INDEX TO QUANTIFY THE DEVELOPMENT OF FATIGUE DURING PROLONGED RUNNING

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INTRODUCTION

Fatigue is defined in the physiological sense, as *the inability of the individual to maintain the expected power output* [1]. Based on this definition, the fatiguing effects of an exercise protocol (workload and environment) can be quantified by measuring the duration of exercise that can be sustained before reaching voluntary exhaustion [2]. However, it is an oversimplification to quantify fatigue based entirely on a discrete event that occurs at the failure point where the load exceeds the available power. In reality, fatigue develops throughout the duration of activity, regardless of whether or not the failure point is reached. Changes related to the progression of fatigue are reflected in physical and psychological variables, many of which can be measured in the lab during treadmill running and may be used to quantify the progression of fatigue. The purpose of this study was to develop a tool to quantify fatigue-related changes in an athlete performing a prolonged bout of treadmill running.

METHODS

Twelve female recreational runners participated in this study. Maximum aerobic speed was determined using an incremental treadmill running test. One to three weeks later subjects performed a 1 hour long endurance running session at 95% of this value. Psychological, physiological and biomechanical signals were recorded throughout the duration of each 1-hr running session. These variables were: heart rate, respiration rate, stride frequency rate of perceived exertion, and the responses to the Runners' Questionnaire. The runner was asked at 6 minute intervals to rate their effort on a standard 15 point Borg scale and to respond to the 8 statements of the Runners' Questionnaire (I'm satisfied with myself, I feel strong, I feel relaxed, my head is clear, I feel confident, I'm motivated, I feel pain, how much energy do I have left?). A scale from 0 to 6 was used. The variables were subsequently normalized:

$$X_{norm} = \frac{X_{test} - X_{baseline}}{X_{\max} - X_{\min}} \times 100$$

The baseline values were measured at T = 8 or 12 minutes. The max/min values were the limits of the scales. The maximum heart rate was 217–(0.85 x age) and the minimum was 70% of that value. The max–min difference for the respiration rate and stride frequency were taken as 4 standard deviations of all the data. At each time point a vector **m** consisting of the normalized variables was obtained (input data). The mean of the input data over all subjects was subtracted from **m** and a principle component analysis (PCA) was performed on the resulting vectors. The first eigenvector, **PC,** explains the greatest variability of the input data. It was expected that during the course of a prolonged run the greatest variation in the data would be due to the progression of fatigue. Therefore, **PC** was used to quantify the fatigue index (`f`).

$$f = \mathbf{m} \cdot \mathbf{PC}$$

The elements of **PC** indicate the relative contribution of each of the variables to the calculation of `f`. The `f` values were plotted vs. time and the rate of change (fatigue slope) was calculated. The index is generalizable if `f` is valid for an unknown new subject. The consistency of **PC** was assessed using a leave-one-out cross validation procedure where data from each one of the 12 subjects was omitted from the PCA. The result was a series of $\mathbf{PC_i}$ vectors (i=1…12). The difference in the fatigue slopes calculated using each $\mathbf{PC_i}$ was determined. The generalization error was calculated to be the mean and standard deviation of these differences in % of the mean fatigue slopes. Subjects were classified into 3 effort groups depending on the maximum Borg scale value that they reported during the run (low: 5-12, moderate: 13-16, high: 17-20).

RESULTS AND DISCUSSION

Fatigue index values increase as a function of time into the run with high effort runners showing a steeper `f` slope than low effort runners. The maximum slope of `f` was 0.99 h^{-1} and the generalization error was 1.9%±1.1%. The generalization provides an assessment of the absolute reliability of the measured `f` slopes and the influence that the selection of **PC** had. When using the slope of `f` to rank subjects and if the differences between subjects are greater than 0.03 h^{-1}, then the rank is not influenced by the selection of any $\mathbf{PC_i}$ instead of **PC**.

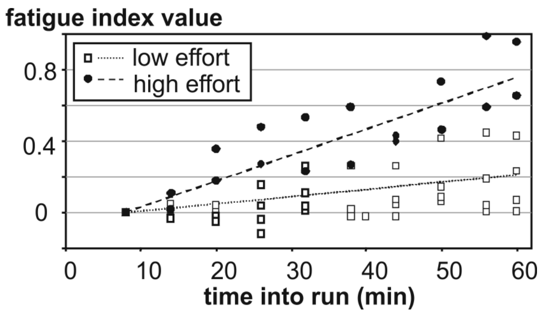

Figure 1: The fatigue index, `f`, vs. time plotted for 4 low and 2 high effort runners.

CONCLUSIONS

The study described here represents the development of a tool to assess and quantify the effects of fatigue in dynamic conditions using multiple, interconnected variables. The variables are combined to form a generally applicable causal index that can be used to rank the effects of fatigue in trials or subjects. A multivariable fatigue index is more reliable than one based on a single variable e.g. Borg scale. The assessment of generalization error is new and only possible with a multivariable fatigue index. The current theoretical framework can easily be expanded to include a wide range of biomechanical, physiological and psychological variables, allowing its application in other modes of exercise.

ACKNOWLEDGEMENTS

This research was supported by: adidas AG and the Alberta Heritage Fund for Medical Research

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