

Rectification of EMG improves detection of motor unit coherence in the beta frequency band

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Abstract

Rectification of surface EMG prior to spectral analysis is a well established pre-processing method used in the detection of motor unit firing patterns. A number of recent studies have called into question the need for rectification prior to spectral analysis, pointing out that there is no supporting experimental evidence to justify rectification. We present an analysis of 190 records from 13 subjects consisting of simultaneous recordings of paired single motor units and surface EMG from the extensor digitorum longus muscle during middle finger extension against gravity (unloaded condition) and against gravity plus inertial loading (loaded condition). We examine directly the hypothesis that rectified surface EMG is a better predictor of the frequency components of motor unit synchronization than the unrectified (or raw) EMG in the beta frequency band (15–32Hz). We use multivariate analysis and estimate the partial coherence between the paired single units using both rectified and unrectified surface EMG as a predictor. We use a residual partial correlation measure to quantify the difference between raw and rectified EMG as predictor, and analyse unloaded and loaded conditions separately. The residual correlation for the unloaded condition is 22% with raw EMG and 3.5% with rectified EMG, for the loaded condition it is 5.2% with raw EMG and 1.4% with rectified EMG. We interpret these results as strong supporting experimental evidence in favour of using the pre-processing step of surface EMG rectification prior to spectral analysis.

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1 Introduction

Single motor units (MUs) from human muscles activated during contraction can be treated as stochastic point processes (Halliday et al., 1995). Simple level detection and other identification techniques can determine spike times with millisecond accuracy, and from these, time and frequency domain analyses may be used to characterise the statistics of MU firing: the inter-spike interval histogram, the auto-correlation function and the auto-spectral density function. The existence of peaks in the auto-spectral density indicates departure from the asymptotic value (Bartlett, 1963), and is thus indicative of structure within the times of occurrence of the motor unit spikes. Such peaks typically result from the mean MU firing rate and any modulatory influences on the firing rate. Through recording simultaneous activity in pairs of motor units further information about the common cortical drive to human motor neurons may be ascertained. In the time domain motor unit synchrony can be detected as a peak centered around time zero (Datta and Stephens, 1990). In the frequency domain the cross-spectrum, the coherence and phase may be extracted. Such approaches have identified important physiological processes underlying normal and abnormal beta range (15-32 Hz) central common drive to human MUs (Farmer et al., 1993), and have also been used fruitfully to explore physiological and pathological tremors and other disorders of movement (Elble and Randall, 1976; Halliday et al., 1999). These methods can be extended to examine directly the communication between the sensorimotor cortex and the muscle through calculation of corticomuscular coherence (CMC). Various frequencies of CMC have been identified, with the beta range being especially important during steady muscle contraction (see Salenius and Hari (2003) for a review).

Providing there is adequate signal separation, two surface EMG signals can be used as a substitute to pairs of MU recordings, and numerous studies have identified the same oscillatory drive as shown in pairs of single MUs in simultaneous EMG-EMG recordings (Farmer et al., 2007). In contrast to motor units treated as point processes, the surface EMG is a complex signal resulting from the superposition of a large number of spatially and temporally summated MUs, affected by volume conduction and with both the positive and negative phases of the action potential contributing to the signal (Farina et al., 2004). In order to access the timing information inherent in the surface EMG signal, filtering and rectification pre-processing steps have been used prior to calculation of time and frequency domain measures (Elble and Randall, 1976). However, recent modelling studies (Neto and Christou, 2010; Stegeman et al., 2010) and experimental work (McClelland et al., 2012) have challenged this approach, and the claim has been made that rectification is ‘inappropriate’ and impairs detection of common drive to motor pools (McClelland et al., 2012). It may be argued that simply finding a stronger EMG-EMG coherence or CMC when using an unrectified as opposed to a rectified EMG signal does not mean that rectification ‘impairs’ common drive detection. Rather what is required is a direct measure of the fidelity of unrectified versus rectified EMG in the detection of the underlying common drive to the motor units.

In this communication we analyse data in which surface EMG and pairs of single MUs were simultaneously recorded (Halliday et al., 1999). Using the frequency domain approach of the auto-spectral density function, we compare directly the spectra of unrectified and rectified EMGs with that of simultaneous

single motor unit firing. Furthermore, through calculation of the coherence and partial coherence between the motor units with the surface EMG as predictor we are able to ascertain whether the unrectified or the rectified surface EMG signal best represents the common drive to pairs of single MUs. The following sections outline the methods, describe results of the partial coherence analysis and discuss, with recommendations, the best strategy for EMG pre-processing in frequency domain studies involving the use of surface EMG.

2 Methods

The data set analysed in the present study comes from the work of Halliday et al. (1999), where full details of the experimental protocol can be found. Here we present a novel analysis of these data focusing on a partial regression analysis to determine if the raw or rectified EMG is a better predictor of the components of motor unit synchronization. To achieve this we use estimates of pooled partial coherence (Amjad et al., 1997). The data set consists of simultaneous recordings of bipolar surface EMG, paired MU recordings and physiological tremor from 13 healthy adult subjects. There were two task conditions, an unloaded condition involving a steady postural contraction of the Extensor Digitorum Communis (EDC) muscle against gravity, and a loaded condition with increased inertial loading using small weights (5–40 grammes) added to the extended finger. The surface EMG was band pass filtered (3–500 Hz) and motor unit firing times were determined using online window discrimination devices which output TTL pulses (sampled with a time step of 1 ms). Full details of the experimental procedure are in the original study (Halliday et al., 1999).

The frequency analysis uses the techniques described in Halliday et al. (1995). Motor unit spike trains are treated as stochastic point-process data allowing individual auto-spectra and cross-spectra to be calculated. These were estimated using the average periodogram approach described in Halliday et al. (1995). MU and EMG spectra were then pooled over all 106 records in the population of recordings made in the unloaded condition, using a total of 150 minutes of data from 13 subjects. Similarly 84 records comprising 125 minutes of data from 13 subjects were pooled for the loaded condition. The pooling technique is described in Amjad et al. (1997), and EMG spectra were calculated for both unrectified (raw) and rectified (full-wave) EMG.

Once pooled auto- and cross-spectra were calculated the pooled MU coherence and pooled MU partial coherence were estimated. Two partial coherence estimates were constructed, one using unrectified EMG as predictor the second using rectified EMG as predictor.

Coherence measures the degree of linear association between two processes. The coherence between signals x and y is given by

$$|R_{xy}(\lambda)|^2 = \frac{|f_{xy}(\lambda)|^2}{f_{xx}(\lambda)f_{yy}(\lambda)}$$

where $f_{xy}(\lambda)$ indicates the cross-spectrum of x and y at frequency λ and $f_{xx}(\lambda)$ indicates the auto-spectrum of x .

Partial-coherence provides a measure of the correlation between two processes, after taking into account any linear interaction between the two processes

and a third process (the predictor). The partial cross-spectra between x and y , with z as a predictor, is defined as per Halliday et al. (1995):

$$f_{xy/z}(\lambda) = f_{xy}(\lambda) - \frac{f_{xz}(\lambda)f_{zy}(\lambda)}{f_{zz}(\lambda)}$$

The partial auto-spectra of x given z as a predictor is defined as per Halliday et al. (1995):

$$f_{xx/z}(\lambda) = f_{xx}(\lambda) - \frac{|f_{xz}(\lambda)|^2}{f_{zz}(\lambda)}$$

The other partial auto-spectrum, $f_{yy/z}(\lambda)$, is defined similarly. From the partial spectra the partial coherence between x and y with z as a predictor, $|R_{xy/z}(\lambda)|^2$, can then be estimated in a similar manner to the ordinary coherence function:

$$|R_{xy/z}(\lambda)|^2 = \frac{|f_{xy/z}(\lambda)|^2}{f_{xx/z}(\lambda)f_{yy/z}(\lambda)}$$

Partial coherence, like ordinary coherence, provides a bounded measure of linear association between 0 and 1. The result can be interpreted as the level of residual coupling between x and y at frequency λ after removal of the common effects of process z . For the present data, partial coherence is used to quantify to what degree MU synchronization (coherence) can be accounted for by rectified or unrectified surface EMG. Pooling of partial coherence estimates is achieved by a direct extension of the framework presented in Amjad et al. (1997), where partial auto- and cross-spectral estimates are pooled in the same way as ordinary auto- and cross-spectra. An adjustment to take into account the loss of 1 degree of freedom from using a single linear predictor is required. In the pooled framework (Amjad et al., 1997), the number of segments in each record L is replaced by $L - 1$.

Confidence limits were calculated for both coherence and partial coherence as in Halliday et al. (1995). These are used to guide interpretation of results. If the partial coherence estimate falls below the confidence level at some frequency, this indicates the surface EMG predictor (either rectified or unrectified) accounts for all the MU correlation at that frequency. A partial-coherence estimate where the values are consistently below the confidence limit over the frequency range of interest, 15-32 Hz in this case, is clear evidence that the surface EMG can account for all components of MU synchronization in this frequency band. Partial coherence thus provides a quantitative means of assessing the relative merits of raw versus rectified EMG in predicting the components of motor unit synchronization.

To quantify the differences and assess statistical significance in partial coherence estimates with rectified and raw EMG as predictors, we calculate two measures. The first is based on the concept of the residual variance bound (Priestley, 1981). We calculate the percentage of residual partial coherence in the beta frequency band that is left after removal of the linear effects of the EMG signal. This is expressed as a percentage of the original motor unit coherence in the beta frequency band. The second measure is a statistical test to determine if there is a significant difference in the magnitudes of the two partial

coherence estimates across the beta- frequency range. This uses the difference of coherence test outlined in Rosenberg et al. (1989) to determine if the partial coherence estimates are significantly different at each frequency. To calculate these metrics we use a multi-taper spectral approach (Percival and Walden, 1993) tuned to cover the beta frequency range in a single frequency bin. The values used are $NW = 4.5$, $\Delta f = 1/0.512\text{Hz}$, and using $K = (2NW - 1)$ tapers gives an effective bandwidth ~ 16 Hz. Selecting the nearest Fourier frequency to the center of the beta range, 23.44Hz in this case, allows the residual correlation and significance test across the beta frequency range to be undertaken using the values from that single frequency. P -values are calculated using the two-sided significance test in Rosenberg et al. (1989). The multi-taper analysis is used to calculate the residual variance metrics and perform the statistical tests, all plots use the average periodogram estimates as in Halliday et al. (1999), with $\Delta f = 1/1.024\text{Hz}$.

3 Results

3.1 Pooled spectra of surface EMG and motor units

Pooled auto-spectral estimates for unrectified EMG, rectified EMG, and single motor unit firing times are shown in Fig 1. These are illustrated separately for the unloaded (Fig. 1, top) and loaded (Fig. 1, lower) populations. The interpretation is similar in both cases. The estimate for the pooled motor unit spike train is a point-process spectral estimate, the estimates for the EMG are time-series spectral estimates. Whilst these will have a different interpretation, inclusion of all three on the same plot can be instructive in identifying where the dominant spectral features are located. The mean firing rate for the population of motor units (11.9 spikes/sec for unloaded and 12.5 spikes/sec for loaded) determines the asymptotic value in the point process spectrum, according to the model presented in Bartlett (1963). For the present data this level is -2.72 dB for the unloaded population and -2.70 dB for the loaded population on a \log_{10} scale. To allow comparison with the EMG time series data the point process spectrum has been plotted with a constant offset such that the peak value matches the peak value in the auto-spectral estimate of the unrectified EMG pooled spectrum. This constant offset aids the visual comparison and does not affect interpretation of the point process spectrum. The standard model for interpretation of point-process spectral estimates is a Poisson (or random) sequence of events. The asymptotic value is $\log_{10}(P_N/2\pi)$, where P_N is the mean rate calculated as spikes per time step (1 ms), in our case $P_N = 0.0119$ for the unloaded data and $P_N = 0.0125$ for the loaded data. Departures from the asymptotic or expected value can be taken as evidence of non-Poisson behaviour at a particular frequency, i.e. the spike train is non-random. For the MU spike train spectral estimate there are significant departures from Poisson behaviour below 35Hz. The main features are dominant spectral peaks around 12 Hz and smaller peaks around 26 Hz seen in both the loaded and unloaded case. The first reflects the periodic firing of the motor units, whereas the second may be the second harmonic or a distinct component indicative of higher frequency modulation of firing rate. There is no evidence of any significant structure in the MU spike train at frequencies above 35 Hz. Note that this interpretation

is not altered by applying a fixed offset when plotting the MU pooled spectral estimate.

[Figure 1 about here.]

The unrectified surface EMG in both cases contains a broad distribution of power, predominantly concentrated in the 40-60 Hz range. A peak is discernible at the mean MU firing frequency, and a more substantial component is present around 3 Hz. In contrast, both the rectified surface EMG spectra have a peak at 12 Hz, and a secondary peak around 24 Hz, with gradually decreasing power at higher frequencies. A comparison of the unloaded and loaded pooled surface EMG spectral estimates with the corresponding pooled single MU spectral estimate shows that most power in the unrectified EMG spectrum is concentrated at frequencies above 35 Hz, the region where there is no obvious rhythmic structure in the motor unit point process spectrum. In contrast, the peak in the rectified EMG spectrum in both unloaded and loaded conditions matches more closely the peaks in the MU spectrum for the same conditions. This suggests that for the low contraction levels in the present study, the rectified EMG signal is better able to capture the rhythmic components of MU firing than its unrectified counterpart (Farina et al., 2013). However it is well known that spectral peaks are not necessarily an indicator of correlation (Rosenberg et al., 1998; McClelland et al., 2012). Therefore we also examine MU coherence and partial coherence estimates.

3.2 Coherence and partial-coherence estimates

For each record three coherence estimates were calculated, these were the ordinary motor unit coherence, and two partial MU coherence estimates, one with raw EMG as predictor, the other with rectified EMG as predictor. The predictor that most effectively represents the common drive will have the smallest MU partial coherence. We consider data for the unloaded case first, and look at coherence and partial coherence estimates pooled across single subjects and across all subjects. Table 1 summarizes the residual correlation data for each subject, it includes the 11 subjects where more than 1 record was obtained.

[Table 1 about here.]

A number of observations can be made for the data in Table 1. The first is the variability across subjects. Two of the subjects (Nos 1, 11) have partial coherence estimates with raw EMG as predictor that were larger than the ordinary pairwise coherence estimates. The reason for this unusual result is unclear (but see discussion below), however it does suggest that the raw EMG is a poor predictor of the frequency content present in the motor unit correlation for these two subjects. For ten of the eleven subjects the residual partial correlation with rectified EMG is numerically smaller than that with rectified EMG as predictor. A worst case scenario view of the data in Table 1 is that the raw EMG will not predict any components of motor unit correlation (residual correlation of 100%; subjects 1, 6, 11) and the rectified EMG will predict up to half of the total correlation in the beta band (residual correlation of 47%; subject 5). A more balanced view is given below where pooled partial coherence across subjects is considered. A second level statistical analysis applying a Mann-Whitney U -test

to the two sets of residual correlation values provides evidence in favour of a significant reduction across this subject group with rectified EMG as predictor compared to raw EMG, $P = 0.022$.

To provide a more comprehensive summary across the complete unloaded data set, we estimated pooled coherence and pooled partial coherence over all records from all 13 subjects in the unloaded condition. The results are plotted over the frequency range 10-50 Hz in Fig 2. The ordinary pooled coherence estimate exhibits clear correlation over the 10-50 Hz range, peaking at 24 Hz (Halliday et al., 1999, Fig 3a). The horizontal dashed line is the upper 95% confidence limit for all estimates, values below this line are consistent with the hypothesis of zero coherence and zero partial coherence at each frequency.

[Figure 2 about here.]

For both unrectified and rectified predictors there is a marked reduction in magnitude of the partial coherence compared with the ordinary MU coherence estimate. The residual partial correlation with the raw EMG as predictor is 22% of that in the original pooled coherence. Using the rectified EMG as predictor the residual correlation is 3.5%. The difference of pooled coherence test applied to data pooled over all subjects using the multi-taper approach outlined above indicates this difference is significant over the beta frequency range 15–32 Hz, $P = 0.0005$. Like the second level analysis above, this suggests that for this subject group, the rectified EMG is a significantly better predictor of motor unit correlation in the beta frequency range than the raw EMG for unloaded finger extension against gravity.

It has recently been suggested that contraction strength can affect prediction of motor unit correlation using surface EMG (Farina et al., 2013). To examine the effects of loading we consider the same analysis for the 84 records in the loaded condition with small weights attached to the distal phalanx of the extended middle finger. The results are given in Table 2, broken down by applied load.

[Table 2 about here.]

The first four entries in Table 2 give a breakdown by load value, the last two lines summarise the results for the pooled analysis over all unloaded and over all loaded data. Considering the breakdown by load, there appears to be less difference in the residual correlation values in the loaded case (Table 2; first four entries) compared to the unloaded case (Table 1). This is supported by a second level comparison which suggests there is no significant difference between the residual correlation values for rectified and raw EMG with load (Mann-Whitney U -test applied to first four entries; $P = 0.2$). The last two entries in Table 2 summarise the complete unloaded and complete loaded populations of data, these also include the RMS rectified EMG value in the beta frequency band. A pooled analysis was repeated for the single set of loaded data using all 84 records with additional inertial loading. The pooled coherence and partial coherence estimates for this combined loaded condition are shown in Figure 3.

[Figure 3 about here.]

Like the unloaded condition (Fig. 2) there is a marked reduction in the magnitude of the partial coherence compared with the ordinary MU coherence estimate. The residual partial correlation with the raw EMG as predictor is 5.2% of that for the original pooled coherence, for the rectified EMG as predictor the residual correlation is 1.4%. Unlike the unloaded condition, this difference is not significant, $P = 0.19$. As an indicator of the increased motor unit recruitment resulting from inertial loading, the RMS value of the rectified EMG can be used. Across all records in the loaded condition the RMS EMG is 17% larger than the same measure across all records in the unloaded condition (Table 2). The RMS EMG allows an assessment to be made of the extent to which amplitude cancellation might be a contributing factor in determining the efficiency of the rectified EMG to predict motor unit coherence (Farina et al., 2013), see below.

In summary, for the loaded and unloaded conditions, the rectified surface EMG gives a numerically smaller residual partial correlation in the beta band, however the improvement in prediction over the raw EMG is not as great as in the unloaded condition.

4 Discussion

Evidence regarding the appropriateness or otherwise of rectification up to this point has primarily been in the form of simulation studies (Boonstra and Breakspear, 2012; Myers et al., 2003; Neto and Christou, 2010; Stegeman et al., 2010; Farina et al., 2013). In Stegeman et al. (2010), rectification was found to reduce coherence in a simulated motor pool between the input drive and surface EMG. This study, however, neglects the fact that a single muscle has a range of action potentials shapes, due to the exponential distribution of motor unit sizes (Fuglevand et al., 1992), instead modelling small and large muscles with identical short and long motor unit action potential (MUAP) shapes. Boonstra and Breakspear (2012) addressed this shortcoming, showing with modelled EMG that when a heterogeneous distribution of MUAP magnitudes is present, the common oscillatory drive is cancelled out, but is recoverable by EMG rectification. Neto and Christou (2010) reconstructed EMG with the same spectral profile as recorded data, but with varying signal-to-noise ratio, concluding that EMG-EMG coherence is impaired by rectification. However, no MU timing information was included in their EMG model, which was based on a sum of sinusoidal signal model. The main aim of EMG spectral analysis is the extraction of information regarding firing patterns in MU activity and the detection of common drive to pools of motor units, for which purpose it has been suggested that rectification is more appropriate (Boonstra, 2010; Halliday and Farmer, 2010).

Two of the individual subjects exhibited pooled partial coherence estimates with raw EMG that were larger than the ordinary motor unit coherence estimates in the unloaded case (Table 1 – subjects 1, 11). There are a number of factors that could contribute to such an unusual result. A key factor is likely to be the variability in the strength of motor unit correlation between subjects (see e.g. Halliday et al., 1999, Fig. 2). The residual correlation values in Table 1 do not take account of the magnitude of the motor unit coherence. In contrast, pooled coherence across subjects (Fig. 2) constructs a weighted sum, where records are weighted inversely proportional to the variance of individual

records (Amjad et al., 1997). This provides an estimate of the consistency of any effects across subjects that takes account of the variations in the strength of motor unit coherence across subjects. This may also in part explain why the residual correlation pooled across subjects (Table 2; row 5) are lower than those for individual subjects (Table 1). We interpret the pooled coherence and pooled partial coherence estimates (Figs. 2, 3) as a more reliable view of the present data. However, in any study it is important to be aware of inter-subject variability in parameters of interest (Halliday et al., 1999; Farina et al., 2013).

Recently it has been suggested that the extent to which raw and rectified EMG reflects the spectrum of common input to motoneurons depends on motor unit action potential amplitude cancellation (Farina et al., 2013), which increases with increasing motor unit recruitment. Farina et al. (2013) further suggest that EMG rectification is preferable at low contraction strengths. In order to get an indication of contraction strength the RMS value of the rectified EMG can be used. For our data this is 17% larger for the loaded condition compared with the unloaded condition. This is approximately 1/3 of the increase seen in the simulated example in Farina et al. (2013, Fig. 1), which suggests that the contraction strengths in our data are at modest levels and likely to involve low levels of amplitude cancellation. Similarly there is only a 5% increase in the single motor unit firing rate in the loaded population over the unloaded population.

Experimental evidence relating to rectification has primarily looked at EEG-EMG or MEG-EMG coherence (Yao et al., 2007; McClelland et al., 2012). Most recently, McClelland et al. (2012) provokingly stated that rectification is an “unnecessary and inappropriate step in the calculation of corticomuscular coherence.” This was based on analysis of power spectra from individual records of unrectified and rectified EMG, and coherence between a simultaneously recorded EEG. This approach, however, does not provide a firm indication of whether rectified or unrectified EMG more faithfully represents the presynaptic motoneuronal drive. Additionally, the failure to detect significant EEG-rectified EMG coherence at a known common frequency component, the 50 Hz mains artifact, is not as the authors suggest evidence for the inappropriateness of rectification, but in keeping with the interpretation that rectification emphasizes the modulatory drive to the motor pool at the expense of action potential shape and other unwanted high frequency information (Halliday and Farmer, 2010).

The key question of whether unrectified or rectified EMG is a better predictor of the frequency components of MU synchronization can only be definitively answered using experimental data consisting of simultaneous recordings of paired MU discharges in which there is synchronization due to common drive and surface EMG from the homonymous muscle. The present study analyses such a data set, and the key result is shown for pooled data in Fig 2. Use of unrectified EMG as a predictor signal does not remove all components of MU synchronization in the 15-32 Hz frequency band. In contrast the rectified EMG has a partial coherence estimate that fluctuates around the significance level. It is worth noting that whilst using unrectified EMG as predictor does greatly reduce the magnitude of the partial coherence, in the context of the present debate as to which is the better predictor of MU synchronization the evidence in Fig. 2 is strongly in favour of the rectified surface EMG. The results verify the improved coherence with rectified EMG observed in previous studies (Boonstra and Breakspear, 2012; Myers et al., 2003). Interestingly, the advantage of

rectified EMG over raw EMG decreased with increasing inertial loading. Importantly, at the population level our data suggests that raw EMG is unlikely to be a better predictor of motor unit correlation than rectified EMG (Fig. 2, 3). The results of partial coherence analysis with increased inertial loading, in which motor unit recruitment is increased compared to the unloaded condition, is supportive of the suggestion in Farina et al. (2013) that EMG rectification is advantageous at low contraction levels. We note that use of rectification has also been found advantageous in suppressing movement artifacts in vibration studies (Sebika et al., 2013).

A number of previous studies have pointed out that rectification is a non linear operation and when used unwisely can distort the frequency components in a signal (Neto and Christou, 2010; McClelland et al., 2012). This is true for sinusoidal signals, however, the issue is less clear cut with respect to EMG. As previously discussed in Halliday and Farmer (2010) the main aim of this type of spectral analysis is to characterise the components of MU timing. Taking the single unit spectra as the reference spectra, clear peaks are present around 12–13 Hz and 26 Hz, with Poisson behaviour (no significant rhythmic features – see Fig 1) above 35 Hz. The rectified EMG spectrum has peaks around 12Hz and 25 Hz, which are the main features. Similarly, the unrectified EMG spectrum has evidence of a distinct feature around 12 Hz and possibly around 25 Hz, although this may be part of the broad increase in power that extends above 60 Hz. The maximum power in the unrectified surface EMG is in the region 40–60 Hz, corresponding to the frequency range where the MU spectrum has no significant rhythmic structure. It has been suggested that this higher frequency range may reflect information due to the shape of MUAPs (Halliday et al., 1995). The alteration of MU action potential shape with fatiguing contractions is known to alter the spectrum of the raw EMG, these changes are often used as a means of quantifying fatigue levels (Hagg, 1992). In the present study we are interested in pre-processing approaches that attempt to suppress shape information while maintaining information regarding timing. The conclusion from the experimental data in Fig 1 is that the rectified EMG spectral estimate is a closer match to the MU spectral estimate than that of the unrectified surface EMG. This is in agreement with the findings of Elble and Randall (1976) who compared MU and rectified EMG spectra, with a focus on the 8-12 Hz frequency band.

In conclusion, analysis of a large data set consisting of paired single motor units recordings and surface EMG from the homonymous muscle has demonstrated: 1) that interpretation of the spectrum of the rectified surface EMG is closer to that of the motor unit spectrum than that of the unrectified EMG, 2) that rectified EMG is a better predictor of the components of motor unit synchronization than the corresponding unrectified EMG at low contraction strengths, and 3) that increasing contraction strength due to inertial loading lessens but does not reverse the advantage of rectification. These findings support the pre-processing approach of EMG rectification prior to spectral analysis of data obtained at low to moderate contraction strengths adopted by Elble and Randall (1976); Halliday et al. (1995) and many others.

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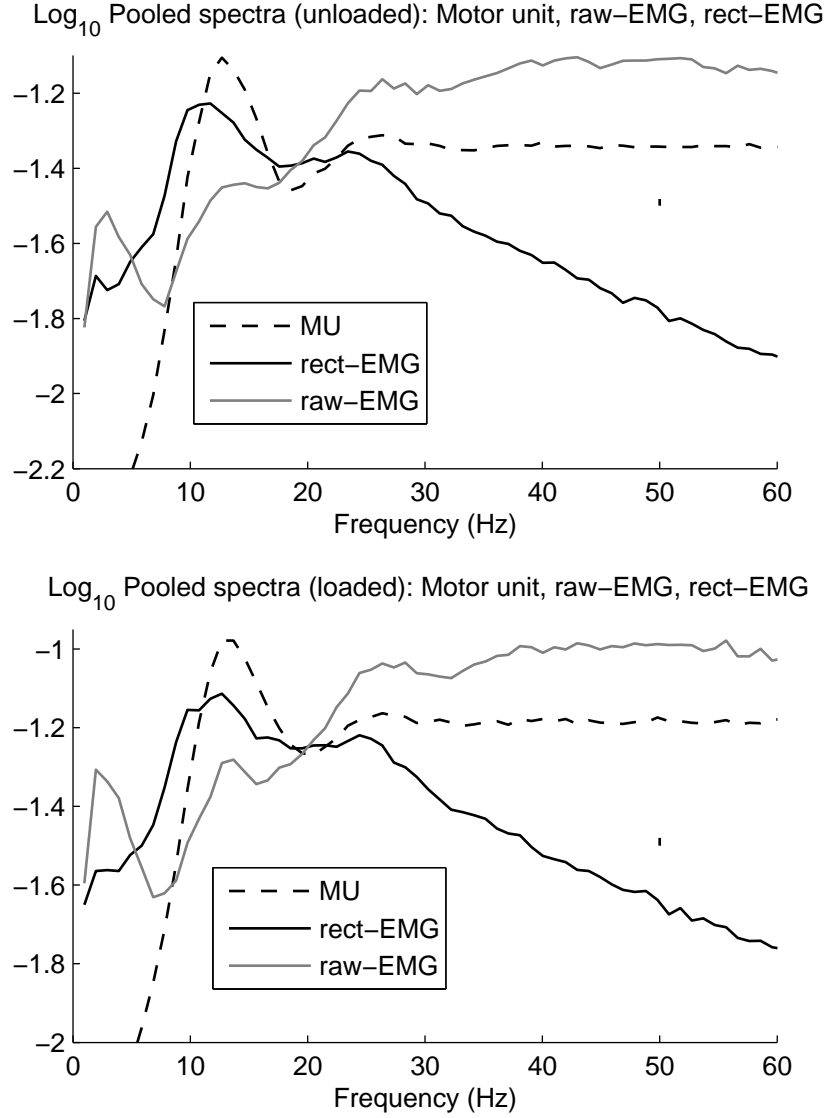


Figure 1: Estimated pooled auto-spectra of motor-unit (dashed line), and simultaneously recorded surface EMG, both unrectified and rectified (solid lines), for unloaded population (top) and loaded population (lower). The motor unit spectrum estimate is calculated using both single units from each of the 106 records (unloaded) or 84 records (loaded), using a total of 212 (unloaded) or 168 (loaded) separate spike trains. Spectral estimates are plotted on a log scale up to 60 Hz, the motor unit spectral estimate has been shifted vertically to facilitate comparison with the EMG spectral estimates (see text for details). The small vertical line to the right represents the magnitude of the confidence band for the pooled spectral estimates, 0.018dB (unloaded), or 0.02dB (loaded).

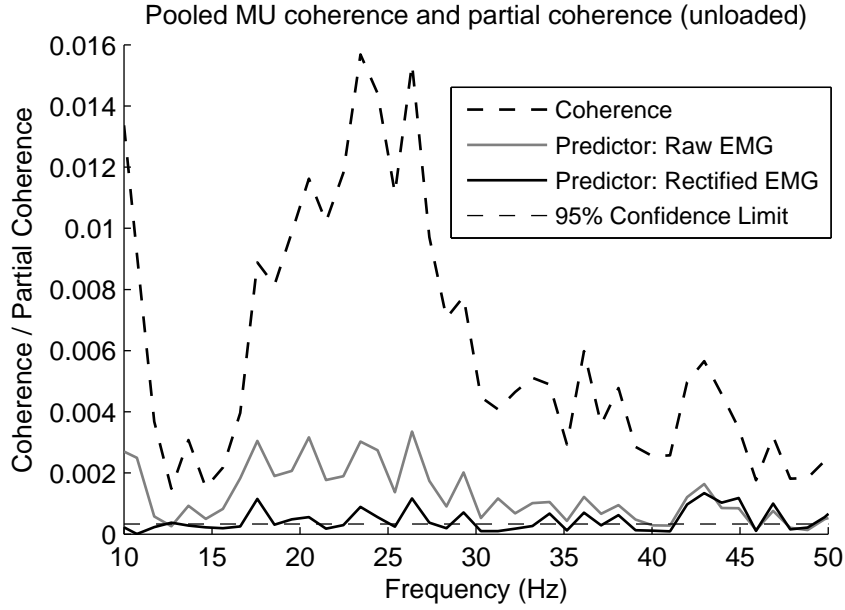


Figure 2: Estimated pooled coherence and pooled partial coherence between paired motor unit recordings. Estimates are pooled over 106 records from 13 subjects in the unloaded condition. The ordinary coherence is shown as the dashed line, the partial coherence with unrectified EMG as predictor is the solid grey line, and the partial coherence with the rectified EMG as predictor is the solid black line. The ordinary coherence is identical to that shown in Halliday et al. (1999, Fig. 3a). The dashed horizontal line is the 95% significance level for coherence and partial coherence estimates, based on a NULL hypothesis of zero coherence or zero partial coherence. Estimates are plotted over the frequency range 10-50 Hz. The residual partial correlation with the raw EMG as predictor is 22% of the original motor unit correlation, with the rectified EMG as predictor the residual correlation is 3.5%. The two partial coherence estimates are significantly different over the beta frequency range (15-32Hz), $P = 0.0005$ (see text for details).

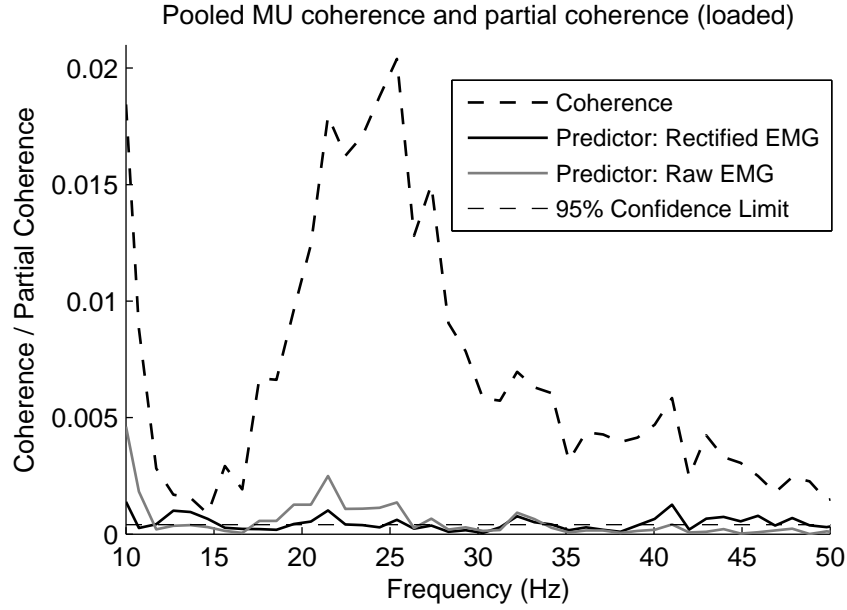


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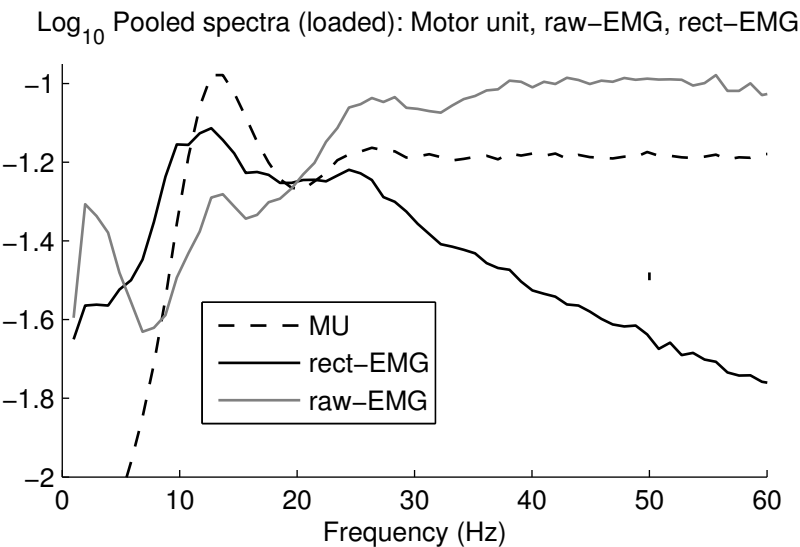
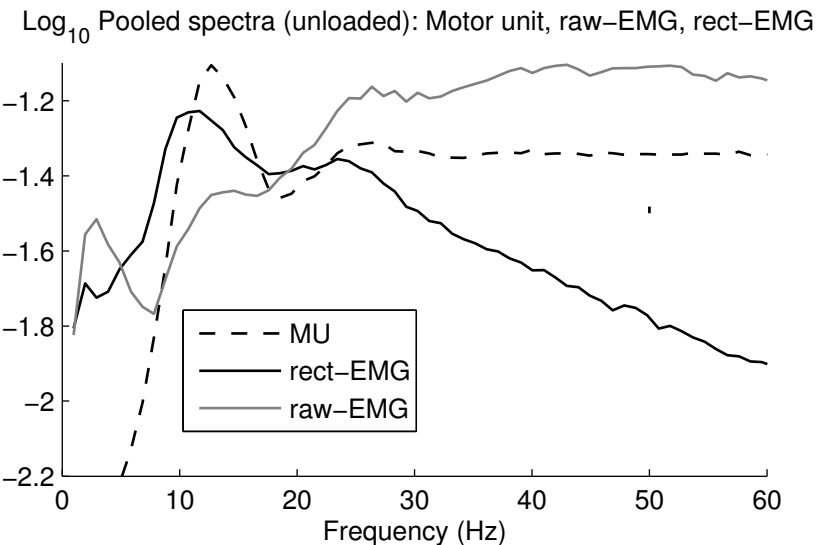
- 1 Residual partial correlation for unloaded data by subject. Table shows: subject ID, Number of records, percentage residual partial correlation with raw EMG as predictor, percentage residual partial correlation with rectified EMG as predictor. The residual partial correlation is expressed as a percentage of the ordinary correlation in the beta frequency band, and was calculated using a multi-taper spectral analysis with an effective bandwidth of ~ 16 Hz (see text for details). A value of 100% indicates that the EMG does not predict any components of motor unit correlation. Subjects 1 and 11 with an indicated residual correlation of $>100\%$ for the raw EMG had partial coherence estimates which were larger than the original ordinary pairwise coherence estimates. 18
- 2 Residual partial correlation for all data by load. Table shows: load applied to distal end of middle finger (grammes), number of records with this load, number of subjects, percentage residual partial correlation with raw EMG as predictor, percentage residual partial correlation with rectified EMG as predictor and (for complete unloaded and loaded populations only) RMS value of rectified EMG normalised to the unloaded population. The residual partial correlation is expressed as a percentage of the ordinary correlation in the beta frequency band, and was calculated using the same approach as Table 1. Thee last two rows are for data pooled over the complete unloaded (load 0) and loaded (load 5–40 grammes) populations. 19

| Subject | Records | Raw % | Rect % |
|---------|---------|-------|--------|
| 1 | 7 | >100 | 16 |
| 2 | 12 | 83 | 4 |
| 3 | 16 | 13 | 19 |
| 4 | 17 | 0.57 | 0.11 |
| 5 | 5 | 68 | 47 |
| 6 | 14 | 76 | 28 |
| 7 | 7 | 80 | 34 |
| 8 | 6 | 100 | 36 |
| 9 | 10 | 82 | 13 |
| 10 | 5 | 9 | 3 |
| 11 | 5 | >100 | 29 |

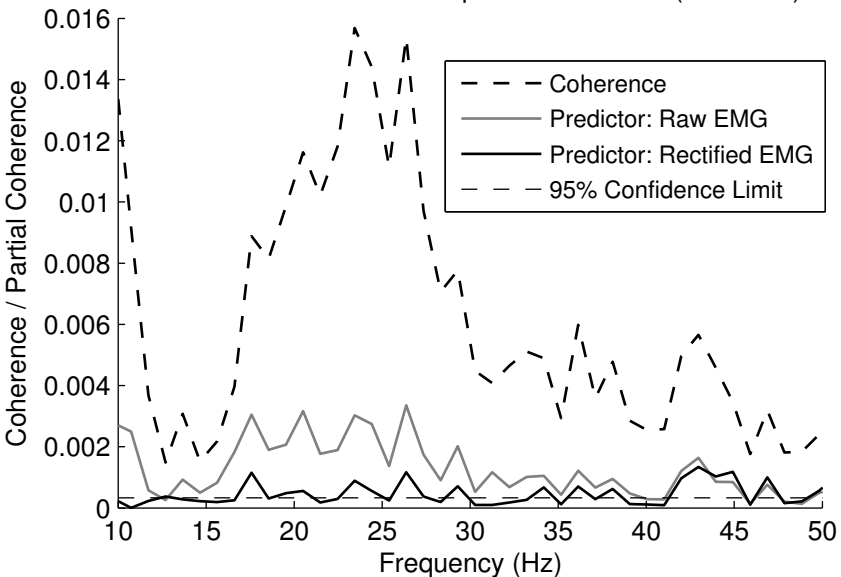
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| Load | Records | Subjects | Raw % | Rect % | RMS |
|------|---------|----------|-------|--------|------|
| 5 | 30 | 6 | 18 | 5 | - |
| 10 | 26 | 7 | 5 | 0.07 | - |
| 15 | 13 | 6 | 6.4 | 6.6 | - |
| >15 | 15 | 4 | 0.9 | 2.9 | - |
| 0 | 106 | 13 | 22 | 3.5 | 1.00 |
| 5-40 | 84 | 13 | 5.2 | 1.4 | 1.17 |

Table 2: Residual partial correlation for all data by load. Table shows: load applied to distal end of middle finger (grammes), number of records with this load, number of subjects, percentage residual partial correlation with raw EMG as predictor, percentage residual partial correlation with rectified EMG as predictor and (for complete unloaded and loaded populations only) RMS value of rectified EMG normalised to the unloaded population. The residual partial correlation is expressed as a percentage of the ordinary correlation in the beta frequency band, and was calculated using the same approach as Table 1. The last two rows are for data pooled over the complete unloaded (load 0) and loaded (load 5-40 grammes) populations.



Pooled MU coherence and partial coherence (unloaded)



Pooled MU coherence and partial coherence (loaded)

