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EMG Frequency Spectrum, Muscle Structure, and Fatigue During Dynamic Contractions in Man

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Summary. Fatigue of the vastus lateralis muscle was studied in healthy well-conditioned students, who differed considerably regarding their muscle fibre type distribution. Muscle force decline during repeated maximum voluntary knee extensions at a constant angular velocity ($180° \times s^{-1}$ or π rad $\times s^{-1}$), using isokinetic equipment, was taken as the criterion for the degree of fatigue. In an attempt to study quantitative as well as qualitative changes in the EMG pattern, integrated EMG (IEMG) and the frequency of the mean power (MPF), computed from the power spectral density function (PSDF), were analysed. It was found that individuals with muscles made up of a high proportion of fast twitch (FT) muscle fibres demonstrated higher peak knee extension torque, and a greater susceptibility to fatigue than did individuals with muscles mainly composed of slow twitch (ST) muscle fibres. An IEMG decline ($p < 0.01$) was demonstrated during 100 contractions in individuals rich in FT fibres. Only a slight, but not significant, reduction in IEMG occurred in individuals with a high percentage of ST fibres. Concomitantly, MPF decreased ($p < 0.001$) in individuals with a high percentage of FT fibres, while their opposites demonstrated only a slight decrease (non-significant). It is suggested that muscle contraction failure might also be related to qualitative changes in the motor unit recruitment pattern, and that these changes occur more rapidly in muscles composed of a high proportion of FT muscle fibres than in muscles composed of a high proportion of ST fibres.

Key words: Electromyography – Isokinetic contractions – Mean power frequency – Muscle fatigue – Muscle fibre types

From animal experiments it is known that muscles composed of slow twitch (ST) fibres possess a greater resistance to fatigue than muscles containing predominantly fast twitch (FT) fibres (e.g., Edström and Kugelberg, 1968; Kugelberg and Edström,

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1968; Baldwin and Tipton, 1972). In human skeletal muscle, both fibre types exist in one and the same muscle. Recently, it was found that subjects with a relatively higher proportion of FT fibres in the quadriceps muscle were more susceptible to fatigue when performing 50 consecutive maximal knee extensions than subjects rich in ST fibres (Thorstensson and Karlsson, 1976; Nilsson et al., 1977; Tesch et al., 1978a). In addition, large amounts of lactate were found to have accumulated preferentially in the FT fibres after only 25 contractions (Tesch et al., 1978a, 1978b). Lactate formation and/or associated pH changes within engaged muscle fibres may be responsible for muscle contraction failure (cf. Fitts and Holloszy, 1976).

In experiments using electromyographic (EMG) techniques, it has been suggested that the shift in EMG spectral density function towards lower frequency components is associated with reduction in muscle action potential conduction velocity (Mortimer et al., 1970). In addition, the shift in EMG frequency spectrum under isometric fatigue conditions has been shown to be related to the fibre type composition of the muscle (Larsson, 1978; Viitasalo and Komi, 1978). The present study was undertaken to investigate EMG spectral changes under maximal dynamic fatigue conditions where lactate formation is likely to occur preferentially in FT fibres (Tesch et al., 1978a, 1978b).

Methods

Eleven male physical education students volunteered to participate in the study. Prior to the experiments, all subjects were informed about the possible discomforts and risks associated with the experimental procedures. After muscle biopsy sampling and histochemical analysis (see below), the subjects were divided into two groups, based on individual muscle fibre type distribution. Table 1 summarizes their physical characteristics with respect to age, weight, height, per cent distribution, and relative area of fast twitch (FT) fibres in the vastus lateralis muscle, as well as maximum dynamic strength. Muscle biopsies were taken from M. vastus lateralis prior to experiments according to Bergström (1962). Classification of the fibres into slow twitch (ST or type I) and fast twitch (FT or type II) fibre types was based on histochemical staining for myofibrillar ATPase after preincubation at pH 10.3 (Padykula and Herman, 1955; Engel, 1962). Muscle fibre area was measured according to Thorstensson (1976) from transverse muscle sections stained for NADH diaphorase activity (Novikoff et al., 1961). The relative area occupied by FT fibres was calculated according to Tesch et al. (1978a).

Table 1. Physical characteristics (mean ± SE) of the two subject groups. Per cent distribution and relative area of fast twitch (FT) fibres were obtained from muscle biopsy sample of M. vastus lateralis. The peak torque expresses the maximum torque of the unilateral knee extension

	Group I < 50% FT area ($n = 5$)	Group II > 50% FT area ($n = 6$)	Difference
Age (year)	27.8 ± 2.8	23.1 ± 1.1	n.s.
Weight (kg)	74.0 ± 3.4	69.6 ± 2.0	n.s.
Height (cm)	180.4 ± 1.8	178.0 ± 1.3	n.s.
% FT	41.2 ± 3.2	60.3 ± 3.0	$p < 0.01$
% FT area	43.2 ± 1.0	67.0 ± 3.4	$p < 0.001$
Peak torque (Nm)	165.8 ± 5.8	190.8 ± 5.6	$p < 0.05$

Each subject performed 100 maximal voluntary knee extensions in an isokinetic device (Cybex II, Lumex Inc., New York) through a motion range from 100° (0.55 π) flexion to a fully extended knee joint and at an angular velocity of 180° × s^{-1} (π rad × s^{-1}). The passive recovery time between contractions was 0.7 s. The subject was firmly fixed in the dynamometer chair to ensure that movement was limited to the knee extensor muscles (for details see Thorstensson, 1976).

Electromyographic activity (EMG) was registered from the vastus lateralis muscle during the entire experiment. Bipolar surface electrodes (Hellige, Stockholm, Sweden) of 10 mm diameter were placed over the vastus lateralis muscle as close as possible to the site of the biopsy insertion, which was always over the belly of the muscle. The interelectrode distance was 10 mm in the direction of patella-crista iliaca. EMG was amplified with Brookdeal type 9432 preamplifiers with a gain of 60 dB and a frequency range of 10 to 10.000 Hz. The amplified signal was immediately stored on magnetic tape (Philips Analog 7) with a recording speed of 380 mm × s^{-1}. EMG analysis was limited to the mid-range of knee extension.

The data processing system (Komi and Lehtiö, 1973; Viitasalo and Komi, 1975) built around the HP 2116 C laboratory computer produced the following two EMG parameters: integral (IEMG), and power spectral density function (PSDF). PSDF was computed according to formulas of Bendat and Piersol (1971). To investigate the detailed changes in PSDF during fatigue, the frequency of the mean power (MPF) was computed (Kwatny et al., 1970) and the relative (per cent) proportions were calculated for the bandwidths 24–48 Hz, 56–88 Hz, 96–128 Hz, and 136–400 Hz.

Results

The two groups studied differed in the distribution of FT fibres as well in the relative area occupied by FT fibres in the vastus lateralis muscle (Table 1). In group I, the average values were 41.2 and 43.2, respectively, for % FT distribution and % FT area. The corresponding values for group II were 60.3 and 67.0 (Table 1). The peak knee extension torque values were also different: 165.8 (group I) and 190.8 (group II) Nm (Table 1 and Fig. 1a).

When the two groups were subjected to 100 maximal dynamic contractions of the knee extensors, observed mean fatigue curves were obtained as shown in Figs. 1a and 1b. Both the absolute (Fig. 1a) and relative (Fig. 1b) decline in torque were greater in group II ($p < 0.01$ and $p < 0.05$) and tension outputs at termination of experiments had decreased to 51 and 38% of initial value in groups I and II, respec-

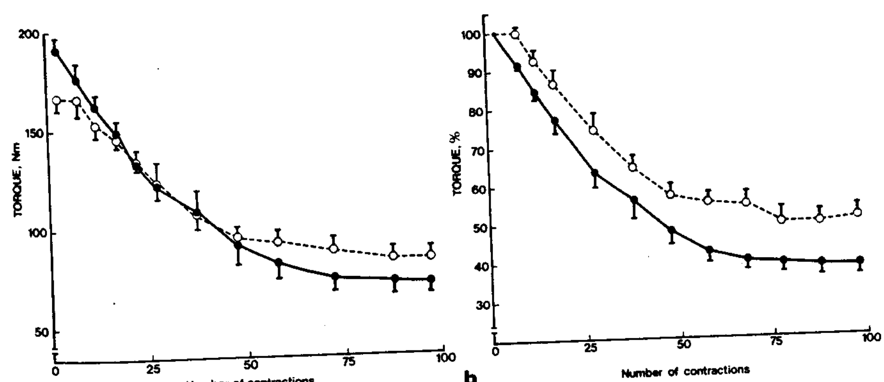

Fig. 1a and b. Mean (± SE) torque expressed as Nm (**a**) and per cent of initial value (**b**), respectively, during 100 repeated knee extensions at an angular velocity of 180° × s^{-1}. Filled and open dots represent groups of subjects with a relative area of 67% ($n = 6$) and 41% ($n = 5$) fast twitch fibres, respectively

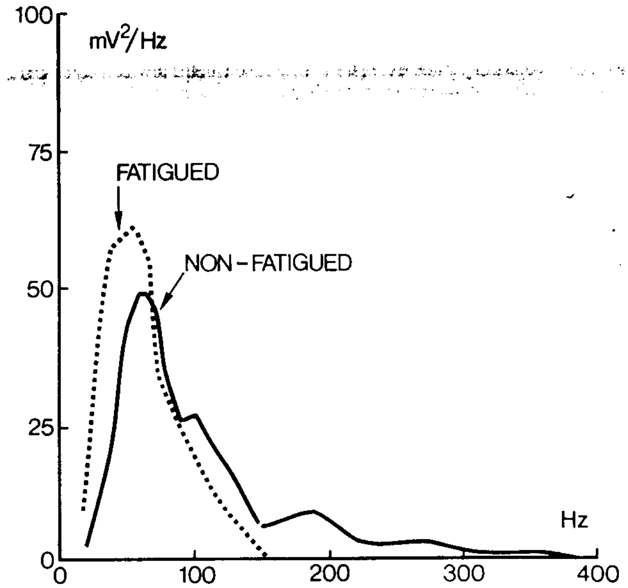

Fig. 2. Power spectrum density function (PSDF) recorded for one subject (65% FT area) initially ("non-fatigued") and at end of exercise ("fatigued")

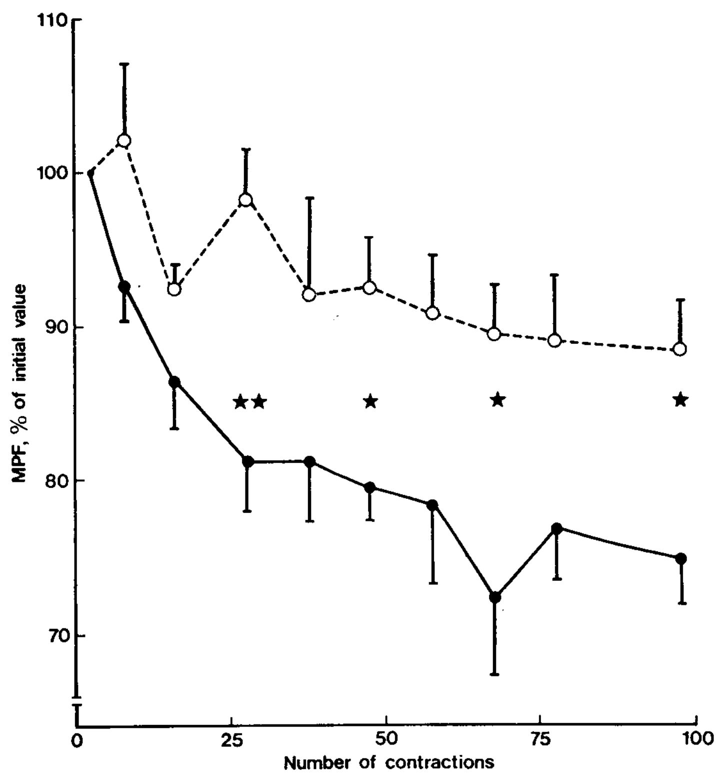

Fig. 3. Mean values (± SE) of mean power frequency (MPF) expressed as percentage of initial value for the two groups studied during 100 contractions. Differences between groups are denoted with * = $p < 0.05$ and ** = $p < 0.01$. For further explanation see Fig. 1

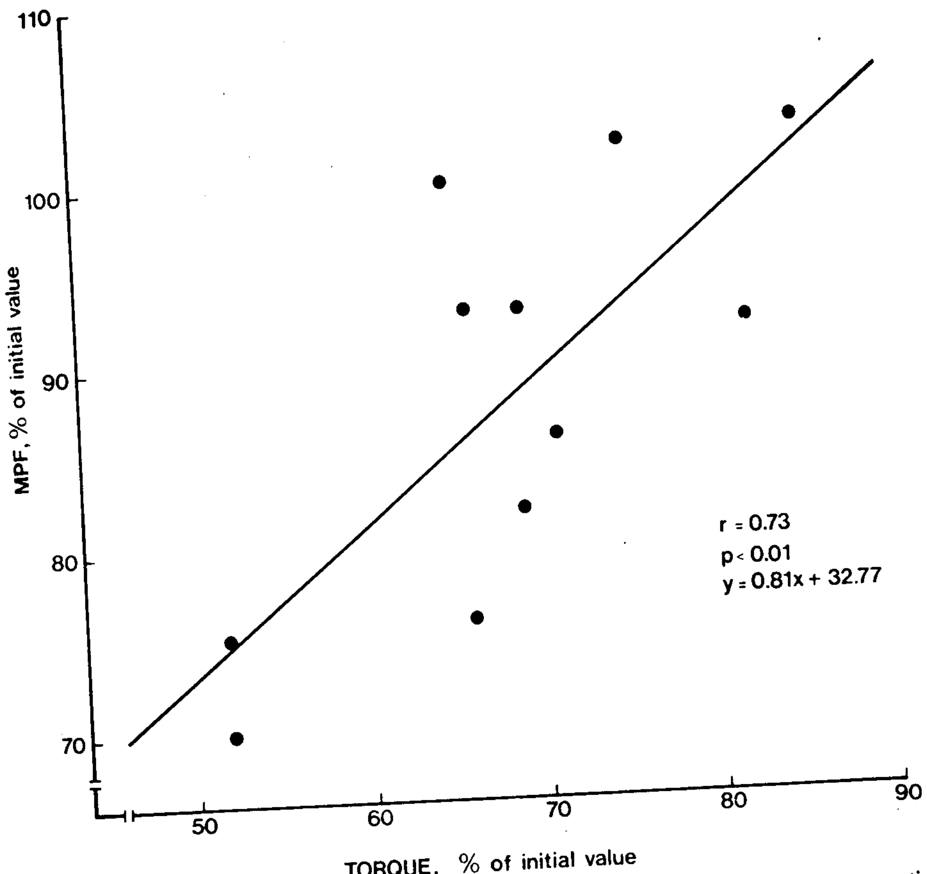

Fig. 4. Relationship between relative changes in peak torque and MPF after 25–30 contractions ($n = 11$)

tively. If the torque decline during the 100 contractions was expressed per kg body weight, mean (± SE) reductions were 1.1 ± 0.1 Nm × kg^{-1} and 1.7 ± 0.1 Nm × kg^{-1}, respectively, for groups I and II ($p < 0.001$). The decline in torque was correlated positively to the % FT area ($r = 0.73, p < 0.01$). Moreover, as shown in Fig. 1a and 1b, the initial torque decline in group I was delayed until the 7th–10th contractions.

EMG measurements revealed that integrated electromyographic activity (IEMG) declined as follows: group I, 4 ± 3% (n.s.); group II, 15 ± 3% ($p < 0.01$). An increase in IEMG/torque ratio occurred with fatigue ($p < 0.01$), and it was slightly, but not significantly, more pronounced in group II. Furthermore, a relationship was established between the relative increase in IEMG/torque ratio and torque decline ($r = 0.88, p < 0.001$). PSDF changed considerably in group II during fatigue loading (Fig. 2). For instance, mean power frequency (MPF) declined 13 ± 4 Hz or 12 ± 4% (n.s.) (group I) and 26 ± 3 Hz or 25 ± 3% ($p < 0.001$) (group II) (Fig. 3). Differences in the PSDF change between the two groups were observed after only 25–30 contractions ($p < 0.01$).

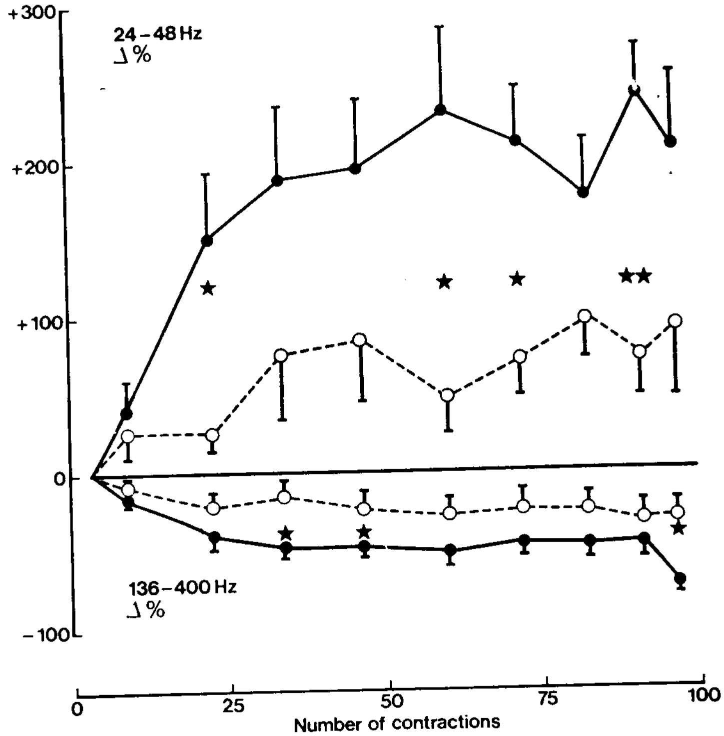

Fig. 5. Relative changes in the power of different bandwidths during 100 contractions for the two groups studied. For further explanation see Figs. 1 and 3

Both the magnitude of maximum torque decline as well as muscle structure were found to be correlated to the changes in PSDF during fatigue loading. Thus, individual torque decline after 25 contractions was positively related to the simultaneous shift in PSDF expressed as a relative change in MPF ($r = 0.73$, $p < 0.01$) (Fig. 4), and individual decrease in MPF was greater in subjects with a greater relative area of FT fibres in the vastus lateralis muscle ($r = -0.60$, $p < 0.05$).

The difference in frequency spectrum change between the two groups is exemplified in Fig. 5 by comparing the increases in the lowest bandwidth (24–48 Hz) and decreases in the highest bandwidth (136–400 Hz) throughout the fatigue loading of 100 dynamic contractions. Group II had a significantly ($p < 0.01$) higher relative content of the lower bandwidth and a lower content ($p < 0.05$) of the higher bandwidth as compared to group I. This pattern was significant after 25–30 contractions.

Discussion

In the present study, repeated maximum voluntary contractions of approximately 25–30% of maximum contraction velocity (Thorstensson, 1976) were performed. In accordance with previous studies of the same experimental design (Thorstensson and Karlsson, 1976; Nilsson et al., 1977; Tesch et al., 1978a), muscle fatigue, assessed by the decline in maximum torque, increased with an increasing proportion of FT muscle fibres.

The decrease in torque was accompanied by a significant reduction in maximum IEMG activity in a group of subjects with a high percentage of FT muscle fibres. The increase in IEMG/torque ratio was also found to be most pronounced in muscles of the fast twitch type. These findings are in good agreement with those of Ochs et al. (1977), who reported a relatively high increase in EMG/tension ratio in the gastrocnemius as compared to the soleus muscle during repeated plantar flexion movements.

Integrated EMG during repeated maximal contractions has been reported as decreasing in some other investigations (e.g., Komi and Ruski, 1974) but others (e.g., Nilsson et al., 1977) found no significant decrease. Conflicting results can be partially explained not only by differences in the experimental subjects (or their muscles) but also by the possibility of migration of electrical activity from one muscle to another. This migration has been demonstrated in finger muscles by Lippold (1955), and probably also in leg extensor muscles by Komi and Viitasalo (1976).

The changes in the power spectral density function (PSDF) expressed as a decrease in MPF during fatigue was correlated positively to force decline as well as to the cross-sectional area occupied by FT fibres. This result can be examined from the point of view that MPF changes reflected differential fatiguability of the FT and ST fibres. It seems reasonable to assume that at the onset of exercise almost the whole FT fibre population is recruited. It is also possible that at maximal effort the ST population is less involved (see Minagawa et al., 1978). During development of muscle fatigue, FT motor units will decrease their firing frequency more rapidly (Gydikov and Kosarov, 1974). Increase in the lower frequency component of PSDF cannot, however, directly represent any changes in firing frequency of the individual motor units. EMG frequency spectrum is influenced primarily by the form of the motor unit potentials. It must, however, be questioned whether these changes, e.g., slowing of the wave form of motor unit potentials, occur more readily in FT than in ST units.

It would be logical to expect that the form of the PSDF-curve is influenced by the muscle structure. The present results, however, failed to demonstrate any significant relationship between the absolute levels of MPF and the muscle fibre type distribution. This may partly explain why the changes in MPF, as expressed in absolute figures, were not related to the fibre composition. However, these observations should not rule out the possibility that relative shifts during fatigue both in MPF and the bandwidths of 24–48 Hz and 136–400 Hz reflects differences in the fatigue patterns of FT and ST motor units.

It is known that ischaemia increases muscle lactate levels (cf. Karlsson, 1971) and also results in a decreased muscle action potential conduction velocity (Stålberg, 1966; Mortimer et al., 1970). Probably for these reasons, it has been suggested that the shift in the EMG frequency spectrum to the lower frequencies during fatigue indicates conduction velocity changes along the active muscle fibres (Kadefors et al., 1968; Lindström et al., 1970).

In experiments with a protocol similar to that in the present study, a greater rate of lactate accumulation has been found in FT muscle fibres during the first 25 contractions. During the subsequent 25 contractions this difference disappeared (Tesch et al., 1978a, 1978b), but force decline correlated positively with the relative distribution of FT fibres. Adding this information, it seems relevant to speculate whether the marked changes observed in force output as well as MPF are related to greater fatigue of FT fibres of the respective motor units. Thus, the present results can be interpreted in the same way as those of Viitasalo and Komi (1978) and Larsson (1978), who demonstrated that the shift in MPF and EMG frequency spectrum during sustained isometric contraction was more pronounced among subjects with muscles composed predominantly of FT fibres.

A block at the neuromuscular junction has been suggested as a possible site for peripheral fatigue, thus indirectly affecting the contractile apparatus (Stephens and Taylor, 1972). However, there are reasons to believe that the disturbances in the impulse propagation due to ischaemia may also be indicative of affected sensory mechanisms in the muscle spindles as speculated by, e.g., Lippold et al. (1960) and Dahlbäck et al. (1970). Nilsson et al. (1977), using the present experimental procedure, claimed that fatigue is initiated in the contractile compartments and located mainly in the FT fibres. Their hypothesis was based on an increase in time lag between EMG activity and the onset of torque at a preset angular velocity. This time lag change was correlated with the percentage of FT fibres. Stimulating frog and rat muscles to fatigue, Fitts and Holloszy (1976, 1977) found no evidence that the force decline could be attributed either to nerve fatigue or to block at the neuromuscular junction. As an alternative suggestion, these authors postulate that substrate depletion, especially an inadequate availability of ATP in the myofibrillar regions, is responsible for impaired contractile function. Decrease in intracellular pH as demonstrated by, e.g., Sahlin (1978) may also inhibit muscle contractility. There are indications that increase in H^+ concentration influences calcium binding capacity to troponin and sarcoplasmic reticulum (Fuchs et al., 1970; Nakamura and Schwarz, 1972). The latter possibility seems to be applicable to the present and previous results obtained using the same experimental set-up (Thorstensson, 1976; Thorstensson and Karlsson, 1976; Nilsson et al., 1977; Tesch et al., 1978a).

To summarize, muscle force output and signal characteristics of EMG were studied during repeated muscle contractions of high angular velocity. In accordance with some previous studies on isometric fatigue, it is suggested that muscle contraction failure is related to qualitative changes in motor unit recruitment pattern. Muscles characterized by a predominance of FT fibres demonstrate a greater susceptibility to fatigue and this is reflected by a rapid decrease in force output as well as by a pronounced change in EMG signal characteristics.

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