Medical Engineering and Physics 000 (2016) 1–4

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Communication

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

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ARTICLE INFO

*Article history:*
Received 28 April 2016
Revised 13 September 2016
Accepted 26 September 2016
Available online xxx

*Keywords:*
Muscle fatigue
Surface EMG
Geometrical complexity
Muscle fibre conduction velocity

ABSTRACT

During fatiguing contractions, many adjustments in motor units behaviour occur: decrease in muscle fibre conduction velocity; increase in motor units synchronisation; 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 synchronisation 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 synchronisation.


## 1. Introduction

During fatiguing contractions, several motor units (MU) adaptations occur: decrease in muscle fibre conduction velocity (CV); increase in MU synchronisation; 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 synchronisation from the EMG [2–4]. These estimates provide a representative indication of MUs synchronisation, 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 synchronisation, 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 synchronisation 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 synchronisation, 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 synchronisation, 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 synchronisation, FR, ISI variability, and CV on synthetic EMG signals.

## 2. Methods

### 2.1. 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 Fig. 1A. Each action potential was smoothed to simulate a MU action potential (MUAP), as proposed by Mesin et al. [6]. The ratio of innervation numbers was

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http://dx.doi.org/10.1016/j.medengphy.2016.09.022
1350-4533/

**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 |

chosen equal to 20 [6]. The distribution of MU sizes was chosen to be in a linear relationship with that of the recruitment thresholds.

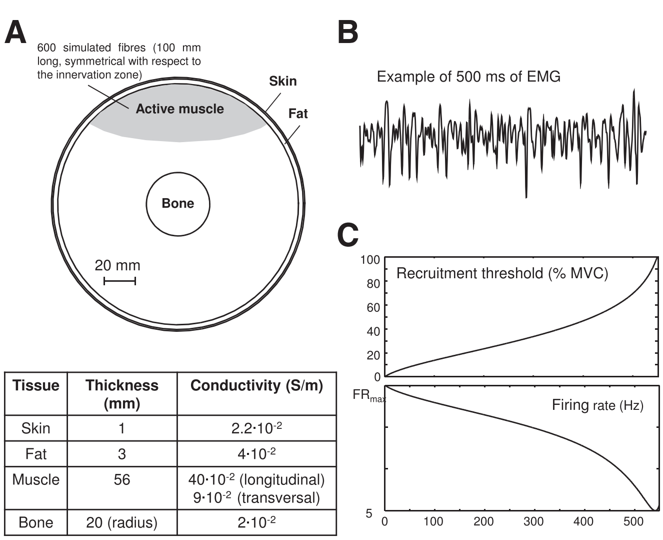
Forty different libraries of MUAPs were built, assigning randomly the size of the MUs to the simulated MUAP waveforms. Different (normally distributed) CVs were assigned to the MUs, with greater CV given to larger MUs.

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

MU synchronisation was the same as that used by Filligoi and Felici [12]: the percentage of synchronised firings in each MU train was assumed to be equal to the percentage of firings synchronised together for each synchronisation event and used to indicate the synchronisation 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.




| Tissue | Thickness (mm) | Conductivity (S/m) |
|---|---|---|
| Skin | 1 | $2.2 \cdot 10^{-2}$ |
| Fat | 3 | $4 \cdot 10^{-2}$ |
| Muscle | 56 | $40 \cdot 10^{-2}$ (longitudinal)<br>$9 \cdot 10^{-2}$ (transversal) |
| Bone | 20 (radius) | $2 \cdot 10^{-2}$ |

**Fig. 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 synchronisation 0%, COV of ISI 5%). (C) Distribution of recruitment thresholds and firing rate of the MUs.

### 2.2. Simulated signals

Stationary interference EMGs of 1 s duration 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 per Contessa and De Luca [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].

### 2.3. Signal processing methods

FD, CV, MNF and average rectified value (ARV) were estimated from each 1 s of simulated signal. CV was estimated considering the three simulated single differential channels; the other indices were computed on the middle channel. The same method as that used by Mesin et al. [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.

### 2.4. 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 $\times$ 5 FR $\times$ 6 synchronisation), with all ISI collapsed, were performed to detect the effect of factors on EMG indices.

## 3. 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 synchronisation ($p \ll 0.001$) (Fig. 2A); MNF increased with increasing CV ($p \ll 0.001$) and decreased with increasing synchronisation ($p \ll 0.001$), but it was not affected by the FR ($p > 0.05$) (Fig. 2B); estimates of CV are influenced only by the simulated CV ($p \ll 0.001$) (Fig. 2C); ARV decreased with increasing CV ($p \ll 0.001$) and synchronisation ($p \ll 0.001$), and increased with increasing FR ($p \ll 0.001$) (Fig. 2D).

## 4. 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.

Please cite this article as: L. Mesin et al., Motor unit firing rates and synchronisation affect the fractal dimension of simulated surface electromyogram during isometric/isotonic contraction of vastus lateralis muscle, Medical Engineering and Physics (2016), http://dx.doi.org/10.1016/j.medengphy.2016.09.022