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WHAT RUNNING CORRELATIONS TELL US ABOUT INTERLIMB COORDINATION?

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(Original scientific paper)

Pablo Vázquez[1], Monika Petelczyc[2], Natàlia Balagué[1], Robert Hristovski[3]
[1]Complex Systems in Sport Research Group, Institut Nacional d'EducacióFísica de Catalunya (INEFC), Universitat de Barcelona, Barcelona, Spain, [2] Warsaw University of Technology, Faculty of Physics, Warsaw, Poland,[3] Complex Systems in Sport Research Group, Faculty of Physical Education, Sport and Health, Ss. Cyril and Methodius University in Skopje, Skopje, Macedonia

Abstract
Fatigue has been overwhelmingly studied in the context of reduced capacity of organisms to perform a certain task. However, research efforts on dynamic inter-limb coordinative effects of fatigue have been much less emphasized. The aim of this paper was twofold: a) analyzing the effects of fatigue on the upper limbs coordination during an exercise performed until exhaustion, and b)proposing a marker for assessing the effects of fatigue based on the Running Correlation Function (RCF). Seven participants performed a quasi-isometric exercise holding a barbell aiming on maintaining an initial elbow flexion of 90 degrees until the fatigue induced spontaneous termination point. Task was performed once a week over a period of four weeks. The variability in the elbow angle during the exercise was recorded through electrogoniometry and the obtained time series were divided in three parts for further analysis. The RCF was applied to the corresponding initial (30%) and the last (30%) segment of the exercise. The results show that the inter-limb correlation for each individual consistently increased between the initial and last part of the exercise. A high magnitude correlation (%RCF>0.8) may prove to be a useful marker to detect the fatigue development effects on coordination. The enhancement of the inter-limb correlations in the last part of the exercise manifests an impaired inter-limb coordinative flexibility. These results may provide information about the fatigue effect that leads to the loss of adaptability during exercise.

Key words: *fatigue, exercise, synergy, running correlation function, inter limb coordination*

Introduction

In line with predictions of the general theory of self-organized change (Haken, 2013), previous studies have shown that the effects of fatigue during exercise produce an enhancement and a change in the structure of the fluctuations in the extremities before the onset of the spontaneous fatigue induced task disengagement (Hristovski and Balagué, 2010; Vázquez, Hristovski and Balagué, 2016). Findings showed that the core mechanism of spontaneous task disengagement is of dynamic (not substrate) nature. In other words, the critical behavior of the organism close to the task disengagement point is similar for a large set of exercise intensities (i.e. biochemical and physiological regimes). Hence, the critical behavior is independent of the exact biochemical or physiological processes that conspire to bring the organism to the critical point. However, still little is known about the effects resulting from *dynamic processes* of exercise induced fatigue on the inter-limb coordination during exercise.

The purpose of this study was to preliminary investigate the effect of fatigue on the coordination between the upper limbs during a quasi-isometric exercise performed until exhaustion, and introduce a novel marker to assess it.

Material & methods

Participants

Seven voluntary physical education students (4 females and 3 males, mean chronological age 22 SD=1.2) participated in the study. They were familiar with strength training and conditioning, and prior to taking part in the study they completed a questionnaire to confirm their healthy status. All experimental procedures were explained to the participants before they signed a written consent to participate in the experiment, and were approved by the Local Research Ethics Committee (ref. 072015CEICEGC)

Procedure

Participants performed a quasi-isometric exercise holding an Olympic bar in an arm-curl position untill exhaustion. To calculate the weight to lift during the exercise, they performed a one-repetition maximum test (1RM) one week prior to take part in the study. Then, the 80% of the weight lifted was calculated for each participant and used for the load during the exercise (M=26,74 kg, SD=2,52). They performed one day per week over a period of four weeks following the instructions described in Vázquez et al., (2016) until the fatigue-induced-spontaneous-termination-point (FISTP) (Hristovski and Balagué, 2010). Participants were encouraged to maintain intentionally a 90º elbow joint angle flexion during the task. If the initial elbow angle was lost, participants were told to persist in maintaining the flexion as close as they can to the initial 90º position. Participants sat on an inclined-forward bench during the trials in order to prevent possible spinal injuries. A reference cord was placed at the level of the participant's wrist in order to facilitate visual feedback on the initial position and its loss. Prior to the exercise, the bench position and the reference cord were adjusted for each participant on every trial. To monitor and record the variations in the elbow angle, an electrogoniometer (Biometrics) was placed in both left and right arms. The sensors of the electrogoniometer were located on marked points on the upper and forearm of both limbs, and were adjusted to the required starting flexion of 90º. The Ebiom software was used to record the data at a sampling frequency of 50 Hz, and an amplitude resolution of 0.1 deg. for each arm.

Data Preprocessing

The time series were detrended before its analysis. Then, the fatigue-induced-spontaneous-termination-point (FISTP) was determined in the datasets. According to the established methodology (Hristovski and Balagué, 2010; Vazquez et al, 2016) the FISTP was detected as the onset of a persistent change toward negative values. This negative trend was determined from linear fit performed in overlapping windows with length 50 points starting from the end of the recording. FISTP was found in time series from both elbows separately. In case of any divergence between its position in left (L) and right (R) arm datasets, the FISTP was set for the earlier position in time. Finally, signals from both elbow joints after FISTP determination had the same length.
In the next step of pre-processing, the linear trend was removed. For each signal, the first order polynomial fit was performed separately. After this procedure, the detrended recordings were raised by the minimum of original data to obtain the referential values of elbow angle.
To quantify fatigue's progress, the recordings were divided into unified segments, which reflected the percentage of time evolution following the FISTP. For comparison purposes, the first 30% (BEG) and the last 30% (END) of the pre-processed data were selected for further analysis.

Running correlation function

The correlation function was applied to two segments of series recorded simultaneously. For all calculations common procedure of overlapping windows was performed. The correlation coefficient was determined in predefined window length W of 100 data points. Then the window was moved one point forward through time series and the correlation coefficient was determined again. The procedure was repeated until the end of the window in the selected data segment (BEG and END separately). The described sliding approach for the temporal correlation coefficient determination is known as running correlation function (RCF). To obtain the limited ranges of RCF values varying between -1 and +1, the normalization by local standard deviations $\sigma_R(n)$ and $\sigma_L(n)$ was proposed:

$$\boldsymbol{RCF(n) = \frac{\sum_{i=1}^{W}\left(L_{n+i}-\mu_L(n)\right)\cdot\left(R_{n+i}-\mu_R(n)\right)}{(W-1)\cdot\sigma_L(n)\cdot\sigma_R(n)}} \quad (1)$$

In the **Equation (1)**, $\mu_L(n)$ and $\mu_R(n)$ refers to mean determined for left and right elbow respectively. Note however, the means and standard deviations in **Equation (1)** were calculated only for current window, which left limit is *n-th* data point in the time series segment. The selected window for the analysis is multiplicities of 2sec due to experimental sampling rate.
The RCF is given in the constant range <-1;1> and the number of data points in BEG and END is the same. The analysis of the correlations magnitudes is represented by the RCF values which follow the rule: RCF(n)>0.8. We introduced the percentages of RCFs in defined inequality as a characteristic markers denoted as **%RCF>0.8**. They were determined for BEG and END separately. Note, that constant number of datapoints in BEG and END segments causes that the results for each individual are not sensitive to the

length of the signal.

Results

The results of the RCF analysis showed a consistent increment in the %RCF>0.8 for the END segment compared to the BEG segments for all individual participants. The Figure 1 shows an example of the RCF analysis in one participant. The upper panel shows the curve of the results of the RCF for the normalized data between the right and the left arms. Note that at the end the curve is moving close to 1. In the bottom panel it is observed how the distribution of the correlations of high magnitude (i.e. larger than 0.8) increased in the END segment compared to the BEG, see the blue bars between 0.5 and 1 in the histogram.
In Table 1, the means of %RCF>0.8 with SD are presented for the analysed windows of 100 data points, which corresponds to 2 seconds of the exercise in both segments. It is observed that the mean values of %RCF>0.8 is 10,53 in the BEG segment and 26,98 in the END segment for all the sample.

Table 1. The mean and SD of %RCF>0.8

Window size	100
Mean BEG	10,53
SD BEG	9,12
Mean END	26,98
SD END	14,94

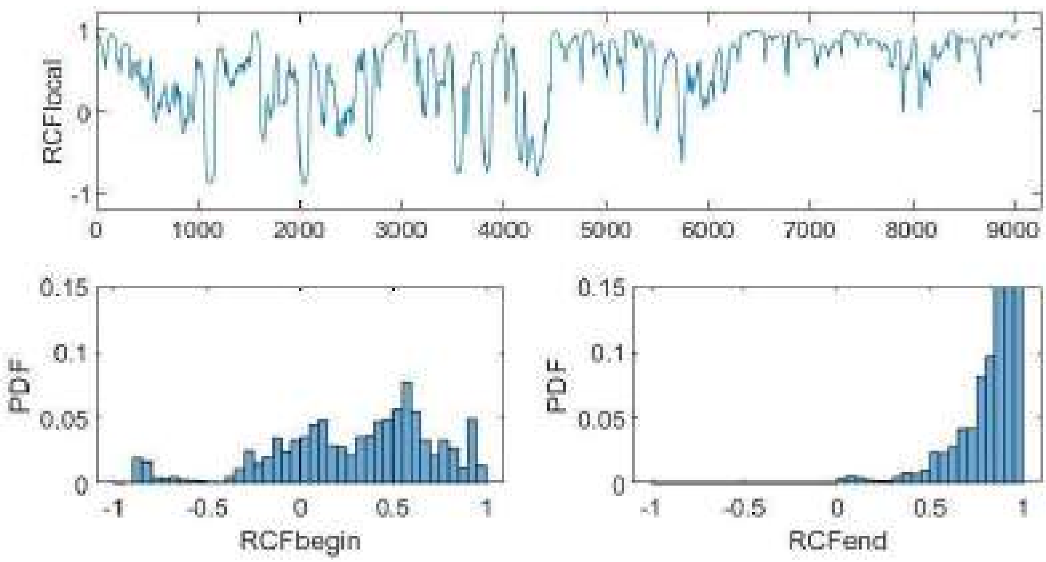

Figure 1.Upper panel: An example of RCF values vs data points. Lower panel: Left - Probability distribution function of RCF for the initial third of the time series; Right - Probability distribution function of RCF for the final third of the time series.

Discussion

RCF captured the fatigue induced changes of inter-limb coordination during a quasi-isometric exercise performed until exhaustion in all individuals consistently. The use of %RCF>0.8 was proposed as a new marker to assess the development of fatigue and approach to exhaustion. The enhancement of the correlation between both arms means that any variation in one of the upper limbs is more probable to be associated by a variation in same direction by the other limb. The increasing mutual dependence of both limbs with the development of fatigue reflects the impaired ability of the psychobiological system to separately control its degrees of freedom. Close to exhaustion, the inter-limb system becomes excessively coupled in contrast to the initial, non-fatigued, state when more refined autonomous spatio-temporal control is possible. The less flexible, and hence, less autonomous control of the arms is proposed as a sign of the approaching exhaustion.

Conclusions

The high magnitide running correlation function (% RCF>0.8) informed about the development of fatigue during a quasi-isometric exercise. It may proove to be an important marker for assessing the coordinative aspects of fatigue development.

Conflicts of interest. The authors declare no conflict of interest.

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