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Isometric fatigue patterns in time and time–frequency domains of triceps surae muscle in different knee positions

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ABSTRACT

The occurrence of fatigue in triceps surae (TS) muscles during sustained plantar flexion contraction is investigated by means of the RMS electromyogram (EMG) and the instantaneous median frequency (IMF) of the short time Fourier transform (STFT). Six male subjects realized a 40% maximal plantar flexion isometric voluntary contraction until fatigue in two knee positions. Electrodes were positioned on gastrocnemius medialis, gastrocnemius lateralis and soleus muscles. The torque (TO) and EMG signals were synchronized. The RMS and the median of the IMF values were obtained, respectively, for each 250 ms and 1 s windows of signal. Each signal was segmented into 10 epochs, from which the mean values of IMF, RMS and TO were obtained and submitted to linear regressions to determine parameter trends. Friedman test with the Dunn's post hoc were used to test for differences among muscles activation for each knee position and among slopes of regression curves, as well as to observe changes in TS RMS values over time. The results indicate different activation strategies with the knee extended (KE) in contrast to knee flexed (KF). With the KE, the gastrocnemii showed typical fatigue behavior with significant ($p < 0.05$) IMF reductions and RMS increases over time, while soleus showed concomitant RMS and IMF increases ($p < 0.05$) suggesting an increased soleus contribution to the torque production. With KF, the gastrocnemii were under activated, increasing the role of soleus. Thus, time–frequency analysis represented an important tool for TS muscular fatigue evaluation, allowing differentiates the role of soleus muscle.

1. Introduction

The analysis of electromyogram (EMG) to monitor the muscle fatigue has been studied in the time and frequency domains, showing, respectively, an increase in amplitude and a compression of energy in low frequencies (Basmajian and De Luca, 1985; De Luca, 1997).

The neuromuscular fatigue has been described as a failure or decrease in muscle performance during the execution of a specific motor task leading to inability in maintaining the demand for torque production (Asmussen, 1979; Macintosh and Rassier, 2002; Dimitrova and Dimitrov, 2003). During the fatigue process, the behavior of the EMG signal has been described as the myoelectric manifestation of muscle fatigue, which can be represented by a fatigue plot (Troiano et al., 2008) where the frequency components and the conduction velocity of the myoelectric action potential show a decrease (De Luca, 1985; Troiano et al., 2008) while the signal amplitude rises. The spectral parameter most related to fatigue is the median frequency (MF), which is defined as the value in frequency that divides the power spectrum into two equal parts (Cram et al., 1998; De Luca, 1997).

The analysis in time–frequency domain maps the frequency composition characteristics of the signal at each time instant. One of the most used time–frequency methods is the spectrogram, which is a Cohen class distribution member (Cohen, 1989; Williams, 1998). It is represented by the squared magnitude of the short time Fourier transform (STFT) and is based on the assumption that for a short time interval, signals can be considered as stationary.

The major advantages of the STFT are the low computational cost and the absence of cross terms, which are common in other Cohen class distributions. On the other hand, when very short time windows are applied the spectrogram returns a poor frequency resolution, which can explain the choice for other time–frequency methods as Choi–Williams distribution (Bonato et al., 1996; Roy et al., 1998; Molinari et al., 2006) and wavelet transforms (Coorevits et al., 2008) to increase frequency resolution. Moreover, the STFT could not be employed for extremely non-stationary signals (Roy et al., 1998; Cohen, 1989; Choi and Williams, 1989) as in high-speed dynamic contractions.

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The myoelectric signals generated by isometric contractions can be classified as wide-sense stationary (Bonato et al., 1997; Roy et al., 1998), indicating that STFT would be employed. Nonetheless, in the range between 50% and 80% of the maximum isometric voluntary contraction (MIVC), the stationarity of the EMG signal may not be attested (Merletti et al., 1992). This fact becomes mandatory to test for stationarity before applying any Fourier based method.

The triceps surae is an interesting muscle group for biomechanical studies (Arnt et al., 1998; Barret et al., 2007; Delp et al., 1990; Fukashiro et al., 2005; Legreneur et al., 1996), since it is the main responsible for the plantar flexor torque. Additionally, all the three triceps surae components are easily assessable by surface EMG, and have a high functional importance for daily activities and sport practice. Moreover, it is still unclear the activation strategies of the gastrocnemii and soleus as there are anatomical and physiological differences among them (Edgerton et al., 1975; Johnson et al., 1973). For example, the plantar flexion fatigue process leads to hypothesis that the soleus, which has more oxidative fibers, compensates the preview force production failure of gastrocnemii, which are more vulnerable to fatigue. The position of the knee and ankle can drastically influence the force production of these muscles due to the length-tension relationship of each one (Creswell et al., 1995). In this context, some authors found greater susceptibility to fatigue from soleus (Huijing et al., 1986; Ratkevicius et al., 1998), employing protocols of plantar flexion with flexed knee, where the gastrocnemii are in an unfavorable position. The plantar flexors isometric fatigue has been previously characterized (Huijing et al., 1986; Duchêne and Goubel, 1990) by Fourier-based methods. Nevertheless, it was not found any study pointing difference between muscle behaviors due to knee position.

The aim of this study was describing the fatigue process of the triceps surae muscles in isometric contraction during sustained plantar flexion until exhaustion. Each muscle EMG is analyzed in time and time–frequency domains, by the behaviors of the RMS value and the instantaneous median frequency (IMF) of the STFT.

2. Materials and methods

A group of 6 male subjects with age 18.71 ± 0.49 (mean ± SD) years, mass 68.05 ± 9.03 kg and height 173.79 ± 7.58 cm, was selected to participate in the study among military personnel, engaged in the regular regimen of physical activity. All participants provided written consent and did not relate any history of osteomyoarticular injuries at the right knee or ankle. This experiment was approved by the Local Ethical Committee.

Subjects laid prone on a Norm Dynamometer (Cybex, USA), with the ankle at neutral (90°) position. The right foot was firmly fixed to the foot adaptor. Tests were realized in two sessions, separated by at least 48 h, randomly assigned as knee extended (KE) and knee flexed (KF) at 90°. The familiarization session consisted of step trials of submaximal contractions followed by one maximal contraction. Plantar flexion torques associated to maximal isometric voluntary contractions (MIVC) were collected twice within 2 min rest interval and the highest value was selected as the maximum torque. Each subject was instructed to follow a protocol consisting of keeping a torque target at 40% MIVC until exhaustion or for a limiting time of 4 min. A feedback display of actual force output was provided to the subject who attempted to match it to the 40% MIVC line of the protocol.

The torque signal (TO) and surface EMG were synchronously collected using a data acquisition system (EMG System, Brazil) with 106 dB CMRR, analogical band-pass filter with cut off frequencies 10 and 500 Hz, 2 kHz sampling rate, and a 16 bits A/D converter. Ag–AgCl pre-gelled electrodes were positioned on gastrocnemius medialis (MG), gastrocnemius lateralis (LG) and soleus (SOL) muscles according to SENIAM recommendations, after skin preparation (Freriks et al., 1999). The reference electrode was positioned on the left lateral malleolus.

EMG signals were pre-processed with a 4th order band pass Butterworth filter (20–400 Hz). To reduce the mains noise (60 Hz and harmonics), it was used a set of 2nd order notch filters in cascade (Mello et al., 2007). These filters were applied in direct and reverse directions to avoid phase distortions.

The signals were tested for stationarity throughout the run-test and the reverse arrangements test in 1 s windows, according to Bendat and Piersol (1986). The significance level was set at 0.05. As the tests results could disagree, the mean and SD of the signals was obtained at each 100 ms intending to identify the signal characteristics over time.

The RMS value was calculated by the equation:

$$\mathrm{RMS}(n) = \sqrt{\frac{\sum_{i=0}^{U-1} emg(i+n)^2}{U}} \tag{1}$$

where n is the sample number and U is the window length of 250 ms, without overlapping. The resulting value was normalized by the respective maximum RMS value obtained in the MIVC.

The IMF over each second of signal was obtained using the STFT (Cohen, 1989):

$$\mathrm{STFT}[x(n)] \equiv |X(m,\omega)|^2 = \left|\sum_{n=-\infty}^{\infty} x(n)h(n-m)e^{-jn\omega}\right|^2 \tag{2}$$

where $x(n)$ is the signal under consideration and $h(n-m)$ is the windowing function, adopted as hanning, and m is the window length.

As the time until exhaustion differs among individuals, the total time was divided in 10% intervals for analysis. Thus, the mean values of IMF, RMS and TO were obtained for each 10% interval of the entire signal duration. The linear regression was applied to these sequences of ten successive values for trend detection.

The nonparametric Wilcoxon matched pairs test was used to test differences between the mean maximal torques produced and between the torque slopes in different knee positions, as like to compare the time spent until exhaustion (KE × KF). Similarly, the nonparametric Friedman test and the Dunn's post hoc test were employed for testing differences among muscle activations (MG, LG and SOL) in each 10% interval for each knee position (KE × KF), and between the slopes of IMF and RMS regressions).

Friedman test for repeated measures was also employed for comparing the mean RMS values during exercise. The total time was segmented into 10% intervals. Post hoc analysis was also performed with Dunn's test. The significance level was always $\alpha = 0.05$.

Time–frequency maps related to the STFT were generated in order to qualitatively monitor the energy concentration around the frequency bands of the EMG signal.

The software Matlab v. 6.5 (The Mathworks, USA) was applied for signal processing and the GraphPad Prism 5 (GraphPad Software, USA) for statistical testing.

3. Results

The reverse arrangements test indicated signal stationarity, while run test indicated non-stationarity for signal epochs of 1 s. However, the signal means and SD for consecutive periods of 100 ms did not present large changes over each second, suggesting a stationary process (Fig. 1).

All linear regression results are summarized in Table 1, including for each variable the parameters slope, r, r^2 and p-values.