MUSCULAR FATIGUE FROM ELECTROMYOGRAPHIC RECORDINGS: REAL-TIME MONITORING DURING EXERCISE TRAINING

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Abstract: In this work a novel approach to real-time muscular fatigue detection is presented. Surface ElectroMyoGraphy (sEMG) has been used to monitor muscles work and in particular to detect signs of muscular fatigue. The joint estimation of a pair of electrical indicators (i.e. amplitude and mean spectral frequency of sEMG signal) is the basis for the detection of the muscular status, since their values are strictly influenced by different conditions of force production and fatigue occurrence. These indicators are estimated by adaptive algorithms specifically devised to process signals recorded during either static or dynamic conditions. The algorithms allow real-time processing and are integrated into a single monitor for muscular status. The monitor has been tested on signals recorded during spinning training sessions. Ten able body subjects volunteered for these sessions composed of several tasks characterized by different body postures and flying wheel resistances. A movement analysis system (StepPC©, DEM-Italy), has been used to record cardiac activity, sEMG signal from rectus femoris and angular displacement at knee joint. Preliminary results demonstrate the feasibility of the approach and its capabilities in characterising the evolution of effort and fatigue during extended, sub-maximal training events.

Introduction

Standard definition of localized muscular fatigue relies on mechanical deficit occurring as a consequence of prolonged or exhausting body exercises. In facts, as stated in [1], muscular fatigue can be described as "any exercise-induced reduction in the maximal capacity to generate force or power output". Then, the occurrence of muscular fatigue can be monitored by measuring force or power output.

However, the mechanical deficit is the consequence of physiological modifications connected to muscles metabolism. Many activities, related to rehabilitation, ergonomics and athletes training could greatly profit from a timely indication of physiological modifications driving to muscular fatigue. The most common indication is provided by blood lactate measurements: these are invasive and typically imply the stop of the exercise execution.

Surface electromyography (sEMG) provides an indirect measurement of muscular fatigue: in fact, the amplitude and the mean spectral frequency of sEMG signal can be considered as electrical indicators of the physiological modifications preceding fatigue.

Several studies showed that these indicators provide valuable information during fatiguing protocols characterized by isometric and force-constant contractions (i.e. static conditions). The modifications of the electrical parameters associated to muscular fatigue are the following: the signal amplitude increases [2÷6] and the signal spectrum shifts toward the low frequency band [7÷14]. In these conditions each parameter provides a proper indication of fatigue.

When the force production during the exercise cannot be kept constant, even if the variation is slow such as in semi-static conditions, the parameters loose their reliability because they do not only depend on fatigue state, but also on the force production. Thus, it becomes mandatory to control the current level of force production together with the fatigue signs.

Since muscular status depends on both force and fatigue, the electrical parameters have to be simultaneously monitored. Luttmann and coworkers [15÷17], proposed a protocol, called Joint Analysis of EMG Spectrum and Amplitude (JASA) aiming at coding muscular status on the basis of simultaneous modification of electrical parameters. They applied JASA protocol in essentially static protocols (i.e. ergonomic studies) giving raise to the following code: 1) simultaneous increase of amplitude and mean frequency: force increase; 2) simultaneous decrease of amplitude and mean frequency: force decrease; 3) decrease of mean frequency and increase of amplitude: fatigue; 4) increase of mean frequency and decrease of amplitude: recovery.

However the detection of muscular status from sEMG signal [18÷20] during dynamic protocols is an unsolved problem. Possible solutions are related to the availability of techniques working in real-time (i.e. during exercise execution) and in an adaptive way with respect to the statistical nature of the signal. In fact, sEMG signal recorded during movement is characterized by sources of non-stationarities mainly resulting from the time-varying relationship between force and length of muscles, and from the typical displacement of the sensor with respect to the underlying muscle fibers.

Objective of this work is the analysis of muscular fatigue during dynamic protocols. The study has been carried on by developing a real-time monitor for fatigue detection, based on the simultaneous estimation of mean frequency and amplitude of sEMG signal. The estimation is based on processing adaptive techniques purposely developed by some of the authors [21, 22], whose implementation has been modified in order to work in real-time.

The monitor performance have been tested in a field condition, by analyzing signals recorded during spinning sessions in order to assess the approach during extended, sub-maximal training events.

Materials and Methods

The real-time monitor for muscular fatigue is mainly based on:

- the simultaneous estimation of amplitude and mean spectral frequency (i.e. the electrical indicators of muscular status) of sEMG signal;
- the evaluation of the modifications occurring in the indicators with respect to reference values corresponding to the warm-up period.

The amplitude estimation in dynamic conditions is provided by the algorithm presented in [22] where the authors proposed a technique to extract the envelope of sEMG signal by using filters chosen adaptively according to the time-varying signal characteristics.

In particular, the estimator consists of a whitening block, a detector (order ν) and a smoothing filter, and sEMG signal is modeled as $s(h) = \alpha^{\xi}(h)n(h)$, where $\alpha(h)$ is a modulating waveform representing muscular activity related by ξ to the electrical signal, and n(h) is a member of an ergodic gaussian process.

All the estimator parameters are obtained by minimizing the mean square error of the estimation [23],

$$\varepsilon^2(h) = E\{(\alpha(h) - a(h))^2\} \tag{1}$$

where a(h) is the estimate of the amplitude $\alpha(h)$.

In [24] one of the authors demonstrated that the minimization of (1) provides the optimal value of the smoothing filter length. In [23, 24] for the case of a symmetrical (non-causal) smoothing filter, the optimal value of the filter length in correspondence to the h-th sample of the signal is given by:

$$M(h) = \left[\frac{9\varphi(\xi,\nu)}{(\xi\nu - 1)^2}\right]^{1/5}\left[\frac{a(h)}{\dot{a}(h)}\right]^{4/5} \tag{2}$$

where $\dot{a}(h)$ represents the estimate of the first derivative of a(h), and

$$\varphi(\xi,\nu) = \frac{1}{\xi\nu^2}\left[\frac{\sqrt{\pi}\,\Gamma(\nu+0.5)}{\Gamma^2(\nu+0.5)} - 1\right] \tag{3}$$

with $\Gamma(.)$ the Euler gamma function.

The optimal filter length is obtained by an iterative procedure whose convergence has been theoretically demonstrated in [22].

The mean spectral frequency estimation is provided by the algorithm presented in [21] where the authors used the derivatives of the complex covariance function to obtain the moments of the signal spectrum.

In particular, the mean spectral frequency is calculated as:

$$f(h) = \frac{1}{2\pi j}\frac{\dot{C}(h)}{C(h)}\bigg|_{h=0} = \dot{\theta}(h)\Big|_{h=0} \tag{4}$$

where

$$C(h) = |C(h)|e^{j2\pi\theta(h)} = \frac{1}{2N+1}\sum_{k=-N}^{N} s^{+}(h)(s^{+}(h+k))^{*} \tag{5}$$

is the complex covariance function estimated on a window (2N+1) samples long, with $s^{+}(h)$ being the analytical signal of s(h).

The mean spectral frequency for every signal sample (i.e. h-th sample) is obtained by using an iterative procedure for the complex covariance function estimation:

$$\tilde{C}(h) = R(h) + P(h) + F(h) \tag{6}$$

where:

$$\begin{aligned} R(h) &= s^{+}(h)(s^{+}(h-1))^{*} \\ P(h) &= \sum_{i=1}^{N} w^{i} R(h-i) = \\ &= w(P(h-1) + R(h-1)) - w^{N+1}R(h-N-1) \qquad (7) \\ F(h) &= \sum_{i=1}^{N} w^{i} R(h+i) = \\ &= w^{-1}F(h-1) - R(h) + w^{N}R(h+N) \end{aligned}$$

represent respectively the contributions of the samples in the window preceding and following the h-th sample. w=(N-1)/N is a weight factor, depending on the number N of signal samples contributing to the covariance estimate.

The monitor evaluates muscular modifications by comparing the percentage variation of the indicator pair {a(h),f(h)} (i.e. $\Delta a_{\%}$, $\Delta f_{\%}$) with respect to reference values representative of a no fatigued muscular status. The latter has been considered as that occurring during the warm-up period preceding the exercise session.

The working status of the muscle has been coded as in the following:

- if $\Delta a_{\%}$, $\Delta f_{\%}$ are both positive the muscle increases the exerted force;

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- if $\Delta a_{\%}$, $\Delta f_{\%}$ are both negative the muscle decreases force;
- if $\Delta a_{\%}$ is negative and $\Delta f_{\%}$ is positive the muscle is recovering;
- if $\Delta a_{\%}$ is positive and $\Delta f_{\%}$ is negative the muscle is going into fatigue.

Spinning training sessions have been used to test the approach. Ten able bodied subjects, with different training levels, volunteered for a spinning session, around 50 minutes long. The exercise session is composed of several tasks characterized by different combinations of body posture and percent resistance of the flying wheel (RFW%), referred to the maximum resistance offered by the brake.

sEMG signals have been acquired by using a movement analysis system (StepPC©, DEM-Italy), also used to record simultaneously cardiac activity and angular displacement at knee joint. Signals were acquired at 2000 samples/s and digitized by means of a 12 bit A/D converter.

Sensors positioning on the dominant leg is drawn in Figure 1. Circular sEMG electrodes (6 mm diameter and 20 mm electrode spacing, center-to-center) have been positioned on rectus femoris of the dominant leg, while ECG probes were positioned by using Lead I configuration (positive electrode on the left arm, negative electrode on the right arm). Double differential active probes have been used to record sEMG and ECG activity. The electrogoniometer, positioned on the knee of the dominant leg, can measure angles in range (–170°÷170°).

The percentage of Heart Rate (HR%) with respect to the Maximal HR (MHR=220-age) has been calculated from ECG signal. The cycling frequency is obtained by the angular signal as a Revolutions Per Minute (RPM) value.

The fatigue monitor, running simultaneously to the signal acquisition, provides the experimenter with on-line information on muscular status, cardiac frequency and cycling speed. Data were hidden to the exerciser to prevent biofeedback that was not in the aims of the present work.

Results

The real-time monitor has been tested on signals acquired during spinning exercises sessions.

Muscular activity is represented on a "work-plane" where any of the four quadrants (covered anti-clockwise) is representative of the following conditions: force increase, recovery, force decrease and fatigue. Every point that will be drawn on the plane will represent the muscular status ($\Delta a_{\%}(h)$, $\Delta f_{\%}(h)$) at the time h.

Results are presented by using a panel, which is shown in Figure 2, where muscular status on the work-plane (sub-panel (a)) sEMG signal (sub-panel (b)), RPM time series (sub-panel (c)), and HR% time series (sub-panel (d)), are simultaneously drawn. The background of sub-panels (b), (c) and (d) presents different textures related to the different quadrants of the work-plane. Moreover, in sub-panel (a) each point is drawn by using a gray-scale (black to white) to code temporal information (black is the starting point, white is the ending point).

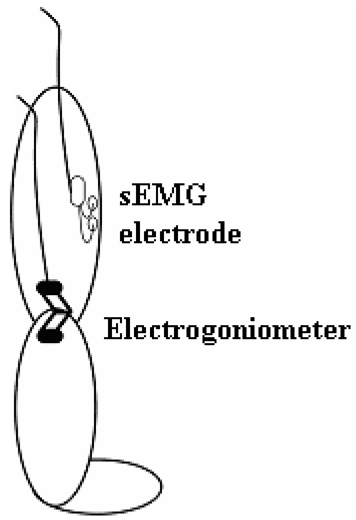

Figure 1: Positioning of sEMG electrodes and of the electrogoniometer.

Figure 2 reports the analysis of a spinning session portion (i.e. 110 seconds long) characterized by a transition from a "jump on the hill" to a "running" task, when subject pedals in standing position. The task transition can be described by using the nominal values of the exercise variables: velocity 90-100 RPM in task 1 9, 55-60 RPM in task 2, HR% 85% in task 1, 70% in task 2, flying wheel resistance 70 RFW% in the final end of task 1, 30 RFW% in task 2. The analysis provides the following results:

- sub-panel a: muscle status evolves through all the four conditions. At the beginning of the first task, the subject increases the force exerted as it is shown by the percent increase of both amplitude and mean frequency up to respectively 60% and 9%. Going on with the first task, a fatigue status is reached, even if mixed with some force decrease symptoms: mean frequency decreases up to 5%. At the task transition, the muscle starts exerting less force due to the recovery time which divides the two tasks, and both signal amplitude and mean frequency decrease respectively by the 60% and the 10%. After the 75-th second of the observation period, the muscle goes into recovery before exerting force at the beginning of the second task.
- - sub-panel b: sEMG signal changes its structure according to the physiological muscular status. In both tasks where muscular status is coded as force increase (initial and final epochs of the signal) the signal structure presents high bursts continuous through time. When muscular status is coded as fatigue, mean frequency decreases

by the 10% of the value of the warm-up, and bursts structure appears discontinuous. In force decrease status bursts are small and short. The recovery status shows an increase of both duration and amplitude of the bursts.

- - sub-panel c: cycling speed decreases from 100 RPM to 55 RPM, at around 35 seconds. At this stage the flying wheel resistance is diminished by the subject in order to recover from the first task thus justifying a force decrease status.
- - sub-panel d: HR% is high during first task (about 85%) but it starts decreasing at the exercise transition when flying wheel resistance decreases and less force is required by the motor task. At the end of the force decrease status, HR% is about 77% and reaches a plateau until the force generation status is reached again when HR% starts increasing.

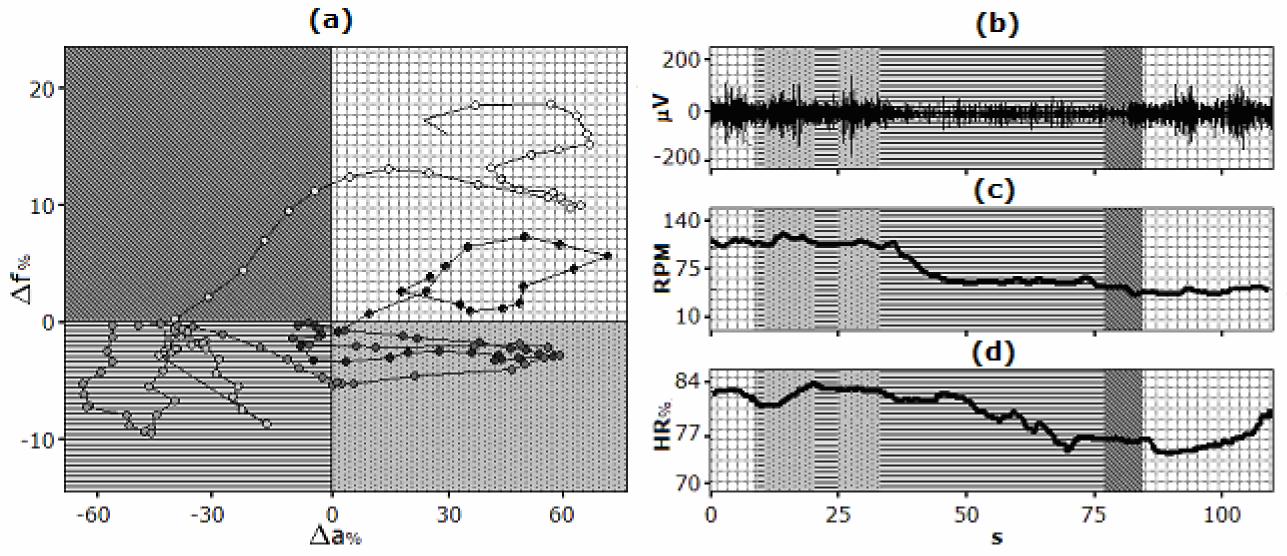

Figure 2 Report of exercise monitoring: A) sEMG signal, B) RPM value, C) HR%, D) muscular status on the work plane.

Discussion and conclusions

Preliminary results obtained with the proposed monitor appear encouraging for muscular monitoring during prolonged exercise training.

Since the computational complexity of the algorithms is limited, the monitor provides real-time information related to localized muscle fatigue. The properness of the estimation techniques, already demonstrated in previous works, guarantees the consistency of results. Moreover, the possibility of monitoring simultaneous changes of frequency and amplitude of sEMG signals guarantees the use of the monitor in on-field situations, without controlled force conditions.

The obtained results show the effectiveness of the approach in real exercise situations, and the monitoring of HR and RPM data confirms the validity of the indications on muscular status provided by the monitor. In fact, it clearly emerges that insights on muscular conditions are in agreement with both cardiovascular trends and training conditions.

In conclusion, this study proposes a new way of monitoring muscular fatigue from experimental myoelectric signals recorded during dynamic protocols.

The importance of such an approach is related to the prevention and management of muscle failure due to fatigue. In fact, muscle failure prevents force to be produced as needed and alters the precision of the movement. Then, indication of muscular fatigue is needed to quantify the time for performing a certain activity without reaching the state of immoderate fatigue and preventing the person to continue the activity.

For all these reasons the fatigue processor becomes an interesting tool for a wide range of activities, such as the follow-up of sports training efficiency, but also for ergonomic analyses, and monitoring of therapeutic methods' efficiency in rehabilitation.

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