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POWER SPECTRAL ANALYSIS OF ELECTROMYOGRAM AND COMPOUND MUSCLE ACTION POTENTIAL DURING MUSCLE FATIGUE AND RECOVERY

BY K. R. MILLS

From the Department of Human Metabolism, Rayne Institute, School of Medicine, University College London, University Street, London WC1E 6JJ

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SUMMARY

1. The power spectral changes of the voluntary electromyogram (e.m.g.) and of the compound muscle action potential (c.m.a.p.) evoked by supramaximal nerve stimulation have been compared in fatigue and recovery of human voluntary muscle contraction.

2. The mean power frequency (m.p.f.) of the voluntary e.m.g. and that of the c.m.a.p. are similar during fatigue. Power spectral shift can be largely accounted for by change in shape of muscle action potentials.

3. The recovery rates of force and action potential amplitude are similar, being half complete at 30 s. M.p.f. and relaxation rate recover more slowly, being half complete at 3 min.

4. It is suggested that the recovery of power spectral changes is dependent on the metabolic state of the muscle.

INTRODUCTION

The power spectral shift to lower frequencies of the surface electromyogram (e.m.g.) during fatigue is well documented (Kogi & Hakomada, 1962; Kadefors, Kaiser & Petersén, 1968; Lindström, Magnusson & Petersén, 1970; Petrofsky & Lind, 1980), but the mechanism of this phenomenon remains unclear. Several explanations are possible. (*a*) The action potentials from individual muscle fibres may change shape, becoming longer in duration and therefore changing in frequency content. The summation of these slower potentials, in the form of the surface e.m.g., would show a spectral shift to lower frequencies. (*b*) The firing frequency of motor units may change either through synchronization of firing at lower frequencies or through an over-all fall in firing frequency, and this may influence the spectrum of the e.m.g. (*c*) The action potentials from slow (type I) and fast (type II) motor units may differ in their frequency content; if the fast, fatigue-sensitive type II units have a higher frequency content, then as these units fail with continued force production, the slower fatigue-resistant units would remain, contributing more low-frequency components to the over-all spectrum.

In order to test the first of these possibilities, experiments were performed in which the spectrum of the voluntary e.m.g. was compared with that of the compound muscle action potential (c.m.a.p.) evoked by supramaximal stimulation of the motor nerve during a series of isometric contractions of maximal force.

Various indices of muscle function recover at different rates from the fatigued state (Edwards, 1981). For instance, action potential amplitude recovers quickly over 30–60 s, maximal isometric force recovers over 5–10 min, and other measures of the contractile mechanism, such as the force produced by 20/s nerve stimulation, may remain depressed for 24 h. (Edwards, Hill, Jones & Merton, 1977.) These phenomena indicate that recovery is taking place by several mechanisms, and it would be of interest to determine the recovery rate of the power spectral shift after fatigue and to compare this with the recovery rates of force, action potential and relaxation rate, to throw further light on these mechanisms. Because stable estimates of the power spectrum require at least 1 s of electrical activity, the voluntary e.m.g. after a series of contractions may well be subject to further fatigue effects. The recovery rate of spectra of single c.m.a.p. evoked by supramaximal stimuli was therefore determined.

METHODS

Recording and stimulation technique

Monopolar recordings were made from the left adductor pollicis muscle of five normal subjects who gave their informed consent to the experiments. Surface recordings were made in order to detect as large a sample of the motor unit population as possible. Since electrode position and geometry influence the spectrum of the signal (Lindström, 1970), electrode position was standardized (see below) and was marked in each subject to eliminate this source of variability. The active electrode (Disa Type 13K60) was located midway along a line joining the base of the proximal phalanx of the index finger and the centre of the first wrist skin crease. The inactive electrode was placed on the pulp of the index finger. The e.m.g. signal was amplified and displayed on an oscilloscope (Disa Type 14A11) and was bandpass filtered between 2 Hz and 2 kHz (−3 dB points). The output of the oscilloscope was passed to an eight-bit analogue-to-digital converter for subsequent computer analysis. The ulnar nerve was stimulated at the wrist by the passage of 50 μs pulses between a saline-soaked button electrode held tightly in place over the nerve and a saline-soaked felt and aluminium foil electrode on the dorsum of the wrist. At the start of each experiment, the voltage for maximal peak-to-peak muscle action potential amplitude was determined and a voltage of at least 50 % greater than this was used throughout the experiment to ensure stimuli were supramaximal. The hand and forearm were immobilized on a hand board based on that of Merton (1954), and the force developed by the adductor pollicis was measured by a strain gauge attached by an inextensible loop around the base of the thumb. Relaxation rate was measured using the differential of the force signal.

Analysis

A CBM 3032 microcomputer was used to calculate the power spectra (Mills, 1981). For analysis of the voluntary e.m.g., records of length 1·024 s digitized at 2 kHz were entered into the computer memory, and each record was split into sixteen segments. The data were smoothed digitally using a 0·25, 0·5, 0·25 moving weighted average technique to limit the high frequency content to 500 Hz, and then reduced by half in number to give an effective sampling rate of 1 kHz. This procedure is necessary to prevent aliasing of higher frequency noise into the final spectrum. Spectra were calculated by the fast Fourier transform method on 64 ms records and gave frequency estimates of 0–500 Hz with a band width between estimates of 15·625 Hz. The sixteen spectra from each record were then averaged and the variance of the estimate at each frequency calculated. The power at each point is quoted as a percentage of the total power of the whole spectrum. A similar procedure was used to compute the spectra of c.m.a.p.; the signal was digitized at 5 kHz, smoothed as above and then reduced by 5 times to give an effective sampling rate of 1 kHz. The mean power frequency (m.p.f.) of each spectrum was calculated. This is the frequency at which half of the total power is at higher frequencies, and half at lower frequencies. Previous workers (Gross, Grassino, Ross &

Macklem, 1979) have used the ratio of power in a high-frequency band (150–350 Hz) to that in a low frequency band (20–46·7 Hz) to measure the power spectral shift in fatigue. This suffers from the drawback that estimates of only two points on the frequency spectrum are used and their ratio may well be highly variable. The present method uses information from the whole of the spectrum.

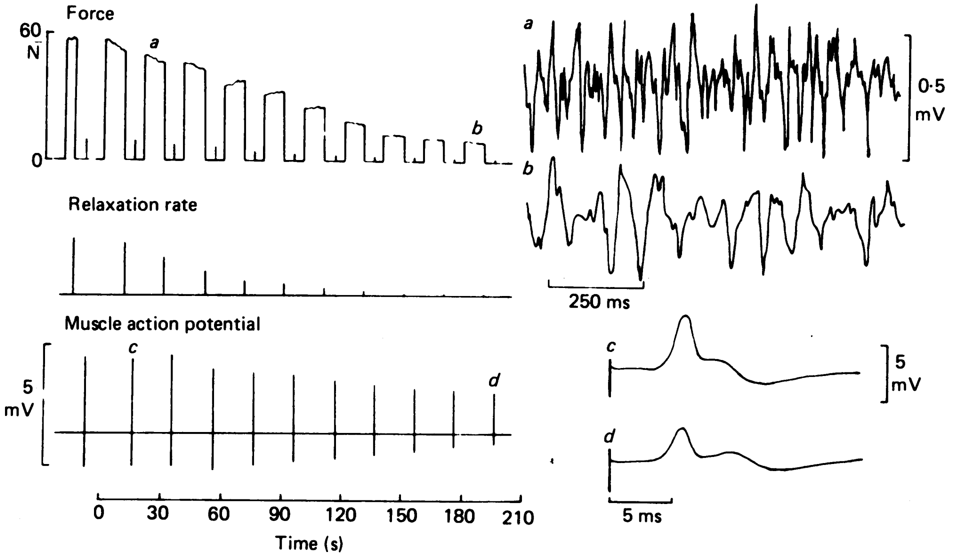

Fig. 1. Force, muscle relaxation rate and muscle action potential amplitude recorded during a typical experiment. The voluntary e.m.g. recorded during the mid-points of contractions marked *a* and *b* are shown at the upper right. The compound muscle action potentials *c* and *d* are shown in expanded form at the lower right.

Experimental protocol

Because of the well known effect of temperature on nerve conduction, muscle activation and metabolism, an attempt was made to standardize muscle temperature by warming the hand and forearm of the subject in a water-bath at 45 °C for 10 min and then maintaining the temperature by using an infra-red lamp during the experiment (Edwards *et al.* 1977). The force of maximal voluntary contraction was first determined and the size of the maximal c.m.a.p. measured. A sphygmomanometer cuff was then inflated to 250 mm Hg around the upper arm and subjects were requested to maintain maximal voluntary contraction forces for 10 s periods alternating with 10 s periods of rest with continuing ischaemia. Subjects were asked to relax as rapidly as possible at the end of the contraction. A total of ten such contractions were performed; subjects were encouraged to produce their maximum throughout and the force signal was displayed to them. This particular protocol was chosen so that recording of c.m.a.p. could be taken in the rest periods free from voluntary activity. There is little recovery of force in the rest periods (Fig. 1). Each subject performed this experiment twice, at least 6 h elapsing between experiments. In the first, the spectra of the c.m.a.p. in each rest period and at intervals after the release of the cuff were computed; in the second the spectra of voluntary e.m.g. taken at the mid-point of the 2nd, 4th, 6th, 8th and 10th contractions were computed. Also in the second experiment the recovery of force and relaxation rate were measured by asking subjects to perform maximal contractions at intervals after the release of the cuff. To rule out the possibility that the action potential may recover during the ischaemic rest period, in one subject, spectra of c.m.a.p. were determined during fatigue and at 5 s intervals after the excercise but with continued ischaemia for 35 s (Fig. 2).

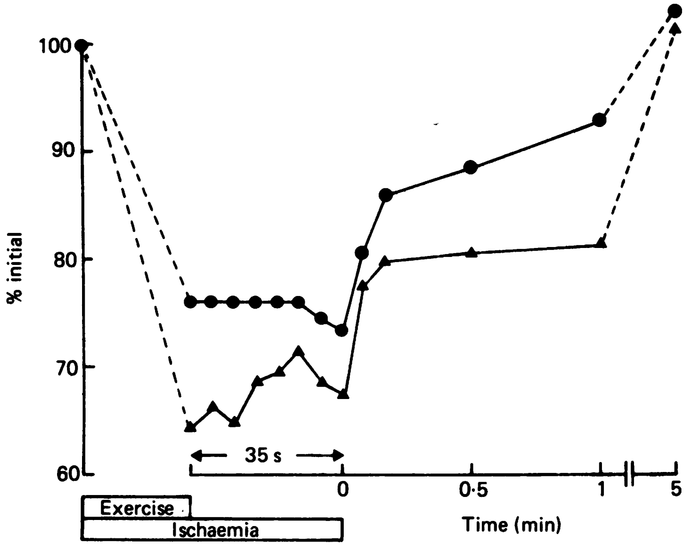

Fig. 2. Mean power frequency (▲) and action potential amplitude (●) during an experiment on one subject in which ischaemia was maintained for 35 s after the fatiguing contractions. There is no recovery of action potential amplitude, and only a small rise in m.p.f. during this time.

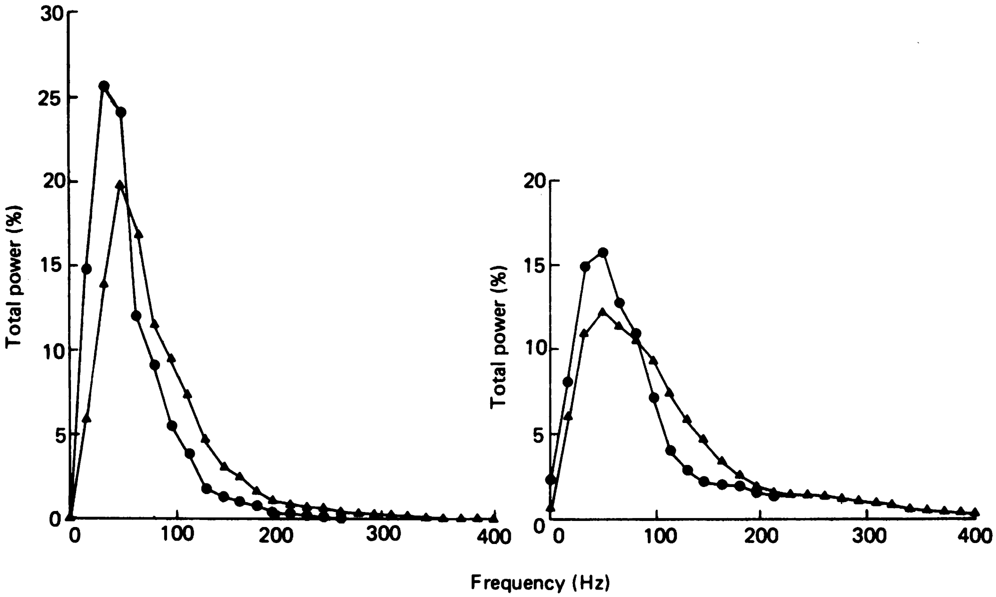

Fig. 3. Power spectra of voluntary e.m.g. (left) and c.m.a.p. (right). Spectra were taken at the beginning of the fatigue run (▲) corresponding to points *a* and *c* in Fig. 1 and at the end of fatigue (●) corresponding to points *b* and *d* in Fig. 1.

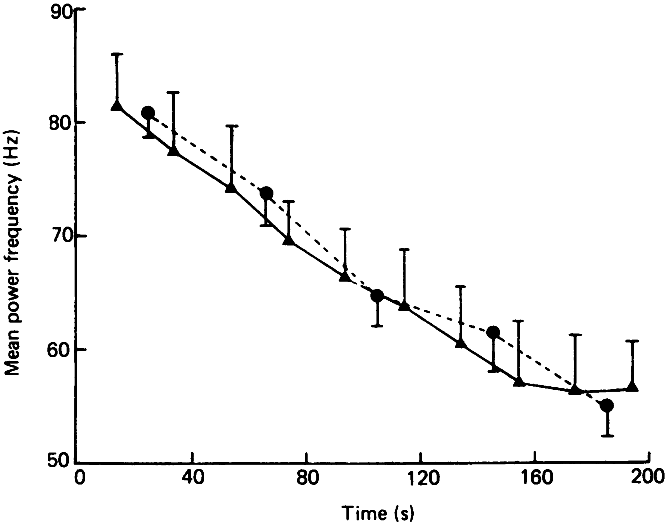

Fig. 4. Mean power frequency (Hz) determined from the spectra of voluntary e.m.g. (●) and the c.m.a.p. (▲) during fatigue. Values are the mean (±s.e. of mean) for five subjects.

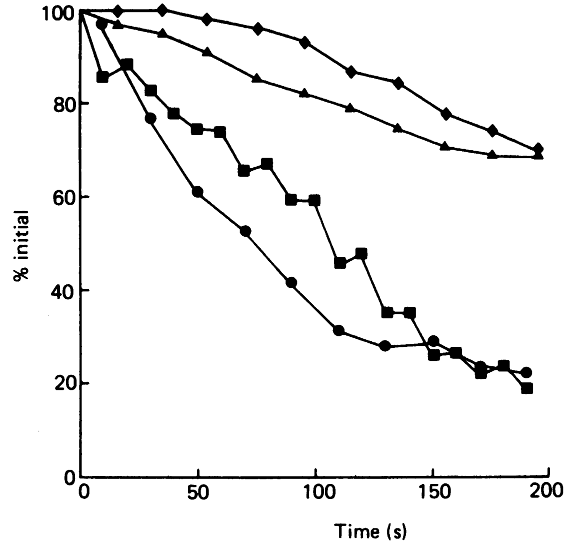

Fig. 5. Force (■), maximum relaxation rate (●), action potential amplitude (◆) and m.p.f. of the c.m.a.p. (▲) during fatigue. Values are the means for five subjects. s.e. of means are omitted for clarity but in no case exceeded 5%.

RESULTS

Typical power spectra of voluntary and evoked c.m.a.p. activity are shown in Fig. 3. The spectral shift is similar in the two situations. The change in m.p.f. with time during fatigue is shown in Fig. 4; there is no significant difference between the fall in m.p.f. of voluntary e.m.g. and the m.p.f. of the c.m.a.p. The time courses of force, relaxation rate, action potential amplitude and m.p.f. of the c.m.a.p. spectrum during fatigue are compared in Fig. 5, while the recovery rates of these four measures are seen in Fig. 6. Action potential amplitude and force recover most rapidly, the time to half recovery in both cases being 30 s. Relaxation rate and m.p.f. of the c.m.a.p. spectrum recover more slowly; the time to half recovery of these two measures was 3 min. There is little recovery of the action potential or of force during the ischaemic rest periods or of the c.m.a.p. or its spectrum in 35 s of rest with ischaemia in the experiment illustrated in Fig. 2.

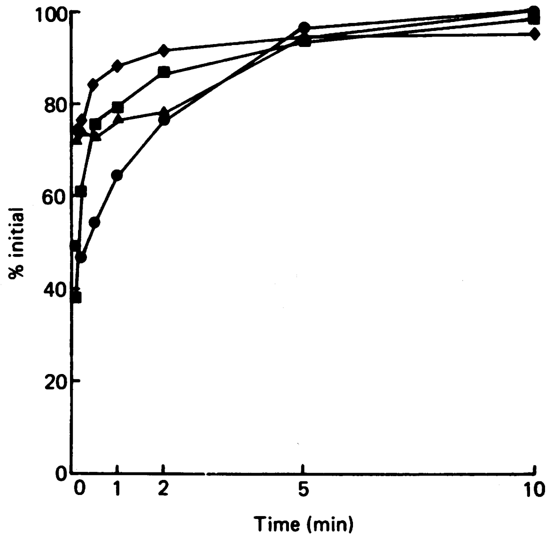

Fig. 6. The recovery of force (■), maximum relaxation rate (●), action potential amplitude (◆) and m.p.f. of c.m.a.p. (▲) after fatigue. Values are the means for five subjects. S.E. of means are omitted for clarity, but in no case exceeded 5%.

DISCUSSION

During maximal voluntary contraction it is assumed that all motor units of the muscle are recruited and that all are firing optimally for the production of force. When the motor nerve to the muscle is stimulated supramaximally all motor units are again activated, but almost synchronously (allowing for a small dispersion of the activation by conduction along distal nerve branches). Since the recording electrode lies in the same position in the two experiments, it is assumed that it is affected by the same population of motor units in both. Power spectral analysis of the voluntary e.m.g. signal and that of the maximal c.m.a.p. should, therefore, yield identical results.

Several parameters can be used when comparing spectra. When over-all shape of spectra is of interest, indices such as the maximum power, the frequency at maximum power and the band width at, say, half maximum power may be useful. Since the variance of a spectral estimate is proportional to its mean (Bendat & Piersol, 1971), comparison of maximum power and band width at half maximum power are likely to be unreliable. When spectral shift is to be analysed, as is the case here in fatigue, m.p.f. is the most reliable measure, since information is used from the whole of the spectrum. Table 1 compares these parameters from voluntary e.m.g. and c.m.a.p. spectra in the fresh and fatigued states. The only index that is significantly different between voluntary e.m.g. and c.m.a.p. spectra is the maximum power, although there is a suggestion, not reaching statistical significance, that the band width at half maximum power is broader in the c.m.a.p. spectra. It can also be seen in Fig. 4 that the m.p.f. of voluntary e.m.g. and c.m.a.p. spectra are not significantly different througout the fatiguing contractions.

TABLE 1.

	Fresh				Fatigued			
	P_{max} (%)	F_{max} (Hz)	B.w. (Hz)	M.p.f. (Hz)	P_{max} (%)	F_{max} (Hz)	B.w. (Hz)	M.p.f. (Hz)
Voluntary e.m.g. spectrum								
Mean ($n = 5$)	20·0	50·0	68·0	80·7	29·2	40·6	42·1	55·3
s.e. of mean	3·7	3·1	8·1	1·7	2·2	3·8	11·1	2·1
C.m.a.p. spectrum								
Mean ($n = 5$)	12·3	50·0	97·2	81·2	16·1	43·8	77·0	55·9
s.e. of mean	1·1	3·1	13·2	4·9	1·2	3·1	10·5	4·6
Probability that data* derive from same population	$< 0·005$	1·0	0·1	$> 0·9$	$< 0·001$	0·5	0·15	$> 0·9$

P_{max}: maximum power. F_{max}: frequency at maximum power. B.w.: band width at half maximum power. M.p.f.: mean power frequency.

* Data from five subjects compared with paired *t* test.

The reason for the difference in shape between voluntary e.m.g. spectra and c.m.a.p. spectra is not clear. It is possible that during the initial 5 s of a maximal contraction, some fatigue sensitive motor units fail and then recover in the initial 5 s of the following ischaemic rest period before the test shock is applied. If these units contributed relatively higher frequencies to the over-all spectrum, then the results seen here may be obtained. It is known that the membrane properties of type I and II cat motor units are different (Buller, Lewis & Ridge, 1965; Hammarberg & Kellerth, 1975), and if this finding can be extended to man (Buchthal, Dahl & Rosenfalk, 1973) then the possibility remains that fast and slow motor units contribute different proportions to the over-all spectrum and an alteration in these proportions during fatigue could result in the observed changes.

Over-all motor unit firing frequency falls during fatigue (Marsden, Meadows & Merton, 1971) and motor units may show synchronized activity at about 10/s. If these factors were contributing to the phenomenon of spectral shift, it would be expected that the shift in the voluntary e.m.g. spectrum would exceed that of the c.m.a.p. spectrum. Lindström & Petersén (1981) has shown by computer modelling that repetition rate of simulated muscle action potentials has little effect on the m.p.f. or the shape of the resulting spectra. Also several workers (Kaiser & Petersén, 1963; Petrofsky & Lind, 1980; Lindström & Petersén, 1981) have shown that the m.p.f. of voluntary e.m.g. spectra is unrelated to the force of contraction. It seems unlikely then that fall in motor unit firing frequency contributes to the spectral shift.

It is therefore contended that the well described spectral shift in the e.m.g. seen in fatigue can be accounted for largely by change in the frequency content of summated individual muscle action potentials.

The time courses of recovery of maximal voluntary contraction force and compound muscle action potential amplitude after fatigue appear to proceed at roughly the same rate, both being about half complete at 30 s. It is likely that these phenomena are dependent upon recovery of the neuromuscular junction or the mechanism of excitation–contraction coupling. On the other hand, maximum relaxation rate and m.p.f. of the c.m.a.p. recover more slowly, both being about half recovered at 3 min. Relaxation rate is thought to reflect the metabolic state of the muscle (Edwards, Hill & Jones, 1972), and its recovery after fatigue is thought to parallel the resynthesis of phosphorylcreatine (Wiles, 1980). Because of the similarity of recovery rate of relaxation rate and m.p.f., it is suggested that both measures are dependent on either resynthetic processes in the muscle or to degradation or removal of the metabolites of contraction.

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