject in a more successful way. Some concepts and tools offered by complexity sciences may allow enabling a hint of it. In particular the analysis of a temporal ensemble of states of a chosen representative variable during the fatiguing task performance enables the detection of the serial dependency present in the system's behavior. This variable should be the hypothesized order parameter of the system, i.e. should be able to capture the macroscopic behaviour that arises as a consequence of the highly coordinated and cooperative behaviour of the system's components. The scaling relationships in the dynamic fluctuations of the variable under study may show their potential fractal structure. This type of scaling relationship is typical of the non linear self-organized systems which do not need any programmer inside or outside ordering their behavior.

The present research approaches this issue from the perspective of time series analysis of stochastic processes which, among the others, enables the detection of the structure of temporal dynamics of some variable under investigation and may offer a better explanation of the type of integration present in the system's behaviour. In Brownian motion processes (Delignières, Torre & Lemoine, 2004b) the dependency within time series may be such that after the increment of certain value of the variable it is highly likely that a decrement will follow. This type of dependency is called antipersistent and the slope of its spectral power in logarithmic coordinates is between -2 and -1. Another type of dependence exists when after an increment/decrement of the previous value it is highly likely that a further increment/decrement will follow. This type of dependence is called persistent, since the system tends to persist in the decrements or increments of previous values. The values of the spectral slopes of such processes are between -2 and -3.

The values of spectral slopes may provide answers to the issue whether these characteristics occur through processes of a relatively permanent nature, or the phenomenon under investigation reflects an emergent organization that is strongly dependent on the immediate and changeable configuration of the factors constraining the system's dynamics (Delignières, et al., 2004b).

In motor control, scale invariance or power law scaling has been reported in human gait control (Hausdorff et al., 1996), force production tasks (Gilden, 2001; Vaillancourt & Newell, 2003; Wing, Daffertshofer & Pressing, 2004) and unimanual and bimanual rhythmic movements and coordination (Chen, Ding & Kelso, 1997; Ding, Chen & Kelso, 2002; Delignières, Lemoine & Torre, 2004a; Torre, Delignières & Lemoine, 2007; Delignières, Torre & Lemoine, 2008). Scale invariance of a system's dynamics may signify that the latter are self-organizing. For example, Van Orden, Holden & Turvey (2003) raised the issue about the general class to which cognitive systems belong and explained cognition as a scale-invariant and interaction–dominant complex system functioning in a self-organized critical regime (Van Orden & Holden, 2002; Van Orden, Holden & Turvey, 2005; Kello, Beltz, Holden & Van Orden, 2007; Kello, Anderson, Holden & Van Orden, 2008).

The aim of this paper is to show how time series analysis may unravel significant information about the behavior of systems under exertion-induced fatigue. Particularly we aim to show that fatigue changes very specifically the dynamics of the cooperatively working components of athlete's movement system as seen by changes of spectral slopes. We also aim to show that these effects are probably universal and do not depend on the type of exertion.

Material and methods.

Twelve physically active participants previously familiarized with the experiments tasks participated voluntarily in the study.

In the first experiment, participants performed a quasi-static elbow flexion exercise with an initial flexion of 90º holding an Olympic bar (80% of the subjects´ 1-repetition maximum). To maintain the initial elbow flexion they had a reference cord placed at the level of their wrist. An electrogoniometer (Biometrics, software by Ebiom) was used to record the changes in the elbow angles during the trials. In the second experiment, participants performed a continuous cycle ergometer exercise at 200 W (70 rpm). The rpm during the trials were continuously recorded (Sport Excalibur 925900). In both exercises the participants had to keep the established criteria of each task and not to stop exercising even if the criteria was not satisfied. A virtual competition was organized in order to increase the likelihood that the FISTP would be reached in all trials.

Time series analysis.

From both experiments time series of the hypothetical order parameters (elbow angle and RPM, respectively) were recorded and then analysed.

The time series were analyzed by the common spectral analysis method. Before the final analyses of the spectral characteristics of time series, and in order to remove possible global trends, we first detrended and then standardized the series (Chen, Ding & Kelso, 2001).

By checking the behaviour of the spectral indexes (β) under conditions of less and more liberal detrending procedures we were able to draw conclusions about the stability of the spectral indexes with respect to these transformations, and hence about the reliability of the time series' fractality (Hausdorff et al., 1996). Spectral indexes were obtained using standard procedures, by estimating the linear fit slope of the power spectrum with respect to frequency in logarithmic coordinates.

Results and discussion.

Typical results from the spectral analysis are given on Fig. 1 and 2. One can see that the spectral slope of the fluctuations of order parameters (revolutions per minute - RPM, and elbow-joint angle) change under fatigue. A dominant result in the first phase of exertion is the antipersistent fluctuations dynamics (-2 < slope <-1) and in the last part weakly or strongly persistent dynamics (-3 < slope < -2). The persistent dynamics was particularly present in participants who worked in deep exhaustion and still tried to reach/maintain the initial 70 RPM or 90 deg. task criteria.

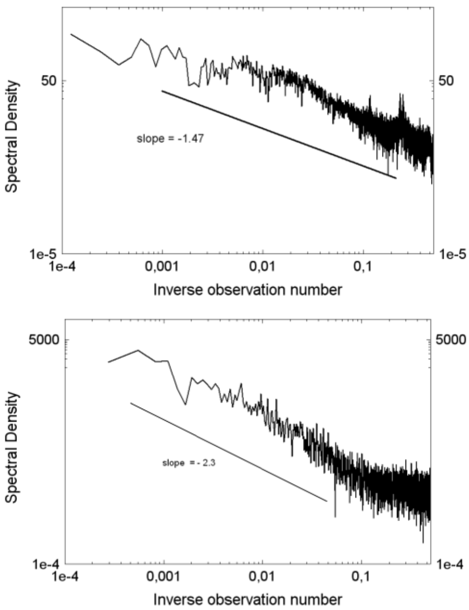
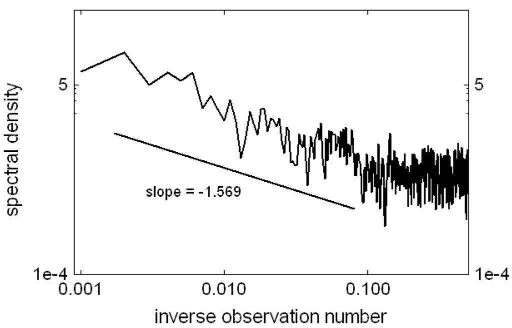


Figure 1. A. Typical power spectrum of fluctuations of the RPM measure in bicycle-ergometer exercise - the first 30 seconds. B. The last 20 seconds. Note the change of the slope between A and B.



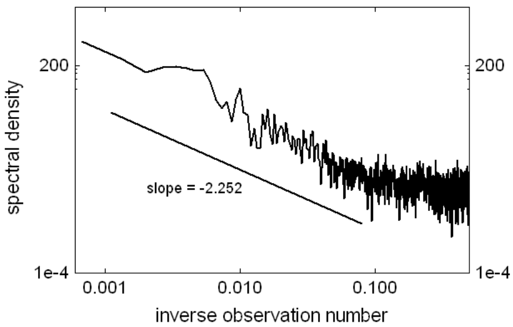


Figure 2. A. Typical power spectrum of fluctuations in quasi-isometric elbow flexion exercise first 20 seconds. B. Last 30 seconds. Note the change of the slope between A and B.

The results point to a possible self-organized process underpinning the exercise-induced fatigue manifest in the temporal fractal self-similar structure. The temporal structure of order parameter fluctuations shifts from antipersistent to persistent which signifies a drastic reconfiguration of the movement system components coordination. As the antipersistent dynamics is based on correcting the previous events by counter-events (higher increments are followed by higher decrements) it seems that this type of control is a tailor – made for keeping a constant intensity which was actually a task in both experiments. Thus a non-fatigued system, at the beginning of the exercise is capable of such control. As the fatigue accumulates another dynamics emerges, probably as a result of a weakening of the quick degrees of freedom of the movement system. This dynamics is characterised by a persistent sequential dependence. As the system is not able to make quick corrections with aim to keep the order parameter value close to the initial value, larger deviations emerge and longer periods of correction characterise the dynamics. This signifies that the previous stable cooperative structure of movement system's components becomes increasingly unstable and brings to spontaneous reconfigurations of those component relations. These increasing reconfigurations of motor control component processes is most likely a hallmark of exercise-induced fatigue and probably a major stimulator of delayed processes of adaptation working on larger time scales during the training process. It is particularly interesting that not withstanding the enormous differences in tasks (cycling vs. quasi-static exercise) the order parameter fluctuations seem to have the same dynamic structure. This points to a probably universal nature of these phenomena. A further detailed research is needed to unravel the specificities of these control changes.

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