Effects of Contraction Level on the Changes of Surface Electromyogram During Fatiguing Static Contractions

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Changes of the surface electromyogram (EMG) during a fatiguing static contraction were studied at contraction levels of 5, 10, 15, 20, 30, 40, and 50% of the maximum voluntary contraction (MVC). Seven subjects performed the static contractions of the elbow flexion and 6 subjects performed those of the planter flexion. Bipolar surface EMG was led from biceps brachii (BB) in the elbow flexion and from soleus in the planter flexion. Power spectra, mean amplitudes of EMG (AEMG) and durations of averaged waves classified by amplitude (AWCA) were calculated from EMG. The AWCA was calculated by averaging EMG waves separately for the 5 amplitude ranges of the trigger points.

Relative power increased below 50Hz in BB and 120Hz in soleus during the contractions with time. Relative power in low frequencies (RPWL) increased with time even at the low contraction levels during one third part of the contraction from the start. But the RPWL decreased with time in some cases below and equal to 20%MVC. The increase in the RPWL was larger at 20-50%MVC than at 5-15%MVC contraction. The duration of AWCA increased with time at 30-50%MVC and decreased at 5-20%MVC. The duration, however, correlated positively with RPWL in part even at 5-20%MVC.

The changes in the AWCA duration were attributed to the changes in conduction velocity (CV) of muscle action potential, since the relation between the changes in the duration by fatigue and the contraction levels was the same with the reported relation between changes in CV and the contraction levels. Though the duration affected slowing of EMG, the effects were not large. Strict synchronization of motor unit activity was not considered to affect the slowing strongly.


Key words: EMG, Fatigue, Contraction level, Wave duration, Frequency spectrum

INTRODUCTION

Muscle fatigue has been thought to be estimated by the surface electromyogram (EMG), since amplitude of EMG increases and its frequency spectrum shifts toward lower frequencies (slowing) with the progress of fatigue (Chaffin, 1973). The application of the slowing in EMG was expected more in the field work. In fact EMG has been applied to the field work (Jørgensen et al., 1989; Örtengren et al., 1975) and was related to the physical disorders of workers (Bjelle et al., 1981; Hägg and Suurkula, 1991). But relations between EMG and muscle fatigue have not been clear yet. The application of the EMG slowing to the estimation of fatigue was even denied (Westgaard, 1988), since the contraction level and muscle length were known to affect the frequency spectrum of EMG (Bazzy et al., 1986; Hagberg and Ericson, 1982). The greatest trouble for the application of EMG is that the frequency spectrum of EMG often shifts towards higher frequencies during contraction
at low contraction levels: less or equal to 20% of the maximum voluntary contraction (MVC) (Arendt-Nielsen et al., 1989; Hägg and Suurküla, 1991). Though the slowing was observed below 10% MVC (Jørgensen et al., 1988), reports of EMG changes at weak contractions are few.

Decrease in conduction velocity (CV) of muscle action potential had been considered as the main cause of the EMG slowing (Lindström et al., 1970). However, there were some cases where the changes of CV were not parallel to those of the slowing and where the decreases in CV were not sufficient to explain the slowing (Bigland-Ritchie et al., 1981; Zwarts et al., 1987; Krogh-Lund and Jørgensen, 1991). The relation between the synchronization of motor units (MU) and the slowing of EMG was suggested in some reports (Kogi and Hakamada, 1962). This relation, however, is not confirmed, since there was no method that demonstrates this relation practically.

The property of the slowing has not been known sufficiently in spite of many studies. Mean power frequency and median frequency often have been used as an index of the slowing. Though mean power frequency and median frequency reflects changes of EMG spectrum as a whole, they cannot discriminate the frequency where changes occur. Mathematical models of EMG showed the effect of the CV changes and the MU activities on the frequency spectrum of the surface EMG (Suzuki et al., 1986), but the changes in the wave shape of the EMG were not shown. Though filtered EMG was compared with raw EMG to investigate the relation between frequency in the EMG spectrum and the wave shape of the EMG, clear relations were not obtained (Ohashi, 1986).

When the slowing is discussed, the term “synchronization” usually includes grouping of MU activities. One reason these two terms are not distinguished is that the grouping is thought to be a weak synchronization as Chaffin (1973) wrote “grouping (strict synchronizing is not necessary)”. The other reason is that the contribution of the synchronization and the grouping to the slowing cannot be defined separately because of the insufficient correspondence between the slowing of the surface EMG and the wave shape of the EMG. Manifesting the characteristics of the wave shape of the EMG is necessary to investigate the contribution of the synchronization to the slowing.

The purpose of this study is to investigate the slowing of the surface EMG during static contractions at several contraction levels including weak ones. This study is also the first step to investigate the slowing connecting with the EMG wave shape by showing the changes of the wave shape with averaged waves classified by amplitude (AWCA, see method).

**METHODS**

Static contractions of the elbow flexion and the planter flexion were performed by holding weights in a sitting posture. The elbow angle was kept at 90 degrees with the forearm supinated and kept horizontal in the elbow flexion. The knee and ankle angles were kept at 90 degrees in the planter flexion. Contraction levels were set at 5, 10, 15, 20, 30, 40, and 50% of the maximum voluntary contraction (MVC), considering the limb weight. MVCs were measured more than 2 times, and the largest one was used. The details of the posture and apparatus were written in Sato and Ohashi (1988). The subjects were requested to hold the load as long as they could. However, the contraction time was limited to 45 min. Subjects were requested to report fatigue sensations. The planter flexions at 5%MVC were omitted for two subjects because of no report of fatigue sensation at 10%MVC in these subjects. Intervals of the experiments were longer than a day. The sequence of the contraction levels examined was randomly assigned. Bipolar surface EMG was recorded from long head of biceps brachii (BB) in the elbow flexion and soleus in the planter flexion to the FM tape recorder. The disc electrodes were
10mm in diameter and the centers of two electrodes were about 25mm apart. The subjects (age 22-42 years) were 7 males for the elbow flexion (mean MVC at the wrist was 267N, ranged 230-310N) and 6 males for the planter flexion (mean MVC was 98Nm, ranged 84-122Nm).

The EMG was analyzed in two ways. In one way, EMG was sampled at 1024Hz, and power spectrum was calculated by FFT method. Relative powers to the total power in 8-400Hz were obtained every 4Hz in the range of 8-200Hz and for the 200-400Hz range in BB and every 8Hz in 8-400Hz in soleus. The spectra were obtained continuously for the analysis time of 2, 4, 8 or 16sec. In another way, the contractions were divided to 3.5 or 10 periods, and mean amplitude of EMG (AEMG), relative power, and AWCA were calculated. AEMG was calculated as the mean value of absolute amplitude and was divided by AEMG at the first period. Relative powers in 8-20Hz and in 20-43Hz to the total power in 8-394Hz were used as the indices of the slowing and were called RPWL20 and RPW40 respectively in this report. These 2 relative powers are also called RPWL without discrimination, since changes of these 2 relative powers were not usually different.

AWCA was obtained as follows (Fig 1). At first, amplitude levels were defined. EMG was sampled at 1000Hz for shorter time of 2min or 1/5 of endurance time from the start of the contraction. The amplitudes obtained were for 0, 40, 70, 90, and 99 percentile. The amplitude levels were defined as the zone between the two successive percentiles, and named level 1, 2, 3, 4, and 5 from low amplitude: level 1 was 0-40 percentile and level 5 was above 99 percentile. After the amplitude levels were defined, EMG was sampled at 4000Hz and moving averages were applied to the samples of the width of 4 data point. The positive peaks in the positive amplitude levels and the negative peaks in the negative ones were used as trigger peaks. Waves were averaged for 64 msec before and after the trigger peaks for each amplitude level. I call this averaged wave AWCA (averaged wave classified by amplitude).

Though AWCA was calculated for positive and negative peak, both were not discriminated. In this report duration of AWCA was used. The duration was the sum of times taken to change over 90% amplitude from the peak to the next and last turning points.

Paired-t-test and correlation coefficient were used for statistical analysis. The level of significance was chosen at p<0.05. EMG spectra were sometimes considerably different between subjects as been reported (Sato, 1976). The interindividual differences obscure tendencies of EMGs during work, which are main subject in this study. In order to

![Diagram of amplitude levels and duration of AWCA](image)

Fig. 1 An example of the amplitude levels and the duration of AWCA. The curve on the right side of raw wave shows the distribution of sampled point.
manifest the changes during contraction, all values were used as the deviations from their mean values for each subject to even out the differences in the means among subjects, when correlation coefficients were calculated. The degree of freedom that this offset operation for the mean uses is 1 for each mean (subject). In the tables significance is shown in character 'H', '+', '-', and '='. These characters mean as follows.

Significance level
H, =: p<0.01
+, -: p<0.05
.: not significant

Direction of change
H, +: positive correlation or the value is larger at larger compared condition (increase with condition)
=, -: negative correlation or the value is smaller at larger compared condition (decrease with condition)

In this report I use words 'below' and 'above' as 'below and equal to' and 'above and equal to' respectively.

Abbreviations in this report are listed below.
AEMG: mean amplitude of EMG
AWCA: averaged wave classified by amplitude
BB: muscle biceps brachii
CV: conduction velocity of muscle action potential
MU: motor unit
MVC: maximum voluntary contraction
R: correlation coefficient
RPW40: relative power in 20-43Hz
RPWL: RPWL20 and RPW40
RPWL20: relative power in 8-20Hz

RESULTS
Means and ranges of the endurance time for each contraction level are shown in Table 1. The endurance times were longer in the planter flexion than in the elbow flexion. Four subjects reported pain at 10%MVC in the elbow flexion. Continuing contraction in this condition was not easy, though only 1 subject could not continue the contraction for 45min. At 10%MVC in the planter flexion 4 subjects reported moderate and/or light fatigue sensation. The light fatigue sensation was reported by 3 and 1 subjects at 5%MVC in the elbow and planter flexions respectively. The details of the endurance time and the fatigue sensations were written in Sato and Ohashi (1988).

A contraction was divided into 3 parts. Correlation coefficients (R) between time and relative power for each frequency were calculated for each part (Fig 2). Most Rs were positive below 50Hz in BB and below 120Hz in soleus. Most Rs above the frequency were negative. These patterns between R and frequency mean slowing of EMG with time. Though another and even opposite patterns were seen below 20%MVC, Rs were positive at lower frequencies in the first part of each contraction. The frequency at which the sign of R changed near 50Hz was smaller at low contraction levels than at high contraction levels in BB, though the tendency was not steady. Table 2 shows correlation coefficients of AEMG and RPWL to time. AEMG and RPWL increased with time in most contraction levels. Fig 3 shows these results.

Regression lines of AEMG and RPWL to time which was transformed into percentage of contraction time were calculated. Slopes of the regression lines were compared between the contraction levels (Table 3). The slopes of AEMG above 15%MVC were larger at the weaker contraction levels than at
Fig. 2 Correlation coefficient between time and relative power for each frequency. Thick lines are the first one-third of the contraction. Thin solid lines are the second one-third of the contraction. Dotted lines are the last one-third of the contraction. The symbol ‘+’ at biceps brachii means value between 200-400Hz. Horizontal dotted lines symmetrical to 0 show the significant level at p=0.01.
Table 2  Significance of correlation coefficient between time and AEMG, relative power, and the duration of AWCA (use all amplitude levels).

<table>
<thead>
<tr>
<th>biceps.br</th>
<th>Contraction level(%MVC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>biceps.br</td>
<td>5 10 15 20 30 40 50</td>
</tr>
<tr>
<td>AEMG</td>
<td>. H H H H H H</td>
</tr>
<tr>
<td>RPWL20</td>
<td>. H H H H H H</td>
</tr>
<tr>
<td>RPW40</td>
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<tr>
<td>duration</td>
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</tr>
<tr>
<td>soleus</td>
<td>H H H H H + .</td>
</tr>
<tr>
<td>AEMG</td>
<td>H H H H H H H</td>
</tr>
<tr>
<td>RPWL20</td>
<td>H H H H H H H</td>
</tr>
<tr>
<td>RPW40</td>
<td>H H H H H H H</td>
</tr>
<tr>
<td>duration</td>
<td>= = = = H H H</td>
</tr>
</tbody>
</table>

$H_0 = p < 0.01, + : p < 0.05$

. : not significant

$H_{+} : r > 0$, = : $r < 0$

Fig. 3 Changes of AEMG and relative power in 8-20Hz and 20-43Hz during contractions. Thick lines are means of all subjects. Thin lines are the results of each subject.

Table 3  Comparison of the slopes of regression lines of AEMG, relative power, and duration of AWCA to time in percentage of the contraction time between contraction levels.

<table>
<thead>
<tr>
<th>biceps.br</th>
<th>AEMG</th>
<th>RPWL20</th>
<th>RPW40</th>
<th>duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>10 15 20 30 40 50</td>
<td>10 15 20 30 40 50</td>
<td>10 15 20 30 40 50</td>
<td>10 15 20 30 40 50</td>
</tr>
<tr>
<td>5</td>
<td>H H H H H H</td>
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<tr>
<td>15</td>
<td>. . . . .</td>
<td>. . . + H H H</td>
<td>H H H H H</td>
<td>H H H H H</td>
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<tr>
<td>20</td>
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<td>. H H H H</td>
<td>H H H H H</td>
<td>H H H H</td>
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<td>30</td>
<td>. . . . .</td>
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<td>. . H H H</td>
<td>H H</td>
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<tr>
<td>40</td>
<td>. . . . .</td>
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</tbody>
</table>

Soleus

<table>
<thead>
<tr>
<th>AEMG</th>
<th>RPWL20</th>
<th>RPW40</th>
<th>duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>10 15 20 30 40 50</td>
<td>10 15 20 30 40 50</td>
<td>10 15 20 30 40 50</td>
</tr>
<tr>
<td>5</td>
<td>H H H . .</td>
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<td>15</td>
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<td>20</td>
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<td>. . . H H H</td>
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<tr>
<td>30</td>
<td>. . . . .</td>
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<td>. . . . .</td>
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<tr>
<td>40</td>
<td>. . . . .</td>
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</tbody>
</table>

CL : contraction level(%MVC)

$H_0 = p < 0.01, +,- : p < 0.05, . : not significant$

$H_{+} : $increase with CL, -,- : decrease with CL
the stronger levels in soleus. The slopes of AEMG at 5% and 10%MVC, however, were smaller than those at 15% and 20%MVC. The smaller slopes of AEMG at 5 and 10%MVC would be caused by lighter fatigue state, since the contraction ended not by exhaustion but by the time limit of 45min at 5 and 10%MVC. The slopes of RPWL below 15%MVC were smaller than those above 20%MVC.

The examples of AWCA are shown in Fig 4. AWCA had a spike wave around the trigger point. I call this spike wave 'trigger peak', 'main wave' or 'main peak'. The extension of the main wave before and/or after the peak sometimes make an apparent peak opposite to the main peak. When this opposite peak was large in level 5, AWCA in the positive level resembled that in the negative level except phase. This resemblance between both sign levels means that identical waves that had similar peak in size in both signs were averaged in both sign levels. In low amplitude levels the main peak often had this opposite peak before and after the peak. In this case AWCA had 'W' shaped wave. The shapes of an AWCA varied and significant trends were not observed about subjects and contraction levels. AWCA had some small waves besides the main wave. AWCA did not change much during the contraction if the number of added wave for the AWCA was large. Though the small waves changed their amplitude, their positions were often reserved at low contraction levels.

![Diagram showing AWCA levels and examples](image)

Fig. 4 Samples of AWCA. AWCA in all parts of the contraction are overlapped.

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj C 10%MVC biceps brachii</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Subj B 30%MVC soleus</th>
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</thead>
</table>

| 100msec |

**Table 4** Duration of AWCA for each amplitude level (msec) in one-fifth of the part of the contraction from the start.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Amplitude level</th>
<th>mean of all contraction level (and standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>biceps br.</td>
<td>5.5 (1.2)</td>
<td>6.7 (1.5)</td>
</tr>
<tr>
<td>soleus</td>
<td>3.0 (0.3)</td>
<td>3.4 (0.5)</td>
</tr>
</tbody>
</table>
The durations of AWCA in one-fifth part of a contraction from the start were compared between the contraction levels and between the amplitude levels. The durations were significantly longer in the higher amplitude levels than in the lower ones in 97% and 94% cases in BB and soleus respectively. The durations were significantly longer at 5%MVC than at the other contraction levels in 50% cases in levels 3, 4, and 5 in BB. But other significantly different cases between contraction levels were only 4%. As the differences of the durations between the contraction levels were not large, the mean durations for all contraction levels are shown in Table 4. RPWL in the same part of the contraction were also compared between contraction levels. Significant differences were seen only between 50%MVC and the other levels in BB, though contraction levels were reported to affect the frequency spectrum of

<table>
<thead>
<tr>
<th>Contraction level(%)MVC</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>biceps br.</strong></td>
<td></td>
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<tr>
<td>RPWL20</td>
<td>H</td>
<td>.</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td></td>
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<tr>
<td>RPW40</td>
<td>.</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td></td>
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<tr>
<td><strong>soleus</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>RPWL20</td>
<td>H</td>
<td>H</td>
<td>.</td>
<td>H</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPW40</td>
<td>.</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

H = : p < 0.01, . : not significant  
H : r > 0, = : r < 0

EMG(Ohashi et al., 1986). Changing experimental days for each contraction level would make unclear the differences between the contraction levels.

In the tables the results about the durations are not discriminated between the amplitude levels, since the results were almost the same among the amplitude levels. The present results were calculated with data of all durations. These results became significant more easily than those for each amplitude level, since number of freedom for all amplitude levels is 5 times as large as that for each amplitude level. The durations of AWCA were analyzed in the same manner of AEMG and RPWL (Fig 5, Table 2). The durations decreased below 20%MVC, and increased above 30%MVC with time. However, the duration increased near the end of contraction at levels 4 and 5 at 20%MVC in BB. The slopes of the regression line of the duration to time were larger for the positive direction at higher contraction levels than at lower contraction levels.

The correlation coefficients (R) of AWCA durations to RPWLs are shown in Table 5. At high contraction levels the Rs were positive because both the RPWLs and the durations increased with time. At low contraction levels the Rs are supposed to be negative because RPWLs increased and the duration decreased with time. But some Rs were posi-
tive. When Rs between the durations and the RPWLs were calculated without compensation of the average between subjects, the Rs always became positive. These show that the RPWLs correlate positively to the durations. The positive Rs at low contraction levels resulted from the larger variation of the RPWLs and the durations during the contractions and between subjects than the mean changes of the RPWLs and the durations with time.

**DISCUSSION**

Characteristics of AWCA

Viitasalo and Komi (1977) calculated averaged motor unit potential (AMUP) using the peak in surface EMG as trigger. The AWCA is different from the AMUP in averaging waves for plural trigger levels separately. They reported that the rise time of the AMUP at 60%MVC of knee extensions increased with time. This result agrees with the present result of the increases in the duration of the AWCA with time. However, their result couldn't discriminate which caused the increase in the rise time, the prolongation of the duration of each EMG wave or the increase in the rate of large wave with long duration. The merits of limiting trigger levels are that the changes in components itself and the changes in structure can be discriminated.

Though shapes of AWCA changed a little during the contraction, many shapes existed. 'W' shaped waves were often observed in level 1 and level 2. Their peaks in opposite direction to the main peak had sometimes larger deviation in amplitude than the main peak. This 'W' wave can be made by composing waves that have a large opposite peak before or after the trigger peak. Amplitude of waves in AWCA became smaller with the point being apart from the trigger point. The decrease of amplitude is caused by the decrease of consistent relation in timing to the trigger point. Since nothing more than surface EMG including trigger is used for the averaging of AWCA, AWCA will be appropriate for relating frequency spectrum of surface EMG with the wave shape. However, it is difficult to interpret shapes of AWCA waves.

The main factors that affect the EMG spectrum are period and its regularity of wave, a shape of the single wave, which is defined as a wave from a peak to next peak of the same direction, and the shape of successive waves. These factors are related to MU activities as follows. The shape of a single wave of surface EMG is determined by the shape of a MU action potential and the degree of overlap of action potentials. The shape of successive waves is determined by relations between MU activities. The period and its regularity of wave is determined by those of MU discharge. The CV, which is considered as the cause of the EMG slowing, affects the duration of a MU action potential. The strict synchronization of MUs activities also affects the duration of it. The grouping of MUs activities affects the shape of successive waves. The effects of CV and the synchronization of the EMG spectrum are discussed in this report, since the AWCA duration represents the shape of a single wave. But the first purpose of the AWCA is not the determination of the origin of wave changes but the determination of the relations between a wave shape of surface EMG and its EMG spectrum. If the grouping and the periodicity are strong, the AWCA will have waves besides the main wave. Only the shape of a single wave, the duration of the main wave, is discussed in this report as the first study about AWCA.

Differences in the changes of the AWCA duration between the contraction levels

During a fatiguing contraction CV was reported to increase at low contraction levels and decrease at high contraction levels (Arendt-Nielsen et al., 1989). In this study the duration of an AWCA decreased at low contraction levels and increased at high contraction levels. The duration of an AWCA reflects the average duration of MU action potentials. Since the increase in CV shortens the duration of a MU action potential (Dimitrov, 1987), CV will affect the
duration of an AWCA. The recruitment of MUs is more important to compensate failure in force generation by fatigued MUs than the increase in the discharge rates of MUs already active (Kato et al., 1981). The recruitment of a fresh MU with fast CV is thought to increase CV at low contraction levels (Arendt-Nielsen et al., 1989; Krogh-Lund and Jørgensen, 1991). Since MUs will be recruited at high contraction levels during a fatiguing contraction (Maton, 1981), what makes the changes of CV different between the contraction levels should be discussed. The relation between AEMG and force was non-linear below 30%MVC and linear above 30%MVC in BB(Woods and Bigland-Ritchie 1983). Solomonow et al. (1990) showed that the increase in force by the recruitment causes non-linear relation between AEMG and force. Though the recruitment was observed up to 80%MVC (Kukulika and Clamann, 1981; Kanosue et al., 1979), the non-linear relations imply that the recruitment is more important for the increase in force below 30%MVC than above it. During fatiguing contractions in soleus MUs would be recruited more at the lower contraction levels than at the higher levels, since the increases in the AEMG were smaller in the higher contraction levels than in the lower levels. The smaller decrease in the AWCA duration at 5%MVC than at 10 and 15%MVC (Table 3) will also be attributed to the smaller recruitment suggested by the smaller increase in the AEMG (Table 2, 3). The amount of the MU recruitment, however, is not the main factor of the effect on the CV, because the AWCA duration increased with the increase in the AEMG near the end of 20%MVC contractions in BB.

The relation between MUs already active and newly recruited MUs can also affect the change of CV and the duration of an AWCA. The MUs recruited below 15%MVC were non-fatiguable, and the MUs recruited above 25%MVC were highly fatiguable(Stephens and Usherwood, 1977), though this result was obtained in the first dorsal interosseous of the hand. This shows that changes in MUs type recruited are larger between 15 and 25%MVC than above 25%MVC. While mean power frequency and/or relative power in low frequencies increase with force (Ohashi et al., 1986), this increase was reported to be insignificant above 25-30%MVC (Hagberg and Ericson, 1982), 40%MVC (Hagberg and Hagberg, 1989), and 60%MVC (Gerdle et al., 1988). Gantchev et al. (1992) found CV increases proportional to the square root of the recruitment threshold with constants in BB, and noted that the increase in CV was not significant above 40%MVC. These reports suggest that additional MUs activities to compensate muscle contractile failure by fatigue does not accompany significant changes of CV and the duration of the action potential at high contraction levels.

But this explanation is not sufficient since the changes of the AWCA duration with time were also different between different contraction levels in soleus that is dominantly consisted of type I fiber (Johnson et al., 1973). The decreases in CV are thought to be caused by the increased concentration of extracellular potassium(Jørgensen et al., 1988). Zwarts and Arendt-Nielsen (1988) showed that the decrease in CV changed to the increase when exerted force dropped to 30-50%MVC during sustained maximal voluntary contractions. Partial restoration of blood flow was thought to affect this increase in CV. In planter flexion half of the subjects could endure the contraction for 45min at 20%MVC, and at 30%MVC the endurance time decreased to 12'57" at the longest with the mean value of 7'59". Since the muscle fiber in soleus is mainly type I, occlusion of blood flow must relate this difference of fatigability between 20 and 30%MVC. But the endurance time did not relate to the amount of the decrease in the duration of the AWCA. The difference of the changes in the AWCA duration between contraction levels would be affected by all of these factors: the amount of MU recruitment, fiber types in the recruitment and blood flow.
Relation between the AWCA duration and the RPWL

AWCA durations were positively correlated to RPWLs in some cases even at low contraction levels where the durations shortened with the slowing. The RPWLs were smaller in soleus than in BB, and the durations were shorter in soleus than in BB. Although the durations at each amplitude level shorten with time, an increase in the ratio of large waves prolongs the mean AWCA durations, because the durations were longer at the higher amplitude levels than at the lower levels. The increases of the amplitude would help the increase in the relative power in the low frequencies by prolongating the mean duration of the wave of surface EMG. From these results I think that the wave duration of surface EMG influenced the frequency spectrum. The shortening of the duration during the contraction would be a reason for the smaller increase in the RPWL in the low contraction levels. But the AWCA durations at level 5 at 10-20%MVC in BB were about 10msec, and the period of the wave at 20Hz, where the correlation coefficients between relative power and time were large, is 50msec. The duration of each wave would not influence the slowing dominantly.

Effects of the synchronization of MUs activities on the slowing

As mentioned above, the difference of the changes in the AWCA duration between the contraction levels can be explained by the changes of the CV. Though the synchronization of MUs activities is thought to have affected the duration, the degree of the effect is not known. Increase in the synchronization may not always prolong the duration, since complete synchronization can shorten the duration. There is no evidence that the increase in the synchronization shortened the duration at the low contraction levels, and prolonged it at the high levels. If the synchronization largely prolonged the duration of MUs action potentials at all contraction levels, the decrease in the AWCA duration at the low contraction levels would become small or even change to an increase. If the synchronization largely shortened the duration, then vice versa. The results of this experiment only show that the changes of the synchronization during the contractions would affect the duration less than those of CV.

The AWCA duration increased with the amplitude level. High threshold MUs have large action potential (Kukulika and Clamann, 1981). Twitch torque positively correlates CV (Andreasen and Arendt-Nielsen, 1987) and twitch amplitude positively correlates the recruitment threshold (Nordstrom and Miles, 1990). From these relations newly recruited MUs with high amplitude would have faster CV than MUs with small amplitude. The longer duration with high amplitude derives from the synchronized activity of plural MUs or plural muscle fibers in MUs, since action potential with faster CV makes the duration shorter. The synchronization of MU activities may influence the slowing by changing the duration of each wave on surface EMG. But the influence of the synchronization on the slowing is not large, since the influence of the duration on that was not large as mentioned in the last section. Moderate waves were sometimes observed before and after the main wave, though these waves were not mentioned in this report. These waves may be related to the grouping discharge and/or periodic discharge of MUs. Since CV and the synchronization of MUs are not the main origin of the slowing of surface EMG, the grouping and/or periodicity of MUs activities are thought to be the main origin. AWCA out of the main peak will be examined in the other report.

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REFERENCES


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