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Motor unit activity and surface electromyogram power spectrum during increasing force of contraction

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Summary. Twelve male subjects were tested to determine the relationship between motor unit (MU) activities and surface electromyogram (EMG) power spectral parameters with contractions increasing linearly from zero to 80% of maximal voluntary contraction (MVC). Intramuscular spike and surface EMG signals recorded simultaneously from biceps brachii were analyzed by means of a computer-aided intramuscular MU spike amplitude-frequency (ISAF) histogram and an EMG frequency power spectral analysis. All measurements were made in triplicate and averaged. Results indicate that there were highly significant increases in surface EMG amplitude (71±31.3 to 505±188 μV, $p<0.01$) and mean power frequency (89±13.3 to 123±23.5 Hz, $p<0.01$) with increasing force. These changes were accompanied by progressive increases in the firing frequency of MU's initially recruited, and of newly recruited MU's with relatively larger spike ampltitudes. The group data in the ISAF histograms revealed significant increases in mean spike amplitude (412±79 to 972±117 μV, $p<0.01$) and mean firing frequency (17.8±5.4 to 24.7±4.1 Hz, $p<0.01$). These data suggest that surface EMG spectral analysis can provide a sensitive measure of the relative changes in MU activity during increasing force output.

Key words: MU activity — Surface EMG power spectrum — Ramp force

Introduction

Since the "size principle" of Henneman et al. (1965) was first proposed based upon results from cat motoneurones, strong evidence has been presented that in muscle contraction there is a specific sequence of recruitment in order of increasing motoneuron and motor unit (MU) size (De Luca et al. 1982; Fruend et al. 1975; Henneman and Olson 1965; Milner-Brown et al. 1973; Tanji and Kato 1973). Recently, Kukulka and Clamann (1981) and Moritani et al. (1986a) have demonstrated in humans that, for a muscle group with mainly type I fibers (adductor pollicis), rate coding plays a more prominant role in force modulation. For a muscle group composed of both type I and II fibers, MU recruitment seems to be the major mechanism for generating extra force above 40 to 50% of maximal voluntary contraction (MVC) (De Luca et al. 1982; Kukulka and Clamann 1981; Moritani et al. 1986a). Goldberg and Derfler (1977) have also shown positive correlations among recruitment order, spike amplitude, and twitch tension of single MU's in human masseter muscle.

To study quantitative changes of MU activity, investigators (Komi and Viitasalo 1976; Moritani and deVries 1979; Petrofsky and Lind 1980a, 1980b) have employed various surface electromyogram (EMG) techniques. Particularly in recent years, the use of surface EMG power spectral parameters to characterize underlying myoelectric signals has received considerable attention (Broman et al. 1985; Hagberg and Ericson 1982; Komi and Viitasalo 1976; Petrofsky and Lind 1980a, 1980b; Moritani et al. 1982, 1985b, 1986b; Muro et al. 1983). The results obtained from these studies regarding power spectral parameter changes such as mean power frequency (MPF) and the

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Offprint requests to: T. Moritani, Human Performance Laboratory, Hoken-taiku, Kyoto University, Sakyo-ku, Kyoto 606, Japan level of muscle contractions are somewhat contradictory. For example, a series of studies by Petrofsky and Lind (1980a, 1980b) showed no systematic relationship between tension levels and MPF for hand grip muscles. Hagberg and Ericson (1982) demonstrated in the elbow flexors that MPF increased with contraction strength with low level contractions but became independent of contraction level above 25—30% MVC. Recent studies by Muro et al. (1983) and Broman et al. (1985), on the other hand, have shown almost linear increases in MPF with force of contraction up to near MVC levels. These different results might be at least in part due to differences in the musle groups studied, electrode size and inter-electrode distance which could act as various stage low-pass filters (Lindström et al. 1970), muscle fiber types (Moritani et al. 1985a) and underlying motor unit (MU) firing statistics and potential conduction velocity (Broman et al. 1985; De Luca and Creigh 1985; Largo and Jones 1977).

The purpose of the present investigation was therefore to determine systematically the relationships between the surface electromyogram (EMG) frequency power spectral parameters and underlying MU recruitment and firing frequencies during linearly increasing force of isometric contractions of biceps brachii. This was accomplished by recording the surface EMG and intramuscular MU spikes simultaneously so that surface EMG frequency power spectral analysis and intramuscular spike amplitude-frequency (ISAF) histogram analysis (Moritani et al. 1985b, 1986b) could be obtained under the same physiological conditions. In some cases, the effects on the EMG spectral parameters of different sizes and inter-electrode distances of the surface electrodes were also studied.

Methods

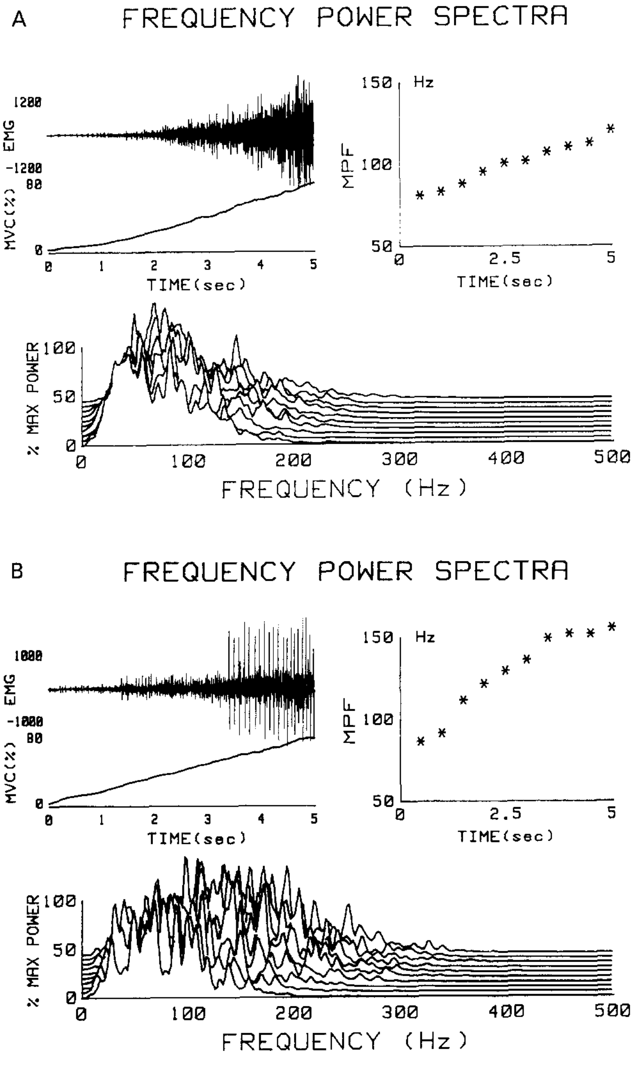
Subjects. Twelve male subjects (26.3±2.5 yrs, 176.1±6.4 cm, 74.8±5.9 kg, mean ±SD) volunteered for this investigation. The right biceps brachii was tested during isometric contractions increasing linearly (ramp force) from zero to 80% MVC in 5-s. The MVC was defined as the greatest force recorded during three brief maximal efforts. Each subjects was positioned on a table according to the methods described by Clarke (1966), with a webbed sling situated just below the wrist joint. The right hand was kept in a position midway between pronation and supination. Prior to any data collection, all subjects practiced the force output protocol 20 times on three different occasions to minimize variability in performance. By the end of the third practice session, all subjects could almost match the ramp force output to the target force level. The force was transmitted through a strain gauge which was linear up to 1000 N (GENESCO AWU-300) and amplified (Grass 7P122 DC amplifier, 0.1 to 30 Hz). The actual force output and target force were displayed on a conventional X-Y plotter for visual feedback. The five second duration for the ramp force output was chosen to avoid the effects of muscle fatigue (Moritani and deVries 1978). Each trial was followed by a 2-min rest period.

Surface and intramuscular EMG analysis. Our surface EMG spectral analysis and intramuscular MU spike amplitude-frequency (ISAF) histogram analysis procedures have been described in detail elsewhere (Moritani et al. 1985b, 1986b). Briefly, for surface EMG frequency power spectral analysis, bipolar silver/silver chloride electrodes (4 mm pick-up area, 6 mm inter-electrode distance) were applied over the belly of biceps brachii. The reference electrode was attached to the left wrist. In some cases ($N=3$), larger electrodes (10 mm pick-up area, 4 cm inter-electrode distance) similar to those used by Petrofsky and Lind (1980a) were also used. The myoelectric signal was amplified (Grass P511, 3 to 1000 Hz) and recorded on an analog FM data recorder (HP 3964A). The recorded signal was then digitized and stored on a floppy disk at a sampling rate of 1024 Hz, with anti-aliasing low-pass filtering at 520 Hz by the use of an HP 9836 desk-top computer. The digitized data from three separate trials were processed with the Hamming window function and 512 point fast Fourier transform (FFT) to obtain mean power frequency (MPF) and the root mean square value of EMG amplitude (rmsEMG). MPF was defined as the ratio between spectral moments of orders one and zero (Moritani et al. 1982).

The intramuscular spikes of the biceps brachii were recorded from high impedance bipolar wire electrodes (50 µm diameter; one with 50 µm and the other with 500 µm uninsulated areas) with a hook for fixation. These electrodes were passed through a 24-gauge, 3-cm steel hypodermic needle and inserted approximately 2 cm from the skin surface into the muscle. The needle was subsequently withdrawn. No discomfort was experienced from these micro-electrodes during testing. Spike recordings were made in triplicate, as in the case of the surface EMG recordings. The spike signals were fed through a high impedance probe (300 MΩ input impedance) with 100 dB common mode rejection ratio and amplified (Grass P511, 100 Hz – 10 kHz). Both the force and spike signals were monitored visually for any artifacts on a Tektronix 4-channel dual time base oscilloscope. The amplified MU spike signals were digitized at a sampling rate of 20 kHz with 12-bit fast A/D converters paced by precision pulse train cards and stored on a floppy disk by the desk-top computer. During the experiments, the force signal was continuously fed through the computer so that A/D converters for recording intramuscular spikes could be triggered at preset force levels of 20, 40, 60, and 80% MVC. Spikes above the iso-electric line were isolated by a window discriminant subroutine and counted according to their amplitude in 100 µV increments to obtain intramuscular spike amplitude-frequency (ISAF) histograms. For statistical comparison of the ISAF histograms, mean spike amplitude and frequency together with standard deviations were calculated for each ISAF histogram obtained at the different levels of contraction. With this procedure, we were unable to discriminate between motor units with spike amplitudes differing by less than 100 µV, leading to random additions and subtractions of individual spikes within this range. Therefore, in a strict sence, our data on MU firing frequency may not represent the absolute firing rates of single MU's, but rather represent the relative changes in firing frequency of a selected population of MU's. However, readly discriminable intramuscular spikes could be obtained with our computer-aided ISAF histogram techniques, and our procedures have repeatedly demonstrated that different threshold MU's are recruited in order of increasing spike amplitude even at high muscle contraction levels (Moritani et al. 1985b, 1986a).

Results

Figure 1A represents a typical set of computer outputs showing the recorded surface EMG and corresponding EMG power spectral changes during linear increases in force output from 0 to 80% MVC. The calculated mean power frequencies (MPF's) at every 500 ms (corresponding to 8% MVC increments) are also shown. As can readily be seen, both amplitude and MPF progressively increased in response to the linear increase in force. Without any exception, we found progressive increases in these parameters among the subjects tested under our experimental conditions. For comparison, the results obtained from one of the United States representatives for the 1984 World Power Lifting championship are shown in Figure 1B. Note the sharp EMG recordings similar to those normally obtained by intramuscular recording, and the much greater changes in the MPF's.



Figs. 1A, B. A typical set of computer outputs showing raw EMG, force, normalized power spectra and calculated mean power frequency *(MPF)* plots during ramp force output for a normal subject **A** and a highly trained power lifter **B**

Simultaneously recorded surface EMG with larger electrodes and wider inter-electrode distance ($N=3$) revealed no systematic increases in the MPF's, but showed progressive increases in EMG amplitude. These results are entirely consistent with those reported by Petrofsky and Lind (1980a, 1980b). This may point out the fact that surface EMG frequency power spectra could, among other things, be influenced by the size and inter-electrode distance used for recordings.

Figure 2 represents the group data (mean + SE) of the surface EMG root mean square amplitude (rmsEMG) and MPF during the ramp force output. It was found that there were significant increases in MPF ($89+4.4$ to $123+7.8$ Hz, $p<0.01$) and rmsEMG ($71+10$ to $505+62\,\mu V$, $p<0.01$) as a function of ramp force output.

A typical force curve and the relevant intramuscular spike recordings are shown in Fig. 3. The intramuscular spike recordings were made at 20, 40, 60, and 80% MVC during the increasing force output. The intramuscular spike amplitude-frequency (ISAF) histogram analyses were performed for a period of 250 ms at each sampling point. These data suggest that a considerable increase in MU spike amplitude and closely fired

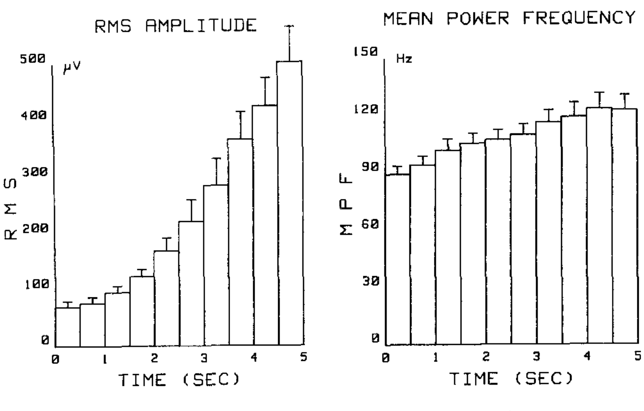


Fig. 2. Changes in surface EMG amplitude and mean power frequency ($N=12$, mean + SE) during ramp force output

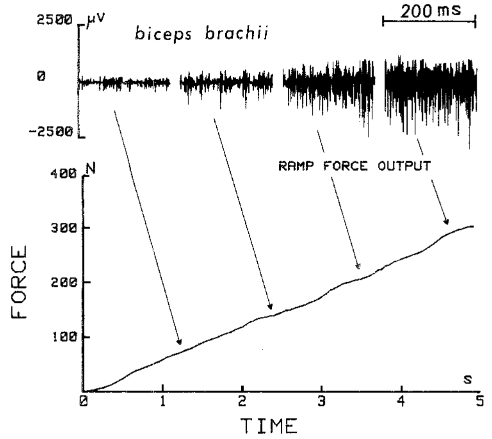


Fig. 3. Intramuscular MU spike recordings obtained at 20, 40, 60 and 80% *MVC* during ramp force output

spikes could be observed even above 60% MVC.

Figure 4 represents data from the same subject in averaged ISAF histograms from three repeated measurements. The mean intramuscular MU spike amplitude and firing frequency together with SD's were calculated. Considerable increases in both MU firing frequency (rate coding) and recruitment were evident in this subject, e.g., 12.8 to 21.8 Hz and 417 to 1050 µV, respectively. Progressive increases in firing frequency of already recruited MU's, and of newly recruited MU's with relatively larger spike amplitudes, can also be seen during the ramp force output.

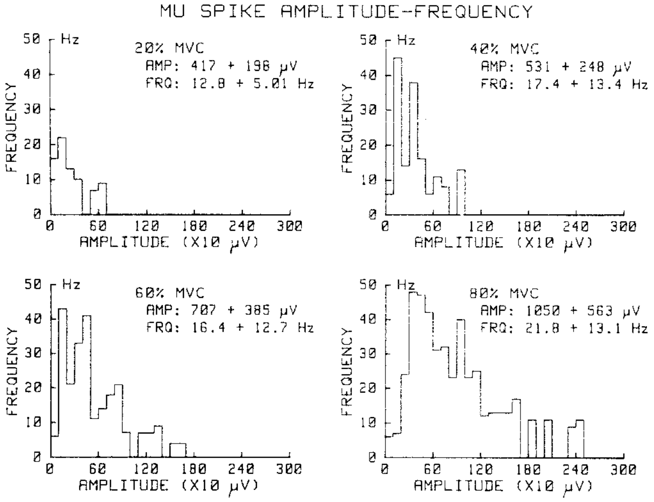


Fig. 4. Computer-aided intramuscular spike amplitude-frequency *(ISAF)* histograms obtained from the subject in Fig. 3. Note that the intramuscular MU spike signal polarity is inverted for the ISAF histogram analysis. The mean intramuscular spike amplitude *(AMP)* and firing frequency (FRQ) are shown with standard deviations

Paired *t*-test results for the group data indicate that there were significant increases in both mean MU spike amplitude (412±79 vs 972±117 µV, $p<0.01$) and firing frequency (17.8±5.4 vs 24.7±4.1 Hz, $p<0.01$).

Discussion

Experimental data on the relatinship between surface EMG amplitude and force have most often led to reports of a linear relationship (deVries 1968; Moritani and deVries 1978; Petrofsky and Lind 1980b), but some investigators have reported curvilinear relationships with IEMG varying in a positively accelerated fashion as force of contraction increases (Bigland-Ritchie 1981; Zuniga and Simmons 1969). The differences in these experimental results could be largely accounted for by such factors as the electrodes employsed (size, placements, unipolar vs bipolar, etc.), innervation ratios, fiber types and series connective tissue that one may not be able to generalize from the relationship found in any one muscle (Moritani and deVries 1978). The detailed discussion on the EMG/force relationship has been thoroughly presented by Stephens and Taylor (1972) and more recently by Bigland-Ritchie (1981).

Since the earlier work of Denny-Brown (1949), experimental data in humans seem strongly to confirm the "size principle" expounded by Henneman et al. (1965). For example, Goldberg and Derfler (1977) have shown that MU's with a high recruitment threshold possess larger spike amplitudes and generate twitches of greater pek tension than MU's recruited at lower forces. The present findings of a significant increase in intramuscular spike amplitude seem to provide some evidence that newly recruited MU's are involved during the ramp force output. It seems most likely that the changing EMG/force relationship with increasing muscle activation may relate to differences in the properties of the various MU types and the force range at which each MU is recruited (Bigland-Ritchie 1981). Since there is some evidence suggesting that a greater concentration of type II fibers can be found near the surface of the biceps brachii muscle (Clamann 1970), disproportionately large increases in rmsEMG amplitude could thus be result of a greater contribution of these type II fibers as high-threshold MU's are progressively recruited, together with the possible supratetanic firing of the low-treshold MU's during the ramp force output (see Figs. 3 & 4).

As to the changes in surface EMG frequency power spectra during the ramp force output, the progressive and statistically significant increases in MPF observed in the present study are in good agreement with the results reported by Muro et al. (1983) and Broman et al. (1985), but are inconsistent with those reported by Petrofsky and Lind (1980a, 1980b) and Hagberg and Ericson (1982). These different results might be explained by the differences in the muscle groups studied, electrode size, inter-electrode distance, MU firing statistics, and MU potential conduction velocity (Broman et al. 1985; De Luca and Creigh 1985; Hagberg and Ericson 1982; Largo and Jones 1977; Lindstrom et al. 1970; Moritani et al. 1982, 1985a). Petrofsky and Lind (1980a, 1980b), for example, employed a set of large electrodes (4 cm apart) for recording and found no systematic relationship between force levels and MPF in the hand grip muscles. Subsequently, Hagberg and Ericson (1982) investigated the myoelectric power spectrum dependence on muscular contraction level of the elbow flexors with bipolar miniature electrodes similar to those used in the present study, but placed 2 cm apart. They found that MPF increased with low level contractions but became independent of contraction level above 25 to 30% MVC. Muro et al. (1983) reported almost linear increases in MPF during isometric contractions ranging from 20 to 100% MVC for both biceps brachii and rectus femoris: they employed a set of minitature electrodes with 6 mm inter-electrode distance, as used in the present study. It is interesting to note that they were able to demonstrate highly significant differences in MPF during fast (1.5 rad/s) and slow (0.2 rad/s) concentric contractions with a load corresponding to 20% MVC for both muscle groups studied.

From these results it seems most likely that, among the other factors mentioned above, electrode size and inter-electrode distance could play a crucial role in determining the relationship between surface EMG frequency spectral parameters and levels of musclular contraction. For instance, particularly with surface bipolar electrodes, the presence of tissue between the muscle fibers and the recording site, acts as a low-pass filter (Lindström et al. 1970) whose bandwidth increases if the distance between the active muscle fibers and the electrodes decreases. The effective bandwidth may also increase when the inter-electrode distance decreases. Is is therefore reasonable to believe that the different results obtained by previous investigators (Petrofsk and Lind, 1980a, 1980b; Hangberg and Ericson,1982) might be at least in part due to the difference in effective frequency bandwidth as determined by the electrode size and interelectrode distance used for recording. Our data and those reported by Muro et al. (1983) thus seem to suggest that an increase in the higher frequency components of the myoelectric power spectrum can be expected as large superficial MU's are recruited and if the bandwidth is capable of accommodating for such changes in MU activity. The intramuscular MU spike data give further support to this notion in that the significant increases in mean MU amplitude and firing frequency are accompanied by significant increases in both rmsEMG amplitude and MPF during the ramp force output. The spectral changes observed for the power lifter (see Fig. 1B) and the results of Moritani et al. (1982), which showed a significantly higher MPF (mean difference of 35.7 Hz) for biceps brachii than that of soleus during a brief MVC, may also indicate the possibility that EMG frequency power spectral analysis can serve as a useful estimate of the underlying muscle fiber composition and relative changes in different MU activities.

In summary, the present experimental data suggest that surface EMG frequency power spectral analysis can provide a sensitive measure of the relative changes in MU activity during the ramp force output. In view of the discussion provided above, this technique may also be useful in determining the relative contribution of different MU types during rapid movements for which the use of conventional needle electrodes may not be suitable. However, the use of this technique must be considered carefully when studying strong or sustained contractions which bring about muscular fatigue and subsequent changes in the power spectrum. In view of the lack of unanimous interpretation of spectral changes under a variety of experimental conditions, we strongly advocate standardization of electrode size and inter-electrode distance for surface EMG recordings in future studies so that the results obtained from different research institutions are fully comparable.

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