INTERPRETING CHANGES IN SURFACE EMG AMPLITUDE DURING HIGH-LEVEL FATIGUING CONTRACTIONS OF THE BRACHIORADIALIS

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Abstract-**The amplitude of the surface EMG signal may provide a more accurate reflection of motor unit activity during sustained fatiguing contractions than spectral parameters which are more commonly used to estimate muscle fatigue. In this paper, theoretical relationships between surface EMG amplitude measures and mean motor unit firing rates and muscle fiber conduction velocity (MFCV) are established. It is proposed that using these relationships, under conditions where motor unit recruitment and synchronization can be assumed to be negligible, such as at high force levels or in smaller muscles, it may be possible to obtain an estimate of relative changes in motor unit firing rates during a sustained isometric contraction. Using EMG amplitude and MFCV data gathered from the brachioradialis muscle during 80% maximum voluntary contraction, relative changes in mean motor unit firing rates were estimated in this manner. MFCV and the estimated firing rate changes were then incorporated into a model of the surface EMG signal. Simulated EMG data was generated individually for each subject and EMG amplitude and spectral parameters calculated from the simulated and experimental data were found to compare well.**
***Keywords* - EMG, amplitude, conduction velocity, motor unit firing rates.**

I. INTRODUCTION

Many studies have focused on changes that occur in the power spectrum of the surface electromyographic (EMG) signal and on the use of EMG spectral parameters to estimate muscle fatigue during sustained contractions [1],[2]. Although the amplitude of the EMG signal is an easily monitored and commonly used measure of muscle activity, the relationship between changes in EMG amplitude and the physiological processes associated with muscle fatigue are not as well established. Nevertheless, it has been suggested that EMG amplitude may reflect underlying motor unit activity better than frequency spectrum shifts [3].

Surface EMG amplitude depends on a wide range of parameters. Assuming that the physical properties associated with the detection and recording of the signal are invariant with time, changes observed during sustained isometric contractions may be attributed to time dependent properties of the EMG signal in particular, muscle fiber conduction velocity (MFCV), motor unit recruitment, firing rates and motor unit synchronization. It is known that certain muscles rely predominantly on firing rate modulation to control the force output of the muscle. Similarly, studies indicate that during high-level contractions, muscles such as the biceps no longer continue to recruit additional motor units. Under conditions where motor unit recruitment and synchronization can be assumed to be negligible, by establishing relationships between EMG amplitude and MFCV and motor unit firing rate, it may be possible to infer information about firing rate behavior from changes in surface EMG amplitude and measured MFCV. A technique which could provide information on motor unit firing statistics without necessitating the use of intramuscular electrodes, and during high level contractions where it is difficult to distinguish between individual motor unit action potential trains, would potentially be a very valuable tool.

In this paper, changes in conduction velocity and mean firing rate are related to two commonly employed measures of surface EMG amplitude - the root mean square (RMS) value and the average rectified (AR) value. Based on these relationships, measured MFCV and EMG RMS amplitude are used to estimate changes in mean motor unit firing rates during sustained isometric contractions of the brachioradialis muscle at 80% MVC. The MFCV and estimated firing rate changes are simulated using a model of the surface EMG signal. The RMS and AR values of the simulated and experimental data are compared. Three spectral variables are also examined - the median frequency of the EMG amplitude spectrum, the median frequency of the EMG power spectrum and the spectral distribution function (SDF) estimate (the mean shift in the amplitude spectrum between the 60th and 90th percentiles [4]).

II. ANALYTICAL APPROACH

The voluntary EMG signal may be considered as the sum of N independent motor unit action potential (MUAP) trains and is commonly described in the following manner, [5][6],

$$EMG(t) = \sum_{i=1}^{N} \psi_i(t) \tag{1}$$

where $\psi_i(t)$, denotes the i^{th} MUAP train, characterised by the motor unit firing statistics, the conduction velocity and the extracellular action potentials. Assuming that the MUAPs are of zero mean, the RMS value of the EMG signal, RMS_{EMG}, is given by [7]

$$RMS_{EMG}^2 = \sum_{i=1}^{N} RMS_{MUAPT_i}^2 + 2\sum_{i<}\sum_{j} E[\psi_i(t).\psi_j(t)] \tag{2}$$

where RMS_{MUAPT_i} is the root mean square value of the i^{th} MUAP train, $\psi_i(t)$ and $E[\psi_i(t).\psi_j(t)]$ is the expected value of the product of the MUAP trains $\psi_i(t)$ and $\psi_j(t)$. For independent or uncorrelated motor units, $E[\psi_i(t).\psi_j(t)]$ will be zero [7]. Assuming that the shape and conduction velocity of successive action potentials remain constant and the period over which the RMS value is calculated, T, contains an integral number of MUAPs (or is large relative to the mean inter-pulse interval) then the RMS value of each MUAP train may be approximated as follows

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$$RMS_{MUAPTi} = \sqrt{\frac{1}{T}\int_{t}^{t+T}\psi_i^{\,2}(t)} \approx \sqrt{\frac{\int_0^{ipi_i}\varphi_i^{\,2}(t)\,dt}{ipi_i}} \qquad (3)$$

where $\varphi_i(t)$, is the MUAP generated by the i^{th} motor unit and ipi_i is the mean inter-pulse interval of the i^{th} motor unit The average rectified value of each MUAP train, $AR_{MUAPT\,i}$, may be similarly approximated as

$$AR_{MUAPT\,i} = \frac{1}{T}\int_{t}^{t+T}\left|\psi_i(t)\right|dt \approx \frac{\int_0^{ipi_i}\left|\varphi_i(t)\right|dt}{ipi_i} \qquad (4)$$

A Conduction velocity

Assuming a constant spatial distribution of the transmembrane potential along the muscle fiber, the single fiber action potential will scale proportionally with changing MFCV. If the time dispersion effects of individual fiber action potentials within the MUAP are regarded as negligible [1] and the conduction velocities of all fibers in the motor unit are scaled by $c\hat{v}$ then

$$\varphi_{i_2}(t) = \varphi_{i_1}(c\hat{v}.t) \qquad (5)$$

where φ_{i_1} and φ_{i_2} are the MUAPs detected before and after the conduction velocity has been scaled. Assuming that the motor units are independent and hence uncorrelated, substituting the expression for the RMS value of a train of MUAPs from (3) into the RMS value of the EMG signal, (2), and scaling the conduction velocity of all motor units by $c\hat{v}$, (5), the following relationship between the RMS values before and after the change in MFCV, $RMS_{EMG\,cv1}$ and $RMS_{EMG\,cv2}$, is obtained

$$RMS_{EMG_{cv2}} = \frac{1}{\sqrt{c\hat{v}}}RMS_{EMG_{cv1}} \qquad (6)$$

This relationship holds regardless of the number of motor units that are active. For a single action potential, this result has been previously derived [8] and also illustrated using simulation methods [9].

It follows similarly from (4) and (5) that the AR value of a single train of MUAPs is inversely proportionally to the fibre conduction velocity. However, as the number of action potentials detected at the electrode increases the energy lost to motor unit interference must be accounted for. If a sufficiently large number of action potentials are detected, the Law of Large Numbers may be applied. The signal can then be assumed to have a Gaussian probability density, for which the average value of the rectified signal is defined as follows [7], [10]

$$AR_{EMG} = E[|\,EMG\,|] = \sqrt{\frac{2}{\pi}}\sigma_{EMG} \qquad (7)$$

where $E[|EMG|]$ is the expected value of the absolute value of the EMG signal and σ_{EMG}, is the standard deviation of the EMG signal. For a signal of zero mean, the RMS value is an estimate of the standard deviation of the signal [11]

$$RMS_{EMG} = \sigma_{EMG} \qquad (8)$$

It follows from (7) and (8) that for large numbers of active motor units, the AR value will be proportional to the RMS value and under the conditions for which (6) was derived will also vary inversely proportional with the square root of the fiber conduction velocity.

$$AR_{EMG\,cv2} = \frac{1}{\sqrt{c\hat{v}}}AR_{EMG\,cv1} \qquad (9)$$

where $AR_{EMG\,cv1}$ is the average rectified value of the original EMG signal, and $ARV_{EMG\,cv2}$ is the AR value after the conduction velocity has been scaled.

B. Motor Unit Firing rates

Consider now the EMG signal as motor unit firing rates are allowed to change. If the firing rates of all motor units are scaled by a factor $\hat{fr}$, then substituting $1/ipi_i$ with $\hat{fr}/ipi_i$ in equation (3) and then into (2), it follows that

$$RMS_{EMG\,fr2} = \sqrt{\hat{fr}}RMS_{EMG\,fr1} \qquad (10)$$

where $RMS_{EMG\,fr2}$ is the RMS value of the EMG signal after the change in firing rate, and $RMS_{EMG\,fr1}$, the initial RMS value. For the single MUAP, the AR value will be proportional to the mean motor unit firing rate, (4). Once there is a sufficiently large number of motor units active for a Gaussian approximation to hold, the AR value of the EMG signal will vary proportional to the RMS value as before (7), and from (10)

$$AR_{EMG\,fr2} = \sqrt{\hat{fr}}AR_{EMG\,fr1} \qquad (11)$$

Under conditions where MFCV and motor unit firing rates are the dominant mechanisms responsible for changes in EMG amplitude, if it is assumed that the mean firing rates of all motor units change proportional to one another, and the conduction velocities of all motor units change proportional to one another, then the RMS value of the EMG signal can be related to the RMS value at the start of the contraction as follows

$$RMS_{EMG_2} = \frac{\sqrt{\hat{fr}}}{\sqrt{c\hat{v}}}RMS_{EMG_1} \qquad (12)$$

III. Experimental Methods

A. Methods

EMG amplitude and muscle fiber conduction velocity were simultaneously measured from the right brachioradialis muscle during sustained isometric flexion of the elbow at 80% maximum voluntary contraction (MVC) in 6 normal subjects (2 female, aged 20 to 33 years). A specially designed rig was used to enable the subjects to sit with their elbow flexed to a ninety-degree angle in a rigid brace with the upper arm vertical, next to the trunk, and the forearm horizontal. The subject's back was supported, as was the back of the upper arm, underneath the forearm and the elbow. The arm was in a neutral position, semi-prone, with the palmar surface of the hand in the vertical plane. Two straps were attached to a plate connected to a load cell (SM-500N, Interface Inc.) which was fitted to the rig. These two straps were fastened about the subject's wrist and another strap was fastened about the subjects upper arm and the back of the rig.

Each subject was instructed to flex the arm, pulling directly upwards against the wrist straps using the brachioradialis muscle. Subjects were asked to keep the elbow fixed at a right angle and to bear down upon it to avoid shoulder lifting. The force produced at the load cell was displayed to the subject on a monitor placed at eye level.

An electrode was constructed consisting of four bar electrodes, each 20mm long, mounted parallel to one another, 8 mm apart, on a perspex block. The electrode block was placed on the brachioradialis muscle, so that each electrode was positioned perpendicular to the fiber direction, and away from the innervation zone of the muscle. The four bar electrodes, grouped into pairs, were connected to the inputs of three differential amplifiers, band-pass filtered between 1Hz and 500Hz, and recorded on a computer at a sampling frequency of 2kHz, using the MP100 EMG System (Biopac Systems, California). Each contraction was maintained until task failure, which was defined as the point at which the force fell below 90% of the target value.

B. Data Analysis

The three signals from the single differential amplifiers were grouped into two pairs which were then differentially amplified off-line yielding two double differentially amplified signals. MFCV was estimated at 500ms intervals as proposed by [12] by locating the maximum of the cross correlation of the two double differential signals. Signals were temporarily over-sampled at 40 kHz, to obtain a sufficiently high time resolution for the MFCV estimates. The AR and RMS value of the surface EMG signals were also calculated.

Using the relationship expressed in (12), the relative change in mean muscle fiber firing rate, with respect to the beginning of the contraction, was estimated individually for each subject using the measured EMG RMS and MFCV values.

IV. Simulations

For each subject, the estimated change in motor unit firing rate and MFCV changes, normalized with respect to their values at the start of the contraction, were each fitted with a 4^{th} order polynomial. These values were then used as input data for the simulation of a set of surface EMG data for each subject. The data was simulated using the surface EMG model described in [4]. 197 motor units from a total pool of 213 were activated during each simulated contraction. MFCV ranged from 3.02-4.25 m/s. Mean motor unit firing rates had a mean value of 25 Hz and standard deviation of 5 Hz. Electrodes were placed 8 mm apart as in the experimental protocol. EMG data was simulated as MFCV and mean motor unit firing rates were altered according to the polynomials obtained from the experimental data. The RMS value, AR value, amplitude spectrum median frequency, power spectrum median frequency and SDF estimate were calculated each set of simulated data. EMG variables from the simulated and experimental data were compared.

V. Results

In Fig. 1, the estimated relative change in motor unit firing rates, along with a 4^{th} order polynomial fitted to the data, are presented for subject 1. In Fig. 2, the spectral and amplitude variables calculated from the simulated EMG are compared with the experimentally obtained values for the same subject. Results are presented for only one subject, as these are representative of the results obtained for all subjects. In all but one subject a good agreement between simulated and experimental variables was obtained.

VI. Discussion

EMG spectral variables are commonly used to examine muscle fatigue during sustained isometric contractions. The spectral changes observed are most commonly associated with variations in MFCV. The amplitude of the surface EMG signal may, however, provide a more accurate reflection of changes that occur in motor unit firing and recruitment patterns [3]. However, it is difficult to extract the desired information as the amplitude of the surface EMG signal is very sensitive to changes in many different parameters. Establishing analytical relationships between EMG amplitude measures, and physiological parameters, such as MFCV and motor unit firing rates, may enable more information to be extracted from the amplitude of the signal, under controlled conditions. A prerequisite for applying the relationships derived here is that motor unit recruitment and synchronization can be assumed to be negligible. If it can be assumed that the changes in the EMG amplitude are predominantly due to changes in motor unit firing rates and MFCV, it should be possible to 'reverse engineer' the problem to obtain an estimate of the relative change in mean motor unit firing rates from measured EMG amplitude and MFCV. An example of how this technique may be applied is presented here. Clearly a more extensive analysis, preferably where motor unit firing rates can be directly measured, is required to verify the accuracy of these estimates. However, the assumptions made seem reasonable under the experimental conditions described. Furthermore, the model simulations indicate that the measured MFCV and estimated motor unit firing rate changes are consistent with the amplitude and spectral changes observed experimentally.

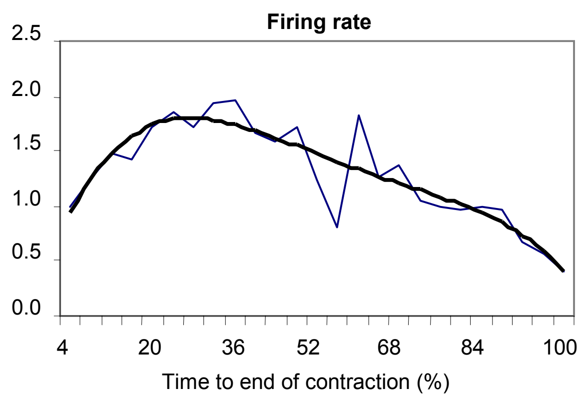

Fig. 1. Estimated mean motor unit firing rates from subject 1, during a sustained isometric contraction of the brachioradialis muscle. The data is normalized with respect to the start of the contraction and fitted with a 4^{th} order polynomial.

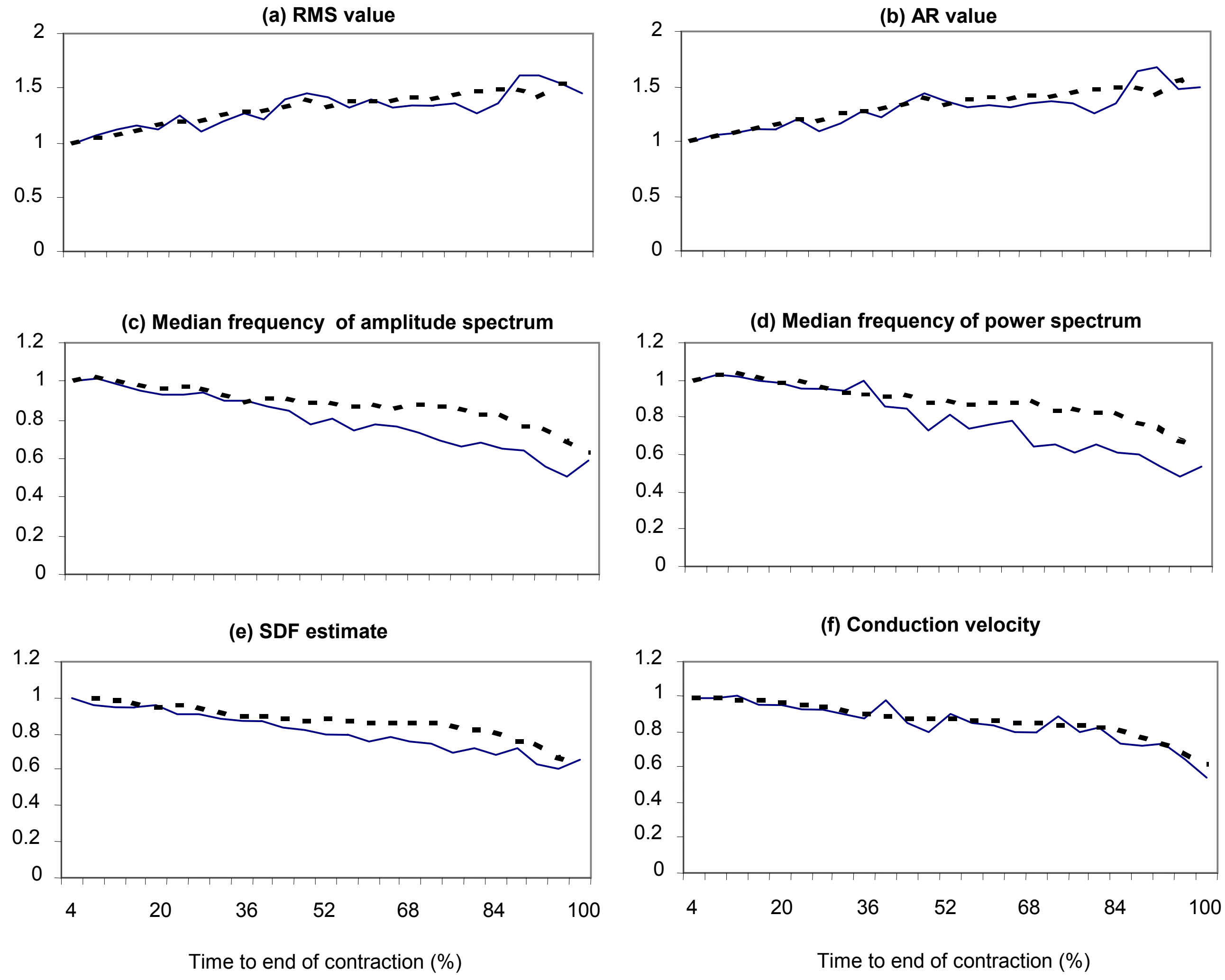

Fig. 2. Comparison of simulated (dashed line) and experimental (solid line) EMG variables for subject 1. All variables have been normalized with respect to their initial values.

V. CONCLUSION

By establishing theoretical relationships between changes in EMG amplitude and MFCV and motor unit firing rates, it may be possible to reveal information about underlying motor unit activity. Using relationships derived here, it is proposed that it may be possible to obtain an estimate of changes in motor unit firing rates from measured changes in EMG amplitude and MFCV, either during very high-level contractions, or in small muscles at levels where recruitment of motor units no longer occurs. Model simulations confirm that the measured MFCV and estimated firing rate changes can cause the observed changes in EMG amplitude. However, a more extensive analysis is required to test the accuracy of the proposed technique.

REFERENCES

[1] L.H. Lindstrom and R.I. Magnusson, "Interpretation of myoelectric power spectra: a model and its applications," *Proc. IEEE*, vol. 65, pp. 653-662, 1977.

[2] F.B. Stulen and C.J. De Luca, "Frequency parameters of the myoelectric signal as a meaure of muscle conduction velocity," *IEEE Trans. Biomed. Eng*., vol. 28, pp. 515-523, 1981.

[3] T. Moritani, M. Muro and A. Nagata, "Intramuscular and surface electromyogram changes during muscle fatigue," *J. Appl. Physiol.,* vol. 60, pp. 1179-85, 1986.

[4] M. Lowery, C.L. Vaughan, P. Nolan and M.J. O'Malley, "Spectral compression of the electromyographic signal due to decreasing muscle fibre conduction velocity," *IEEE Trans Rehab Eng* 8: 353-361, 2000.

[5] C.J. De Luca and E.J. Van Dyk, "Derivation of some parameters of myoelectric signals recorded during sustained constant force isometric contractions," *Biophys. J.* vol. 15, pp. 1167-1180, 1975.

[6] G.C. Agarwal and G.L. Gottlieb, "An analysis of the Electromyogram by Fourier, Simulation and experimental techniques," *IEEE Trans. Biomed. Eng*, vol. 22, pp 225-229, 1975.

[7] H.J. Larson *Introduction to probability theory and statistical interference*, John Wiley & Sons, 1982.

[8] R. Merletti, M. Knaflitz and C.J. De Luca, "Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions," *J. Appl. Physiol.,* vol. 69, pp. 1810-1820, 1990.

[9] D.F. Stegeman, and W.H.J.P. Linssen, "Muscle fibre action potential changes and surface EMG: A simulation study", *J. Electromyogr. Kinesiol.*, vol. 2, pp. 130-140, 1992.

[10] N. Hogan and R.W. Mann, "Myoelectric signal processing: optimal estimation applied to electromyography – Part 1: derivation of the optimal myoprocessor," *IEEE Trans. Biomed. Eng*., vol. 27, pp. 382-395, 1980.

[11] A. Papoulis, *Probability, Random variables, and stochastic processes.* Singapore: Mc-Graw-Hill, 1991.

[12] H. Broman, G. Bilotto, and C.J. De Luca, "A note on the noninvasive estimation of muscle fiber conduction velocity," *IEEE Trans. Biomed. Eng*., vol. 32, pp 341-344, 1985.