A SIMULATION STUDY TO INVESTIGATE THE SENSITIVITY OF THE ELECTROMYOGRAM TO CONDUCTION VELOCITY CHANGES OF INDIVIDUAL MOTOR UNITS

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Abstract - **The sensitivity of a simulated surface electromyogram (SEMG) to changes in conduction velocity (CV) of individual motor units was assessed. Changes in the conduction velocity measurement and the median frequency and spectral compression measures of both the amplitude and power spectra of the SEMG were calculated. Results show that motor units close to the electrodes dominate the SEMG signal. Results also show that for changes in CV of individual motor units the CV measurement and the spectral measures differ. In the case of uniform changes in the CV of all motor units, changes in these measures are similar and unity sensitivity is observed. Indications from this preliminary study highlight the need for care when deducing the physiological significance of changes observed in the SEMG.**

Keywords – **Electromyogram, conduction velocity, spectral measures, sensitivity.**

I. INTRODUCTION

Needle electromyography is a conventional electrodiagnostic evaluation tool with a proven and long established history in the diagnosis and treatment of disorders of nerve and muscle, [1]. According to the same report from the American Association of Electodiagnostic Medicine, surface electromyography (EMG) is not a valid clinical tool for the diagnosis and treatment of muscle and nerve disorders, as many questions are as yet unanswered. Some investigators believe electrophysiological diagnosis tests are obsolete, [2]. Conflicting opinions exist however, with Rainoldi and co-authors claiming that EMG is a "very promising" clinical technique for detecting information about the global activity of the muscle, [3]. A changing muscle fiber conduction velocity (CV) is the most direct electroneurophysiological sign of a changing excitability of the muscle fiber membrane, [4]. The question of how best to record changes in muscle fiber conduction velocity naturally arises. The limited extent to which changes in muscle physiology may be inferred from the recorded surface signal needs to be recognised. Noninvasive measurement of conduction velocity is often perceived to be the most valuable tool in EMG.

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Spectral changes in the EMG signal during fatiguing contractions are generally attributed to progressive changes in CV. Experimental studies, however, consistently report that changes in spectral measures (e.g. median frequencies of the EMG power spectrum) are substantially different to changes in CV [4], [5], [6]. This is largely explained by concluding that the spectral measures are more influenced by other factors, including firing rates, recruitment, synchronisation and motor unit action potential (MUAP) shape. The EMG signal is sensitive to all these factors and is also strongly dominated by motor units (MU's) located in the vicinity of the recording electrodes. In a simple MUAP model, Fuglevand and colleagues, demonstrated that only MU's within 10-12mm of the electrodes would contribute any significant energy to the surface signal, [7]. Despite this awareness of the limited pick-up range of surface electrodes, results from EMG analysis continue to be interpreted as indicative of the overall physiological state of the muscle.

A better understanding of the relationship between CV and measures of spectral compression require insight into the factors influencing the EMG signal. This relationship has been partially investigated using a mathematical model of the electromyograph [8], [9]. The aim of our study is to investigate by simulation how sensitive the CV calculation, obtained from cross-correlation, and spectral measures of the EMG signal are to CV changes of individual MU's.

II. METHODOLOGY

The model used is based on the previous EMG model of Lowery *et al.* [8]. Improvements made to the model are described below.

A. Model description

The model may be split into three parts; muscle generation, MUAP calculation, and SEMG creation.

Muscle generation:

The muscle has a cylindrical cross section and is randomly filled with fibers according to a predetermined uniform density. The fiber type is randomly assigned in accordance with the required percentage of type I and II fibers for a specific muscle. All fibers in a MU are of the

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Abstract

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same type and are assigned an appropriate diameter, length, conduction velocity, and end plate position.

Three electrodes, two bipolar pairs, are placed 8 mm apart along the fiber direction and 3 mm distant from the outer surface of the cylindrical muscle. Axial conductivity is 0.33 mho/m, radial conductivity is 0.063 mho/m and internal conductivity is 1.01 mho/m. Table 1 gives details of the muscle model parameters.

Motor unit action potentials:

The transmembrane current is represented as a multipole (100 points), obtained from the discretisation of the transmembrane potential according to a line source model, [8]. Seven CV levels were generated, ranging from 100-58% of the original CV in decrements of 7%. The resulting database contains the MUAP's seen by each bipolar electrode pair for all calculated levels of CV sampled at 10kHz.

B. EMG Creation

The surface EMG signal is created from the generated database of MUAP's. The user can define recruitment, firing rates and conduction velocity levels of individual MU's. Correct recruitment order, i.e. that obeying Hennmann's size principle, is facilitated by MU's being listed in order of type, type I then II, and in order of increasing muscle fiber diameter within each type, [10].

Firing statistics:

A Gaussian distribution of mean MU firing rates was assumed, with a 25Hz mean and a coefficient of variance of 0.2, thus lying within the standard range for human muscle, i.e. 0.1-0.33, [11]. Higher mean firing rates are assigned to larger MU's. The firing statistics, i.e. the interpulse intervals (ipi's) of each MU are calculated based on Clamann's equation for interpulse interval standard deviation, [12]. The motor unit action potential trains, (MUAPT's) seen by each electrode pair are generated and stored for all MU's. This is repeated for each CV level. The same MU firing statistics are used for all CV levels, thus enabling the effects of changing CV to be studied in isolation.

TABLE I
Muscle generation properties

Muscle Geometry	Diameter Fiber length Area		20 (mm) 250 (mm) 314 (mm^2)
Fiber Density ($fibers/mm^2$)	Muscle MU		400 14
Fiber Type	Total	Type I	Type II
No. MU's	213	157	56
No. Fibers	121335	50055	71280
% Total Area	74	26.4	47.5
Diameter (μm)	42 – 55	42 – 49	48 – 55
CV ($m.s^{-1}$)	3.05-3.7	3.05-3.4	3.35-3.7

Recruitment:

EMG signals corresponding to a desired maximum voluntary contraction (MVC) level and comprising MU's with specified CV's can be easily generated. The number of active MU's required for a given output force is determined according to fiber diameter, i.e. for a 50% MVC, MU's are gathered, respecting recruitment order, until 50% of the total muscle volume is activated. This study has been carried out on signals of 30, 50 and 80 %MVC. The resultant EMG signal is the sum of the MUAPT's for all active MU's.

C. Signal Analysis

The most popular frequency analysis method used on EMG's, is the Fourier Transform. One issue arising with its use is the necessary assumption of stationarity. In our case, stationarity is a valid assumption as there are no changes in CV within a signal segment. Therefore an epoch length of 4 seconds was chosen, giving 0.25Hz frequency resolution. Four spectral measures are monitored in this study: the median frequency of the power and amplitude spectra, $Fmed_{pwr}$, $Fmed_{ampl}$, and spectral compression from the 60^{th}-90^{th} percentile for both the power and amplitude spectra, $Comp_{pwr}$, $Comp_{ampl}$, [9].

Conduction velocity is calculated by upsampling (to 100kHz), and cross correlating the EMG signals from the two bipolar electrode pairs, giving a resolution of less than 14mm/sec.

III. RESULTS

MU's were ranked according to the normalized maximum peak-to-peak amplitudes of all active MUAPT's for a given MVC level. CV's of individual MU's were changed, keeping that of all others constant. The sensitivity of each measure to these changes was assessed. The sensitivity of any measure, X, being defined as, sensitivity = $\Delta X_{EMG}/\Delta X_{MUAPT}$. 'MUAPT' signifies the motor unit action potential train of the MU who's CV is changing. See Fig.1 for an illustration of the relative ranking of the twenty most significant MU's, note how the signal is dominated by very few MU's for each MVC level. When testing sensitivity to changes in MU behaviour, it is important to keep MU ranking in mind. As expected, the sensitivity of all measures dropped with decreasing MU rank, see Fig. 2. Deviations about the mean values in this figure, and other cases not illustrated here, demonstrate that the cross-correlation technique is the most reliable measure for tracking changes in CV of superficial/high-ranking motor units. $Fmed_{pwr}$ was consistently the most variable and unpredictable measure. Fig. 3 shows the normalised values obtained by each measure across a 42% change in CV of the second ranked MU for a

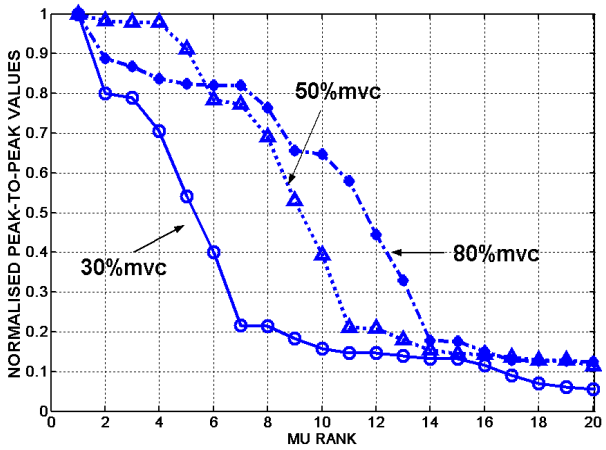

Fig.1. Ranking of the top 20 MU's for each of 30, 50 & 80%MVC. MU's are ranked according to the normalised peak-to-peak values of their MUAPT's. %MVC(Total no.of active MU's): 30(151), 50(173), 80(197).

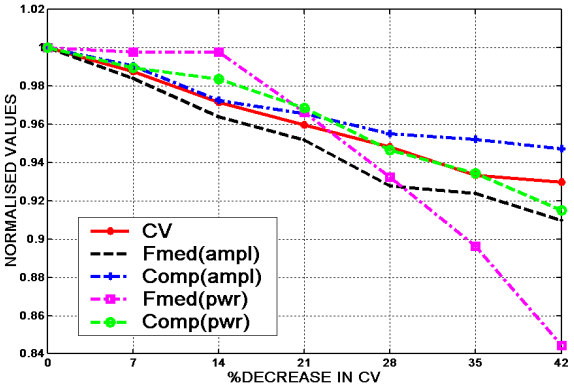

Fig. 3. Results obtained when the CV of the 2nd most significant MU at 30% MVC, is decreased from 100% to 58% in steps of 7%. All other CV values remain constant. All measures are normalized to their initial values.

30% MVC signal. This figure also illustrates the divergence between measures when CV of only one MU is changing. At a 42% decrease in CV the normalised value of $Comp_{ampl}$ drops by 5% while that of $Fmed_{pwr}$ drops by more than 15%. In contrast, Fig. 4 shows the convergent response of all measures to common changes in CV. Local MU activity had a strong influence on all measures.

Changes detected in EMG signal characteristics are assumed to be indicative of changes in the physiological activity of the muscle be it CV, firing rates, recruitment, synchronization or metabolite build-up. A simulation was run where a single MUAPT was time-shifted before being added to the EMG signal. This was repeated for twenty time shifts, where each shift corresponded to approximately $^1/_{20}{}^{th}$ of the averaged ipi duration for that MU. All measures showed significant sensitivity to these shifts, except the CV measure, which varied by less than 0.5%. See Fig. 5 for details.

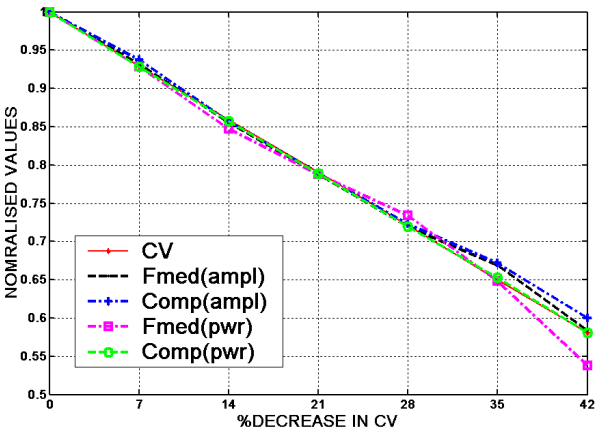

Fig. 4. Results obtained when the CV of all MU's changed simultaneously, at 30% MVC. Note the convergence of all measures. This is the only situation found where changes in the CV and spectral measures directly reflect CV changes i.e. sensitivity of unity. All measures are normalized to their initial values

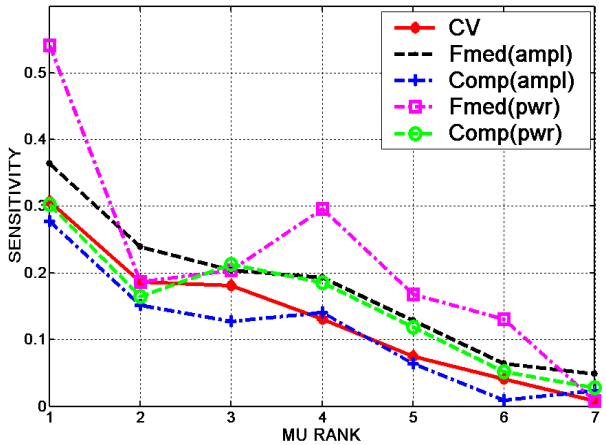

Fig. 2. Illustration of the mean sensitivities to CV decreases from 100-58% in steps of 7%, for each of the seven most highly ranked MU's. (30% MVC shown, similar results were observed for 50 & 80%MVC.)

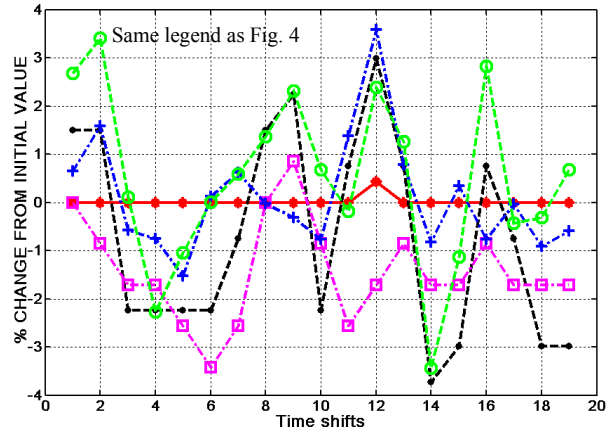

Fig. 5. Results obtained from time-shifting a single MUAPT in steps of $^1/_{20}{}^{th}$ of its average ipi, for a 30%MVC signal.

IV. DISCUSSION AND CONCLUSION

We have demonstrated the bias of SEMG to localized activity. The sensitivity of all measures was shown to decrease with decreasing MU rank. A striking outcome of our simulations is the level to which the possible information content of the EMG signal is restricted. Restrictions being primarily in terms of localization, but also due to the variability of each measures' sensitivity to a range of CV changes. Note the particularly significant changes appearing in $Fmed_{pwr}$, $Fmed_{ampl}$, $Comp_{pwr}$ and $Comp_{ampl}$, in Fig. 5, despite there being no physiological changes – all firing rates, conduction velocities, recruitment and synchronization patterns remained constant. Such fluctuating results indicate the need for caution when interpreting changes seen in the EMG signal.

Merletti *et al*. proposed that a non-uniform decrease in CV was a possible explanation for the different rates of change observed between the median and mean power spectrum frequencies and CV, [6]. Similarly, our results have shown variations in CV of local MU's to yield a divergence between changes observed in spectral measures and those observed in the CV measure obtained from cross-correlation, all other influences remaining constant. This is evident by comparing Fig. 3, where the conduction velocities of all MU's change together, to the situation illustrated in Fig. 4 where, by altering the CV of just one MU, a wide divergence is apparent - the most significant divergence occurring between $Fmed_{pwr}$ and CV. It was observed that though a good indicator of the general trend of activity, with a low variance, the CV measure did not have a 1:1 relationship to the actual CV changes. The only case where unity sensitivity was achieved was when the CV of *all* MU's decreased simultaneously and by the same amount. In this case all measures, (CV, $Fmed_{pwr}$, $Fmed_{ampl}$, $Comp_{pwr}$ and $Comp_{ampl}$) converged and had a 1:1 relation, to CV changes, see Fig. 3.

It is difficult to conclude that any one measure is a good indicator of the overall physiological state of the muscle, however, as a preliminary conclusion the divergence of the measures appears to be a significant indicator of varying CV's particularly amongst the higher-ranking MU's. From the representative results presented here, it seems that unless an assumption of uniform CV changes is made, little information can be gained from the signal.

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