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EMG spectral indices and muscle power fatigue during dynamic contractions

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ABSTRACT

The purpose of this study was to examine acute exercise-induced changes on muscle power output and surface electromyography (sEMG) parameters (amplitude and spectral indices of muscle fatigue) during a dynamic fatiguing protocol. Fifteen trained subjects performed five sets consisting of 10 leg presses (10RM), with 2 min rest between sets. Surface electromyography was recorded from vastus medialis (VM) and lateralis (VL) and biceps femoris (BF) muscles. A number of EMG-based parameters were compared for estimation accuracy and sensitivity to detect peripheral muscle fatigue. These were: Mean Average Voltage, median spectral frequency, Dimitrov spectral index of muscle fatigue (FI_{nsm5}), as well as other parameters obtained from a time–frequency analysis (Choi–Williams distributions) such as mean and variance of the instantaneous frequency and frequency variance. The log FI_{nsm5} as a single parameter predictor accounted for 37% of the performance variance of changes in muscle power and the log FI_{nsm5} and MFM as a two factor combination predictor accounted for 44%. Peripheral impairments assessed by sEMG spectral index FI_{nsm5} may be a relevant factor involved in the loss of power output after dynamic high-loading fatiguing task.

1. Introduction

Fatigue-related decreases in voluntary muscle activation to maintain given muscle power output (i.e. dynamic task failure) have been exclusively assessed by the measurement of the EMG signal during maximal voluntary isometric contractions, before and after a repetitive isokinetic (Komi and Tesch, 1979) and isotonic dynamic exercises (Bigland-Ritchie et al., 1983; Cheng and Rice, 2005; Klass et al., 2004; Linnamo et al., 1998). Fatigue assessment during dynamic tasks is likely to be more relevant to daily function. During dynamic contractions, however, several factors such as the change in the number of active motor units, changes in force/power though the range of motion, changes in fiber and muscle length, together with the change in muscle fiber conduction velocity due to muscle fatigue (Bonato et al., 1996, 2001a, 2001b; Farina, 2006; Karlsson et al., 2000), may increase the non-stationarity of the myolectrical signal. Therefore, this implies that parameters commonly used as indicators of spectral changes (i.e. median and mean frequency) during dynamic contractions may not accurately reflect muscle fatigue. It is also likely that extracting information from the EMG signal obtained during a static contraction to infer fatigue-elicited changes during dynamic contractions may be also questionable (Cheng and Rice, 2005), since the pattern of neural activation is likely to be different during dynamic and static contractions.

Recent developments in time–frequency analysis procedures have been proposed to identify new EMG parameters to asses muscle fatigue and overcome the non-stationary condition. Bonato et al. (1996, 2001a,b) studied different Cohen class time–frequency distributions and concluded that the Choi–Williams distribution was the most suitable for the analysis of the surface EMG recorded from dynamic isokinetic tasks. During repeated isokinetic contractions (i.e. constant velocity type of actions) Karlsson et al. (2000) compared different time–frequency analysis methods to estimate the accuracy and precision of myolectrical signal analysis (i.e. short-time Fourier Transform, the Wigner–Ville distribution, the Choi–Williams distribution and the wavelet transform). It was found that the estimations provided by the continuous wavelet transform have better accuracy and estimation capacity than those obtained with other time–frequency distributions on simulated data sets. In an effort to report methods that allow reliable assessment of sEMG recordings during dynamic fatiguing tasks, Dimitrov et al. (2006) recently proposed a reliable new spectral index (FI_{nsm5}) which allows more precise evaluation and classification of muscle fatigability in comparison with the traditionally used EMG median frequency. To overcome the problem of the relatively low sensitivity of the median and mean frequency (F_{med}, F_{mean}), this spectral index was calculated as the ratio between the signal spectral moment of order (-1), and the spectral moment of order five during a dynamic protocol of 10

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sets of 15 repetitions with moderate load (i.e. 50% of one repetition maximum) in a variable resistance machine. These indices are based on EMG spectral characteristics in the frequency domain obtained by the conventional fast Fourier transformation (FFT) algorithm and have been constructed as the ration between the signal spectral moment of order (-1) and normalizing spectral moment of order $k = 2, 3, 4$, or 5. In doing so, it was reported that fatigue-related changes in spectral moment of order (-1) across repetitions emphasize the changes in low and ultralow frequencies in EMG spectrum, and moment of order five confers greater magnitude of changes in high frequencies attributable to the increased duration of the intracellular action potentials and decreased action potential propagation (Dimitrov et al., 2006). Therefore, the larger range of change observes in this spectral index (e.g. up to eightfold increased of the initial value for FI_{nsm5} vs. 32% for F_{med}) across repetitions may confer greater sensitivity for assessing peripheral muscle fatigue during dynamic contractions (Dimitrov et al., 2006).

In contrast to isokinetic fatigue assessment (i.e. with constant velocity adjustments by the isokinetic device), during muscle daily function or in a classical training session (i.e. 3–5 sets of 10 repetition maximum) the speed of the repetitions slows down naturally as fatigue increased (i.e. with variable velocity adjustments). To our knowledge, however, a limited number of studies have reported neural adjustments over time in subjects' capacity to generate neural drive and EMG power spectrum changes over a set of repetitions leading to failure with relatively high load (i.e. 70% or more of one repetition maximum) during a variable velocity setting. Indeed, we hypothesize that EMG fatigue quantification of peripheral impairments based on more sensitive time–frequency parameters may provide useful information of the loss of power output during dynamic contractions with high-intensity fixed loads [i.e. 10 repetition maximum (10RM)] and maximal power output at a velocity allowed by the resistance used in a volitional manner. Therefore, the purpose of this study was to examine different EMG-based fatigue indices related to muscle power loss during dynamic high fatiguing tasks. The fatigue indices included in our study comprised the mean and variance of the instantaneous frequency, mean of the frequency variance (all these were based on the Choi–William distribution), spectral median frequency, Dimitrov spectral index of muscle fatigue, and amplitude. They all were studied comparatively regarding estimation accuracy and sensitivity to detect peripheral muscle fatigue.

2. Materials and methods

2.1. Subjects

Fifteen physically active men (age, 34.2 ± 5.2 yr; height, 177.3 ± 5.6 cm; body mass, 73.1 ± 6.4 kg) (mean ± SD) volunteered to participate in the study. The subjects had experience with recreational training, although none had been involved in any regular strength training program at the beginning of the study. Subjects were informed about the experimental procedure and the purpose of the study. Subsequently, subjects gave their written informed consent to participate. The experimental procedures were approved by the Institutional Review Committee of the Instituto Navarro del Deporte according to the Declaration of Helsinki. Before inclusion in the study all subjects were medically screened and considered healthy by a physician (i.e. free from any orthopedic, electrocardiographic, endocrinal or medical problems).

2.2. Experimental design

The experimental design comprised one acute heavy-resistance exercise protocol (AHREP). The protocol consisted of five sets of 10 repetition maximum leg press (10RM) with 120 s of rest between sets. The subjects were familiarized with the experimental testing procedures about 2 weeks before the AHREP session. One week before the AHREP session the subjects participated in a control testing day where resistance-load verifications were made for maximal strength (1RM and isometric), muscle power and the maximum load of the experimental leg press for 10RM.

2.3. Maximal strength assessment

One repetition maximum (i.e. the heaviest load that could be correctly pressed only once using the correct technique) was determined for the leg press exercise machine (Technogym, Gambettola, Italy). The subject was in a seated position so that the knee angle was 90°. Warm-up consisted of a set of five repetitions at 50% of the estimated maximum. Thereafter, three to four repetitions at 75% of perceived maximum and 1 repetition at 90% of perceived maximum. Three to four subsequent attempts were made to determine the 1RM. The rest between maximal attempts was always 2 min. In doing so we calculated the % level of the 1RM used during the 10RM loading.

2.4. Acute 10RM loading protocol

The load used was estimated one week before the experiment and was calculated as the maximum load to perform 10 consecutive leg extensions. Each trial was performed on a bilateral leg extension exercise machine (i.e. leg press action in a sitting position) (Technogym, Gambettola, Italy). The sitting position was individually adjusted to minimize displacement between the lower back and the backrest during muscular force exertion. The trial began with a knee angle of 90° and a hip angle of 45°, and finalized when subjects extended their legs to achieve a knee angle of 180° and a hip angle of 90°. Strong verbal encouragement was given to all the subjects to motivate them to perform each action as maximally and rapidly as possible. Testing procedures for a 10RM was similar to that of the 1 RM test. In this case, warm-up consisted of a set of five repetitions with 50% of the estimated 10RM. Thereafter, one attempt was made to determine the load that the subject was just able to finish the required 10RM. If the subject did not accomplish 10RM in the first attempt, re-testing with the adjusted load was performed after 24 h rest. One to two subsequent attempts were made to determine the 10RM.

Muscle power output of the leg extensor muscles was measured during the concentric phase of leg press action using the individual maximum load corresponding what they could perform 10 times (10RM). The subject was instructed to move the weight as fast as possible. The exercise machine incorporates four force transducers on a foot platform located below the subject's feet. They recorded the horizontal applied force to an accuracy of 1 Newton at a sampling rate of 1000 Hz. In addition, a rotational encoder (Computer Optical Products Inc, California, USA) was set to record the position and direction of the displacement to an accuracy of 0.2 mm and time events to an accuracy of 1 ms. Customized software was used to calculate range of motion, peak power output and average velocity for each repetition. For comparison purposes, power output of each repetition was expressed in relative values as a percentage of the power output attained during the first two repetitions of each set.

2.5. Surface electromyography

EMG activity during the extension actions of the leg muscles was recorded from the vastus medialis (VM), vastus lateralis (VL) and biceps femoris (BF) of the right leg by pairs of bipolar surface electrodes (Blue Sensor N-00-S, Medicotest) with a distance between the electrode's centers of 22 mm. After careful preparation of the skin (shaving, abrasion, and cleaning with alcohol), electrode pairs were placed longitudinally on the middle portion of the muscles.

EMG signals were recorded at a sampling rate of 1 kHz with a Muscle Tester ME3000 (Mega Electronics Ltd.) (bandwidth of 8–500 Hz/3 dB and a common mode rejection ratio > 100 dB). To facilitate and normalize the analysis, the knee movement was divided into four intervals of 22.5°. The parameters analyzed in the present study corresponded to the first interval of the movement of the dynamic contractions (from 90° to 112.5° of knee movement) for the VM and VL and to the fourth interval (from 157.5° to 180°) for the BF, where those muscles had their maximal activation. An average of the sEMG parameters obtained from the VM and VL was calculated as a more representative index of muscle extension.

2.6. Data processing

Data analysis was performed off-line using the MATLAB 2006a software environment (The MathWorks Inc., Natick, Massachusetts, USA). The following EMG parameters were calculated:

(a) Mean Average Voltage (MAV) calculated after a full-wave rectification and filtered by a moving root-mean-squared filter with a time constant of 50 ms, as the integrated EMG divided by the integration time. We normalized this parameter by the value of the muscle activation of the corresponding quarter of a maximal dynamic contraction.

(b) Median frequency (F_{med}) calculated numerically from the following equation

$$\int_{f_1}^{F_{\mathrm{med}}} PS(f)\cdot df = \int_{F_{\mathrm{med}}}^{f_2} PS(f)\cdot df \tag{1}$$

where $PS(f)$ is the EMG signal power spectrum calculated using Fourier Transform, $f1 = 8$ Hz and $f2 = 500$ Hz (determined for the bandwidth of the surface electromyograph).

(c) The new spectral parameter proposed by Dimitrov ($\mathrm{FI}_{\mathrm{nsm5}}$) (Dimitrov et al., 2006)

$$\mathrm{FI}_{\mathrm{nsm5}} = \frac{\int_{f_1}^{f_2} f^{-1}\cdot PS(f)\cdot df}{\int_{f_1}^{f_2} f^{5}\cdot PS(f)\cdot df} \tag{2}$$

where $PS(f)$ is the EMG power spectrum calculated using Fourier Transform and f1 = 8 Hz and f2 = 500 Hz.

(d) Choi–Williams distribution (CWD)Choi and Williams (1989) proposed a new time–frequency distribution that does not generate spurious values and preserves desirable properties such as marginal densities. The main characteristic of this Cohen class distribution is the exponential kernel, which determines the cross-term reduction and the elimination of undesirable terms.
The Choi–Williams distribution was calculated following the suggestions of Bonato et al. (1996) (i.e. kernel width, $\sigma = 1$).

From the Choi–Williams time–frequency distribution certain parameters were calculated, as follows:

(d.1) Instantaneous mean frequency (MF) calculated as

$$\mathrm{MF}(t) = \frac{\int_{f_1}^{f_2} f\cdot PS_{CW}(f,t)df}{\int_{f_1}^{f_2} f\cdot PS_{CW}(f,t)df} \tag{3}$$

where $PS_{CW}(f,t)$ is the time-dependent power spectrum obtained from the Choi–Williams distribution and again, f1 = 8 Hz and f2 = 500 Hz.

Owing to the fact that this parameter is a data array, and we need only one value to compare it with the other sEMG parameters, we calculated its time mean and variance (MFM and MFV, respectively) as indicator parameters of the total changes (Boashash, 1992).

(d.2) Instantaneous frequency variance

$$F_{var}(t) = \frac{\int_{f_1}^{f_2} (f-\mathrm{MF})^2\cdot PS_{CW}(f,t)df}{\int_{f_1}^{f_2} PS_{CW}(f,t)df} \tag{4}$$

where MF is the instantaneous mean frequency calculated as in (3), $PS_{CW}(f,t)$ is the time-dependent power spectrum obtained from the Choi–Williams distribution and $f1 = 8$ Hz and $f2 = 500$ Hz.

As in the previous case, we used its mean value (FV) (Boashash, 1992).

2.7. Statistical analysis

Results in the figures are given as mean and error standard values. All the variables (power output as sEMG-based parameters) were normalized with respect the first two contractions of the first set. Power output and sEMG-based parameters were compared in relative terms via a one-way analysis of variance with repeated measures design. When a significant F-value was achieved, Sheffé post hoc procedures were performed to locate the pairwise differences between the means. For comparison purposes, power output and EMG changes of the last five repetitions were compared to the first five repetitions. Pearson correlation was used to analyze the relationship between changes in mechanical power and changes in the different sEMG variables. Those percentage changes that did not follow a normal distribution were log-transformed (log). In addition, a stepwise multiple linear regression analysis was used to detect power output changes. The independent variables (changes in log $\mathrm{FI}_{\mathrm{nsm5}}$, mean and variance of instantaneous frequency, mean of the frequency variance, spectral median frequency and amplitude normalized by the amplitude of the 1RM) that correlated most significantly with power output loss were entered into the stepwise procedure. The $P < 0.05$ criterion was used to establish statistical significance.

3. Results

3.1. Maximal strength and acute 10RM loading

The maximal dynamic strength (1RM) was of 190.6 ± 30.2 kg. The % level of the 1RM used during the 10RM loading was 84.1 ± 4.8% of 1RM.

3.2. Power output

Muscle power output of the last five repetitions of each set, was significantly lower ($P < 0.05$) than the muscle power recorded in the first five repetitions (Fig. 1). The muscle power output attained during the last repetition of the fifth set was 45% lower than that attained during the initial two repetitions of the first set.

3.3. Surface EMG activity

The average MAV (averaged for VM and VL muscles) of the last five repetitions of each set, as well as that recorded during the first five repetitions of the 5th set, was significantly higher ($P < 0.05$) than that recorded during the first five contractions (Fig. 2A). In

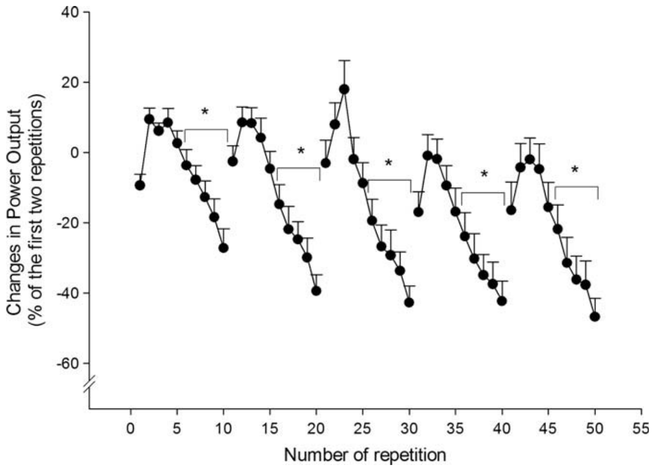

Fig. 1. Muscle power changes (mean ± SD) during the five sets of 10 repetitions maximum.

contrast, the median frequency (averaged for VM and VL muscles) recorded during the last repetitions of each set was significantly lower ($P < 0.05$) than that recorded during the first five repetitions (Fig. 2C).

The average FI_{nsm5} parameter (averaged for VM and VL muscles) of the last five repetitions of each set was significantly higher ($P < 0.05$) than that recorded during the first five repetitions of the 1st set (Fig. 2E). In addition, the average log FI_{nsm5} parameter (averaged for VM and VL muscles) of the first five repetitions of the 3rd, 4th and 5th sets was significantly higher ($P < 0.05$) than that recorded during the first five repetitions of the 1st set (Fig. 2E).

The MAV of the antagonist BF significantly ($P < 0.05$) increased during the last five repetitions of the 1st, 2nd and 3rd sets compared to the neural activity recorded during the corresponding five repetitions of the 1st set. (Fig. 2B). No significant differences were found between the repetitions of the last sets (4th and 5th) and the initial values. The average log FI_{nsm5} values of the antagonist BF recorded during repetitions of the 3rd, 4th (only the first five repetitions) and 5th sets were significantly higher ($P < 0.05$) than those obtained from the first five repetitions of the 1st set (Fig. 2F). No significant differences were found between the F_{med} values of the antagonist BF (Fig. 2D).

3.4. Relationships between EMG indices and muscle power changes

Pearson correlation analysis revealed that the sEMG parameter (averaged for VM and VL muscles) that most correlated with mechanical power changes was the log FI_{nsm5} ($R = -0.592$; $P < 0.01$), MFM calculated in the time–frequency domain ($R = 0.570$; $P < 0.01$), F_{med} ($R = 0.495$; $P < 0.01$) and the amplitude parameter MAV ($R = -0.389$; $P < 0.01$) (Table 1 and Fig. 3).

The sEMG parameters of BF muscle that correlated with muscle power changes were the log FI_{nsm5}, ($R = -0.315$; $P < 0.01$) and the amplitude parameter ($R = -0.226$; $P < 0.01$), as well as, F_{med} ($R = 0.110$; $P < 0.01$), MFM ($R = 0.200$; $P < 0.01$), FV ($R = 0.177$; $P < 0.01$) and MFV ($R = -0.009$).

3.5. Fatigue estimation using sEMG parameters

Stepwise multiple linear regression analysis with muscle power changes as a dependent variable and the individual values of the different sEMG parameters obtained during the fatiguing dynamic protocol as independent variables showed that the average log FI_{nsm5} (averaged for VM and VL muscles) as a single parameter predictor accounted for 37% of the performance variance of changes in muscle power, and the log FI_{nsm5} and MFM, as a two factor combination predictor, accounted for 44% of the performance variance of changes in muscle power.

4. Discussion

The main results obtained in this study showed the logarithm of spectral index proposed by Dimitrov (FI_{nsm5}) could be useful for monitoring muscle power fatigue after multiple sets of dynamic fatiguing high-power contractions, accounting for 37–44% of the performance variance of changes in muscle power output. These results are in agreement with those obtained by Dimitrov et al. (2006) during a dynamic protocol consisting of 10 sets of 15 repetitions of right knee-extension exercise, lifting 50% of their one-repetition maximum. It was found that the application of their new spectral index (FI_{nsm5}) on surface EMG provided a better assessment of peripheral muscle fatigue in comparison with the traditionally used EMG median frequency. Similar findings were also reported by Gerdle et al. (2000) in a study of 100 repetitive maximum isokinetic knee extensions. Similarly to the present study, they found that sEMG frequency related parameters showed good criterion validity with respect to biomechanical fatigue (i.e. with changes in power output) at the individual level in comparison to that obtained from sEMG amplitude parameters (Gerdle et al., 2000).

Despite the no-stationarity of the sEMG signal recorded during dynamic exercises, some of the sEMG parameters used as fatigue indexes in our study were based on stationary analysis. Some authors, however, have demonstrated their validity as fatigue indicators during high-intensity dynamic exercises. Shankar et al. (1989)) showed that spectral sEMG analysis could be used to reveal changes in electrophysiological characteristics and, therefore, its validity to assess muscle fatigue. Other authors validated spectral parameters such as mean frequency (MNF) as fatigue indexes during dynamic contractions until exhaustion (Komi and Tesch, 1979; Potvin and Bent, 1997). However, during low and medium intensity dynamic exercises some authors failed to show decreases of MNF. van Dieen et al. (1996) found that during a dynamic protocol consisting of a series of 250 contractions at 25% and 50% of their MVC, the frequency content of the EMG signals showed weak relationships with fatigue. Similar results have reported by Ament et al. (1996) for MNF during an uphill run at a speed of 5 km h^{-1} and a gradient of 20%. In this case, because the intensity of the dynamic exercise performed in this study was relatively high (i.e. 10RM or approximately 84% of 1RM), in agreement with the previous studies, sEMG spectral analysis could be valid to assess muscle fatigue. Moreover, a small range of motion was selected for the sEMG analysis and therefore the non-stationary nature of the sEMG signal may be minimal. Thus, these results suggest that the peak power loss achieved after the dynamic high-loading fatiguing exercise (i.e. 10RM) may be related in part to changes in the log sEMG spectral index FI_{nsm5} and may therefore infer peripheral muscle fatigue to some extent.

In agreement with previous studies, the present dynamic fatiguing exercise led to major neuromuscular fatigue, observable from the acute increase in the surface EMG amplitude, with a shift of EMG power spectrum toward lower frequencies and a fivefold increase in the magnitude of the spectral fatigue index analyzed. In the present study, increased EMG amplitude and decrement in the median frequency might primarily be attributed to additional motor unit recruitment and/or increased spatial or temporal motor unit synchronization, presumably to compensate muscle fiber fatigue (Masuda et al., 1999; Potvin, 1997; Tesch et al., 1990). Moreover, the new spectral parameter proposed by Dimitrov et al. (2006) showed a more notable increase in the presence of fatigue

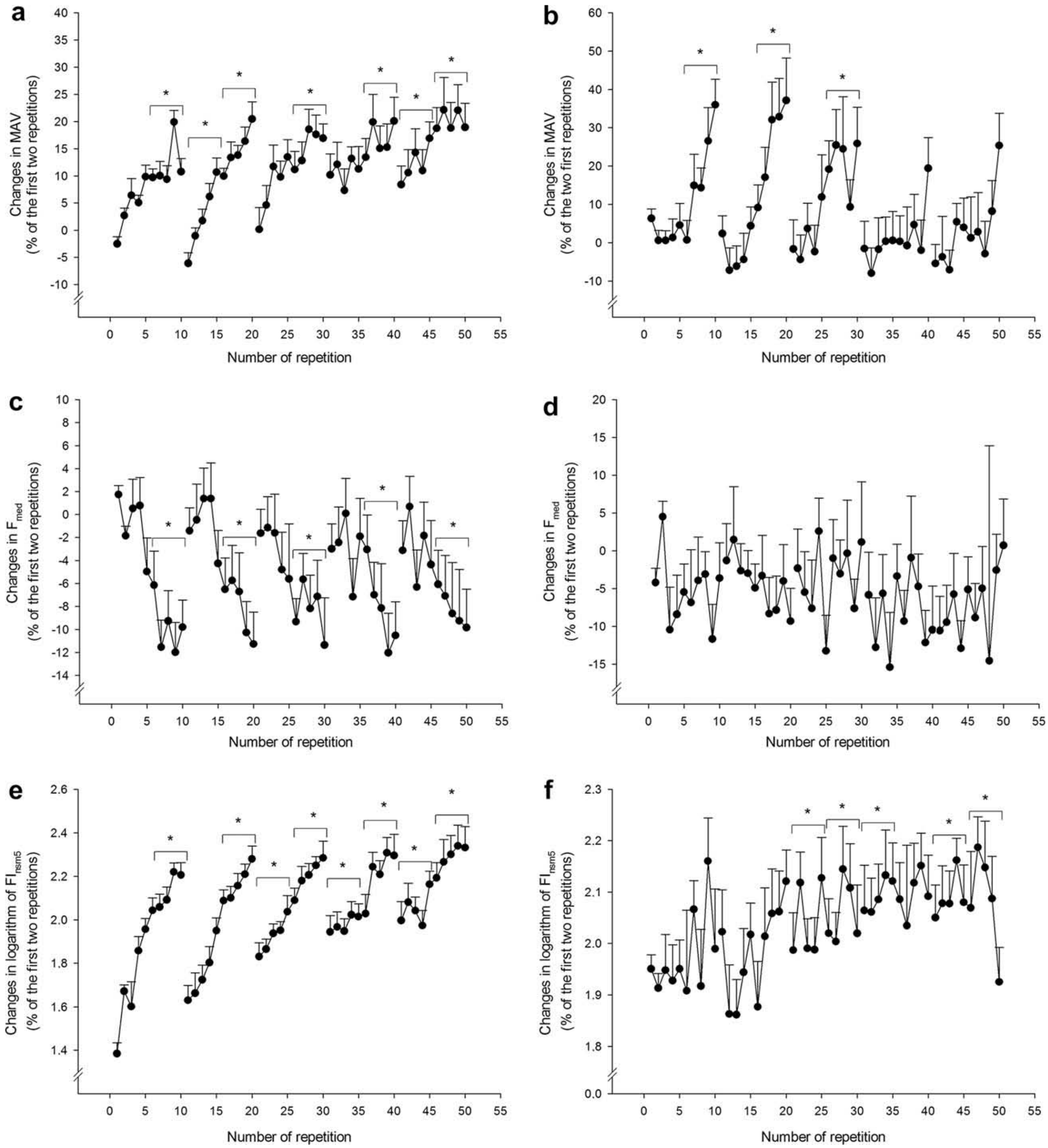

Fig. 2. Changes in sEMG parameters (mean ± standard error) during the five sets of 10 repetitions maximum. (a) Mean Average Voltage (MAV) (averaged for vastus lateralis and medialis muscles), (b) Mean Average Voltage (MAV) of the biceps femoris, (c) median frequency (F_{med}) (averaged for vastus lateralis and medialis muscles), (d) median frequency (F_{med}) of the biceps femoris, (e) logarithm of Dimitrov's parameter (log FI_{nsm5}) (averaged for vastus medialis and lateralis muscles), (f) logarithm of Dimitrov's parameter (log FI_{nsm5}) of the biceps femoris. (* Significant differences ($P < 0.05$) compared to the first five contraction of the 1st set).

Table 1
Correlation coefficients between changes (%) in the average of various sEMG parameters (averaged for VL and VM muscle) and the corresponding individual changes (%) in peak power output.

	F_{med}	log (FI_{nsm5})	MFM	MFV	FV	MAV	Peak power
F_{med}	–	−0.61**	0.86**	0.12**	0.54**	−0.41**	0.50**
log (FI_{nsm5})		–	−0.53**	−0.077*	−0.42**	0.67**	−0.59**
MFM			–	0.16**	0.40**	−0.31**	0.57**
MFV				–	0.22**	−0.20**	0.021
FV					–	−0.55**	0.22**
MAV						–	−0.39**

** $P \leqslant 0.01$; * $P \leqslant 0.05$.

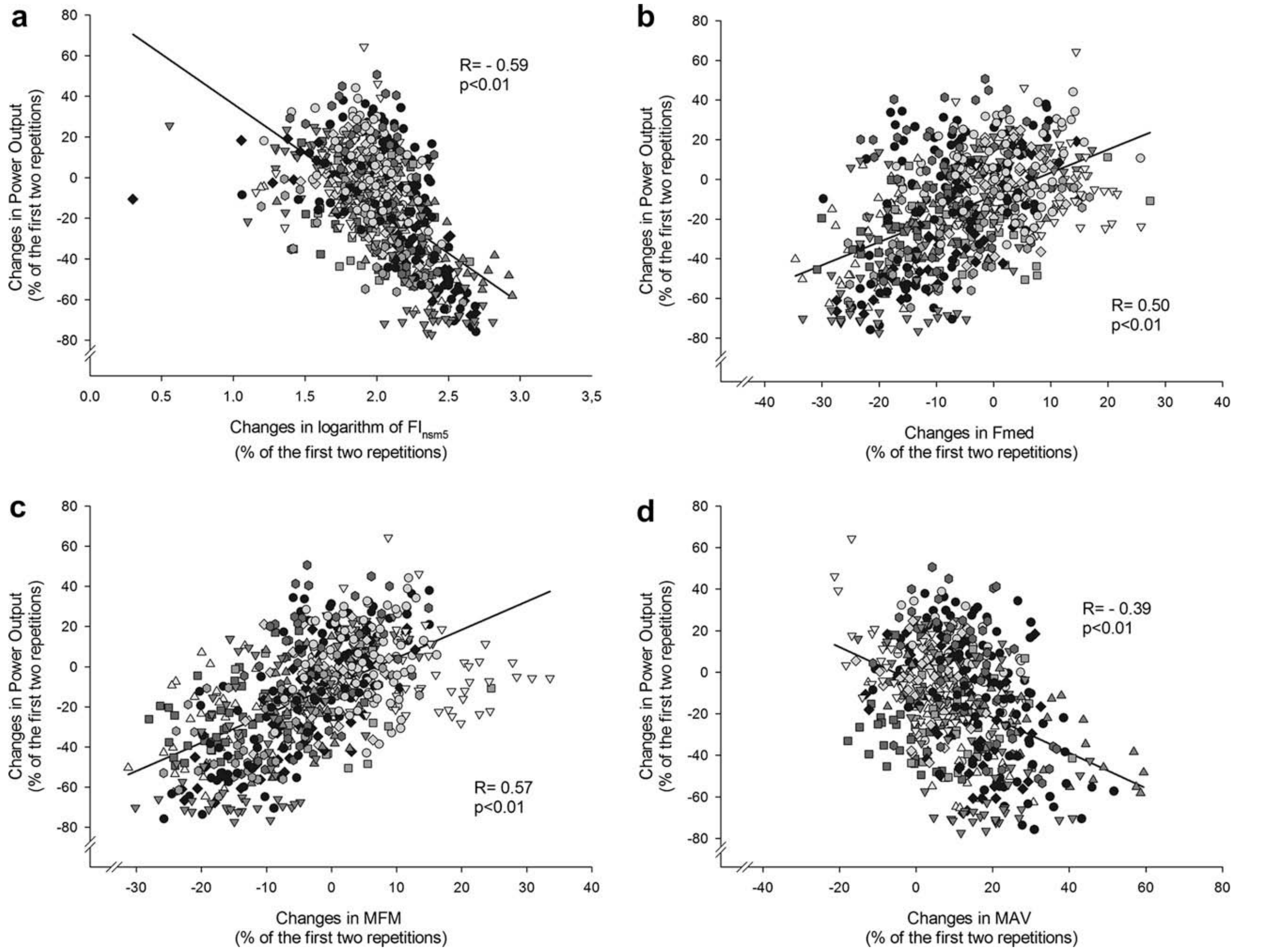

Fig. 3. Linear representations of changes in power output (% of the first two repetitions) versus changes in different sEMG parameters (% of the first two repetitions) for all the subjects (averaged for vastus lateralis and medialis muscles). (a) Changes in power output (%) versus changes in logarithm of Dimitrov's parameter (log FI_{nsm5}) (%). (b) Changes in power output (%) versus changes in F_{med} (%). (c) Changes in power output (%) versus changes in Mean of the instantaneous mean frequency (MFM) (%). (d) Changes in power output (%) versus changes in Mean Average Voltage (MAV) (%).

than that reported by the median frequency (Dimitrov et al., 2006). These changes in the frequency spectrum, shown by the median frequency and the new spectral parameter towards the low frequencies, may be partly related to an increase in the duration of the motor unit action potential waveform and a subsequent decrease in muscle fiber conduction velocities (Bigland-Ritchie et al., 1981).

These results would suggest that neural adjustments such as the subjectś capacity to generate neural drive and EMG spectral indices and their modification over time to attain a certain level of muscle power output may be compromised after a dynamic fatiguing task when fatigue is examined after dynamic contractions with submaximal loads (i.e. 83–84% of 1RM) but maximal effort (i.e. maximal velocity). Similar findings have also been reported from EMG fatigue quantification based on isometric contractions before and after other repetitive isokinetic (Komi and Tesch, 1979) and isotonic dynamic exercises (Cheng and Rice, 2005; Klass et al., 2004), suggesting that peripheral impairments may be also the primary factor involved in the loss of performance after moderately loaded (i.e. 50% or less of MVC) repetitive dynamic contractions.

According to the results obtained for the antagonist BF muscle, no significant changes were detected in the median frequency of BF EMG signal across sets during the dynamic protocol, although significant increases were observed in the logarithm of Dimitrov's parameter during the last 3 sets performed. These results agree with Dimitrov's objective of finding a parameter that is more sensitive to changes in frequency spectrum related to muscle fatigue (Dimitrov et al., 2006). Another interesting finding was that sEMG amplitude of the antagonist BF muscle increased from set 1 to set 3 but decreased to the previous baseline activation level during the last two sets of the dynamic exercise protocol. Hassani et al. (2006) also found that, during a submaximal isokinetic protocol consisting of 60 knee extension efforts at 60% of peak torque at $60\ s^{-1}$, the BF activation increased until the 46th trial followed by a decline approaching the initial values at the end of the protocol, while the activation of the agonist VL muscle continued increasing. Therefore, these results suggest that the logarithm of Dimitrov's parameter could be also used as a fatigue index, not only in the agonist but also in the antagonist muscles activity, providing more information on changes in the power spectrum than spectral median frequency. Moreover, Dimitrovś parameter changes were muscle length independent since significant increases were observed not only in the maximal activation portion of the BF muscle (i.e. from 157.5° to 180°) but also during the corresponding maximal activation of the VM and VL (i.e. from 90° to 112.5°) of knee movement on the extension phase.

Within the limitation of the study, the interpretation of the sEMG during dynamic tasks is complicate and requires caution. Thus, during dynamic contraction, several factors (i.e. change in the number of active motor units, changes in force/power though the range of motion, changes in fiber and muscle length, together with the change in muscle fiber conduction velocity due to muscle fatigue) (Bonato et al., 1996, 2001a,b; Farina, 2006; Karlsson et al., 2000), may increase the non-stationarity of the myolectrical signal. Hence, to extract valid physiologically relevant information future types of EMG-signal based analyses should thus require analysis of the possible confounding movement factors. In this context, the use of high-density, multichannel EMG, as well as direct estimation of conduction velocity could improve the interpretation of fatigue during dynamic tasks. To what extent, the activation of the neighbouring muscles (cross talk) (De Luca, 1997; Farina, 2006) could affect the estimation of the surface parameters during fatiguing dynamic task need to be also examined. Although this factor can not be totally excluded and probably partly affected the estimated parameters, the carefully placement of the electrodes in the middle between the innervation zone and tendon and amplitude normalization could minimize its influence on the results (De Luca, 1997). It is also likely that although the subjects were in a seated fixed position, the force sharing in the bilateral leg press may have varied under each foot. Another limitation related to the fact that only one antagonist muscle (biceps femoris) was evaluated in this study. Future research is necessary to determine if these same observations apply to other antagonist muscles during fatiguing dynamic contractions.

In summary, during a high-intensity dynamic protocol (i.e. 84% 1RM) where the velocity of the repetitions slows naturally as fatigue increases, the fatigue index that shows changes in muscle power (37% of the performance variance of changes in muscle power) most accurately is the logarithm of the spectral index proposed by Dimitrov, more than other frequency or amplitude sEMG parameters. Moreover, the log FI_{nsm5} and MFM as a two factor combination predictor accounts for 44% of the performance variance of changes in muscle power. These results therefore suggest that peripheral impairments assessed by sEMG spectral index FI_{nsm5} may be a relevant factor in the loss of power output after a dynamic high-loading fatiguing task.

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