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Rectification and non-linear pre-processing of EMG signals for cortico-muscular analysis

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Abstract

Rectification of the electromyographic (EMG) signal is a commonly used pre-processing procedure that allows detection of significant coherence between EMG and measured cortical signals. However, despite its accepted and wide-spread use, no detailed analysis has been presented to offer insight into the precise function of rectification. We begin this paper with arguments based on single motor unit action potential (AP) trains to demonstrate that rectification effectively enhances the firing rate information of the signal. Enhancement is achieved by shifting the peak of the AP spectrum toward the lower firing rate frequencies, whilst maintaining the firing rate spectra. A similar result is obtained using the analytic envelope of the signal extracted using the Hilbert transform. This argument is extended to simulated EMG signals generated using a published EMG model. Detection of firing rate frequencies is obtained using phase randomised surrogate data, where the original EMG power spectrum exceeds the averaged rectified surrogate spectra at integer multiples of firing rate frequencies. Model simulations demonstrate that this technique accurately determines grouped firing rate frequencies. Extraction of grouped firing rate frequencies prior to coherency analyses may further aid interpretation of significant cortico-muscular coherence findings.

Keywords: Rectification; EMG; Coherence; Motor unit firing rate; Surrogate data; Model

1. Introduction

A number of recent studies have investigated coherence between cortical signals obtained from electroencephalographic (EEG) or magnetoencephalographic (MEG) measurements and electromyographic (EMG) signals (Salenius et al., 1997; Halliday et al., 1998; Mima and Hallett, 1999a,b; Gross et al., 2000; Marsden et al., 2000; Mima et al., 2000; Ohara et al., 2000). These studies have suggested that coherent synchronization between these separate neural systems reflects an underlying functional coupling or communication between them. However, the precise function and meaning of this cortico-muscular coherence still remains unknown and is widely debated.

A common processing step in all these studies is to rectify the surface EMG prior to subsequent coherence analysis. Whilst this procedure is almost always implemented, the rationale behind this step has received very little attention. The few offered explanations are empirical arguments based upon reasoning applied to single motor unit (MU) trains. These arguments suggest that 'full wave rectification of the EMG signal provides the temporal pattern of grouped MU firing regardless of its (the action potential (AP)) shape' (Halliday et al., 1995; Mima and Hallett, 1999a,b). Thus a detailed analysis of the effect of rectification on the power spectrum of the EMG signal could potentially offer useful insight into the interpretation of cortico-muscular coherence.

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The assumption in the literature is that rectification enhances timing or firing rate information of the EMG signal. However, it remains speculative that observed peaks in the spectrum of rectified EMG signals are indeed indicative of such information. We investigate this assumption with an analysis of the effect of rectification that is initially based upon single motor unit AP trains (MUAPT's). This analysis is subsequently extended to composite EMG signals containing many MUAPT's. A priori knowledge of the actual timing information would allow an accurate evaluation of whether the rectified EMG does indeed extract this information. In addition, an objective means of detecting firing rate frequencies is required. Thus the approach adopted here is to generate synthetic EMG signals, with known properties and of varying degrees of complexity. We begin by generating single MUAPT's with known firing rates and these are used to evaluate rectification effects. This is then expanded for more realistic simulations containing multiple MU's. The model utilised in this paper is a physiologically based model of the voluntary EMG signal developed by Lowery et al. (2000). The method of surrogate data is introduced to provide an objective threshold for determination of firing rate frequencies.

2. Analytic methods

The most commonly accepted EMG models represent a MUAPT as a series of unit impulses, or dirac delta functions, $\delta(t)$, applied to a linear time-invariant system with impulse response $h(t)$, which describes the MUAP waveform (Agarwal and Gottlieb, 1975; Basmajian and de Luca, 1985). Thus the output of this filter will be the input delta function spike train, $\delta_T(t)$, convolved with $h(t)$. The EMG signal is the summation of the MUAPT's generated by all of the active MU's within the measured muscle (cf. Fig. 1). We proceed by analyzing a single motor unit spike train before extending this to a composite EMG signal.

2.1. Single motor unit

Coggshall (1973) formulated a number of models for the power spectra of biological transducers and impulse train spectra. These include a strictly periodic spike train, a constant frequency spike train with jitter, a Poisson process and a gamma-erlang process. Of these, the MU firings are best modelled as a periodic spike train with added jitter. The resulting power spectrum, $S_x(\omega)$, is therefore given as

$$S_x(\omega) = \frac{1}{T}\left[1 - |\phi(\omega)|^2 + \frac{2\pi}{T}|\phi(\omega)|^2 \times \sum_{n=-\infty}^{\infty} \delta\left(\omega - \frac{2\pi n}{T}\right)\right] \quad (1)$$

where $1/T$ is the mean motor unit firing rate and $\phi(\omega)$ is the Fourier transform of the probability density function of the random jitter component added to each firing time. The power spectrum of a MUAPT is then the product of the periodic spike train power spectrum with the power spectrum of a single AP, $|H(\omega)|^2$. The resultant spectrum will, therefore, contain peaks at the mean firing rate and its harmonics. In general firing rates of high force contractions are approximately below 40 spikes per s and would be well below this for low to moderate level contractions (Enoka and Fuglevand, 2001). Thus the frequency component located at the firing rate frequency is weighted by the tail end of the AP spectrum and the resultant value of the MUAPT power spectrum at this frequency will be largely reduced. The power spectrum of a single AP was obtained by zero-padding the simulated AP to 1024 samples and then taking the square of the magnitude of a 1024 point FFT of the time series. The power spectrum normalised to its maximum value is depicted in Fig. 2. Superimposed on this is the normalised power spectrum

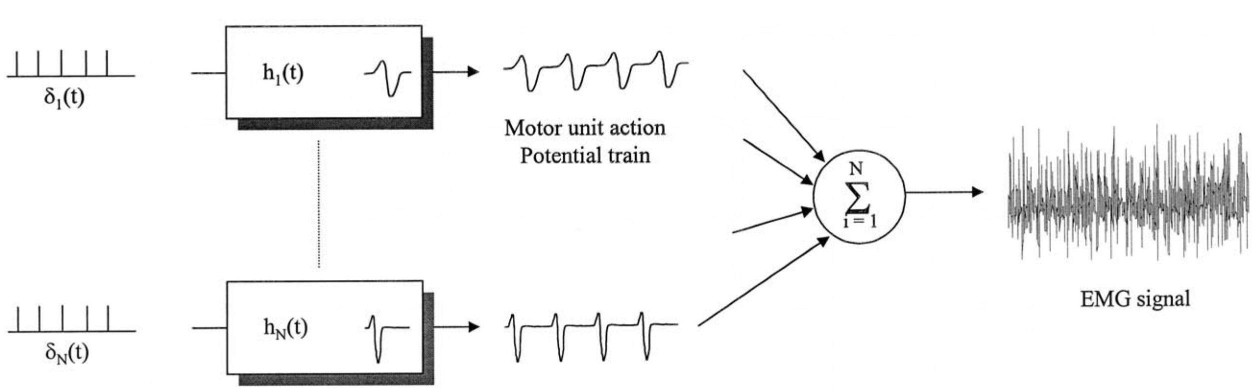

Fig. 1. Linear model for the generation of surface myoelectric signals. Each MUAPT is represented as the response of a linear time-invariant filter to a train of unit impulses.

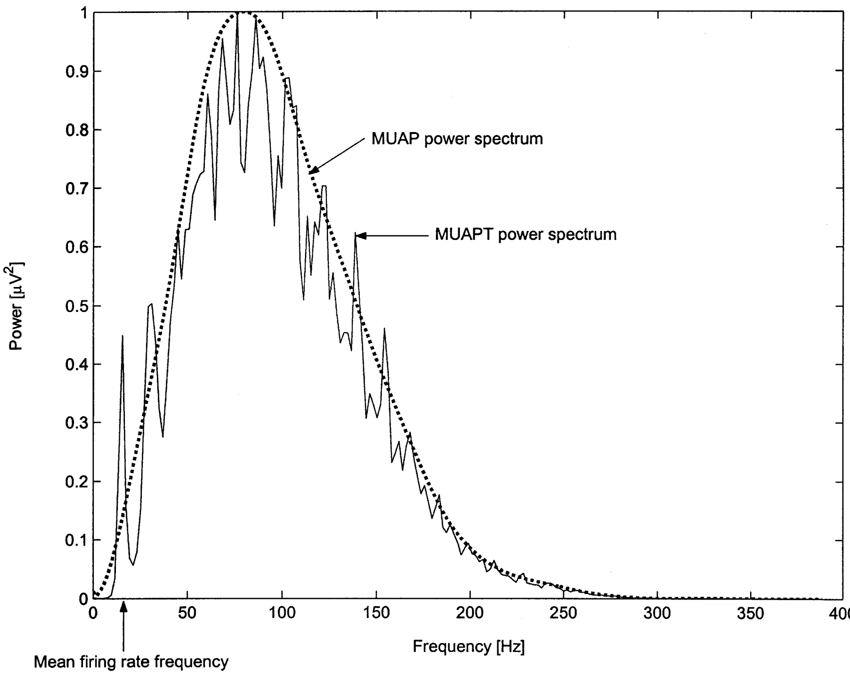

Fig. 2. Power spectrum of a single AP, $|H(\omega)|^2$ (dotted line), along with the power spectrum of a single motor unit firing with a mean rate of 15 spikes per s and a Gaussian distribution about the mean inter-pulse interval (ipi) with a S.D. of 8 ms (solid line). Both figures are normalised to their maximum values, which demonstrates that the power spectrum of a MUAPT is similar in shape to that of a single MUAP. The mean firing rate frequency is indicated in order to demonstrate the relatively low value the product will have at this frequency.

of a single motor unit firing with a mean rate of 15 spikes per s and and a Gaussian distribution about the mean inter-pulse interval (ipi) with a standard deviation (S.D.) of 8 ms in accordance with the experimental observations of Clamann (1969). The constructed MUAPT was sampled at 2000 Hz. The effect of the jitter is visible on the spectrum, as it tends to 'spread' each impulse function, although the basic shape remains intact with visible peaks centered at integer multiples of the mean firing rate frequency.

Many time signals consist of rapidly oscillating components with amplitudes that vary slowly in time. The shape of this slow time variation is often called the signal envelope and removal of the rapid oscillations produces a direct representation of the envelope alone. This concept is frequently used in communication systems to demodulate a signal from a higher frequency carrier wave (de Coulon, 1986) and also has applications in damage diagnosis in motors (Feldman and Seibold, 1999) and EEG analysis (Clochon et al., 1996) amongst others. The MUAPT may be viewed as containing a rapidly oscillating part (the AP shape) with a slow varying amplitude (the timing information) which may be obtained from the waveform envelope. Envelope extraction is in general a non-linear operation and an effective envelope extraction technique may be achieved via the Hilbert transform (de Coulon, 1986; Boashash, 1992). For a given real signal, $x_r(t)$, an analytic signal, $x_a(t) = x_r(t) + ix_h(t) = a(t)e^{i\phi(t)}$, is constructed, where $x_h(t)$ is the Hilbert transform of $x_r(t)$. This is defined as

$$x_h(t) = H[x_r(t)] = p.v. \int_{-\infty}^{\infty} \frac{x_r(t-\tau)}{\pi\tau}\, d\tau \qquad (2)$$

where $p.v.$ denotes the Cauchy principal value of the integral. The envelope of $x_r(t)$ will be given by $a(t)$ and is often referred to as the instantaneous amplitude. Now $a(t) = \sqrt{x_r^2(t) + x_h^2(t)}$ and, therefore, $a(t) \geq |x_r(t)|$. This indicates that the curve representing the rectified signal does not intersect with the curve representing the envelope of the signal. Fig. 3a illustrates the envelope and rectified signals for a single AP waveform used to construct the simulated 15 spike per s MUAPT from above. Thus rectification may be considered as an approximation of the envelope.

Rectification or envelope extraction of a MUAPT only alters the shape of the AP waveform and does not alter the actual delta function spike train. Thus the rectified MUAPT may be considered to be $\delta_T(t)*|h(t)|$, where * denotes the convolution operator. Therefore, the power spectrum of the rectified MUAPT will be the product of the power spectrum of the spike train with

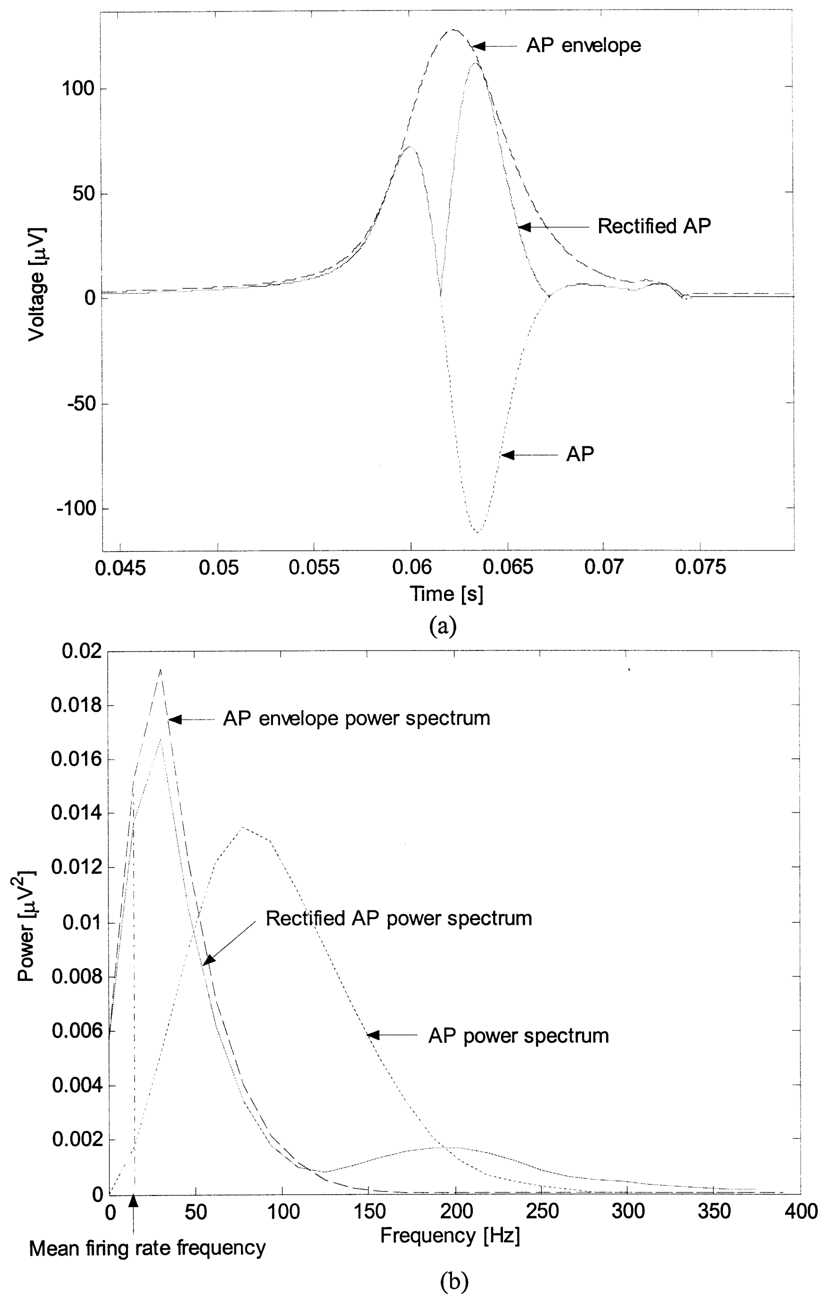

Fig. 3. (a) Time domain: single action potential (AP) waveform (dotted line). The envelope of this waveform is extracted using the magnitude of the analytic function constructed via the Hilbert transform. This envelope (dashed line) is displayed over the waveform, along with the rectified version (solid line) of the waveform. (b) Frequency domain: power spectrum of a single AP (dotted line), along with the power spectra of its envelope (dashed line) and of the rectified signal (solid line). The signals are normalised to have the same RMS values and the mean firing rate frequency is indicated.

the power spectrum of the rectified AP waveform. This is illustrated in Fig. 3b, where the power spectra of a rectified AP and envelope of the AP are represented, along with the power spectrum of the original AP. The signals are normalised to have the same RMS values. From this figure it is clear that the delta function located at the firing rate frequency is now weighted by a far larger value than for the non-rectified signal and thus facilitates easier location. The spectra of the rectified AP and the envelope of the AP are relatively similar. Fig. 4 depicts the power spectra of the rectified and envelope versions of the simulated 15 spikes per s MUAPT from above. The signals are normalised to have the same RMS values. Thus from Fig. 4, it may be seen how the firing rate information is visibly enhanced for the rectified and envelope spectra.

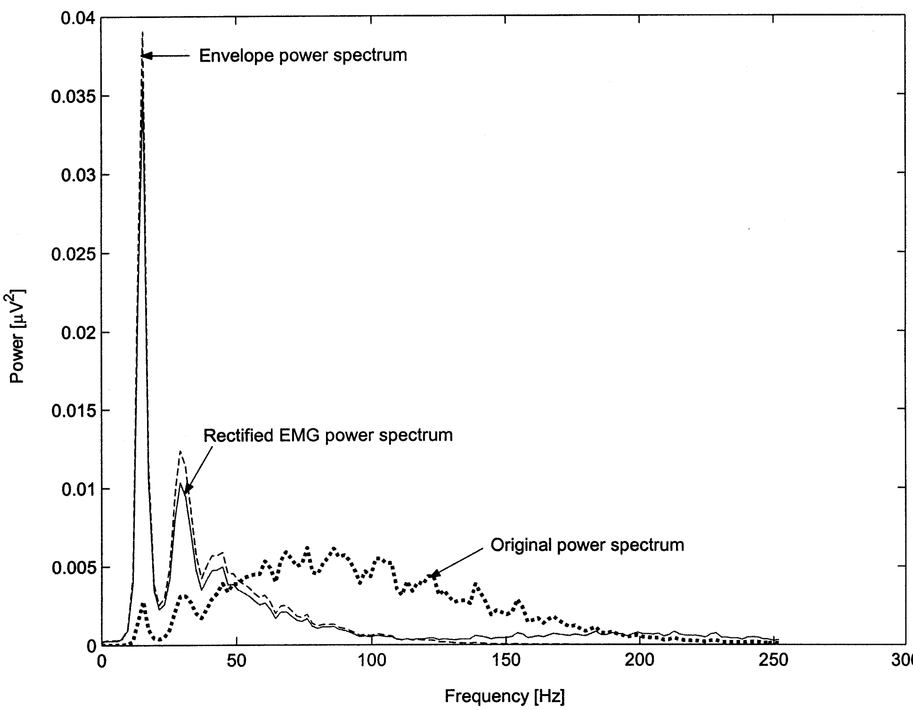

Fig. 4. Power spectrum of a single motor unit firing with a mean rate of 15 spikes per s and a Gaussian distribution about the mean inter-pulse interval (ipi) with a S.D. of 8 ms (dotted line), along with the power spectra of the envelope (dashed line) and rectified versions (solid line) of the signal. The signals are normalised to have the same RMS values.

2.2. Composite EMG

The composite EMG signal is the asynchronous summation of many different MUAPT's. Lago and Jones (1977), De Luca and Creigh (1989) and Pan et al. (1989) have demonstrated that for above 40 Hz approximately, the power spectrum of the EMG approaches the power spectrum of the MUAP, as may be seen in Fig. 2. The firing frequency in the EMG power spectrum is in general not clearly detectable. Due to the similarity of the EMG spectrum with a single MUAP spectrum, the maximum of the spectrum of the envelope of the EMG signal or the rectified EMG signal would similarly be shifted toward lower frequencies. Should the firing rate spectrum remain unaltered by these processes, spectral content located at these firing rate frequencies will be magnified.

An effective way to determine if this is indeed the case is via model simulations. However, a more robust method of determining firing rate frequencies than visual inspection is required. This may be achieved through the introduction of surrogate time series data (Theiler et al., 1992; Schreiber and Schmitz, 2000). Here it is assumed that a specific structure is inherent in the rectified EMG data, and that it is the timing or firing rate information that gives it this structure. We may form a null hypothesis that the rectified EMG was generated by a Gaussian linear stochastic process and that this process provides a complete account of the statistics of the data. Should specific timing structure be present in the rectified EMG, we may then reject the null hypothesis. Thus the rectified EMG power spectrum may be compared with an empirical distribution on a collection of Monte Carlo realizations of the null hypothesis. These realizations are designed to have the same linear properties as the data and thus surrogate time series may be thought of as *constrained realisations* of the original time series. There are a number of effective ways of generating surrogate data (Dolan and Spano, 2001). For this application we use the method of Fourier-transformed surrogates (Theiler et al., 1992). This method takes the spectrum of the original data and assigns a uniformly distributed random phase to each positive frequency component. The negative frequency components are assigned corresponding phases to ensure that the inverse Fourier transform will be real. This results in a time series with the same power spectrum as the original data, but which is random in every other respect, i.e. it does not contain the specific timing information.

Thus if the rectified power spectrum of the original EMG signal is statistically equivalent to the averaged rectified power spectra of the surrogate signals, we must accept the null hypothesis and assume that rectification does not reliably enhance timing information. However, if the original rectified spectrum exceeds the mean surrogate spectrum at certain frequencies, then we must reject the null-hypothesis and assume that there is some structure in the signal at those frequencies. If these frequencies correspond to the a priori known firing rate frequencies then we may assume that rectification does indeed reliably enhance this information.

2.3. Simulation methods

A number of realistic simulations were constructed to test whether the spectra of the envelope of the EMG or the rectified EMG reliably extract the firing rate frequencies. These were generated with the model described in Lowery et al. (2000).

Twenty seconds of data at a sampling rate of 2000 Hz were simulated. The inter-electrode distance was 10 mm along the fibre direction. Typical coherence studies examine maximum voluntary contractions of weak to moderate strength. In these circumstances, firing rates would on average be below 20 spikes per s and it is reasonable to assume that around 100 motor units would be recruited. Thus the following representative scenarios were tested: (1) 100 active MU's with all MU's firing with mean firing rates uniformly distributed between 7.5 and 12.5 spikes per s. Each MUAPT has a Gaussian distribution about the mean ipi with a S.D. of 8 ms; (2) 100 active MU's with all MU's firing with mean firing rates uniformly distributed between 15 and 18 spikes per s. Each MUAPT has a Gaussian distribution about the mean ipi with a S.D. of 8 ms; (3) 100 active MU's with all MU's firing with mean firing rates uniformly distributed between 15 and 25 spikes per s. Each MUAPT has a Gaussian distribution about the mean ipi with a S.D. of 8 ms.

Power spectra were formed by averaging consecutive, Hamming windowed, non-overlapping, 2048 point epochs resulting in a frequency resolution of 0.98 Hz. With any averaged periodogram there will be a trade-off between the bias and variance of the estimate and thus we may form confidence intervals surrounding the estimated spectrum. Here 95% confidence intervals were used according to the framework set out in Halliday et al. (1995). Thus to be more conservative in our estimation of the firing rate frequencies, the lower 95% confidence interval estimate of the rectified spectrum was compared with the threshold set by the averaged rectified surrogates. Averaging the power spectra of rectified surrogates yields an estimate of the actual power spectrum. Thus to be more precise, confidence limits must be constructed around this estimate. The 95% confidence intervals are given by the mean value $\pm 1.96 \times \sigma/\sqrt{n}$, where σ is the S.D. and n is the number of averaged samples. The upper 95% interval was used and 200 samples were generated.

3. Results

Fig. 5 depicts the power spectrum for the simulated EMG signal in scenario 1, along with the power spectrum of the rectified EMG signal for this simulation. From the figure it may be seen that although the peak at the firing rate frequency in the non-rectified signal's power spectrum is detectable, it would not be possible to easily discriminate this peak from the rest of the signal without a priori knowledge. However, the firing rate frequencies visibly stand out in the power spectrum of the rectified signal.

Fig. 6 displays the lower 95% confidence bound of the power spectrum of the rectified EMG signal of scenario 1 along with the averaged power spectrum of the rectified surrogates. This enables quantification of significant peaks in the power spectrum and these peaks may be seen to occur at the firing rate frequencies (6.9–10.7 Hz), as well as at approximate integer multiples of these frequencies (14.6–19.5 Hz).

Table 1 contains the frequencies of the first two significant peaks of the power spectra of the rectified EMG signals for each scenario. Here significance is defined as those frequencies where the lower 95% confidence bound of the power spectrum of the rectified EMG signal exceeds the averaged power spectrum of the rectified surrogates. This data is for both the rectified EMG and envelope methods. As may be seen from the table, both methods offer essentially similar results with the envelope method yielding slightly more narrow peaks for the first significant peak. The second peaks are clearly multiples of the first peaks although, as displayed in Fig. 6, subsequent peaks are often of lower magnitude.

4. Discussion

The power spectra of rectified or envelope extracted simulated EMG data exceeds the power spectra of the average rectified or envelope extracted surrogates over certain frequency ranges. Thus for those frequencies, we may reject the null hypothesis that the rectified EMG was generated by a Gaussian linear stochastic process and assume that additional information is contained at those frequencies. A priori knowledge of firing rate distributions indicate that the significant frequencies are indeed centered around the mean firing rates and thus we may conclude that the power spectra of the rectified or envelope extracted EMG signal do enhance firing rate information. Both techniques are non-linear techniques that perform a similar function and it appears that either may be reliably used. However, the envelope method has not yet been applied to coherence studies of cortico-muscular data and it may be of value to test this technique with real data.

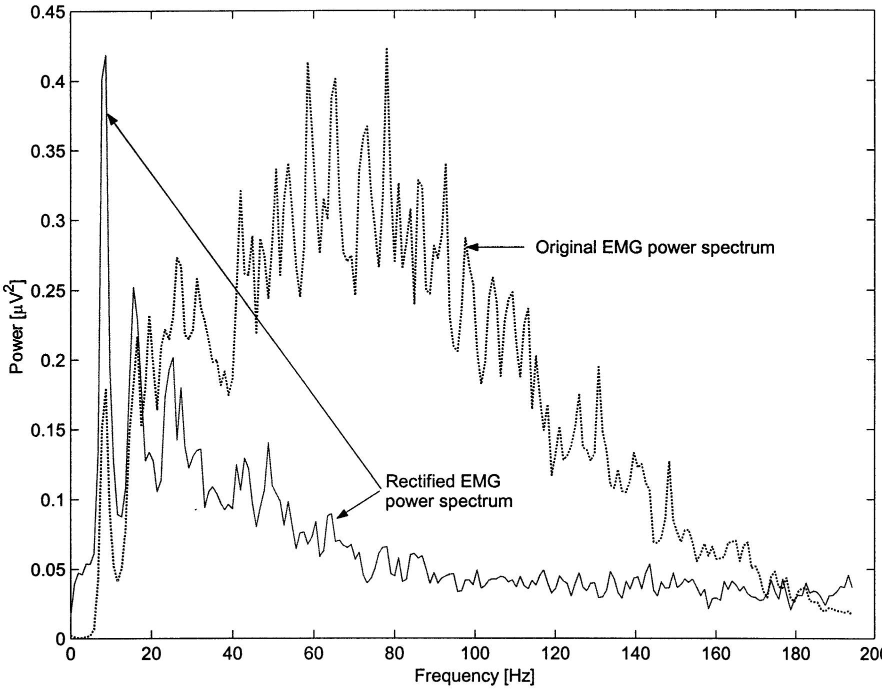

Fig. 5. Power spectra of simulated EMG signal. The signal consists of 100 active MU's with all MU's firing with mean firing rates uniformly distributed between 7.5 and 12.5 spikes per s. Each MUAPT has a Gaussian distribution about the mean ipi with a S.D. of 8 ms. Power spectra are given for original (dotted line) and rectified (solid line) versions of the signal.

Farmer et al. (1993) found that motor units tend to discharge synchronously during voluntary action and they suggested that this synchronization may be in part due to a rhythmic drive to muscle, which may originate in the primary motor cortex. This grouped firing of motor units has not been accounted for in the EMG

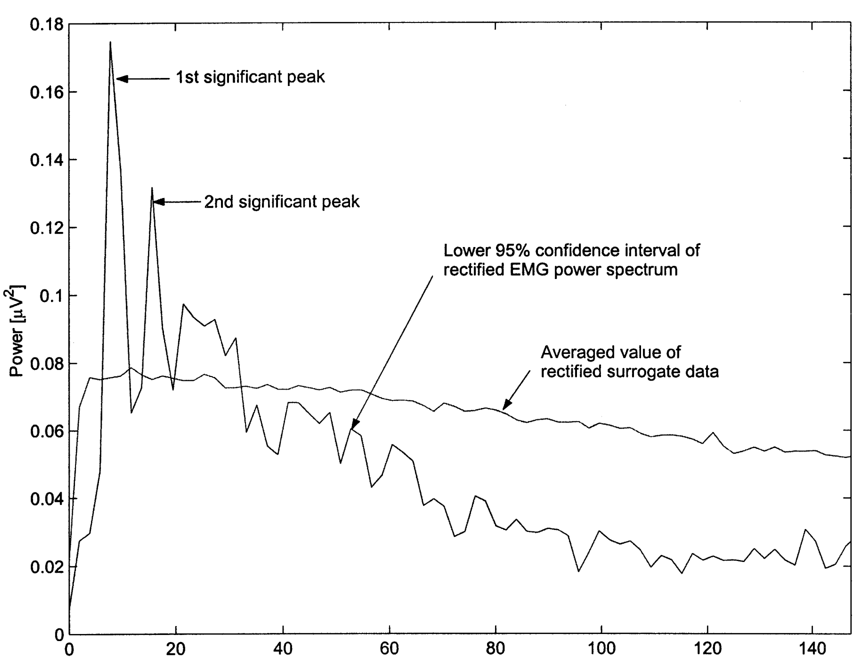

Fig. 6. Power spectrum of simulated EMG signal. The signal consists of 100 active MU's with all MU's firing with mean firing rates uniformly distributed between 7.5 and 12.5 spikes per s. Each MUAPT has a Gaussian distribution about the mean ipi with a S.D. of 8 ms. The power spectrum is the lower 95% confidence interval of the rectified signal. Superimposed is the mean power spectrum of 200 rectified surrogates. The first two significant peaks are indicated.

Table 1
Detected firing rate frequencies of simulated EMG signals

Scenario	First peak frequency (Hz)	Second peaks frequency (Hz)	Firing rate distribution (Hz)
1-rectified	6.9–10.7	14.6–19.5	7.5–12.5
1-envelope	6.9–9.8	14.6–19.5	7.5–12.5
2-rectified	13.7–17.6	28.3–35.2	15–18
2-envelope	13.7–16.6	29.3–35.2	15–18
3-rectified	14.6–18.6	31.3–38.1	15–25
3-envelope	14.6–17.6	31.3–38.1	15–25

The significant frequencies of the first two peaks in the spectra of the rectified and envelope extracted versions of the signals are displayed. The known firing rate distributions are included in the table for comparison purposes.

model. However, if synchronous firings of motor units were to reduce the variance of firing rates, this would improve the ability of rectification to enhance mean firing frequencies.

These findings could aid the interpretation of the results of coherence investigations and the identification of the mean firing rates prior to coherence analyses is recommended. The above analysis demonstrates that EMG rectification enhances firing rate information and this is why it is a necessary precursor to cortico-muscular coherence studies. This study demonstrated and explained the mechanisms behind this effect using simulated data. However, it is further possible that the technique of using surrogate thresholds may be used to extract mean firing rates from real data for a variety of applications. Thus future work is necessary to perform a thorough assessment of the limitations and validity of this technique on real data.

5. Conclusions

A detailed investigation of the power spectrum of rectified EMG signals was carried out. Model simulations of surface EMG signals with known parameters indicate that the power spectra of rectified EMG signals is magnified at the firing rate frequencies. This is achieved by shifting the peak of the AP spectrum toward the firing rate frequency, whilst leaving the firing spectrum unchanged. Thresholds set using surrogate EMG data generated by phase randomization may be used to reliably extract the firing rate frequencies of EMG signals. Rectification of a single MUAPT is an approximation of the envelope of the MUAPT. No significant difference was found whether extracting firing rate information from rectified EMG or the envelope of the EMG signal and these two methods may be used interchangeably for this purpose. Rectification is a necessary step prior to cortico-muscular coherence analysis and the extraction of firing rate frequencies should be performed to aid interpretation of such analyses.

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