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ORIGINAL ARTICLE

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Activity of single motor units in attention-demanding tasks: firing pattern in the human trapezius muscle

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Abstract Activity of single motor units in relation to surface electromyography (EMG) was studied in 11 subjects in attention-demanding work tasks with minimal requirement of movement. In 53 verified firing periods, single motor units fired continuously from 30 s to 10 min (duration of the experiment work task) with a stable median firing rate in the range of 8–13 Hz. When the integrated surface EMG were stable, the motor units identified as a rule were continuosly active with only small modulations of firing rate corresponding to low-amplitude fluctuations in surface EMG. Marked changes in the surface EMG, either sudden or gradual, were caused by recruitment or derecruitment of motor units, and not by modulations of the motor unit firing rate. Motor unit firing periods (duration 10 s–35 s) in low-level voluntary contractions (approximately 1%–5% EMG_{max}) performed by the same subjects showed median firing rates (7–12 Hz) similar to the observations in attention-related activation.

Key words Electromyography · Task-irrelevant electromyogram activity · Single motor unit · Recruitment · Firing frequency

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Introduction

Recent studies have emphasized the high risk of developing trapezius myalgia for workers with repetitive or monotonous work tasks, performed at a low level of muscle activity. Many workers who develop presumed work-related trapezius myalgia, have been shown to have activity levels in this muscle below 5% of the muscle activity at maximal force (5% maximal electromyogram, EMG_{max}) (Veiersted et al. 1993). In a recent study of workers performing office work and light manual work there was found to be no association between the mean level of trapezius muscle activity measured in the vocational setting (between 1% and 10% EMG_{max}) and the level of shoulder pain (Jensen et al. 1993). Those experiencing a stressful psychosocial work environment had a markedly higher pain score in spite of a similar vocational electromyogram (EMG) level compared to those not reporting such stress.

A possible hypothesis to explain these results is that the development of trapezius myalgia is linked to prolonged activity in low threshold motor units. It must further be assumed that such activity can be caused by psychosocial stress at work. This relationship has been indicated by studies showing increased muscle activity with increasing task complexity in VDU work (Wærsted et al. 1991) and when motivation for high performance is induced by a monetary reward (Wærsted et al. 1994). These experiments have related to a much older psychophysiological tradition showing that muscle activity may follow solely from psychological influences and with no task-specific need for force development (Goldstein 1972). The phenomenon has been labelled "tasks-irrelevant EMG activity" (Yemm 1968; van Boxtel and Jessurun 1993) or "psychogenic muscle tension" (Svebak 1988; Wærsted et al. 1994). In the present paper the label "attention-related muscle activity" is used to emphasize the specific experimental circumstances of this study.

Attention-related muscle activity has been characterized by low moment-to-moment variability in integrated surface EMG, resembling a static muscle contraction (Westgaard and Bjørklund 1987; Wærsted et al. 1994). Typically no movement or change in postural load is observed, either in periods of constant muscle activity or in the event of a sudden or gradual change in activity level. The surface EMG activity can be present for long periods, from a few minutes and up to 1 h in our own experiments. If the surface EMG activity represents continuous activity in a small group of motor units, even fatigue-resistant motor units could be under unacceptable strain.

The aim of the present study was to examine motor-unit firing in attention-related muscle activity. An experimental protocol known to have a potential for eliciting attention-related EMG activity in the upper trapezius muscle (Wærsted et al. 1994) was replicated, but the experimental design now included the recording of action potentials from single motor units in parallel with the surface EMG.

Methods

Subjects

A group of 11 healthy subjects (8 men, 3 women) volunteered to participate, including the authors, 1 research colleague, and 7 medical students. Median age was 24 years (range 22–45). The experiments were performed according to the Declaration of Helsinki, and the subjects gave their informed consent. The protocol was approved by the regional Ethics Committee.

Protocol

The protocol consisted of two elements:

1. The main work task (see below) which lasted 10 min and was repeated four times with a 2–5 min pause in between.
2. Voluntary low-level muscle activation that was performed before and after the series of work tasks.

For calibration purposes, the subjects finally performed two isometric shoulder elevations with maximal voluntary contraction force (MVC). This calibration procedure was not performed by the first 2 subjects, who only performed the first of the four repetitions of the work tasks.

Work task

The subjects were seated with the lower arms resting on arm supports to minimize postural demands on the trapezius muscles. Two response buttons were placed under the fingers of the right hand. In a complex two-choice reaction-time task displayed on a computer screen, the subject had to decide whether or not alphanumerical and graphical information agreed. Feedback on precision and speed of the task response was given on the screen during a 1-s pause between single problems [see Wærsted et al. (1994) for more details on the work tasks and the feedback procedure]. The subjects were instructured to solve the problems quickly, but avoid errors. The total number of problems solved in the 10-min work task varied between 180 and 295. Each work tasks was analysed separately, giving a total of 38 recordings.

Intramuscular EMG

Three 50-μm diameter teflon coated platinum/iridium wires (A-M Systems, Inc.) were twisted tightly together and inserted into the muscle through a disposable syringe needle. Before insertion the insulation of the electrodes was tested for leakage by submerging the insulated part in a drop of saline and attempting to pass a 5-mA current into the fluid. The electrode bundle was either cut transversely to achieve a localised recording (fine electrode), or the final 5 mm was untwisted, the wires cut 2 mm apart and their final 0.5 mm uncoated in order to obtain an electrode with greater pick-up volume (coarse electrode).

The electrodes were inserted obliquely into the left upper trapezius muscle approximately 5–10 mm laterial to the midpoint between the C7 spinous process and the acromion, with approximately 10-mm final depth of the recording surfaces. The skin insertion area was treated with local anaesthetic cream for 30 min before the needle insertion. One or two fine electrodes and one coarse electrode were inserted into the muscle. In 2 subjects, one coarse electrode was also inserted into the corresponding position in the right upper trapezius muscle. After testing with low-level voluntary muscle activation two of the three wires of each electrode were chosen for bipolar intramuscular EMG recording.

In all the subjects at least one of the electrodes in the muscle gave EMG signals of satisfactory quality. The interference EMG was fed to A.C. amplifiers with pre-amplifiers, band-pass filtered at 80 Hz–32 kHz, and stored on an FM tape recorder (Kyowa Data Recorder, RTP-600B, frequency response 0–5 kHz).

The stored signal was further high-pass filtered (at 0.5, 1, 2, or 5 kHz) or low-pass filtered (at 0.5, 1, or 2 kHz) to increase the signal-to-noise ratio of a motor unit. When a filter setting was obtained which gave an accentuation of the motor unit spike of interest, the filtered signal was fed into a spike discriminator (Slope/Height Window Discriminator, Frederick Haer and Co.).

An oscilloscope with signal delay and storage circuitry triggered by the discriminatory output pulse displayed all the individual unfiltered EMG waveforms superimposed at high sweep speeds. This allowed for visual verification that all discriminated spikes had similar waveforms and hence probably belonged to the same motor unit. In addition, a reference spike was stored on a digital storage oscilloscope with pretrigger circuitry at the beginning of an analysis session. This oscilloscope displayed incoming discriminated single spikes superimposed on the reference spike for a selected period.

The two waveforms were visually compared to ensure that the current spike waveforms were similar to the waveform at the beginning of the session. The criteria for similarity were close resemblance in all parts of the complex motor unit action potential, including the amplitude and duration of the different slopes of the waveform. The point of recruitment or derecruitment of a motor unit was scrutinised, to avoid the possibility that a change of electrode position with a resulting change in spike waveform would be erroneously noted as recruitment or derecruitment. When the discrimination of a motor unit had been verified, the spike discriminator output pulse was used to calculate the motor-unit firing rate and to obtain a spike-triggered average of the unit as detected by the intramuscular and surface electrodes. These final analyses were performed with custom-built *virtual instruments* developed with the LabVIEW system (National Instruments).

The present analysis system was designed to monitor single motor units at low contraction levels. A maximum of 2, but usually only 1 motor unit (or none at all) could be verified and followed from each of the 1–3 intramuscular electrodes in each individual. In 7 recordings, 2 motor units firing simultaneously were detected, while 3 or 4 units were followed in 3 recordings. The analysis was performed by the first author. Approximately one-third of the recordings were reanalysed independently by the second author, obtaining the same results regarding motor-unit identification, firing rates and duration of firing periods. The second author also evaluated the analytical material for all the remaining motor units.

Median firing rates in voluntary activity at low contraction levels (approximately 1%–5% EMG$_{max}$) were determined for periods of 10–35 s. The voluntary activation was performed with visual and auditory feedback of the intramuscular EMG signal to obtain an EMG activity level suitable for analysis.

Surface EMG

The two electrodes of a custom-made electrode assembly (electrode diameter 6 mm, interelectrode distance 20 mm) with AgCl electrode paste were attached to the skin above the intramuscular electrodes. After amplification and band-pass filtering at 10 Hz–1 kHz, the interference EMG was stored on the FM tape recorder. In the analysis, the signal was A-D converted at 2 kHz, full-wave rectified and integrated. The integrated EMG was calibrated in percent of EMG activity at maximal voluntary isometric shoulder elevation (% EMG$_{max}$) . For further details on the surface EMG analysis, see Westgaard (1988) and Wærsted et al. (1991).

A digital pulse going high when the problems of the work task were presented and low when the subject responded, was stored in parallel with the physiological signals. This pulse was used as a trigger signal to obtain the averaged integrated surface EMG activity at response execution. These peri-stimulus time histograms (PSTH) had a time resolution of 0.05 s and covered the period from 1 s before until 1 s after the response execution.

Video recording

Video filming with a two-camera system (Eken and Kiehn 1989) recording both the subject from the left hand side and an oscilloscope display of the interference surface EMG, was used to document the behaviour of the subjects and the simultaneous EMG activity in the work periods.

Results

Surface EMG in attention-related activation

Of the 38 recordings, 28 of them in 8 of 11 subjects, showed attention-related activity in the integrated surface EMG, characterized by low moment-to-moment variability (Westgaard and Bjørklund 1987). The EMG activity in individual time plots at 1-s resolution showed consistent features that allowed a categorization of the surface EMG response into four groups: no increase from baseline in EMG activity (Fig. 1A), the EMG activity remained stable or showed small oscillations around a mean value (Fig. 1B), the EMG activity increased or decreased steadily (*EMG gradient*, Fig. 1C), and sudden changes in the EMG activity (Fig. 1D). One recording could contain from one to all of these features, which have also been observed in other studies (Westgaard and Bjørklund 1987; Wærsted et al. 1994).

The mean EMG activity level varied from 0.1% to 7% EMG$_{max}$, but could be as high as from 10% to 15% EMG$_{max}$ in periods of a few minutes. The video recordings showed no discernible movements corresponding to this muscle activity, as the subjects sat quietly without moving their left shoulder and rested the lower arm on the arm support. One recording from each subject with attention-related activity was selected for generating a PSTH linked to the response execution. Only in one instance did the PSTH show a transient change in activity at response execution, but this component only constituted a small perturbation of the dominant static activity.

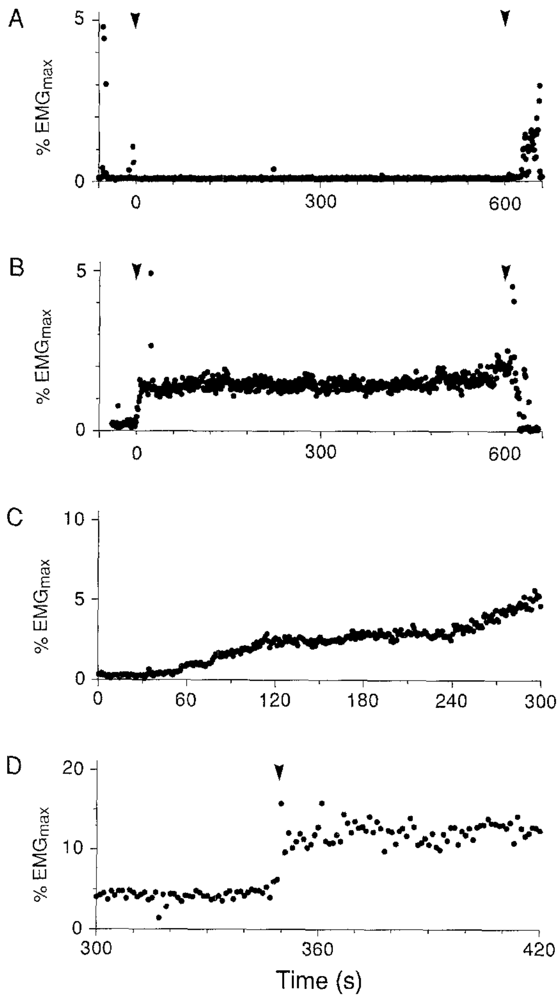

Fig. 1 Examples from recordings of integrated surface electromyograms (*EMG*) from the left upper trapezius muscle showing no activation **A** and three profiles typical of attention-realted activation; **B** the activity varies around a constant raised level; **C** gradually increasing activity level over several minutes; **D** sudden increase in activity (*arrow*). *Each point* represents integrated *EMG* with a time resolution of 1 s, calibrated as a percentage of *EMG* activity in a maximal voluntary shoulder elevation (% *EMG*$_{max}$) . The time is given in seconds from start of the work task. *Arrows* in panels **A** and **B** indicate start and end of the 10-min work task. The transient *EMG* activity before the start and at the end in panel **A** is due to shoulder and arm movements.

Single motor unit firing in attention-related activity

Single motor units were identified and followed in 22 of the 28 recordings with surface EMG activity as shown in Fig. 2. In the remaining 6 recordings the intramuscular electrodes either failed to discriminate discrete motor unit potentials (3 recordings in 1 subject), or recorded too many with subsequent difficulty in discriminating single units (3 recodings in 1 subject). Single motor units were not detected and followed with certainty in any of the 10 recordings without surface EMG activity.

The total duration of firing within a recording and the maximal duration of continuous firing, i.e. without stretches of firing below 4 Hz for more than 4 s, was determined for 53 motor units (Table 1). 7 motor units from 6 recordings in 5 subjects were active throughout the work task (Fig. 3). The median firing rates are given in Table 2, together with median

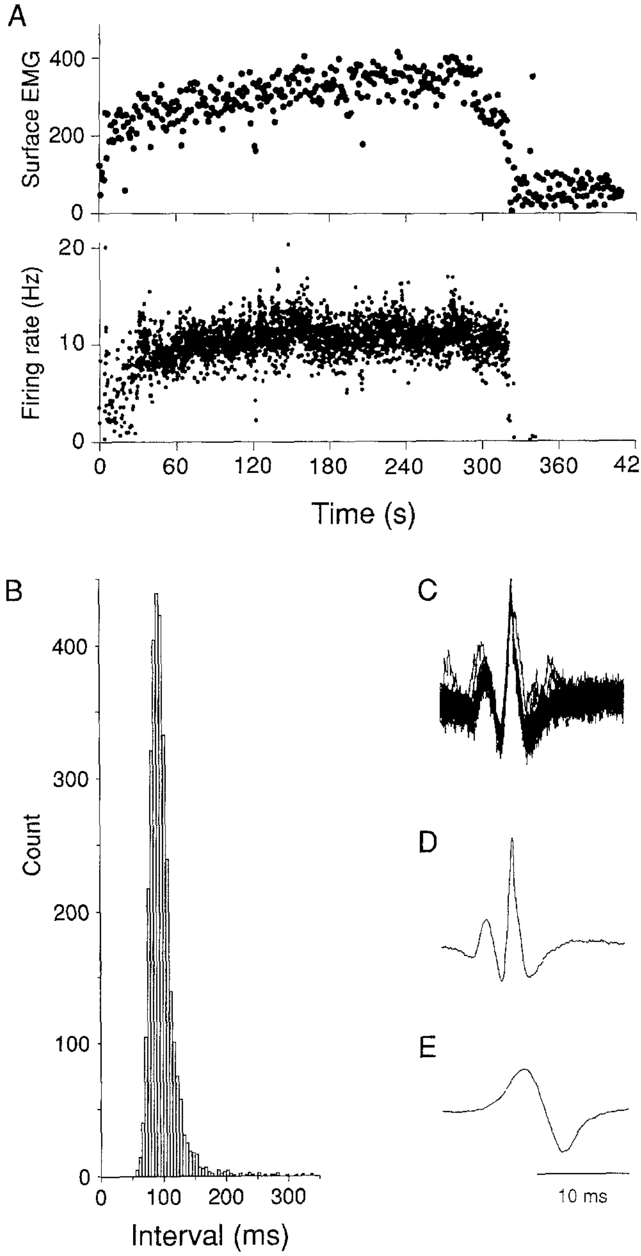

Fig. 2 **A** Integrated surface electromyogram (*EMG*; arbitrary units, otherwise plotted as in Fig. 1) and instantaneous firing rate of a motor unit recorded from the left upper trapezius muscle, showing attention-related activation during the first 5 min. **B** Interspike interval histogram of the total motor unit firing period, with a marked peak illustrating the stable firing rate. **C** Here 25 consecutive motor unit action potentials have been superimposed to illustrate the stable waveform. **D**, **E** Show 100 sweep spike-triggered averages of simultaneous recordings of the motor-unit potential in the intramuscular *EMG* (**D**) and the surface EMG (**E**). The work task in this pilot recording lasted less than 7 min and there was no calibration of surface *EMG*

Table 1 Duration of 53 single motor unit firing periods within single recordings

	30 s– < 60 s	60 s– < 120 s	120 s– < 300 s	300 s– < 600 s	600 s[a]
Total firing[b]	3	8	18	17	7
Continuous firing[c]	3	8	24	11	7

[a] Motor units firing the total duration of the work task (10 min)
[b] Total firing within one recording
[c] The firing period of longest duration is given for motor units having more than one firing period within a recording

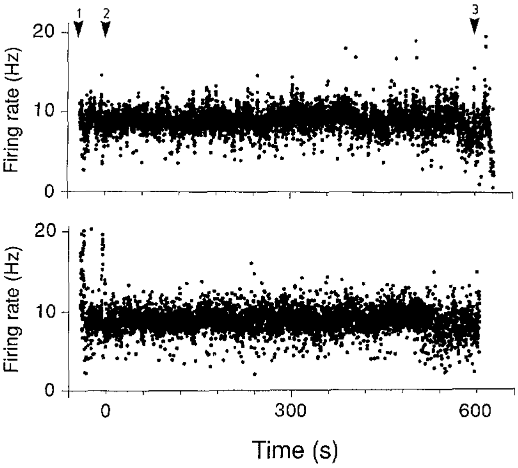

Fig. 3 Instantaneous firing rates of two motor units that were simultaneously active during the whole 10 min of the experiment work period. The motor units were recorded in parallel from the left (*upper panel*) and right (*lower panel*) upper trapezius muscles. *Arrows* indicate (1) start of the recording, (2) start of the work task, and (3) end of the work task

Table 2 Median firing rate of single motor units

	6Hz– < 8Hz	8Hz– < 10Hz	10Hz– < 12Hz	12Hz– < 14Hz	Total
Attention-related[a]	0	20	25	8	53
Voluntary[b]	2	15	10	0	27

[a] Single motor units firing during the work tasks (same units as in Table 1)
[b] Low-threshold motor units activated in low-level voluntary contractions approximately 1%–5% maximal electromyogram before or after the work tasks

firing rates from periods of stable continuous firing in voluntarily activated motor units (27 motor units in 8 subjects).

Relationship between single motor unit firing and overall muscle activation

The typical muscle activation response was that of a stable level of integrated surface EMG, upon which low-amplitude fluctuations were superimposed. In this situation the motor units modulated their firing rate in parallel with the similar modulation of the surface EMG (observed in 35 motor units from 20 recordings in 8 subjects). Figure 4 shows one of these recordings: 3 motor units were followed in parallel until 1 was derecruited in a common depression of firing rates also expressed in the integrated surface EMG (arrow labelled 1). The firing rate of the 2 remaining motor units and the surface EMG activity then fluctuated in parallel until the 2nd motor unit was derecruited (arrow labelled 2).

The gradual or sudden changes in surface EMG activity offered the opportunity of observing single motor unit activity patterns in situations where the overall muscle activation showed marked changes. Figure 5 shows the response of 2 motor units that were recruited during a gradual increase in surface EMG to a final activity level of 8% EMG_{max} (EMG gradient; Malmo 1965). Once recruited the motor units fired at a stable frequency. The steady firing rate in face of a gradually increasing (or decreasing) surface EMG activity was typical of motor-unit behaviour in this category of attention-related activity (observed in 16 motor units from 11 recordings in 6 subjects).

When there was a sudden change in the level of integrated surface EMG during an ongoing work task, new motor units were generally recruited or derecruited (17 motor units from 11 recordings in 6 subjects). Figure 6 shows an example where 2 motor units were recruited at a sudden increase in integrated surface EMG. However, a 3rd motor unit already active did not change its firing rate despite the increase in surface EMG of about 5% EMG_{max}. Figures 2A and 4 give examples of motor units which were derecruited at a sudden drop in surface EMG activity.

The firing pattern of the motor units was checked in relation to surface EMG, to look for deviations from the above activity patterns. This would happen if a motor unit started or ceased firing when the surface EMG changed in the opposite direction, a motor unit was recruited or derecruited at a stable level of surface EMG, a unit was recruited and derecruited at clearly different levels of surface EMG, or a unit modulated its

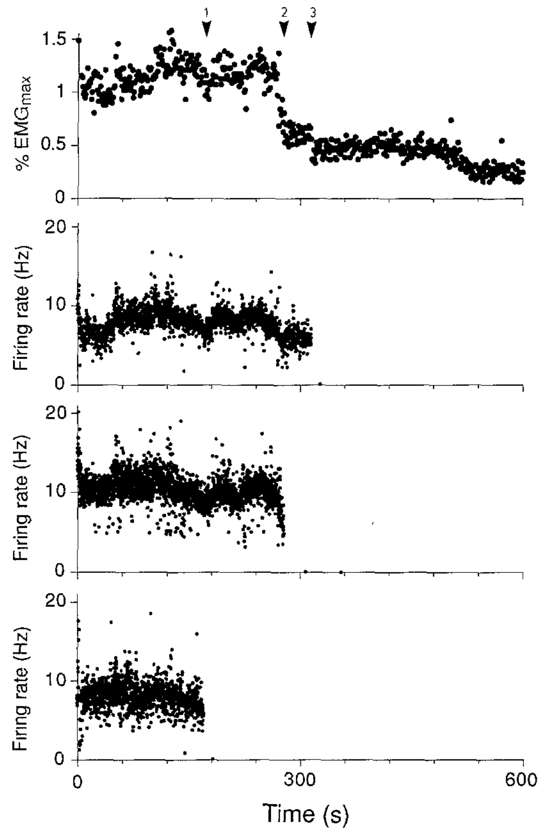

Fig. 4 A recording demonstrating modulation of motor-unit firing rates in parallel with integrated surface electromyogram (*EMG*). *All panels* are recorded from the left trapezius muscle of one subject. *Arrows* indicate derecruitment of the motor units. Calibration of integrated surface *EMG* as in Fig. 1

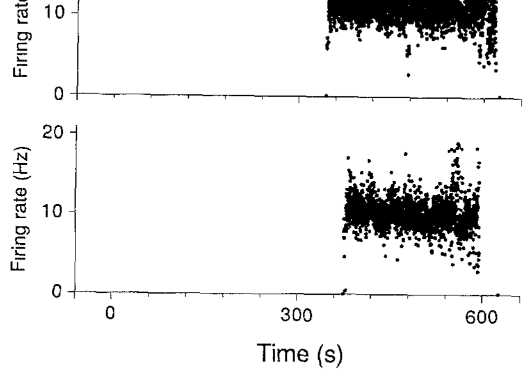

Fig. 5 Example of motor units recruited to fire with a stable frequency in spite of steadily increasing surface electromyogram (*EMG*) activity. Calibration of integrated surface *EMG* as in Fig. 1

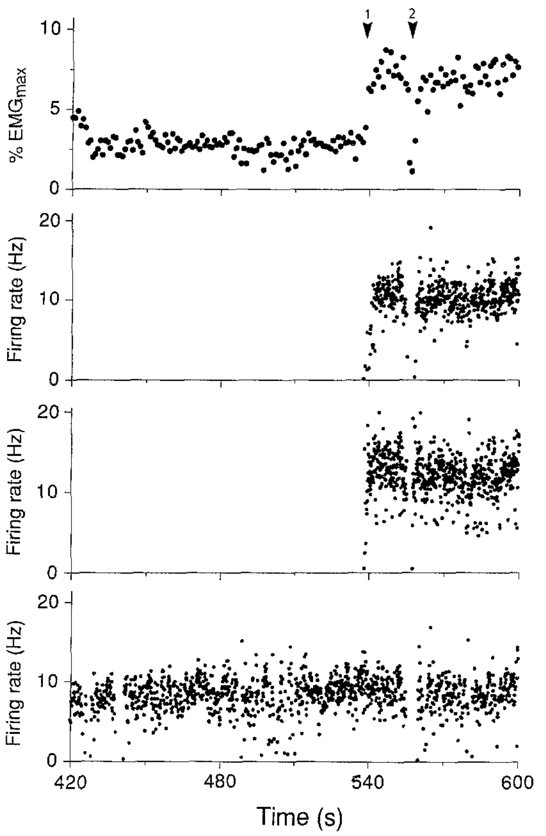

Fig. 6 Final 3 min of the work task in a recording demonstrating recruitment of motor units in parallel with a sudden increase in surface *EMG* activity (*arrow labelled* 1). *Arrow labelled* 2 indicates a short silent period *in all panels*. The motor units were detected with two different bipolar intramuscular electrodes in the upper left trapezius muscle. Calibration of integrated surface *EMG* as in Fig. 1

firing in a pattern different from the fluctuations in surface EMG level. Most motor units fired in complete or near complete agreement with the above patterns. There were 2 units which ceased firing at a surface EMG level that was clearly above the level at recruitment; 1 unit, firing approximately 40 s, was in complete conflict with the above patterns, being recruited at a decreasing surface EMG level and derecruited at an increasing surface EMG level.

Single motor units in attention-related and voluntary activation

As motor-unit waveforms are highly sensitive to electrode movements, it was difficult to be certain that waveforms of similar shape picked up by the same electrode in different recordings belonged to the same motor unit. However, spike amplitude, spike duration, and waveform of the motor unit potentials were compared in some subjects with very stable recordings. In five instances motor units with a similar complex waveform appeared both during one of the work period recordings and during low-level voluntary activation, indicating recruitment in attention-related activation and at low threshold in voluntary activation. In two of these instances and in four other instances we considered there was a high probability that the same motor unit was recruited in two or more of the four experimental work periods.

Discussion

The main finding of this study was the demonstration of long-lasting firing of a few motor units in attention-related activity. This motor unit activity was very stable, even in the face of a considerable change in surface EMG level. Recruitment and derecruitment happened abruptly to or from the stable firing pattern. There was however good correlation between low-amplitude variations in motor-unit firing frequency and surface EMG, once the unit had been recruited. Thus, the firing pattern of single motor units in attention-related muscle activity can, to a certain extent, be predicted from the integrated surface EMG, but important aspects of their firing pattern can only be determined by single-unit recordings.

The active motor units in the present study were likely to have been low threshold type I units in view of the size principle (Henneman et al. 1965). The long firing periods at low discharge frequencies and with no late adaptation are consistent with type I activity (Hennig and Lømo 1985; Kernell and Monster 1982). On some occasions we were convinced that motor units observed during attention-related activation were activated among the first 2–3 motor units in voluntary contractions.

The finding of prolonged motor unit firing is a necessary, but not sufficient requirement to support the hypothesis on the significance of low level muscle activity in the development of trapezius myalgia, formulated in the *Introduction*. This hypothesis may be criticised on physiological grounds: the metabolism of low-threshold type I fibres is specialized towards maintaining activity over long periods. Type I fibres in rat soleus muscle have been shown to be active in up to 35% of the recording time, observed throughout a 24-h day (Hennig and Lømo 1985). This criticism is not decisive, presumably there is a limit of acceptable activation also for type I fibres. Furthermore, a considerable heterogeneity with respect to this parameter can be expected to exist within the type I fibre population, and possibly also among similar fibre types in different muscles. It has been shown that back muscles with an anti-gravity function have longer endurance time in low-level static contractions than other muscles in the body (Jørgensen 1970). Conversely, the trapezius muscle has been found to contain less mitochondria per volume of muscle fibre and to have a lower capillary per fibre ratio than other muscles such as the deltoid and the quadriceps (Lindman 1992), and may be less fatigue resistant.

There is evidence that can be interpreted in indirect support of the hypothesis. The type I fibres of workers with prolonged loading of the trapezius muscle have shown hypertrophy (Lindman et al. 1991), possibly due to excessive activation. There has been an increased number of *ragged red* fibres, i.e. fibres with mitochondrial dysfunction, in the trapezius muscles of these workers compared to controls without such loading (Larsson et al. 1988; Bengtsson and Henriksson 1989; Larsson et al. 1992). The *ragged red* fibres are always type I and are more frequent in the trapezius muscle than in most other muscles.

The observed behaviour of human motor units in attention-related muscle activity resembles the activity of tonic motor units seen in rat soleus muscle (Eken and Kiehn 1989). Individual soleus motor units in rats are recruited to fire at high frequencies for several minutes with only transient changes in activity in the rest of the muscle, and without major changes in posture. A possible mechanism underlying this phenomenon is the recruitment of motoneuron monoamine-dependent plateau potentials (for review, see Kiehn 1991). Mono-aminergic projections to motoneurons are provided by descending pathways from the medullary reticular formation, in particular the raphe nuclei and the locus coeruleus/subcoeruleus. These structures are part of the "third motor system" of Holstege (1991), thought to convey emotive stimuli to the motoneurons. Motoneuron activation through such pathways would be in keeping with the *emotional flavour* of attention-related muscle activity.

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