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Short communication

# A model computation of how synchronization and clustering of motor unit action potentials alter the power spectra of electromyograms

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ABSTRACT

*Introduction:* The duration of bursts of muscle activity e.g. while running or walking, is too short for long pulse trains of motor unit action potentials (MUAPs) to develop. A pool of motor units is likely activated simultaneously which generates clustered MUAPs. The hypothesis is that the EMG power spectra are modulated by the fact that MUAPs cluster. The purpose is to quantify this modulation analytically.
*Methods:* A model of an EMG signal is presented that includes clustered MUAPs.
*Results:* According to the model the influence of MUAPs clustering is shown to be largest at lower frequencies and increases when the width of the time window containing the clusters decreases.
*Discussion:* The power at frequencies below 60 Hz strongly reflects changes of the degree of clustering. The mean frequency of the EMG therefore decreases when MUAPs cluster more tightly. Thus, clustering of MUAPs competes with other physiological properties that influence the mean frequency. The EMG power is proportional to the number of active MUAPs at high frequencies but approaches a value proportional to the square of the number of active MUAPs at very low frequencies. To obtain a measure of amplitude that is proportional to the number of active motor units, one should focus on the higher frequency power components only, however, to monitor the effect of clustering of MUAP one should focus on the lower frequency power. That could become relevant for comparing pre- and post-operative clinical gait studies where changes in MUAPs clustering may play a significant role.

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## 1. Introduction

Forces generated by muscles control human movements and stability. These diverse tasks require a high flexibility of the motor control system. In summary, motoneurons contain the receptors for common and independent presynaptic or supraspinal nerve signals [1]. Upon summing the internal potentials caused by the signals, the neurons fire and activate the motor neuron end plates on the muscle fibers, which causes the activated fibers to contract. Analytical descriptions of transduction of motor unit spike trains into muscle force can be used to understand the development of force [2,3]. Ultimately, contractile properties of the muscle fibers such as their efficiency and cross-bridge work and length or shortening velocity then determine the force production [4]. The easiest way to obtain an insight into the neural system during activation of the muscle is to measure the electrical effects caused by the depolarization and repolarization of the muscle fibers known as the electromyogram (EMG).

Two basic concepts, among less frequently used ones, of EMG analysis are used in the assessment of muscle functions. 1) As the muscle activity increases and more motor units (MUs) are recruited, the EMG amplitude increases. 2) With increasing fatigue conduction velocity of motor unit action potentials (MUAPs) along the muscle fibers decreases which in turn lowers the mean frequency [5]. Both effects are non-linear, the amplitude suffers from signal canceling and signal augmentation [6,7]. However, the relationship is still thought to be monotonic, i.e. the amplitude increases in a non-linear fashion with the number of activated MUs but it does not decrease. With respect to the mean frequency, one knows that during isometric contractions conduction velocity is not the only parameter that influences the decay of the mean frequency with fatigue [5]. During explosive tasks the instantaneous mean frequency computed from the Choi–Williams time–frequency transform, was significantly lower in the explosive than in the isometric exercises for vastus laterialis and medialis [8]. The same Choi–Williams time–frequency transform showed that during a short burst of muscle activity the EMG amplitude measured as the relative energy of the signal is very high at low frequencies [9]. These experimental results suggest that the clustering of MUAPs during short bursts of muscle activity alters the power

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spectrum of the surface electromyogram. During other dynamic tasks such as walking running or squatting the muscles of the leg are activated for a short period of time only. Therefore, the MU must all fire in short time intervals or in a synchronized way to produce the required muscle force. Independently of the background process, the MUAPs all occur in a short time window, a process which is defined most generally as clustering of MUAP in this study. There are multiple processes that generate clusters of MUAPs. The MUs may be synchronized by a common input to a pool of motor nerves [1] or cluster because they are activated after a specific trigger event like a foot contact with the ground [10]. After an initial activation subsequent periodic activations can be observed that are referred to as Piper rhythm. Thus, clustering can be caused by the central nervous system.

Many examples for EMG analyses of dynamic muscle contractions can be found, where the clustering of MUAPs could have influenced the observed spectral changes in the surface EMG. For example, elaborate gait analysis show specific, frequency dependent changes in EMGs for pre- and post-operative surgical interventions [11]. Further, precise short time muscle activation result in distinct, step specific EMG intensity patterns when running [12]. These patterns are very variable and often show large EMG intensities in the lower frequency range of their power spectra or wavelet spectra. The clustering of MUAPs that is required during a short burst of muscle activity has been shown to be task dependent being higher during dynamic squats than during isometric ones [13]. Thus, when interpreting EMGs recorded during dynamic tasks, the effect of clustering must be considered in addition to the traditional interpretation which is related to motor unit number and conduction velocity. Clustering, according to a numerical model strongly influences the shape of an EMG power spectrum and modifies primarily the low frequency range [14]. However, there is no analytic model that describes the effect of clustering of MUAPs that would allow us to understand the shape of the observed power spectra from a more fundamental point of view. This lack of understanding was the motivation for trying to gain more insight to what governs the intriguing observations we made at low frequencies [12] and explaining this behavior based on first principles.

The purpose of this study is to show the details of the effect of clustering of MUAPs on the EMG power spectrum using a simple theoretical model that is based on first principles. The hypothesis is that clustering results in a modulation of the overall power of an EMG and its frequency components. Therefore, the EMG amplitude, as measured by the power or the square root of the power, changes when the same number of MUAPs cluster. Similarly, the mean frequency changes when more MUAPs cluster. Clustering is therefore an essential aspect that has to be considered when interpreting EMGs that are measured during dynamic motor tasks.

## 2. Methods

It is common practice to model an EMG by superimposing MUAPs [6,7]. The following section explicitly computes such a model under the assumption that the MUAPs cluster in a short time window. It was further assumed that within that time window of width σ the MUAPs are normally distributed in time. Let's assume the EMG has a duration of T and $t_n$ represent the N locations of the MUAPs within T. The model will show that irrespective of the actual shape of the MUAP, the power spectrum can be represented by a product of a modulation spectrum, G, with the power spectrum of the MUAP. To keep the model simple we use only one shape of a MUAP.

The digital Fourier-transform *fMUAP* of a MUAP at location $t_n$ and for the frequency ω is:

$$fMUAP(\omega,\ t_n) = x_{\omega,n}\ \cdot fMUAP(\omega) \tag{1}$$

with $x_{\omega,n} = e^{(i\omega t_n)}$ Whereby the original MUAP was shifted in time by $t_n$ (Stephane Mallat Chapter 2 Table 2.1)[15] The Fourier-transform of the signal, *fsig*, consisting of the Fourier-transform of N superimposed MUAPs that are indexed by n can be expressed as:

$$fsig(\omega) = \left(x_{\omega,1} + \ldots x_{\omega,n} + \cdots x_{\omega,N}\right) \cdot fMUAP(\omega) \tag{2}$$

The power, P(ω) can then be computed

$$P(\omega) = G \cdot fMUAP(\omega) \cdot conj(fMUAP(\omega)) \tag{3}$$

with $G = (x_{\omega,1} + \ldots x_{\omega,n} + \cdots x_{\omega,N}) \cdot conj(x_{\omega,1} + \ldots x_{\omega,n} + \cdots x_{\omega,N})$ Whereby $fMUAP(\omega) \cdot conj(fMUAP(\omega))$ represents the power of one MUAP.

*G* is defined as the modulation spectrum and can be rewritten as follows

$$G = \sum_{n=1}^{N} x_{\omega,n} \cdot conj(x_{\omega,n}) + \sum_{k \neq j}^{N} \left(x_{\omega,k} \cdot conj\left(x_{\omega,j}\right) + x_{\omega,j} \cdot conj\left(x_{\omega,k}\right)\right) \tag{4}$$

The first sum is equal to N because the norm of $x_{\omega,n}$ is 1.

The second sum represent the cross terms, let's call it C; it is equal to

$$C = \sum_{k \neq j}^{N} (e^{(i\omega \Delta t_{k,j})} + e^{(-i\omega \Delta t_{k,j})})$$

$$C = 2 \cdot \sum_{k \neq j}^{N} cos\left(\omega \Delta t_{k,j}\right) \tag{5}$$

Where $\omega \Delta t_{k,j}$ represents the phase angle between the two MUAP and $\Delta t_{k,j}$ the time between them. The sum is taken over all pairs $k \neq j$. There are N(N-1)/2 such pairs.

Thus the modulation spectrum of superimposed identical MUAPs is

$$G = N + 2 \cdot \sum_{k \neq j}^{N} cos\left(\omega \Delta t_{k,j}\right) \tag{6}$$

The EMG power spectrum can be computed according to Eq. (3) as the product of the modulation spectrum and the MUAP power spectrum.

The above equations reflect the basic principle of the analytical model, which can be expanded to MUAPs of different amplitudes by adding an amplitude factor to the $x_{\omega,n}$ values. To expand the model for MUAPs of different shapes one must add the equivalent terms for each group of MUAPs to Eq. (2). One obtains a modulation spectrum G for each group of MUAPs and additional cross terms that add contributions that are proportional to the correlations between the differently shaped MUAPs. If the shapes are very dissimilar the correlations become small and the contribution of the cross terms vanish. If their power spectra are very similar, then we can treat them as a single group. In any case, the computation will be more complex.

The flow of computations that was used to generate the results in Fig. 1 starts by selecting a distribution of the locations of the MUAPs to compute the modulation spectrum. For a selected MUAP one computes its power spectrum. Finally, the modulation spectrum is multiplied by the power spectrum of the MUAP, which yields the modelled power spectrum. The model was applied to a number of N MUAPs that arrived in a cluster and were distributed in time according to a normal distribution of width σ. The width represents the window size of the cluster. To compute a power spectrum, a MUAP was used that has the shape shown by Merletti and Lo Conte [5] in their Fig. 1 for a non-fatigued condition (Fig. 1C insert). The MATLAB-code to compute the modulation spectrum is added in the appendix.

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