Influence of high motor unit synchronization levels on non-linear and spectral variables of the surface EMG

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Abstract

The aim of this study was to investigate the influence of high degrees of motor unit synchronization on surface EMG variables extracted by linear and non-linear analysis techniques. For this purpose, spectral and recurrent quantification analysis (RQA) were applied to both simulated and experimental EMG signals. Synthetic surface EMG signals were generated with a model of volume conductor comprising muscle, fat, and skin tissues. The synchronization was quantified by the percent of discharges of each motor unit synchronized with discharges of other motor units. The simulated signals presented degrees of synchronization in the range 0–80% (10% increments) and three mean values of motor unit conduction velocity distribution (3, 4 and 5 m/s). Experimental signals were collected from the first dorsal interosseous muscle of five patients with Parkinson disease during 10 s of rest and 10 s of isometric voluntary contraction at 50% of the maximal force. Mean power spectral frequency (MNF) and percent of determinism (%DET) of the surface EMG were computed from the simulated and experimental signals. In the simulated signals, %DET was linearly related to the level of synchronization in the entire range considered while MNF was sensitive to changes in synchronization in a smaller range (0–20%), outside which it levelled off. The experimental results indicated that %DET was significantly higher in the resting condition (with presence of tremor; mean ± S.E., 85.4 ± 0.8%) than during the voluntary contraction (which partly suppressed tremor; 60.0 ± 2.3%; P < 0.01). On the contrary, MNF did not depend on the condition (114.3 ± 1.5 Hz and 118.0 ± 0.8 Hz for the resting and voluntary contraction, respectively), confirming the simulation results. Overall, these results indicated that linear and non-linear analyses of the surface EMG may have different sensitivities to the underlying physiological mechanisms in specific conditions, thus their joint use provides a more complete view of the muscle status than spectral analysis only.

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1. Introduction

The extraction of information from the surface EMG signal may be based on the separation of single motor unit (MU) contributions or on the analysis of global signal features, which are indirectly related to the underlying physiology (Farina et al., 2004). In the second case, the major challenge is to determine the factors, which influence global features and to understand how global characteristics provide information relevant from the physiological or clinical point of view.

In the last years, the use of models of surface EMG generation has significantly contributed to the understanding of the main factors which affect classic EMG descriptors, such as amplitude or spectral variables (e.g. Farina and Rainoldi, 1999; Farina et al., 2002a, 2002b). In addition to these signal descriptors, there is a variety of variables that can be extracted from the surface EMG, often with techniques developed in other research areas. Among the methods used to process EMG signals, non-linear techniques have recently
In particular, recurrence gained large attention (Eckmann et al., 1987; Felici et al., 2001a, 2001b, 1999) and has proven to be useful in characterizing dynamical systems. RQA has been used in many surface EMG experimental studies (Webber et al., 1995; farina et al., 2001a, Filligoi and Felici, 1999) and has been proven to provide information on the fatigue-related changes in EMG features (Ikegawa et al., 2000; Farina et al., 2002b). Among the variables extracted with RQA, the percent of determinism (%DET) indicates the presence of recurrent patterns hidden in the interference signal (Filligoi and Felici, 1999; Farina et al., 2002b). For this reason, it has been hypothesized that %DET is more sensitive than spectral variables to specific physiological mechanisms, such as MU short-term synchronization.

In a previous simulation study, we have shown that changes in muscle fiber conduction velocity or degree of MU synchronization affect both spectral variables and %DET (Farina et al., 2002b). Those simulations were however limited to relative small changes in the degree of synchronization, such as those observed experimentally in most physiological conditions (De Luca et al., 1993). In these conditions, linear and non-linear variables provide similar information and the use of one of the two methods can be based on sensitivity or robustness to noise (Farina et al., 2002b). Nevertheless, there can be other physiological or pathological situations in which the level of MU synchronization is higher than that simulated by Farina et al. (2002b). This may occur in physiological tremor (Dietz et al., 1976; Halliday et al., 1999; Filligoi et al., 2001a) or Parkinson’s disease (Burne, 1987; Vaillancourt and Newell, 2000).

We hypothesized that the linear relation between the degree of synchronization and spectral frequencies, observed by Farina et al. (2002b), may not hold for a larger range of synchronization levels, as also reported by Hermens et al. (1992). On the contrary, the relation between %DET and the degree of MU synchronization may be valid for any range of synchronization levels since %DET reflects the repetition of recurrent structures in the signal, which should increase as synchronization increases. If these hypotheses hold, linear and non-linear surface EMG analysis reflect different mechanisms in some conditions, thus their joint use may give a more complete view of the muscle status. The aim of this study was to investigate the influence of high degrees of synchronization on %DET and spectral frequencies. For this purpose, we tested spectral analysis and RQA on a set of simulated and experimental EMG signals.

2. Materials and methods

2.1. Simulations

Simulation of surface EMG signals implies the computation of the electric potential distribution generated by the intracellular action potentials (at the level of the muscle fiber membrane) over the skin. Once the MU action potentials are simulated, the model should generate the activation of the MUs by the central nervous system.

The surface EMG model described by Farina and Merletti (2001) was applied in this study. This model simulates synthetic MU action potentials generated by finite length fibers and detected by surface electrodes with physical dimensions. The volume conductor (i.e. the tissues separating the muscle fibers and the recording electrodes) comprises muscle, fat and skin tissues, separated by planar layers. Muscle tissue was considered anisotropic while the other layers were isotropic. The description of the effect of the volume conductor on the surface potential distribution was performed by the two-dimensional spatial transfer function between the transmembrane current density source and the surface potential. The intracellular action potential was described in the spatial domain as proposed by Rosenfalck (1969). The generation and extinction of the intracellular potential at the end-plate and tendon was modeled under the assumption that the integral of the current density over the muscle fiber length is zero in each instant of time.

The physical parameters of the model were selected as in Farina et al., (2002b). The simulated muscle fibers had a mean semi-length of 65 mm and were grouped in 65 MUs, each comprising a number of fibers in the range 50–450 (uniform distribution of the number of fibers in the MUs). The MU fiber density was 20 fibers/mm² while the fiber density in the muscle was 200 fibers/mm² (Fuglevand et al., 1993). The EMG recording system was bipolar with 20 mm inter-electrode distance.

To obtain the distribution of discharge rates of the active MUs, it was assumed that the generated force was corresponding to the recruitment threshold of the highest threshold MU in the simulated set, with discharge rates increasing linearly with force (minimum discharge rate 8 pulses per second, maximum 35 pps). The recruitment threshold depended on the MU size, following an exponential function, as proposed by Fuglevand et al. (1993). The 65 MUs had a Gaussian distribution of conduction velocity with standard deviation 0.3 m/s. MUs with larger number of fibers had higher conduction velocity than MUs with smaller number of fibers, as observed experimentally (Andreasen and Arendt-Nielsen, 1987).

The activation times of the active MUs were firstly generated independently (no synchronization) on the basis of the calculated mean discharge rates and inter-pulse interval variability (20% of the inter-pulse interval). Then, synchronization was imposed by shifting randomly selected times of occurrences. The percent of synchronization was defined as the percent of activations of a MU, which was synchronized, with activations of other MUs, as proposed by Yao et al. (2000).

Simulated signals were generated by varying (1) the mean value of conduction velocity distribution (3, 4, 5 m/s) and (2) the degree of synchronization (0–80%, 10% increment). For
each pair of mean conduction velocity and synchronization level, 50 signals were simulated as generated by the same MEIs but in different, random locations within the muscle. Thus, 1350 synthetic signals were simulated in total. The sampling frequency was 1024 Hz, the duration 5 s, and all simulated signals were noise free.

2.2. Experimental protocol

2.2.1. Subjects

Five patients (three males; age, mean ± S.D., 66.4 ± 6.8 years) with idiopathic tremor-dominant Parkinson’s disease participated in the study. For all patients, unilateral tremor was the most prominent symptom, being akinesia and rigidity less pronounced, with only minimal head or trunk tremor. None of the patients had a history of neurological diseases other than Parkinson’s disease. When the experiments were performed all subjects were in pharmacological wash-out condition since at least 12 h. All patients involved in the study gave their informed consent. The study was approved by the local Ethics Committee.

2.2.2. Force and EMG recordings

The right (dominant in all cases) hand was positioned in an apparatus where the wrist and fingers, except the index, were constrained with velcro straps (Fig. 1). The index finger was free to move in the horizontal plane. A piezoelectric force transducer (Kistler Instrument, type 9203) was in contact with the first phalanx of the index finger. The force signal was amplified with a charge amplifier (Kistler Instrument AG, type 5001).

A pair of reusable surface EMG silver disc electrodes (diameter 8 mm; SATEM, Italy) were placed on the belly of the first dorsal interosseous (FDI) muscle, 20 mm apart. Before electrode placement, the skin was treated with sandpaper and alcohol to reduce skin-electrode impedance. EMG signals were amplified (portable electromyograph SATEM, mod. VD 1004), filtered (10–400 Hz), sampled at 2048 Hz, and converted in numerical format by a 12 bit A/D converter.

2.2.3. General procedures

Each subject performed three trials of maximum isometric voluntary contraction (MVC), lasting 5 s and separated by 5-min rest. The highest recorded force was assumed as the reference MVC. After the MVC measure, the subject was asked to completely relax the index finger for 5 min. Surface EMG and force signals were then recorded in the following conditions: 10 s of rest and 10 s of voluntary isometric contraction at 50% MVC. During the voluntary contraction, a real time feedback on the force exerted was provided to the subject by an oscilloscope. The same experimental procedure was repeated twice in two sessions separated by 15 min.

2.3. Data analysis

Both simulated and experimental signals were divided in 1-s long portions (epochs). From each epoch, %DET was computed by RQA as described by Filligoi and Felici (1999) and mean frequency (MNF) was estimated from the periodogram. For each 5 s long simulated signal, the five %DET and MNF values were averaged to obtain a value representative of the specific simulated physiological condition. For the

Fig. 1. Schematic drawing of the experimental set-up. The hand is constrained at the wrist level. The index finger is placed in an anatomical support and a piezoelectric transducer measured force. Forward hand shift is avoided with a constraint at the thumb (‘pivot’). All constrains and the index support are adjustable in position to adapt to the anatomy of the patient.
experimental signals, the data analysis resulted in ten %DET and MNF estimates for each trial and each condition (rest or voluntary contraction).

2.4. Statistical analysis

Results are presented as mean ± S.D. or mean ± S.E., as indicated. The experimental data were analyzed using three-way repeated measures analysis of variance (ANOVA) to investigate the influence of trial (two trials for each subject), condition (rest or voluntary contraction), and epoch (10 epochs of 1 s for each trial and condition) on MNF and %DET. Significant interactions were followed by post hoc Student–Newman–Keuls (SNK) pair-wise comparisons. The alpha level for statistical significance was set to \( P \leq 0.05 \).

3. Results

3.1. Simulated signals

MNF and %DET computed from the simulated signals are shown in Fig. 2 for the nine synchronization levels and the three mean conduction velocity values. In each physiological condition, the mean and standard deviation of the measured variables was derived from the 50 simulations with random MU locations within the muscle. The change in MU location had a rather limited effect, especially for high synchronization levels.

In agreement with previous results (Farina et al., 2002b), increase in mean conduction velocity determined an increase in MNF and a decrease in %DET. Sensitivity of both MNF and %DET to mean conduction velocity was maintained for the entire range of investigated synchronization levels.

With increase in degree of synchronization, MNF decreased and %DET increased. However, while %DET linearly increased as the percent of synchronization in the entire range investigated, MNF decreased over a smaller range of synchronization degrees (0–20%) and then remained almost constant. The correlation coefficient between %DET and percent of synchronization was (mean ± S.D.) over the 50 simulated signals 0.97 ± 0.01 (mean conduction velocity 3 m/s), 0.92 ± 0.01 (4 m/s), and 0.95 ± 0.03 (5 m/s).

3.2. Experimental signals

Fig. 3a shows a representative experimental recording. In the first 10 s, during rest, the force signal reflects the finger tremor. At rest, tremor is clearly associated to a periodical burst-like EMG activity. On the contrary, in the voluntary contraction, the activity seems continuous rather than at bursts. MNF and %DET computed along this specific recording are reported in Fig. 3d and e. While MNF does not change in the two conditions, %DET decreases when passing from the resting condition to the voluntary contraction.

A three-way ANOVA of MNF with factors the trial (two tests separated by 15 min), condition (rest or voluntary contraction), and epoch (10 epochs for each trial and condition) was not significant (Fig. 4A). On the contrary, %DET significantly depended on the condition (three-way ANOVA: \( F = 24.4, P < 0.01 \); Fig. 4B). Post hoc SNK test showed that %DET in the resting condition (mean ± S.E., 85.4 ± 0.8%) was significantly higher than during the voluntary activation (60.0 ± 2.3%) \( (P < 0.01) \). From Fig. 4 the different sensitivity of the two variables to the change of condition can be clearly appreciated.

4. Discussion

In this study we analysed the influence of high levels of MU synchronization on MNF and %DET through simulated and experimental EMG signals. The simulations revealed that %DET was linearly related to the level of synchronization in the entire range investigated (0–80% of synchronization) while MNF was sensitive to changes in synchronization in a smaller range (0–20%). The experimental results indicated that %DET, but not MNF, could distinguish between conditions of presence or absence of pathological tremor. Overall, these results indicated that the linear and non-linear analysis of the surface EMG may provide complementary information in specific muscle conditions.

4.1. Effect of motor unit synchronization on surface EMG features

The surface EMG power spectrum depends on the active MU action potential shapes and on MU discharge patterns
In case of independent discharge patterns, the contribution of the discharge statistics is limited to the low frequency portion of the spectrum (Lago and Jones, 1977). The correlation between discharge patterns, such as occurs with MU synchronization, enhances the low frequency peaks of the EMG spectrum (Weytjens and Van Steenberghe, 1984), which determines a decrease in characteristic spectral frequencies (Hermens et al., 1992; Farina et al., 2002b). The results of the present study indicated that for high synchronization levels, the sensitivity of spectral variables to modifications in MU synchronization was small (almost no changes in MNF with increasing synchronization above 20%; Fig. 2). This is in agreement with previous results by Hermens et al. (1992) who noted that, after an initial decrease, spectral variables tended to level off and even increase for high degrees of MU synchronization.

Fig. 3. (A) Surface EMG signal and force recorded from a Parkinsonian subject during the experimental session. Representative zoomed views of the two signals during rest (B) and isometric voluntary contraction (C). Time courses of MNF (D) and %DET (E) estimated from the surface EMG.

Fig. 4. Average (± S.E.) MNF (A) and %DET (B) for the 10 epochs in the two conditions analysed (rest and voluntary contraction). MNF does not change between the two conditions while %DET significantly decreases during the voluntary contraction with respect to the resting condition. In the first 10 s (resting condition), %DET reaches values of approximately 90% that reveal an almost complete deterministic pattern in the surface EMG (Filligoi and Felici, 1999).
As a consequence of its mathematical derivation (Filligoi and Felici, 1999), %DET reveals recurrent patterns in a signal. Synchronization of MUs increases the number of recurrent patterns, thus influencing %DET. This was indirectly observed from experimental recordings (Felici et al., 2001a) and directly proved by surface EMG simulation (Farina et al., 2002b). The hypothesis tested in this study was that the relation between MU synchronization and %DET, observed for relatively low synchronization levels (Farina et al., 2002b), also holds for higher degrees of synchronization, contrary to MNF. The simulation results indeed showed that the linear relation %DET-synchronization observed previously (Farina et al., 2002b) remained almost unchanged when increasing the synchronization range (Fig. 2). As a consequence, the correlation between %DET and MNF was disrupted by high synchronization. This indicated that specific characteristics of the signals cannot be revealed by spectral analysis but by RQA only. The simulations were performed with the same model parameters used in a previous work (Farina et al., 2002b), in order to compare the results. The data obtained for the low synchronization range were indeed in complete agreement with the previous ones.

In order to validate the simulation results on an experimental basis, we analyzed two muscle conditions in which a different degree of synchronization, together with other pathological alterations, was hypothesized. In particular, it was necessary to reach high degrees of MU synchronization, usually not found in physiological conditions. De Luca et al. (1993) showed that during low force isometric contractions in healthy young subjects the amount of synchronous events (coupled discharges of MU pairs) was about 8% of the total number of discharges. On the other hand, Dietz et al. (1976) observed that physiological tremor is associated with a high degree of MU synchronization and that the tremor force produced by one muscle or a pair of synergistic muscles is the result of the synchronized MU activity. Vaillancourt and Newell (2000) provided convincing evidence of MU synchronization in Parkinsonian patients. This view has received further support by the demonstration of the cyclic nature of the activation of many cortical, sub-cortical and spinal motor regions in Parkinson’s disease and of their strong coherence with the EMG bursts (Timmermann et al., 2003). It has to be underlined that only MU synchronization, in an otherwise regular set of discharge patterns, was included in the simulation analysis. This condition is clearly limiting when compared to the complex pathophysiological mechanisms which determine the specific EMG activity during tremor in Parkinsonian patients. Thus, the simulated signals should not be considered as resembling the experimental recordings or as the light of reproducing exactly the experimental signal features. There is no possibility of assessing the degree of MU synchronization in the patients from the present data, thus it is not possible to associate the experimental results to a specific point of the %DET-synchronization curve shown in Fig. 2. The experimental protocol was designed to have sets of experimental signals with different characteristics (tremor and voluntary contraction) determined partly by different levels of synchronization among the activities of the MUs. The main aim of the experimental analysis was to compare two conditions for which %DET and MNF provided different information. This was probably due to synchronization and to other pathological alterations occurring during the tremor phase of the Parkinsonian patients.

It was expected that, according to the simulation results, MNF could not distinguish between the two conditions (rest and voluntary contraction), contrary to %DET. The experimental results matched this hypothesis and showed no changes in MNF with or without substantial tremor, with a concomitant significant modification in %DET (Fig. 4). This contrasts the high correlation between the two variables observed in the fresh and fatigued muscle of healthy subjects (Webber et al., 1995), which was previously interpreted by EMG simulation (Farina et al., 2002b). The lack of correlation between MNF and %DET is explained by the simulation analysis performed in this study which included high degrees of synchronization levels (Fig. 2). This has to be noted that MNF was insensitive to changes in experimental signal characteristics that were clearly evident even by only visual analysis (Fig. 3). Similarly, MNF was insensitive to large changes in MU synchronization in the simulated signals.

4.2. Conclusion

While at low synchronization levels MNF and %DET provide basically the same information (Farina et al., 2002b), the sensitivity of the two variables to high percentages of MU synchronization is very different. In these conditions, %DET reveals signal modifications, which are not detectable by classical spectral analysis. This ability may be useful in characterizing specific conditions of the neuromuscular system.

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