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Motor unit firing rates and synchronization affect the fractal dimension of simulated surface electromyogram during isometric/isotonic contraction of vastus lateralis muscle

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Abstract

During fatiguing contractions, many adjustments in motor units behaviour occur: decrease in muscle fibre conduction velocity; increase in motor units synchronization; modulation of motor units firing rate; increase in variability of motor units inter-spike interval. We simulated the influence of all these adjustments on synthetic EMG signals in isometric/isotonic conditions. The fractal dimension of the EMG signal was found mainly influenced by motor units firing behaviour, being affected by both firing rate and synchronization level, and least affected by muscle fibre conduction velocity. None of the calculated EMG indices was able to discriminate between firing rate and motor units synchronization.

Abbreviations

ARV	average rectified value
COV	coefficient of variation
CV	muscle fibre conduction velocity
EMG	electromyography
FD	fractal dimension
FR	firing rate
ISI	inter-spike interval
MNF	mean power spectral frequency
MU	motor units
MUAP	motor unit action potential
MVC	maximum voluntary contraction

Introduction

During fatiguing contractions, several motor units (MU) adaptations occur: decrease in muscle fibre conduction velocity (CV); increase in MU synchronization; decrease and/or modulation of MU firing rate (FR); increase in variability of MU inter-spike variability (ISI) [1]. Beyond the most common indices of fatigue such as the decrease of muscle fibre CV and power spectral mean frequency (MNF), nonlinear electromyographic (EMG) indices have been introduced.

A number nonlinear methods have been developed to track changes in MUs synchronization from the EMG [2-4]. These estimates provide a representative indication of

MUs synchronization, but they are dependent on CV time course and therefore they cannot be used in fatiguing contractions which affect CV too [5]. In a model study [6], the fractal dimension (FD) of EMG was found to be the nonlinear index able to monitor the level of MU synchronization, but least affected by CV changes. The FD represents the quantification of the geometrical complexity of the EMG signal , and it has been considered as a promising index to monitor the level of MU synchronization in response to fatigue [6, 7]. The FD of EMGs has recently been used as a complementary variable with respect to CV in fatiguing contractions [8, 9].

The influence of MUs synchronization, FR, ISI variability and CV over the surface EMG indices has not been assessed together, yet. As we proposed in a previous study [8], it is likely that also the changes in the FR influence the geometrical complexity of the surface EMG. Consequently, the estimate of the FD, that has been used to track changes in MUs synchronization, can be affected also by another characteristic of MUs discharge, which is the FR. In the herein study, we aimed to assess the reciprocal influence of MUs synchronization, FR, ISI variability, and CV on synthetic EMG signals.

Methods

Simulation Model

We tried to simulate the vastus lateralis muscle. The cylindrical model proposed in [10] was used to simulate single fibre action potentials. The properties of the volume conductor and the location of fibre sources are shown in Figure 1A. Each action potential was smoothed to simulate a MU action potential (MUAP), as proposed in [6]. The ratio of innervation numbers was chosen equal to 20 [6]. The distribution of MU sizes was chosen to be in a linear relationship with that of the recruitment thresholds.

Forty different libraries of MUAPs were built, assigning randomly the size of the MUs to the simulated MUAP waveforms. Different (normally distributed) CVs were assigned to the MUs, with greater CV given to larger MUs.

The control of MUs was described as in [11], considering the distributions of recruitment thresholds (Figure 1C) and FRs of the vastus lateralis muscle (Figure 1D). The ISI was assumed to have a Gaussian distribution with different coefficients of variation (COV) in different simulations.

MU synchronization was set as in [12]: the percentage of synchronized firings in each MU train was assumed to be equal to the percentage of firings synchronized together for each synchronization event and used to indicate the synchronization level [4, 6].

A high force level (80% of MVC) was simulated to recruit most of the MUs. Load sharing between synergistic muscles and possible recruitment/de-recruitment of MUs were not considered [13].

EMGs were detected by an array of 4 rectangular electrodes (4 mm long and 1 mm thick, inter-electrode distance 5 mm), in single differential configuration. The electrodes were aligned to the fibres and placed on the centre of the muscle, between the innervation zone and one of the tendons.

Simulated signals

Stationary interference EMGs of duration 1 s were simulated in different conditions (specified below), for each MUAP library (indicated above), with sampling frequency of 2 kHz. FD, CV, MNF and average rectified value (ARV) were estimated from each signal. CV was estimated considering the 3 single differential channels; the other indices were computed on the second channel.

The effect of the following factors was tested, simulating signals in each condition.

- MU CV distribution: a Gaussian distribution [14] with standard deviation equal to 0.3 m/s and mean in the range 3-5 m/s (0.5 m/s step).
- MU FR distribution: a standard FR distribution was simulated as in [11]; then it was modified by a linear function imposing the minimum FR equal to 5 Hz and the maximum in the range 20-40 Hz (with step 5 Hz).
- ISI variability: the COV was varied in the range 5-20% (step 5%) [11].
- MU synchronization was varied in the range 0-20% (step 5%) [12].

Signal processing methods

FD, CV, MNF and average rectified value (ARV) were estimated from each 1 s long simulated signal. CV was estimated considering the 3 simulated single differential channels; the other indices were computed on the second channel. The same methods as in [6] were used: specifically, FD was estimated by the box counting method (with sizes of the boxes in the range 1/640 to 1/40 of the time/amplitude size of the considered EMG); CV was computed by the maximum likelihood approach; MNF was the mean of the sample spectrum; ARV was the mean of the absolute value of the EMG.

Statistical analysis

Since in preliminary analysis the ISI variability did not show any effect in the estimation of any EMG index, the five ISI were pooled in the successive analysis. Thus, three-way repeated measure ANOVA tests (5 CV × 5 FR × 6 synchronization), with all ISI collapsed, were performed to detect the effect of factors on EMG indices.

Results

The main effects and interactions of the three-way ANOVA are the Table 1. Overall, FD increased with increasing CV ($p \ll 0.001$) and FR ($p \ll 0.001$) and decreases with increasing synchronization ($p \ll 0.001$) (Figure 2A); MNF increased with increasing CV ($p \ll 0.001$) and decreased with increasing synchronization ($p \ll 0.001$), but it was not affected by the FR ($p > 0.05$) (Figure 2B); estimates of CV are influenced only by the simulated CV ($p \ll 0.001$) (Figure 2C); ARV decreased with increasing CV ($p \ll 0.001$) and synchronization ($p \ll 0.001$), and increased with increasing FR ($p \ll 0.001$) (Figure 2D).

Discussion

During fatiguing contractions many adjustments in MU behaviour occur. Non-invasively discriminating these neurophysiological changes may be useful in many clinical and research field. Different EMG indices are affected by each neurophysiological change at a different extent. Thus, in order to discriminate the different contributions, it is important to assess the effect of each manifestation of fatigue on specific EMG indices.

This work indicates that FD, i.e. the geometrical complexity, of the EMG signals was affected by both FR and synchronization level, and least by changes of CV. In particular FD increases and decreases, with increasing FR and decreasing MU synchronization, respectively. Thus, as suggested in [8], being the FD affected by both variations in FR and MUs synchronization, it cannot be considered a selective index able to detect changes in MUs synchronization. Previous research did not take into account the different modulation in FR occurring during fatiguing contraction [6, 8, 9], poorly interpreting the changes of FD as straightforwardly influenced by changes in MU synchronization. During a fatiguing contraction at submaximal levels, the MUs synchronization is expected to increase [15], but the FR can decrease or be modulated [16, 17]. Thus, even in ideal conditions, a monotonic decrease of FD cannot be considered as a unique MUs synchronization index during a fatiguing activity.

Since none of the other EMG indices (FD, MNF and ARV) was exclusively influenced by the FR or the MUs synchronization, a combination of EMG indices or a development of new index is needed to discriminate MUs firing adjustments in occurrence of muscle fatigue. Indeed, the MU firing behaviour changes with age, pathological conditions, and training status [18]. Thus, further work should aim to noninvasively discriminate between variations in MU firing behaviour. Simulated and experimentally recorded EMG signals should be used together to verify the correctness of EMG index interpretations. A further work is also in progress to test our results on experimental data.

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Figure Captions

Table 1. The results of the three-way ANOVA (CV × Synch × FR) for each EMG index are reported. The influences of muscle fiber conduction velocity (CV), synchronization (Synch), firing rate (FR), and their interactions on fractal dimension (FD), mean power spectral frequency (MNF), CV, and average rectified values (ARV) are reported with F statistics and p values. n.s. = non-significant.

Figure 1. Mathematical model. A) Section of the volume conductor. Four layers are considered: skin, fat, muscle and bone. The simulated centres of the simulated fibres are indicated with a small circle. B) Example of simulated signal (force level 80% MVC, mean CV 3 m/s, maximal FR 20 Hz, level of synchronization 0%, COV of ISI 5%). C) Distribution of recruitment thresholds and firing rate of the MUs.

Figure 2. Influence of CV, FR and synchronization level on the estimates of A) FD, B) MNF, C) CV, and D) ARV (median, quartiles, range and outliers are shown; the effect of different COVs of ISI is not shown as it is not statistically significant).

References

[1] Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG: an update. J Appl Physiol (1985). 2014;117:1215-30.
[2] Del Santo F, Gelli F, Schmied A, Vedel JP, Rossi A, Mazzocchio R. Motor unit synchronous firing as revealed by determinism of surface myoelectric signal. J Neurosci Methods. 2006;155:116-21.
[3] Kleine BU, Stegeman DF, Mund D, Anders C. Influence of motoneuron firing synchronization on SEMG characteristics in dependence of electrode position. J Appl Physiol (1985). 2001;91:1588-99.
[4] Farina D, Fattorini L, Felici F, Filligoi G. Nonlinear surface EMG analysis to detect changes of motor unit conduction velocity and synchronization. J Appl Physiol. 2002;93:1753-63.
[5] Arendt-Nielsen L, Mills KR, Forster A. Changes in muscle fiber conduction velocity, mean power frequency, and mean EMG voltage during prolonged submaximal contractions. Muscle & nerve. 1989;12:493-7.
[6] Mesin L, Cescon C, Gazzoni M, Merletti R, Rainoldi A. A bi-dimensional index for the selective assessment of myoelectric manifestations of peripheral and central muscle fatigue. J Electromyogr Kinesiol. 2009;19:851-63.
[7] Troiano A, Naddeo F, Sosso E, Camarota G, Merletti R, Mesin L. Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. Gait Posture. 2008;28:179-86.

[8] Boccia G, Dardanello D, Beretta-Piccoli M, Cescon C, Coratella G, Rinaldo N, et al. Muscle fiber conduction velocity and fractal dimension of EMG during fatiguing contraction of young and elderly active men. Physiol Meas. 2016;37:162-74.
[9] Beretta-Piccoli M, D'Antona G, Barbero M, Fisher B, Dieli-Conwright CM, Clijsen R, et al. Evaluation of central and peripheral fatigue in the quadriceps using fractal dimension and conduction velocity in young females. PloS one. 2015;10:e0123921.
[10] Farina D, Mesin L, Martina S, Merletti R. A surface EMG generation model with multilayer cylindrical description of the volume conductor. IEEE Trans Biomed Eng. 2004;51:415-26.
[11] Contessa P, De Luca CJ. Neural control of muscle force: indications from a simulation model. J Neurophysiol. 2013;109:1548-70.
[12] Filligoi G, Felici F. Detection of hidden rhythms in surface EMG signals with a non-linear time-series tool. Med Eng Phys. 1999;21:439-48.
[13] Fuglevand AJ, Winter DA, Patla AE. Models of recruitment and rate coding organization in motor-unit pools. J Neurophysiol. 1993;70:2470-88.
[14] Farina D, Cescon C, Merletti R. Influence of anatomical, physical, and detection-system parameters on surface EMG. Biol Cybern. 2002;86:445-56.
[15] Holtermann A, Grönlund C, Karlsson JS, Roeleveld K. Motor unit synchronization during fatigue: Described with a novel sEMG method based on large motor unit samples. Journal of Electromyography and Kinesiology. 2009;19:232-41.
[16] Bigland-Ritchie B, Johansson R, Lippold OC, Smith S, Woods JJ. Changes in motoneurone firing rates during sustained maximal voluntary contractions. J Physiol. 1983;340:335-46.
[17] Pascoe MA, Holmes MR, Stuart DG, Enoka RM. Discharge characteristics of motor units during long-duration contractions. Exp Physiol. 2014;99:1387-98.
[18] Duchateau J, Semmler JG, Enoka RM. Training adaptations in the behavior of human motor units. J Appl Physiol. 2006;101:1766-75.

Table 1 – Influences of simulated physiological factors on EMG indices

	CV	FR	Synch	CV × FR	CV × Synch	Synch × FR	CV × FR × Synch
FD	$F(4,156)=2\cdot10^3$, $p\ll0.001$	$F(4, 156)=42$, $p\ll0.001$	$F(5,159)=206$, $p\ll0.001$	$F(16,576)=3$, $p=0.03$	$F(20,640)=9$, $p<0.001$	$F(16,592)=2$, $p=0.003$	n.s.
MNF	$F(4,156)=3\cdot10^4$, $p\ll0.001$	n.s.	$F(5,159)=44$, $p\ll0.001$	n.s.	$F(20,640)=2.2$, $p=0.05$	n.s.	n.s.
CV	$F(4,156)=2\cdot10^5$, $p\ll0.001$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
ARV	$F(4,156)=3\cdot10^3$, $p\ll0.001$	$F(4, 156)=94$, $p\ll0.001$	$F(5,159)=16$, $p\ll0.001$	$F(16,576)=19$, $p\ll0.001$	$F(20,640)=18$, $p\ll0.001$	n.s.	n.s.