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Electrical Manifestations of Muscle Fatigue During Concentric and Eccentric Isokinetic Knee Flexion - Extension Movements

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Abstract—The quantification of the progression of muscle fatigue during a sustained contraction is a valuable tool in several clinical applications, ranging from the evaluation of functional impairment to the development of specific rehabilitative and training protocols. In these fields, great importance is given to isokinetic contractions.

The aim of this work was twofold: first, to propose signal processing methods for assessing the spectral changes of the surface myoelectric signal due to fatigue during isokinetic concentric and eccentric knee flexion - extension movements at a given angular velocity (60 deg/s); secondly, to analyze the electrical manifestations of muscle fatigue of four thigh muscles (vastus lateralis, vastus medialis, rectus femoris and biceps femoris) in the two contraction modalities (i.e. concentric vs eccentric). We demonstrated that, when considering concentric contractions, localized muscle fatigue can be assessed by computing the mean frequency of the frequency marginal of the time-frequency distribution derived from the surface myoelectric signal collected during each contraction cycle. Stronger non-stationarities were observed in the surface myoelectric data recorded within each cyclical movement of the studied eccentric exercise. Thus we propose the computation of the instantaneous mean frequency of the signal based on an original cross-time-frequency algorithm, which proved more sensitive than the frequency marginal in tracking the spectral changes associated with localized muscle fatigue. We derived the average fatigue pattern of the investigated muscles from experimental data recorded from a sample population consisting of twenty healthy subjects and we statistically compared the two contraction modalities. Our results showed that the electrical manifestations of muscle fatigue during concentric contractions were higher than those found during eccentric contractions, although in the latter modality the torque exerted and the mechanical work produced by the subjects were larger than those recorded during the concentric exercise.

The results presented in this paper have potential clinical application and they could play an important future role in investigations of muscle behavior during dynamic, highly fatiguing contractions.

Index Terms—isokinetic exercise, concentric contractions, eccentric contractions, muscle fatigue, time - frequency distributions

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I. INTRODUCTION

IN vertebrates, skeletal muscles are essential for moving as well as for accomplishing most life-related activities. The analysis of the surface myoelectric signal (SMES) recorded during a muscle contraction has been used for over three decades as a means to investigate muscle properties [1]–[3]. Early studies were carried out mainly in isometric conditions [2]. In the past decade, the need for a better understanding of the behavior of human muscles in dynamic conditions caused great interest in isokinetic methodology.

Since 1980, isokinetic exercise has been widely used for functional rehabilitation and assessment [4], [5]. Investigations based on isokinetic tests have been proven useful in acquiring a better comprehension of the mechanisms underlying the force-velocity and the torque-velocity relationships in lower limb muscles during dynamic contractions [6]–[8]. Moreover, isokinetic exercise has been used to investigate muscle composition [7]–[9] and the biomechanical output of the human joints [7], [9], [10], both in healthy and in pathological subjects [11]. A thorough review of the methodology and applications of isokinetic exercise can be found in the work of Cabri [12].

Isokinetic devices allow one to perform eccentric and concentric contractions. The biomechanical differences between eccentric and concentric contractions, in terms of output power, angular momentum and torque produced, were first explored by Komi in 1972 [13], [14] and only in the past ten years researchers started exploring eccentric [15], [16] and concentric [12], [15] isokinetic contractions from a physiological point of view, looking at neural activation and motor unit recruitment.

It is well known and accepted that the spectral analysis of the SMES is a valuable tool for the quantification of the electrical manifestations of muscle fatigue [3] during constant force and isometric contractions. Specifically, it has been demonstrated that during a sustained muscle contraction the power spectrum of the signal is progressively scaled towards the lower frequency end of the spectrum [17]. It has also been demonstrated that, among different spectral variables, the mean and median frequency values of the power spectrum are reliable indicators of muscle fatigue [1], [18].

During a dynamic contraction, the SMES can be considered a realization of a nonstationary stochastic process [3]. In order

to track the evolution of its frequency content in time, a time-frequency (TF) representation is required. The Cohen class of TF transformations is a good candidate for accomplishing this task since such transformations are time and frequency shift invariant [19], [20]. Previous studies demonstrated that some of the TF transforms belonging to the Cohen class are best suited for assessing spectral changes due to the progression of muscle fatigue [21], [22] and described the statistical characteristics of the instantaneous spectral parameters suitable for that purpose [23], [24].

The goal of this study was twofold: a) to develop a methodology for the quantification of the effects of localized muscle fatigue during repetitive isokinetic knee flexion-extension movements performed at a given angular velocity, and b) to study the electrical manifestations of muscle fatigue of the rectus femoris, vastus lateralis, vastus medialis, and biceps femoris muscles while contracting in concentric and eccentric modalities.

We consider this study as an important contribution toward defining appropriate methodologies to assess the electrical manifestations of muscle fatigue in physical medicine, sports medicine, occupational therapy, rehabilitation, and other clinical applications.

II. MATERIALS AND METHODS

A. Experimental setup

Our sample population consisted of 20 healthy volunteers (15 males and 5 females, mean age \pm std: 29 \pm 8 years) with no history of lower limb disorders and with no previous experience with isokinetic exercise devices. Subjects performed the exercises with their dominant leg, while sitting on the bench of the isokinetic machine (Kintrex 1000) with their thigh firmly fastened to the seat and their leg attached to the rotating arm. It has been shown that this movement may be considered as unidimensional [25]. The range of motion was set equal to 80 deg (from 100 deg to 180 deg).

Since the aim of this study was to compare the electrical manifestations of muscle fatigue during concentric and eccentric contractions, we chose the same value of angular velocity (60 deg/s) for the two contraction modalities.

The experimental protocol consisted of three phases: i) a warm-up consisting of five minutes of cycling and five minutes of stretching; ii) a series of ten concentric contractions (performed at 180 deg/s) and a series of ten eccentric contractions (performed at 30 deg/s) aimed at instructing the subjects about the isokinetic movement; iii) four series of isokinetic knee flexion-extension cyclical exercises (the first and the third consisting on 15 concentric contractions, the second and the fourth consisting on 15 eccentric contractions) at 60 deg/s. The subjects were instructed to perform the contractions always exerting their maximal effort. To allow subjects to recover from each series, rest periods of 10 min were permitted in between exercise series.

B. Recording system and preprocessing procedures

We acquired seven signals: angular position, angular velocity, and torque (measured at the shaft of the isokinetic motor)

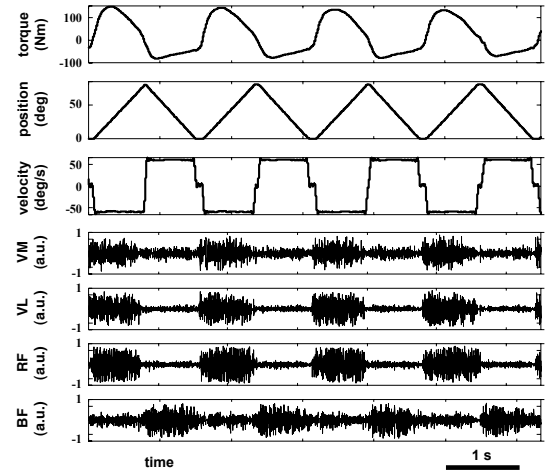


Fig. 1. Example of a set of signals collected during four cycles of concentric isokinetic contractions (repetitions number 2 to 5). Muscles are indicated as: BF for biceps femoris; RF for rectus femoris; VL for vastus lateralis; and VM for vastus medialis. The biomechanical signals (torque, angular position, and angular velocity) were measured directly on the shaft of the isokinetic device.

along with the SMESs recorded from three knee extensor muscles (vastus medialis, vastus lateralis, and rectus femoris) and one knee flexor muscle (long head of the biceps femoris).

SMES recordings were performed by means of a commercially available recording system (Step32, Demitalia, Leini, Italy) equipped with bipolar active probes. Pairs of solid gel Ag-AgCl electrodes with a circular detection surface (6 mm diameter) and interelectrode distance equal to 25 mm were placed on the muscles with particular attention to avoiding the innervation zones. The sampling rate was equal to 2 kHz.

SMESs were bandpass filtered between 40 Hz and 350 Hz by means of a 100 coefficient FIR filter to reduce possible motion artifacts and to lessen the effect of high-frequency noise. Figure 1 shows signals acquired during four concentric knee flexion-extension cycles.

C. Signal processing

The electrical manifestations of muscle fatigue were investigated by tracking the variation of the instantaneous mean frequency (IMNF) of the SMESs during each series of flexion-extension cyclical exercises. To this end, we studied the characteristics of the instantaneous power spectrum of the SMESs within each single signal burst. Following our previous experience [21], [23], we adopted the Choi-Williams TF transform to achieve this objective.

Figure 2 shows the Choi-Williams representation of two bursts of myoelectric signal collected respectively at the beginning and at the end of a series of concentric contractions performed by a subject during one of the isokinetic test exercises. Contour levels are utilized to provide a two-dimensional representation of the distribution of the energy associated with different frequency components at each point in time. This representation collapses on two-dimensions the three-dimensional TF distribution, thus allowing us to superimpose the time course of the instantaneous mean frequency over the

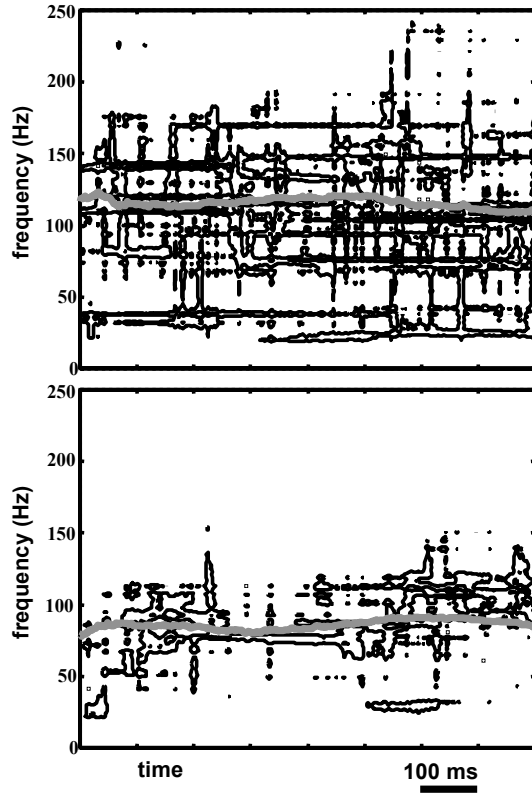


Fig. 2. Contour plot representation of the time-frequency transforms relative to two bursts of myoelectric signal (rectus femoris). Different contour lines correspond to different energy levels. By this representation, the three-dimensional time-frequency distribution is shown via a two-dimensional plot. The upper contour plot is relative to the second burst of muscular activity recorded during a series of fifteen concentric activations of flexion-extension cycles. The lower contour plot corresponds to the fourteenth cycle of the exercise series. The thick gray lines represent the estimated IMNF time course within each burst. The effect of the progression of muscle fatigue is represented by the scaling of the distribution towards the lower frequencies, which causes the decrease in the average IMNF.

interval of muscular activation, which corresponds to the entire range of motion.

Visual inspection of the TF distribution of the SMES recorded during concentric contractions suggests that bursts of muscle activity are not marked by strong non-stationarities. In fact, the frequency components of the SMES do not appear to significantly change within the interval corresponding to the burst of muscular activity. Figure 2 is relative to rectus femoris, but the same behavior, in terms of signal stationarity, was observed in all the investigated muscles. This observation suggested us to attempt two different approaches for the computation of the IMNF and to select the most convenient. First, we utilized a cross-TF transform based algorithm that we previously showed to be highly reliable when working with a non-stationary stochastic process [26]. Secondly, after having observed that in this particular exercise protocol muscle fatigue causes a generalized scaling of the TF distribution towards the lower frequency end, we computed the IMNF value referred to a specific signal burst as the mean (centroid) frequency of the frequency marginal of the SMES time-frequency distribution.

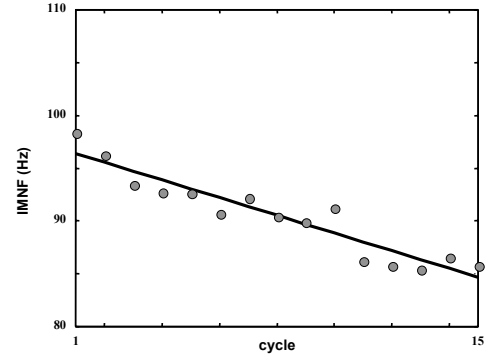


Fig. 3. IMNF values relative to the 15 rectus femoris bursts of muscular activity collected during a series of concentric isokinetic flexion-extension movements. The IMNF estimates are linearly interpolated; the overall percentage decrement shown by the IMNF is considered as an index of the progression of muscle fatigue (in this example the overall IMNF percentage decrement is equal to 13%).

1) *Cross time-frequency approach:* For each signal burst we derived the time course of the IMNF of the signal by applying an iterative algorithm that we developed [26] by modifying a technique previously proposed by Boashash et al. [27]. In Fig. 2 the grey line represents the time course of the IMNF within the signal bursts.

To test whether the electrical manifestations of muscle fatigue were dependent on the knee angular position, we segmented the IMNF profiles in three portions each corresponding to about 15 deg of the spanned angular range of motion. The 45 deg covered the central portion of the angular range of motion. Then we averaged the IMNF time course within each 15 deg portion, thus obtaining three IMNF values for each contraction. The decision of averaging into 15-degree epochs (hence in epochs lasting about 250 ms) was based on previous studies [22], [23].

Taking as reference the angular range of motion, in concentric contractions, the first epoch corresponds to the portion of the exercise in which the muscle is producing force with the maximal fiber length, the third corresponds to the portion in which the muscle fiber length is the shortest, and the second corresponds to an average fiber length. Conversely, during eccentric exercises the first epoch corresponds to the condition of minimum fiber length and the third to the condition of maximum fiber length.

The electrical manifestations of muscle fatigue were assessed for each series of contractions by computing the least squares regression line through the 15 IMNF estimates relative to the 15 signal bursts of each contraction series. The IMNF values were first normalized by the IMNF value derived from the first contraction of each series. The regression coefficient of the line was adopted as an index of muscle fatigue. Figure 3 shows the procedure described above applied to the signal collected from the rectus femoris of a specific subject during a series of concentric knee flexion-extension cyclical movements. With this procedure, we obtained three regression estimates for each contraction series.

Finally, we averaged the values of the regression coefficient obtained for each specific muscle and for each 15-degree

epoch over our sample population. The sample means obtained were used to describe muscle fatigue in the specific contraction modality (concentric or eccentric).

2) *Frequency marginal approach*: When the electrical manifestation of muscle fatigue consists of a generalized scaling of the entire TF representation of the signal bursts towards the lower frequency end (Fig. 2), the mean frequency of the frequency marginal of the entire signal burst appears to be a suitable index for quantifying muscle fatigue [22], [23]. This approach is computationally efficient, and was therefore implemented to estimate IMNF values from each signal burst. Then, a fatigue index was estimated as described above for the cross - TF based approach.

III. RESULTS AND DISCUSSION

Two aspects of the results of this study are separately discussed in the following: 1) the signal processing procedures we utilized, and 2) the comparison between the electrical manifestations of muscle fatigue during eccentric versus concentric contractions.

A. Cross time -frequency vs. frequency marginal

The comparison between the spectral estimation techniques was carried out separately for concentric and eccentric contractions.

We observed that the SMESs recorded during concentric contractions performed according to our protocol are characterized by a TF representation that progressively and uniformly scales towards the lower frequencies. Moreover, the SMES IMNF we estimated depicts a time course that is almost constant within each burst (Fig. 2). When signals are characterized by this uniform scaling, the frequency marginal approach is preferable given its computational efficiency.

If the IMNF varies within a single signal burst, but the SMES time-frequency representation is uniformly scaled towards the lower frequencies, the percent IMNF decrement computed using the TF approach is expected to be statistically equal to the one estimated on the basis of the frequency marginal approach.

Conversely, when the TF representation scales towards the lower frequency end, the IMNF percent decrement is expected to be different for different portions of the SMES bursts. In this specific case, the IMNF based method is preferable because of its higher frequency resolution - compared to traditional FFT-based methods [21] - and possibility of time localization. It is important to observe that, in any of the above mentioned conditions, a TF representation is essential to analyze the spectral content of the SMESs and adopt the appropriate procedure.

1) *Concentric contractions*: There are no studies that we are aware of concerning the spectral changes occurring in the SMES during isokinetic concentric contractions. The TF analysis of the SMES recorded during isokinetic concentric contractions performed at 60 deg/s showed that the spectral content is globally scaled towards the lower frequencies and that the scaling is about the same for different portions of the SMES bursts; consequently, the IMNF profiles are essentially

constant over the entire range of motion (Fig. 2). Figure 4 depicts the percentage decrement estimated from the IMNF values relative to the three 15-degree epochs in which we segmented the angular range of motion and the percentage decrement obtained by means of the frequency marginal (indicated as MNF in the figure). For all the muscles, the estimated percentage decrements in the three epochs and the one derived by means of the frequency marginal approach are statistically equal (repeated measures ANOVA, $p > 0.8$). Therefore, when concentric knee flexion-extension isokinetic tests are performed at a knee angular velocity of 60 deg/s, the frequency marginal approach is preferable to the cross - TF based method because it is computationally efficient.

Figure 4 demonstrates that all the muscles showed manifestations of localized muscle fatigue; the rectus femoris was the most fatigable, followed by the biceps femoris, the vastus lateralis, and the vastus medialis.

2) *Eccentric contractions*: Figure 5 shows the Choi-Williams representation of two bursts of the rectus femoris SMES collected at the beginning and at the end of a series of eccentric contractions. The TF representation is similar to that presented in Fig. 2; the gray line superimposed on the contour plots represents the IMNF of the SMES bursts. It is evident that the IMNF value during each signal burst is not constant. In this case, the frequency marginal approach has to be used with caution. We found that the IMNF estimates demonstrate a clear variation during eccentric flexion-extension cycles: for higher values of the angular position the IMNF value is lower than that corresponding to low angular positions.

Figure 6 shows the IMNF percentage decrements in the three 15-degree epochs as well as the MNF decrement estimated by means of the frequency marginal based method. Results are shown as means and standard error values. The electrical manifestations of muscle fatigue are less evident in the first angular interval, when the muscle fiber length is the shortest. In particular, when considering vastus lateralis and medialis muscles the third 15-degree epoch is to be preferred. The frequency marginal approach underestimates the effects of localized muscle fatigue, while the TF based technique is more sensitive to changes in the SMES frequency content.

It is then concluded that during low-speed eccentric knee flexion-extension movements the electrical manifestations of muscle fatigue are clearer at the end of the angular range of motion and that to obtain the maximum sensitivity one should concentrate the analysis on this specific angular interval and make use of the cross - TF approach.

B. Concentric vs. eccentric contractions

Table I reports the population averaged percentage decrements in peak torque estimated during concentric and eccentric tests. The peak torque reduction observed during the tests is statistically equal for the concentric and eccentric series (repeated measures ANOVA with contraction modality and series number as within factors, $p > 0.14$). Moreover, knee extensor and flexor muscles show the same value of peak torque percentage decrement (same test as above with flexor/extensor as within factor, $p > 0.8$) in all the series and in the two contraction modalities.

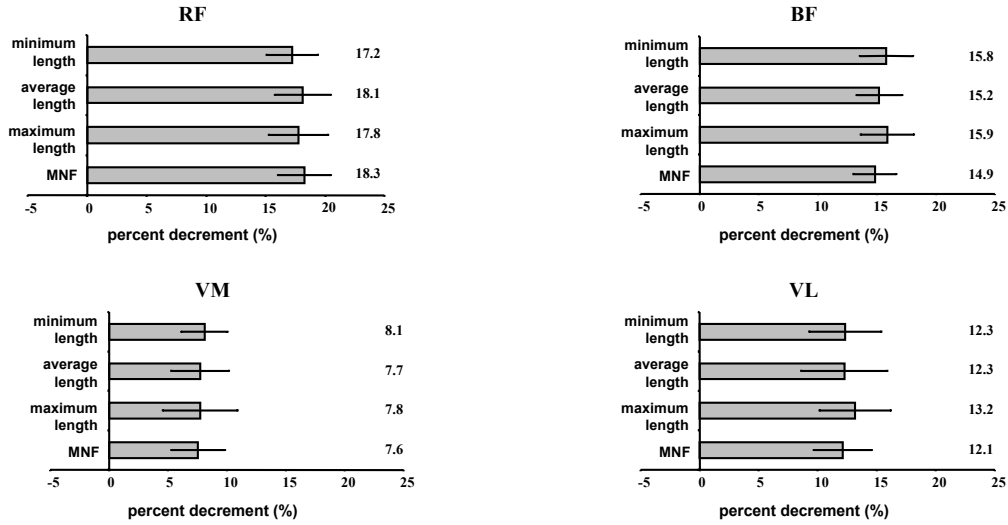


Fig. 4. Overall IMNF percentage decrement for the four monitored muscles during concentric contractions subdivided in three angular intervals corresponding to the initial part (maximum muscle fiber length), the middle (average muscle fiber length), and the final part (minimum muscle fiber length) of the contraction. Each interval corresponds to approximately 15 deg. The fourth bar corresponds to the percentage decrement obtained by means of the frequency marginal technique.

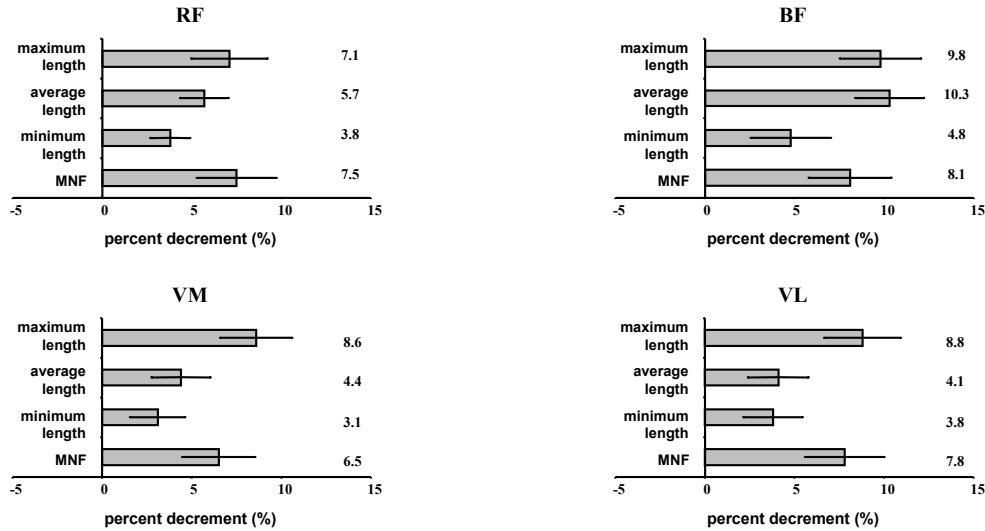


Fig. 6. Overall IMNF percentage decrement for the four monitored muscles during eccentric contractions subdivided in three angular intervals corresponding to the initial part (minimum muscle fiber length), the middle (average muscle fiber length), and the final part (maximum muscle fiber length) of the contraction. Each interval corresponds to approximately 15 deg. The fourth bar corresponds to the percentage decrement obtained by means of the frequency marginal technique.

As in previous studies on isokinetic contractions [12], [14], we observed significantly higher values of torque produced during eccentric than during concentric contractions (repeated measures ANOVA, $p \leq 10^{-4}$).

To compare the electrical manifestations of muscle fatigue in eccentric and concentric contractions we tested the equality of the percent decrements of the IMNF produced by the subjects during the four series of contractions in the two different modalities, computed as explained above. Results are shown in Fig. 7.

We used a repeated measures ANOVA test, with IMNF percentage decrement as dependent factor. We demonstrated that the IMNF percentage decrements for concentric contractions

are greater than those reported during eccentric ones ($p \leq 5 \cdot 10^{-3}$) for all the muscles we studied except vastus medialis ($p > 0.05$). We also demonstrated that the fatigue patterns (i.e. IMNF percentage decrements across the monitored muscles) in the two contraction modalities are significantly different (MANOVA with the percent decrements of the four muscles as repeated measures and contraction modality as within factors, $p \leq 3 \cdot 10^{-3}$). From a physiological point of view, this means that at this angular velocity (60 deg/s) concentric contractions cause higher electrical manifestations of muscle fatigue than eccentric ones.

Since it is accepted [28] that the scaling towards the lower frequencies of the power spectrum of the myoelectric signal

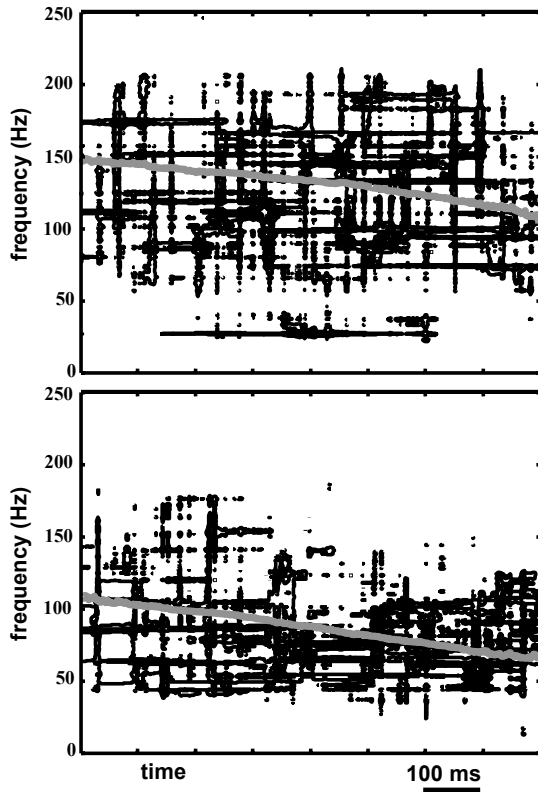


Fig. 5. Contour plot representation of the time - frequency transforms relative to two bursts of myoelectric signal (rectus femoris). The upper contour plot is relative to the second burst of muscular activity recorded during a series of fifteen eccentric activations of flexion-extension cycles. The lower contour plot corresponds to the fourteenth cycle of the exercise series. The thick gray lines represent the estimated IMNF time course within each burst. The IMNF is not constant with respect to the angular position and the scaling towards the lower frequencies is not uniform along the activation interval.

is mainly determined by the increase of H^+ ions in the interstitial fluid, that is principally related to production of lactate, our results support the hypothesis that during eccentric contractions the production of metabolites is lower than during concentric contractions, even if the peak torque developed is higher.

Our results are in agreement with previous studies and specifically with the work of Cabri [12], who reported that during eccentric contractions the consumption of O_2 is lower than during concentric ones. Cabri also reported a lower level of motor unit activation during eccentric contractions. This observation is consistent with results by Moritani et al. [29], who demonstrated that eccentric contractions are associated with a less pronounced motor unit recruitment and modulation of motor unit firing rate, most likely due to stored elastic energy in the actin-myosin cross-bridges. Hence, during eccentric contractions there could be a lower oxygen consumption and a reduced amount of metabolites produced; further studies are needed in order to investigate whether these phenomena depend on the firing rate modulation of the active motor units in the two contraction modalities, on their metabolism (glycolytic, oxidative, or mixed) or on other factors. The different time course of the IMNF we found in eccentric and concentric contractions could be interpreted also as a sign of

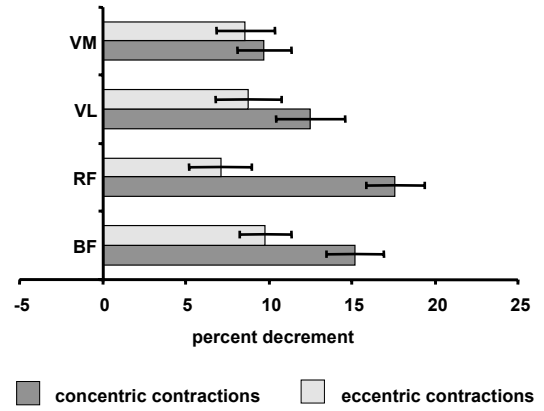


Fig. 7. Comparison between the fatigue patterns obtained over our sample population during eccentric (light gray) and concentric (dark gray) contractions. The error bars represent the standard error. It is evident that three out of four muscles (RF, BF, VL) show higher manifestations of muscle fatigue during concentric contractions. VM shows similar IMNF percentage decrements in the two contraction modalities.

different neural activation, but at this time we do not have sufficient data to support this hypothesis.

IV. CONCLUSION

The goal of this study was twofold: first to propose a signal processing protocol for assessing the progression of muscle fatigue during a series of isokinetic knee flexion-extension movements performed in concentric and eccentric modalities at the angular velocity of 60 deg/s; secondly, to quantify the electrical manifestations of muscle fatigue in the two contraction modalities.

We demonstrated the need for utilizing time-frequency algorithms when one analyzes eccentric contractions. Conversely, concentric contractions may be analyzed using algorithms for traditional spectral analysis. Although it is possible that different results may be obtained for different angular velocities or for other muscle groups, the methodological approach that we propose in this paper has broad applicability: a time-frequency technique has to be used in order to assess whether fatigue has the largest influence on the SMES in a specific portion of the exercise cycle. We see this methodological contribution as essential when investigating the differences between concentric and eccentric contractions via a reliable assessment of the electrical manifestations of localized muscle fatigue.

TABLE I
PEAK TORQUE VALUES AND TORQUE PERCENTAGE DECREMENT (PD) FOR THE KNEE FLEXOR AND EXTENSOR MUSCLE MEASURED DURING THE CONCENTRIC AND ECCENTRIC TESTS (POPULATION AVERAGED VALUES; $AVG \pm STD$). THE AVERAGE TORQUE IS STATISTICALLY SIGNIFICANTLY GREATER IN ECCENTRIC THAN IN CONCENTRIC CONTRACTIONS, WHEREAS THE PD IS STATISTICALLY EQUAL IN ALL THE SERIES.

	Concentric modality		Eccentric modality	
	Torque (Nm)	PD (%)	Torque (Nm)	PD (%)
Flexors	136.1 \pm 47.9	24.8 \pm 8.9	155.5 \pm 49.5	24.2 \pm 7.2
Extensors	205.5 \pm 63.1	27.1 \pm 6.9	257.3 \pm 77.5	23.3 \pm 8.9

We obtained the average fatigue pattern of four leg muscles in the two investigated contraction modalities. Among the monitored muscles, the rectus femoris and biceps femoris showed higher signs of localized muscle fatigue than the vastus lateralis and vastus medialis, particularly when considering eccentric contractions.

In agreement with previous studies based on other physiological variables, our data show that the electrical manifestations of muscle fatigue are more evident during concentric contractions, although subjects developed higher torque and produced a higher amount of mechanical work during eccentric tests.

In conclusion, we demonstrated that the study of the electrical manifestations of muscle fatigue during isokinetic exercises is feasible. The proposed techniques have potential application in rehabilitation medicine, sports medicine, occupational therapy and are an important tool to explore basic muscle physiology during dynamic contractions.

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