The Influence of Force Level and Motor Unit Coherence on Nonlinear Surface EMG Features Examined Using Model Simulation

Author List: Diego Pereira Botelho, Matthew W. Flood, and Madeleine M. Lowery

Corresponding Author: Dr Lara McManus

School of Electrical and Electronic Engineering,

University College Dublin, Belfield, Dublin 4, Ireland

lara.mc-manus@ucdconnect.ie

Affiliations: L. M. McManus, Diego Pereira Botelho, Matthew W. Flood, and M. M. Lowery are with the School of Electrical and Electronic Engineering, University College Dublin, Ireland. (e-mail: lara.mc-manus@ucdconnect.ie, madeleine.lowery@ucd.ie).

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Abstract

Nonlinear features extracted from surface EMG signals have been previously used to infer information on coherent or synchronous activity in the underlying motor unit discharges. However, it has not yet been assessed how these features are affected by the density of the surface EMG signal, and whether changes in the level of muscle activation can influence the effective detection of correlated motor unit firing. To examine this, a motoneuron pool model receiving a beta-band modulated cortical input was used to generate correlated motor unit firing trains. These firing trains were convolved with motor unit action potentials generated from an anatomically accurate electrophysiological model of the first dorsal interosseous muscle. The sample entropy (SampEn) and percentage determinism (%DET) of recurrence quantification analysis were calculated from the composite surface EMG signals, for signals comprised of both correlated and uncorrelated motor unit firing trains. The results show that although both SampEn and %DET are influenced by motor unit coherence, they are differentially affected by muscle activation and motor unit distribution. The results also suggest that sample entropy may provide a more accurate assessment of the underlying motor unit coherence than percentage determinism, as it is less sensitive to factors unrelated to motor unit synchrony.

Introduction

During steady muscle contractions, motor unit discharges are not completely independent, and their firing trains tend to be weakly coupled across a range of frequencies. Motor unit synchrony, or coherence, is widely believed to reflect functional connectivity between the motoneuron pool and oscillatory cortical activity (Baker et al. 2003; Conway et al. 1995). Changes in corticomuscular, intermuscular and motor unit coherence, particularly within the beta frequency range (15-35Hz), have previously been used to investigate changes in connectivity during neuromuscular fatigue and in disease states (McManus et al. 2016; Norton and Gorassini 2006). Traditionally, motor unit coherence was calculated between pairs of units recorded intramuscularly (Kilner et al. 2002). More recently, composite spike trains have been used to generate enhanced coherence estimates, with each composite train consisting of a number of simultaneously active motor units recorded with surface EMG decomposition (Farina et al. 2014; McManus et al. 2016). Estimation of intramuscular coherence from motor unit firing times provides a high degree of accuracy, however, it requires carefully controlled experimental conditions. To allow more experimental flexibility and facilitate recording of motor unit coherence outside of strict laboratory conditions, several studies have explored alternative features that may provide an assessment of synchrony which can be applied to the surface EMG interference signal (Farina et al. 2002; Holtermann et al. 2009).

Nonlinear features of surface EMG signal complexity and deterministic structure can provide a measure of the structure or synchrony in the underlying motor unit activity. Sample entropy (SampEn) and percentage determinism (%DET) of recurrence quantification analysis plots are two such measures that have been shown to capture differences in the surface EMG signal structure under conditions where normal motor unit synchronization is enhanced, including during muscle fatigue (Cashaback et al. 2013; Farina et al. 2002; Mesin et al. 2009; Webber et al. 1995) and in Parkinson's disease (Fattorini et al. 2005; Flood et al. 2019; Meigal et al. 2009). However, these nonlinear features exhibit large intra-subject variability (Flood et al. 2019), and previous studies have suggested that they may be sensitive to factors unrelated to synchrony, including muscle fiber conduction velocity and changes in muscle contraction force (Cashaback et al. 2013; Del Santo et al. 2007; Farina et al. 2002; Istenič et al. 2010; Meigal et al. 2009). Higher levels of muscle activation produce denser surface EMG signals, as additional motor units are recruited, and the firing rates of active units are increased (McManus et al. 2015). Thus, in order to implement SampEn and %DET measures effectively, it is necessary to distinguish how they are affected by alterations in surface EMG density at higher muscle activation levels, in addition to intra-subject differences in physiology (e.g. muscle size, motor unit distribution). The aim of the present study was to investigate how increases in motor unit recruitment and firing rate modulation with increasing muscle activation influence the sensitivity of SampEn and %DET to changes in the underlying motor unit coherence.

Methods

A model of the motoneuron pool receiving a branched, beta-band modulated cortical input was used to simulate motor unit firing times for 10%, 20%, 30% and 40% of the maximum voluntary contraction (MVC). Motoneuron firing times were convolved with motor unit action potentials, generated from an anatomically accurate electrophysiological model of the first dorsal interosseous (FDI) muscle and the action potential trains were summed to generate four surface EMG channels. The sample entropy and percentage determinism of the surface EMG signals were then calculated for different motor unit distributions, densities, and beta-band modulation strengths.

Motoneuron Model

The model of the motoneuron pool was based on the model described in (Lowery and Erim 2005) and was comprised of 100 motoneurons, simulated using a single compartment threshold-crossing model (Powers 1993). In Lowery and Erim (2005) each motoneuron received an independent and common input, comprised respectively of an activation current and a beta-band modulated or oscillatory current. In the present study a more physiologically realistic implementation of the cortical input was used. The correlated common input signal was chosen to generate motor unit coherence spectra qualitatively similar to those recorded experimentally (McManus et al. 2016). First, a beta-band modulated signal was created by summing two band-pass filtered random Gaussian signals, filtered using 4^{th} order Butterworth filters between 12-18 Hz and 27-33 Hz, respectively. This beta-band modulated signal was then used as a common input to an integrate and fire encoder, as described in (Halliday 1998), in order to generate 2000 weakly correlated spike trains ("corticomotoneuronal (CM) neurons", Fig. 1). Each motoneuron (MN) received input from 100 of these colored spike trains, with approximately 15% of the signals shared between motoneurons. Each motoneuron also received two independent asynchronous inputs, one excitatory and one inhibitory. Motoneuron input currents were adjusted to produce motor unit activation patterns comparable to those recorded experimentally (McManus et al. 2016; Seki and Narusawa 1996). The force produced by each motor unit, based on the Fuglevand model (Fuglevand et al. 1993), was summed, and the total force generated was continuously compared to a target force (10%, 20%, 30% and 40% MVC) and adjusted based on the difference between the two. To quantify the level of coherent activity in the motoneuron pool, the magnitude squared coherence estimate was obtained from composite spike trains, generated with 40 randomly chosen motor units from the model (McManus et al. 2016).

Figure 1

Motoneuron Model

The motoneuron pool model was coupled to a model of the FDI muscle based on that described in (Pereira Botelho et al. 2017). Information on anatomically accurate muscle fiber architecture in the FDI muscle during index finger abduction was incorporated into this model, with fiber orientation and curvature derived from diffusion tensor imaging. Physiologically realistic extracellular action potential waveform shapes were generated for the motor unit population using an anatomically accurate finite element model of the hand. This finite element model computed the effect of geometrical and electrical tissue properties on the MUAP shapes and incorporated FDI muscle anisotropy. The electrode used in simulations consisted of five point electrodes located at the corners and center of a 5 × 5 mm square, based on the electrode used in previous experimental studies (McManus et al. 2015). Pairwise differentiation yielded four action potential representations for each motor unit. Motor unit action potential distributions were generated for the FDI muscle during abduction (N = 18). The MUAPs were then convolved with 60 randomly chosen firing trains from the motoneuron model and summed to yield four channels of surface EMG signals. This process was performed for firing trains receiving 1) a weakly beta-band modulated input and 2) no synchronous input.

Nonlinear Measures

Before analysis, the surface EMG signal was lowpass filtered and downsampled to 1kHz. Recurrence quantification analysis was performed on 7 non-overlapping 1.5 s segments of the surface EMG signal during the periods of constant force production in each trial. The parameters selected to calculate the %DET of the recurrence plots were chosen to effectively capture the dynamics of motor unit firing patterns (i.e. time delay = 1, embedding dimension = 15 [typical MUAP duration ~ 15ms], minimum diagonal line = 10 and radius = 20% maximum distance) (Flood et al. 2019; Marwan et al. 2007). The median value over all channels and segments was used as the representative value for %DET. The surface EMG signals were also assessed using SampEn, which is a measure of signal complexity and regularity that has been derived specifically for physiological time-series signals (Richman and Moorman 2000). The SampEn during the constant force trials was calculated over three 7 s windows with an overlap of 4.5 s. The tolerance r for the SampEn calculation was given by 0.2 times the median absolute deviation of the surface EMG signal segment. The embedding dimension was empirically set to 3 and the median value over all windows and channels in the 3rd dimension was used as the

representative value for SampEn. Full details of the parameters and equations used to calculate %DET and SampEn are provided in (Flood et al. 2019).

Statistics

The influence of both the force level of the muscle contraction (Force) and the underlying beta-band motor unit activity (Beta) were investigated with a linear mixed effects model with maximum likelihood fit using the lme4 library in the software R (Bates et al. 2011). Force and level of beta modulation (ON or OFF) were entered as fixed effects in the model and motor unit distribution was included as a random effect. A random intercept chosen for each motor unit distribution to account for baseline differences in motor unit physiology that could account for some of the variance in SampEn and %DET. The intra-class correlation coefficient (ICC) was also calculated to report the proportion of variance in the nonlinear features that could be explained by the grouping structure (i.e. variability due to differences in the motor unit distribution).

Results

Surface EMG signals were generated from 10%-40% MVC, using motor unit firing trains that were uncorrelated, Fig. 2 (A) & (B), or moderately correlated in the beta-band range, Fig. 2 (C) & (D). The SampEn and %DET values for both uncorrelated and correlated motor unit firing trains are shown for each simulated force level in Fig. 3. The relative effect of contraction force and correlation in the motor unit discharges on the nonlinear measures is summarized in Table 1. The ICC for SampEn was 0.04, lower than the 0.31 observed for %DET.

Figure 2

Figure 3

Table 1

Discussion

The present study demonstrates that surface EMG sample entropy and percentage determinism can be used to provide information on correlated or synchronous motor unit activity, but that future studies should consider the level of muscle activation as an additional factor that could significantly influence these measures. The results show for the first time that SampEn and %DET are disparately affected by properties of the surface EMG signal unrelated to motor unit synchrony. The higher ICC value reported for %DET suggests that this measure is more sensitive to motor unit distribution representative of intra-subject differences in motor unit physiology. If few active motor units are distributed within the detection volume of the recording electrode, this could result in a sparse EMG signal with action potentials from a small number of units dominating the EMG signal, particularly at lower force contractions. These sparse EMG signals are likely to affect the accuracy at which recurring states are identified. A recurrence is marked each time the phase space trajectory returns to a location in phase space that it has visited before, within a designated radius. In the present study, the radius was chosen as a percentage of the maximum inter-state distance, which at low forces could effectively be the action potential amplitudes of a small number of motor units. Thus, random fluctuations in the EMG signal voltage that do not contain any information on motor unit activity may be more likely to fall within the radius and be marked as a recurrence. This could also explain why %DET measures were more sensitive than SampEn to increases in motor unit recruitment and firing rate modulation with increasing abduction force, Table 1. As the density of the surface EMG signal is increased, the maximum inter-state distance becomes more representative of the mean amplitude of the signal, and recurrence identification is likely to be more accurate. Accordingly, %DET increased significantly in the presence of beta-band motor unit coherence at 30% and 40%MVC, Fig. 3 (B).

Though SampEn was also influenced by the level of muscle activation, the presence of coherent beta-band activity in the underlying motor unit discharges had a greater effect on the SampEn value, Table 1. Beta-band activity was effectively detected at all force levels, Fig. 3 (A). The results suggest that SampEn should be preferred over %DET to detect changes in motor unit coherence in conditions where changes in coherent activity could be masked by alterations in the composition or density of the surface EMG signals (i.e. at different muscle forces or when comparing EMG between healthy and disease states). Collectively, the results highlight that the utility of SampEn and %DET measures lies in detecting changes or differences in motor unit coherence between conditions or subject groups, and that an individual SampEn/%DET value should not be used in isolation to infer information on the absolute strength of correlated motor unit activity.

The results presented have examined surface EMG signals simulated for an electrode array with small electrode surface area and inter-electrode distance in the first dorsal interosseous muscle. However, the relative sensitivity of both nonlinear features to muscle activation and correlated motor unit activity could be influenced by the muscle geometry and electrode configuration. Further work is needed to investigate whether the results of the present study would change for other electrode configurations. A bipolar electrode with larger inter-electrode distance would have a larger detection volume, with denser surface EMG signals containing information on the activity of a larger motor unit sample. EMG signals simulated for other muscles could also exhibit distinct trends. For example, larger limb muscles have fewer cortical connections than the muscles of the hand, and the correlation between motor unit firing trains from these muscles could be weaker as a result. Higher levels of subcutaneous fat would also influence the structure of the surface EMG signal, as surface-detected action potentials would be longer in duration due to the spatial low pass filtering effect of the tissue (Lowery et al. 2002). Future work could also explore whether alternative methods of calculating the radius are more accurate at detecting recurrences, for example the fixed amount of nearest neighbors method (Marwan et al. 2007). Finally, the results highlight the need for further simulation work to elucidate how each of the nonlinear features could be optimized to expressly detect changes in motor unit coherence.

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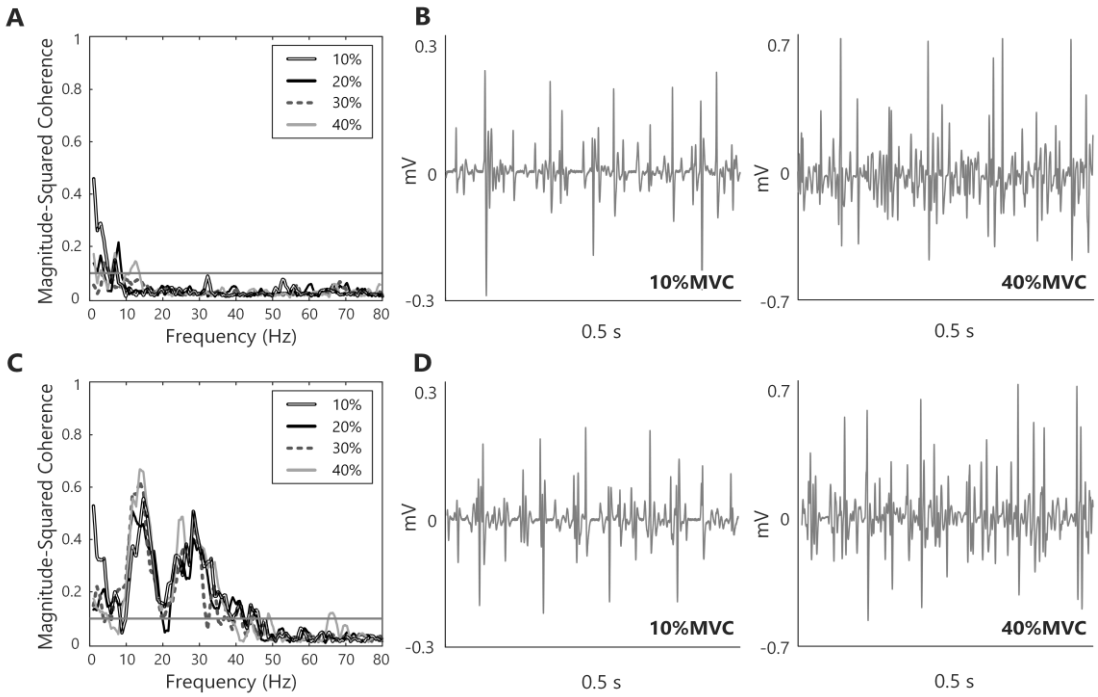

Figure 2. Motor unit coherence when there was (A) no correlated input to the motoneuron and (C) correlation in the beta-band range, and the corresponding surface EMG signals, (B) & (D) respectively, at 10%MVC and 20%MVC.

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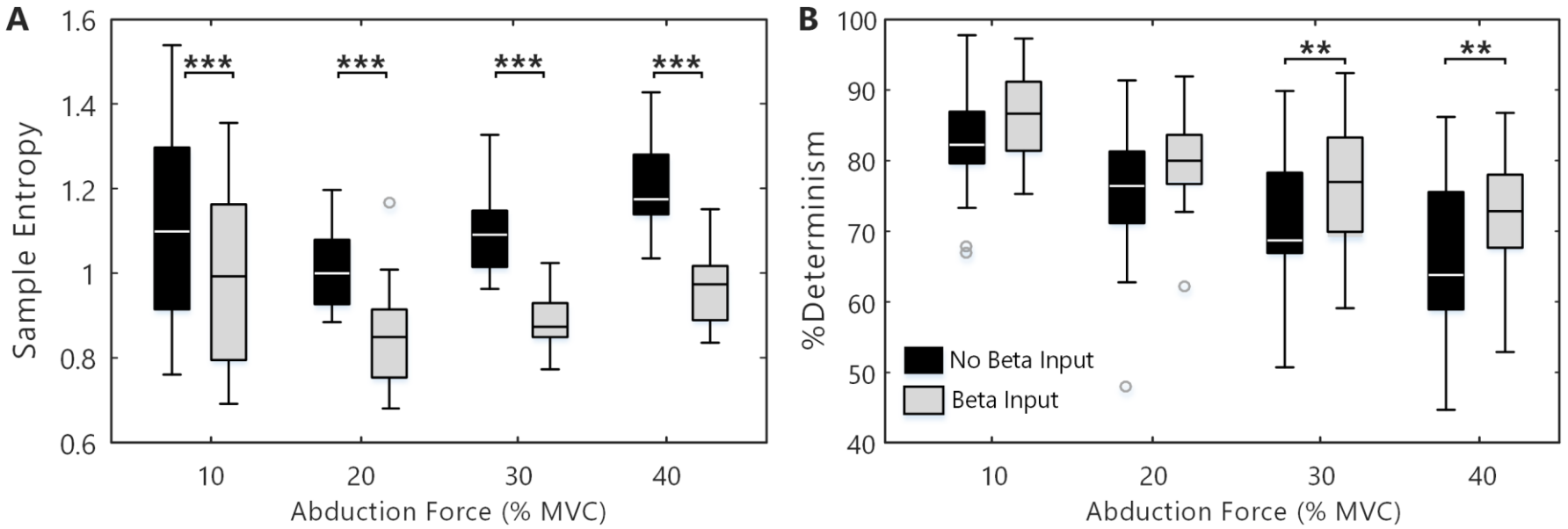

Figure 3. (A) SampEn and (B) %DET at each force level with either no correlated input to the motoneuron or beta-band correlation, **p<.01, ***p<.001.

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TABLE I. MIXED MODEL ANOVA RESULTS

A	**Sample Entropy**			
Model Term	***df 1/2***	***F-Stat***	***p-value***	***Partial R^2***
Force	3/122	8.4	<.001	0.1
Beta	1/122	16.1	<.001	0.26

B	**% Determinism**			
Model Term	***df 1/2***	***F-Stat***	***p-value***	***Partial R^2***
Force	3/122	26.9	<.001	0.62
Beta	1/122	16.6	<.001	0.05

Table 1. Mixed model ANOVA results using the Kenward-Roger approximation for degrees of freedom investigating the effect of abduction force (Force) and correlated beta-band input (Beta) on (A) sample entropy and (B) percentage determinism.