MUSCLE FATIGUE IN RELATION TO EMG DURING REPEATED AND MAINTAINED MAXIMAL ISOMETRIC CONTRACTIONS

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The decrease of muscular force output during two different maximal isometric voluntary contractions of knee extension were studied for 6 male subjects in relation to EMG. EMGs were recorded by bipolar surface electrodes from the m. vastus lateralis and were integrated by a modified Miller’s circuit. In repeated contractions at one-second intervals, only slight changes were observed in the integrated EMG despite a marked decrease in force output to about 45% of the initial value. In counterparts of the maintained contraction for 2 min, both force output and integrated EMG decreased with time, and tended to plateau at a level corresponding to 20% and 45% of the initial value, respectively. From the viewpoint of blood supply, it was concluded that in the repeated contractions the decrease in force output was mainly due to the local factors in the muscle, especially in the fast twitch fibres, while in the maintained contraction the decrease in force output was caused not only by the failures in local factors but also central fatigue.

The feeling of discomfort and pain due to heavy muscular exercise is a familiar experience in most individuals. Housework, occupational work, and leisure, as well as sports activities, will lead to these states, which can be referred to as fatigue experience (Tesch, 1980). Since Mosso’s (1890) first construction of a finger ergograph, muscle fatigue has been extensively studied with biochemical, electrophysiological and histochemical methods. However, there still exist considerable disagreements over the behavior of EMG activity in the course of fatigue. For example, Nilsson et al. (1977) found almost no change in integrated EMG (i-EMG) variables despite a decrease in muscle strength performance in a fatigue test consisting of repeated fast maximal contractions of the quadriceps muscle. Therefore, they ascribed fatigue as mainly being due to local factors in the muscle, primarily in the FT fibres. In contrast, Stephens and Taylor (1972) found that EMG activity decreased with fatigue in maintained maximal voluntary con-
traction (MVC) of the hand muscle. In the first phase, lasting 1 min, force fell to about 50% of initial value and EMG activity fell with the same time course. In the second phase, the force fell relatively faster than EMG activity and tended to stabilize at about 25%. They then concluded that first, neuromuscular junction fatigue was most important, but that later, contractile element fatigue increased.

These disagreements over the behavior of EMG are probably due to the difference in (1) the muscles chosen for fatigue testing and (2) the way in which fatigue testing is carried out, that is, whether the test consists of repeated or maintained contractions, and static or dynamic contractions.

The purpose of the present study was to investigate the difference in EMG changes with fatigue between repeated and maintained isometric contractions of the quadriceps femoris.

METHODS

Six healthy male students (physical education major) volunteered for this study. They were fully informed about the procedures involved in the experiments and had all given oral consent to participation. Their physical characteristics are presented in Table 1.

Table 1. Physical characteristics of subjects.

<table>
<thead>
<tr>
<th>N</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>23.5</td>
<td>174.8</td>
<td>65.4</td>
</tr>
<tr>
<td>Range</td>
<td>(22–25)</td>
<td>(161.0–182.0)</td>
<td>(47.1–77.9)</td>
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Fig. 1. Subject was firmly fixed in a sitting position.
The subjects were firmly fixed in a sitting position. They were required to continue to exert maximal force output until it showed a plateau level. In test 1, they were asked to repeat maximal isometric contractions of the right knee extension for 3 min at a rate of 60 contractions per min with the angle of knee joint fixed at 90° (Fig. 1). Each contraction lasted approximately 0.5 sec and for the remainder of the period 0.5 sec. In test 2, the subjects in the same position as in Test 1 were required to maintain maximal isometric contraction for 2 min.

Muscle force output was measured via a strain gauge located on an iron cord. One end of the cord was fixed on an ankle joint and the other end attached to the immovable iron bar.

In Test 1, each curve of force generated was integrated by time, and the value was divided by the duration. For the determination of mean force output, five continuous values were averaged. In Test 2, mean force output was calculated for every 5 sec. Test 1 was accompanied by Test 2 two days later.

EMG was recorded from the vastus lateralis with surface electrodes of 10 mm-diameter silver plate which were attached 3 cm apart. The electrical resistance was reduced to below 10 kΩ by light abrasion of the skin at the site chosen for electrode application. EMG signals were amplified, rectified, integrated and recorded on a linear pen-recorder (Multipurpose Polygraph RM-6000, Nihon Kohden, Tokyo). The overall frequency response before rectification was 5–300 Hz.

RESULTS

The recordings of force output, EMG and i-EMG in the two fatigue tests are shown in Fig. 2. In test 1, the mean of initial values in force output was 563.5N and its SD was 108.7N. The values of mean force output and i-EMG related to time are shown in percent to the initial value in Fig. 3. Mean force output decreased rapidly and linearly till about the 60th contraction, and thereafter tended to plateau at a level corresponding to 40–45% of the initial value. However, hardly any change was observed in i-EMG.

In Test 2, the mean and SD of the initial maximal value of force output was 597.8±132.3N. The values of mean force output and i-EMG related to time were presented in percent to the initial value in Fig. 4. Force output decreased linearly till about 80 sec and then this variable (about 20% of the initial value) was maintained to the end. On the other hand, i-EMG kept the initial value within the first 20 sec. Thereafter it rapidly decreased till about 80 sec had passed, and then tended to plateau to the end of the experiment.

DISCUSSION

The results obtained in Test 1 that force output decreased progressively to reach a stable level at about 45% of the initial value were in good agreement with
Fig. 2. The recordings of force output, EMG and Integrated EMG (i-EMG). Upper: repeated fatigue test (Test 1), lower: maintained fatigue test (Test 2).

Fig. 3. The values of mean force output (m-force output) and integrated EMG (i-EMG) in percent to the initial value related to the number of contractions in Test 1.

those of the fatigue test consisting of repeated fast maximal contractions of the quadriceps muscle in an isokinetic apparatus. (THORSTENSSON and KARLSSON, 1976; NILSSON et al., 1977; TESCH, 1980). In similar fatigue tests consisting of repeated fast maximal contractions of the quadriceps muscle in an isokinetic apparatus, NILSSON et al. (1977) showed the decrease in torque being accompanied by no significant reduction in i-EMG. However, according to KOMI and TESCH
MAINTAINED MAXIMAL ISOMETRIC CONTRACTIONS

Fig. 4. The values of mean force output (m-force output) and integrated EMG (i-EMG) in percent to the initial value related to the time in Test 2.

(1979), an i-EMG decline ($p<0.01$) was demonstrated in individuals rich in FT fibres and only a slight, but not significant reduction in i-EMG occurred in individuals with a high percentage of ST fibres. In addition, Komi and Rusko (1974) reported a slight decrease in i-EMG during maximal contractions of forearm flexors. The time-related change in i-EMG obtained in the present study coincided well with the previous results described above. Therefore, it can be said that i-EMG keeps a constant value or decreases slightly in the fatigue test of maximal repeated contractions.

In Test 2, the main findings different from Test 1 were that i-EMG decreased in parallel with force output, and that the force output tended to plateau at a level lower than that in Test 1 (20% vs. 45%). In the similar fatigue test of quadriceps muscles, Bigland-Ritchie et al. (1978) reported that four of seven subjects showed a parallel decline in force output and EMG activity. In addition, in experiments on the first dorsal interosseous muscle, Stephens and Taylor (1972) found that the smoothed rectified EMG and force declined in parallel. Therefore, it can be said, based on the results obtained in Test 2, that both i-EMG and force output decrease almost in parallel in the fatigue test of maximal maintained contraction.

During muscular contractions, active muscles require a greater blood supply than at rest. However, it is well known that blood flow is opposed by the mechanical compression of the contracting muscle fibres. According to previous reports (Barcroft and Millen, 1939; Edwards et al., 1972), the blood supply to the leg muscle is occluded during maintained isometric contraction of more than about 20% of the maximal voluntary force. In repeated contractions, on the other hand, the mechanical interference to flow is intermittent and the blood flow during the relaxation periods is high (Lind et al., 1967). It can be, therefore, assumed that in Test 1 consisting of repeated MVC, the occlusion of blood flow did not exist, while in Test 2 consisting of maintained MVC, the blood flow was occluded.
Nilsson et al. (1977) indicated that the development of fatigue during repeated dynamic contractions with high power outputs was caused by local factors in the muscle, primarily in FT fibres because of the positive correlation between the increase in EMG/torque ratio and the individual percentage of FT fibres. On the other hand, lactate accumulation in the muscle has often been cited as being one inhibitory factor in relation to muscle fatigue. The lactate concentration in different muscle fibre types has been reported with biopsy technique for human vastus lateralis muscle after maximal dynamic leg exercise. (Tesch et al., 1978a; Tesch et al., 1978b; Tesch, 1980). These results indicated that lactate or associated pH changes, primarily in FT fibres, could be one factor responsible for the impaired muscle function.

According to these reports, it seems reasonable to assume that the decrease in force output in Test 1 is due to local fatigue in FT fibres. In addition, it can be assumed that the plateau value (40-45% MVC) of force output after 80 sec was generated mainly by oxidative FT fibres (FOG or type II a) and ST fibres (SO or type I) which have a higher oxidative capacity than FT fibres (FG or type IIb). In fact, all the subjects could repeat contractions for 20 min, involving a total of 1,200 contractions, in additional experiments (intensity was the mean value of the final 30 contractions in Test 1). This result would support the assumption that the plateau values were maintained mainly by high oxidative FT fibres and ST fibres.

According to a similar fatigue test consisting of maintained maximal isometric contractions, the concomitant decrease in the EMG can be explained as follows: (a) neuromuscular junction fatigue (Stephens and Taylor, 1972), (b) central fatigue, direct or due to an inhibition elicited by nervous impulses from receptors in the fatigued muscles (Asmussen and Mazin, 1978; Asmussen, 1979). Bigland-Ritchie et al. (1978) reported that despite the parallel decline in force output and the EMG during maintained maximum voluntary contractions of quadriceps, if extra effort was made, force output increased and it was accompanied by a proportionately greater increase in the EMG (generally up to the original value). They concluded that in maintained maximum voluntary contractions of quadriceps, (a) central fatigue may account for an appreciable proportion of the force loss, (b) surface EMG recordings provide no evidence that neuromuscular junction failure in the limiting factor determining the loss of force in this muscle.

In the present study, three of six subjects were asked to exert maximal force output for 5 sec just after the end of fatigue testing (Test 2). They could increase their force (53.1% relative to the initial value) and this was accompanied by a greater increase in i-EMG (slightly up relative to the initial value). It seems, therefore, that the i-EMG decrease with time in the present study was caused by central fatigue rather than by neuromuscular junction fatigue.

In Test 2 it seems certain that the greater decrease relative to the plateau value (20% MVC) as compared with Test 1 might be due to blood occlusion induced by
the mechanical compression of the contracting muscle fibres. During the main-
tained MVC, in other words, ST fibres as well as FT fibres lost their energy
stores with time and the force output decreased to the final value of 20% MVC.
After 80 sec to the end of the experiment, force output kept a constant value (20%
relative to the initial value) and this was probably due to the blood flow, which
was made possible by the mechanical compression lower than 20% MVC of the
contracting muscle fibres. It is concluded that blood shortage was the essential
factor inducing the difference in the results obtained in the present two fatigue
tests.

REFERENCES


BARKCROFT, H. and MILLEN, J. L. E. (1939) The blood flow through muscle during sustained

and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps

EDWARDS, R. H. T., HILL, D. K., and MCDONNELL, M. (1972) Myothermal and intramuscular
pressure measurements during isometric contractions of the human quadriceps muscle. J.

KOMI, P. V. and RUSKO, H. (1974) Quantitative evaluation of mechanical and electrical changes
121-126.

KOMI, P. V. and TESCH, P. (1979) EMG frequency Spectrum, muscle structure, and fatigue during

LIND, A. R., PHIL, D., and McNICOL, G. W. (1967) Muscular factors which determine the cardio-

MOSSO, A. (1890) Ueber die Gesetze der Ermüdung. Untersuchungen an Muskeln des Men-

NILSSON, J., TESCH, P., and THORSTENSSON, A. (1977) Fatigue and EMG of repeated fast volun-

STEPHENS, J. A. and TAYLOR, A. (1972) Fatigue of maintained voluntary muscle contraction

TESCH, P., SJOEDIN, B., and KARLSSON, J. (1978a) Relationship between lactate accumulation,
LDH activity, LDH isozyme and fibre type distribution in human skeletal muscle. Acta

TESCH, P., SJOEDIN, B., THORSTENSSON, A., and KARLSSON, J. (1978b) Muscle fatigue and its rela-
