Muscle fatigue is often associated with slowing of contractile speed (see Refs. 16, 37 for review). This has been demonstrated by reduced rates of force generation and relaxation following intense sustained voluntary contractions and tetanic stimulation of animal muscle in vitro (5, 9, 12). Much less is known about the changes in contractile speed during more normal activation patterns of human skeletal muscle. It is well documented that submaximal voluntary contractions are generated by only a fraction of the motor units and that they are often activated by subtetanic excitation rates (2, 14, 25). Other studies demonstrate a temporal rise in the myoelectrical activity as assessed by the integrated electromyogram amplitude (2, 23). This increase is probably caused in part by a gradual recruitment of fresh motor units, but an increased rate of excitation in units already active could probably also contribute (2). Studies of physiological responses during fatigue from low-force voluntary isometric activity thus introduce additional degrees of freedom not present in other studies. Nevertheless, the interpretation of changes seen during this type of exercise is important to understand the physiological responses to prolonged voluntary muscle activity.

During exercise consisting of voluntary low-force repetitive contractions, Vøllestad and co-workers (35) demonstrated a gradual decline in force-generating capacity, without the concomitant chemical changes seen during sustained ischemic contractions (12, 18). Repetitive isometric contractions also induce a progressive rise in energy cost of contraction, demonstrated by an increased oxygen uptake in the muscle (27, 36) and a higher rate of metabolic heat production during contraction (29). Contractile speed is closely associated with the metabolic heat production and energy cost of contraction (16, 39, 41), suggesting that the rate of force generation and relaxation may increase with fatigue from repetitive isometric exercise. Thus the exercise-induced changes in muscle energetics and activation pattern occur in a direction opposite to that seen during sustained voluntary or electrically stimulated contractions (4, 5, 12, 18).

Prolonged submaximal exercise is associated with a fatigue-induced recruitment of the faster type II muscle fibers, which have a higher energy cost of contraction compared with type I (6, 7). To what extent this increased activation of type II fibers causes a temporal rise in energy turnover can be examined by comparing the responses during repetitive isometric exercise at different target force levels. With an increased target force, a larger proportion of type II fibers will be activated from start, and the rise in energy cost of contraction and, consequently, contractile speed is expected to be smaller.

The aim of the present study was to investigate the changes in muscle contractile speed during and after voluntary repetitive isometric contractions carried out until exhaustion and to compare the changes at different contraction levels. This was accomplished by examining time to peak force and half relaxation time (RT1/2), together with the maximum rate of force change, when the muscle was stimulated electrically at stimulation frequencies from 1 to 50 Hz. Furthermore, we wanted to examine the effects of fatigue and altered contractile speed on the force-fusion properties during submaximal tetanic activation. The relative force oscillation amplitude was examined when the muscle was stimulated at rates similar to those recorded during voluntary contractions at submaximal force levels, i.e., 10–20 Hz (2, 25). Preliminary reports have been given elsewhere (31, 34).

METHODS

Subjects. Five healthy men and two healthy women (age 22–30 yr, height 170–182 cm; weight 59–83 kg) volunteered...
to participate in the present experiments. They were all physically active students but not particularly trained for any sports activity. After a routine medical examination, an informed consent to participate was obtained. During the last 14 days before the experiment, the subjects were familiarized with the experimental setup and the exercise protocol. The study was approved by the Regional Ethics Committee for Medical Studies, Norway.

Protocol. All subjects participated in three separate experiments, with repetitive isometric contractions at target forces of 30, 45, and 60% of maximal voluntary contraction (MVC). The experiments were carried out on separate days with at least 1-wk interval. All subjects carried out the 30% MVC experiments first. The order of the experiments at the two highest force levels was randomized. The exercise was carried out while the subjects were sitting with the knee flexed at an angle of −80° and with the back inclined backward at a hip angle of −110°. The subjects’ hips were strapped to the seat to ensure minimal movement. The force generated with each of the knee extensors was measured with a strain gauge connected to a padded loop around the ankle. Voluntary contractions were generated bilaterally, but electrically evoked contractions were studied in the right leg only. The force responses from the electrically stimulated contractions were obtained. With an interval of 60 s, a twitch contraction and trains of 10 pulses at the different test frequencies were generated. With a twitch, a 6-s target force contraction was performed to facilitate twitch potentiation allowing comparison with the exercise data. The corresponding test force was given after 2 and 6 min of recovery and every 5 min thereafter.

After exhaustion, the subjects remained seated without moving their legs for a recovery period of ~27 min. The test sequence A was performed 3 and 5 min after cessation of exercise and then every 5 min. Before the twitch, a 6-s target force contraction was performed to facilitate twitch potentiation allowing comparison with the exercise data. The test sequence B was given after 2 and 6 min of recovery and every 5 min thereafter.

Three subjects carried out control experiments, in which no voluntary exercise was performed. The subjects sat for 60 min (n = 1) or 90 min (n = 2) in the chair apparatus, and the test sequences (twitch, 10–50 Hz stimulation, and MVC) were performed as in the exercise experiments.

Electrical stimulation and force measurements. The right quadriceps muscle was stimulated through surface electrodes (Tenzcare, 3M, St. Paul, MN) placed proximally and distally over the thigh. Electrical square-wave pulses (0.5-ms duration) were generated by a stimulator (Pulsar 6bp, FHC, Brunswick, ME), and the frequency and number of pulses were controlled by a computer running a custom-made program. In preliminary experiments, it was established that peak force was obtained by a stimulation of 70–80 V. In all experiments, 90-V stimulation was used to ensure activation of the largest possible muscle mass.

Force was measured by a strain gauge (HBW U2AC2, Darmstadt, Germany) connected via a steel rod and an inelastic loop around the ankle. The time constant of the strain gauge was 5 ms. The subjects exercised with both legs, and the target force required, together with that from each contraction, was continuously displayed on a screen in front of the subject. This enabled the subjects to generate a constant target force during the voluntary contractions. Force responses from the electrically stimulated contractions were obtained from the unfatigued muscle. Average values of the two contractions at each frequency were used as the preexercise control values.

The exercise consisted of repeated voluntary contractions at either 30, 45, or 60% MVC. The contractions were maintained for 6 s with a 4-s rest between them (Fig. 1) and were continued until exhaustion, defined as the point when the subjects were unable to maintain target force for the required 6 s. At given intervals during the exercise, two sequences of test contractions were performed. Test sequence A consisted of stimulation with a single pulse, 15 and 50 Hz, given in three consecutive 4-s rest periods, followed by a 3-s MVC instead of one target force contraction. Test sequence B consisted of stimulation at 10 and 20 Hz in two consecutive rest periods. Test sequence A was given after the first target force contraction and repeated after 3, 5, and 10 min and then every 5 min. In addition, this sequence was performed in the last 40 s before exhaustion. The test sequence B was given after 2, 6, and 11 min and repeated every 5 min thereafter.

Table 1. Preexercise control values for force and contractile speed

<table>
<thead>
<tr>
<th>Stimulation Frequency</th>
<th>Target Force, %MVC</th>
<th>Force, N</th>
<th>CT, ms</th>
<th>MCR, ms⁻¹</th>
<th>RT₉₀, ms</th>
<th>MRR, ms⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twitch</td>
<td>30</td>
<td>31 ± 3</td>
<td>41.4 ± 3.0</td>
<td>21.9 ± 0.9</td>
<td>50.9 ± 5.7</td>
<td>13.5 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>35 ± 2</td>
<td>38.5 ± 0.7</td>
<td>22.1 ± 0.5</td>
<td>61.2 ± 9.8</td>
<td>12.0 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>35 ± 4</td>
<td>40.9 ± 2.2</td>
<td>22.1 ± 0.7</td>
<td>53.9 ± 5.5</td>
<td>13.6 ± 1.6</td>
</tr>
<tr>
<td>10 Hz</td>
<td>30</td>
<td>62 ± 10</td>
<td></td>
<td></td>
<td>90.4 ± 7.2</td>
<td>7.2 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>74 ± 8</td>
<td></td>
<td></td>
<td>90.4 ± 6.9</td>
<td>7.1 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>72 ± 10</td>
<td></td>
<td></td>
<td>87.7 ± 8.2</td>
<td>7.5 ± 0.9</td>
</tr>
<tr>
<td>15 Hz</td>
<td>30</td>
<td>90 ± 15</td>
<td></td>
<td></td>
<td>81.9 ± 4.3</td>
<td>8.5 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>100 ± 12</td>
<td></td>
<td></td>
<td>83.8 ± 3.2</td>
<td>8.6 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>108 ± 14</td>
<td></td>
<td></td>
<td>83.0 ± 2.2</td>
<td>8.9 ± 0.4</td>
</tr>
<tr>
<td>20 Hz</td>
<td>30</td>
<td>108 ± 17</td>
<td></td>
<td></td>
<td>80.6 ± 3.9</td>
<td>9.7 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>116 ± 14</td>
<td></td>
<td></td>
<td>80.7 ± 2.6</td>
<td>9.8 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>135 ± 18</td>
<td></td>
<td></td>
<td>76.4 ± 2.4</td>
<td>10.4 ± 0.3</td>
</tr>
<tr>
<td>50 Hz</td>
<td>30</td>
<td>124 ± 17</td>
<td>138.9 ± 4.3</td>
<td>13.3 ± 0.8</td>
<td>95.8 ± 9.3</td>
<td>8.1 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>132 ± 12</td>
<td>142.6 ± 4.1</td>
<td>13.1 ± 0.4</td>
<td>103.7 ± 7.6</td>
<td>8.3 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>137 ± 17</td>
<td>141.1 ± 5.1</td>
<td>13.2 ± 0.6</td>
<td>80.4 ± 3.2</td>
<td>8.6 ± 0.4</td>
</tr>
</tbody>
</table>

Data are means ± SE; n = 7 subjects. CT, contraction time; RT₉₀, half relaxation time; MCR, maximal rate of force generation; MRR, maximal rate of force relaxation.
was continuously analog-to-digital converted (Metabyte Das-16, Keithley, Cleveland, OH) and stored on a hard disk. The data-sampling frequency was 1 kHz during the electrically evoked test contractions and 50 Hz in the other periods.

Calculations. Contraction time (CT) was calculated as the time elapsed for force to increase from 10 to 90% of peak force. The maximal rate of force generation (MCR) was calculated as the peak value of dF/dt divided by peak force, where F is force and t is time (3, 5, 40). Peak force in unfused tetanic contractions elicited by 10- to 20-Hz stimulation appeared after a variable number of pulses (cf. Fig. 4). Hence, reliable assessment of CT could only be obtained from the twitch and the 50-Hz contractions that displayed smooth force increments until peak force was reached. RT_{1/2} was calculated as the time elapsed for force to fall by 50% from peak force after the last stimulation pulse. The corresponding maximal relaxation rate (MRR) was calculated as the nadir value of dF/dt divided by peak force.

Contraction generated by stimulation frequencies of 10 and 15 Hz were unfused and showed clear oscillations. The average amplitude of these oscillations ( ΔF ) was determined after the initial rapid rise in tension had subsided (cf. Fig. 4). The mean force (Fm) in the same period was also determined. Any changes in contractile speed would be expected to affect ΔF. In addition, fatigue will influence both ΔF and Fm. The combined effect of repetitive isometric exercise on force-fusion properties and force-generating capacity was monitored as the the change in the relative force oscillation amplitude (ΔF/Fm).

Statistics. Values are means ± SE, unless otherwise stated. One-way analysis of variance for repeated measures was performed to evaluate the temporal changes, except for the changes in ΔF/Fm, which were tested by paired t-tests.

RESULTS

Force and endurance. The endurance times were 45 ± 5, 15 ± 1, and 5.6 ± 0.3 min for the repetitive exercise at 30, 45, and 60% MVC, respectively. The MVC force decreased gradually by ~35–40% during exercise in all experiments (Table 2). Over the 27-min postexercise recovery period, MVC force increased to 86–88% of preexercise levels in all three protocols. The final values were significantly lower than preexercise control values (P < 0.04).

The force response to all stimulation frequencies declined during the exercise period in all experiments, as illustrated in Fig. 2 for twitches and 15- and 50-Hz stimulus (Ftw, F15, and F50, respectively). The reductions (relative to the preexercise values) were similar to, or larger than, those observed for MVC (Fig. 2, Table 2). The rate of force loss increased with increasing target force. A notable exception from the steady decline in force during exercise was the Ftw, which increased initially, before a gradual decline was seen. This initial rise probably reflected the degree of posttetanic potentiation that occurs predominantly in type II fibers (11). With increasing target force, a larger initial rise in Ftw was observed.

In the postexercise recovery period, the time course of force recovery varied, but none of the force responses was fully restored after 27 min (Table 2 and Fig. 2). After the 30% MVC exercise, Ftw remained stable, whereas a consistent increase in the peak force of the trains at 15–50 Hz was observed (P < 0.007). In the first 3 min, F50 increased rapidly before it leveled off at 80–85% of control values. A similar rapid initial increase was observed after the 45% MVC exercise for twitch force and contractions elicited by 15 Hz or more (Fig. 2). In contrast, F10 remained unchanged in the recovery period (P = 0.88). After exhaustion from exercise at 60% MVC, peak force at all stimulation frequencies recovered rapidly before it declined again during the remaining recovery period (P < 0.0001).

CT and MCR. CT determined from the 50-Hz stimulation remained unaltered during both exercise and recovery at all three intensities (P > 0.23; Fig. 3). Twitch CT decreased in all experiments by ~20% after the first 6-s target force contraction. Thereafter, no further changes were seen in the fatiguing exercise or in recovery (P > 0.5). The initial decline in CT was associated with an increased MCR (Table 3). For all experiments, both CT and MCR remained virtually unchanged during the entire exercise and recovery period.

RT_{1/2} and MRR. RT_{1/2} values for all stimulation frequencies decreased gradually during exercise at 30 and 45% MVC (P < 0.05). During the 30% MVC exercise, RT_{1/2} determined from contractions elicited by 10-Hz stimulation declined most rapidly and reached 34 ± 3% of the preexercise control value at exhaustion. RT_{1/2} from the other stimulation patterns declined to only 25 ± 2% at exhaustion (P < 0.0001). The endurance times were 45 ± 5, 15 ± 1, and 5.6 ± 0.3 min for the repetitive exercise at 30, 45, and 60% MVC, respectively. The MVC force decreased gradually by ~35–40% during exercise in all experiments (Table 2). Over the 27-min postexercise recovery period, MVC force increased to 86–88% of preexercise levels in all three protocols. The final values were significantly lower than preexercise control values (P < 0.04).

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57–73% of control at exhaustion. During the 45% MVC exercise, RT1/2 determined from twitch and 10-Hz stimulation reached 60% of control values at exhaustion. For contractions elicited by higher stimulation frequencies, RT1/2 decreased to 71–87% of the values obtained in unfatigued muscle.

A different and more variable picture was observed from the test contractions carried out during and after exercise at 60% MVC. For twitches, the RT1/2 values increased initially to 121% before they declined to 70% of preexercise values. In contrast, RT1/2 from the 50-Hz contractions increased and remained elevated during the exercise (P = 0.002), reaching 150% of preexercise value after 3 min (Fig. 3). Stimulation at other frequencies caused temporal changes in RT1/2 similar to, but less pronounced than, the responses from 50-Hz stimulation.

In the recovery period after the exercise at 30% MVC, small but significant increases in RT1/2 were observed for all contractions (P < 0.04; Fig. 3), except for the 10-Hz stimulation, which remained low. After the exercise at 45% MVC, RT1/2 values for all stimulations remained at the levels attained at exhaustion (P > 0.07). In contrast, after exercise at 60% MVC, a decline in RT1/2 was seen in contractions generated by all frequencies (P < 0.001), although RT1/2 from twitches increased initially (Fig. 3). The final recovery values of RT1/2 after repeated isometric exercise at the three different target force levels were thus almost the same, despite an 8- to 10-fold variation in endurance times. MRR changed as a mirror image of the RT1/2 for all stimulation frequencies and exercise runs (Table 3). Close and inverse relationships were observed between RT1/2 and MRR throughout the entire exercise and recovery period. The mean correlation coefficients ranged from −0.84 to −0.93 for the different stimulation paradigms.

Mechanical response to low-frequency stimulation. Stimulation at 10 and 15 Hz always generated unfused tetani, which showed clear oscillations in force (Fig. 4). In the 30 and 45% MVC experiments, the amplitude of these oscillations ΔF increased slightly while the Fm decreased, as illustrated for 10-Hz contractions in Fig. 4. However, ΔF decreased during exercise at 60% MVC but increased again in the recovery period. Furthermore, during exercise at 30 and 45% MVC, ΔF/Fm increased two- to fourfold during the exercise period (P < 0.001) and remained elevated in the postexercise recovery period (Fig. 5). In contrast, ΔF/Fm remained unchanged during 60% MVC exercise (P = 0.106) but increased in the postexercise period (P = 0.001) to a value similar to those seen after exercise at the two lower force levels.

Figure 6 shows that there was a close and inverse relationship between RT1/2 and the ΔF/Fm during 10-Hz stimulation. Individual data from resting control muscle, exhaustion, and 27-min recovery all display the same relationship, irrespective of the target force level. The largest effects of changes in RT1/2 values were seen at the lowest values of RT1/2, whereas almost negligible oscillations were found at the longest RT1/2 values (above 80 ms).

Control experiments. For the three subjects who carried out control experiments, in which the test contraction program (MVCs and electrical stimulation) was employed without any voluntary activity, force and contractile speed remained unaltered. After 60 min, the range of RT1/2 for the different stimulation regimens was 96–105%, compared with the control value. Similar small changes were seen for MRR, CT, MCR, and force.

DISCUSSION

The major finding of the present experiments was a gradual fall in RT1/2 during fatigue from repetitive isometric exercise at 30 and 45% MVC target force while the CT remained unchanged. Furthermore, RT1/2
values changed consistently in twitches and trains of stimuli from low to high frequency and always inversely to the MRR. These changes are in sharp contrast to those frequently observed during sustained voluntary contractions or tetanic stimulation (5, 9, 12) but in keeping with a small decline in twitch time recorded during repeated maximal contractions at low duty cycles (22). The amplitude of force oscillations during tetani elicited by low-frequency stimulation (10 and 15 Hz) increased as the Fm declined. These changes were maintained in the recovery period. During exercise at 60% MVC, the changes in RT$_{1/2}$ values were more variable and depended on the stimulation frequency. Furthermore, repetitive isometric exercise at this highest target force induced a parallel decline in the DF in unfused tetanic contractions and Fm. In the postexercise recovery period, however, the oscillation amplitude increased to values comparable to those seen after the exercise at 30 and 45% MVC.

The RT$_{1/2}$ either remained shorter than control (30 and 45% MVC exercise) in the postexercise recovery period or

Table 3. Contractile speed at exhaustion and after 27-min recovery in response to electrical stimulation at different frequencies

<table>
<thead>
<tr>
<th>Stimulation Frequency</th>
<th>Exhaustion</th>
<th>27-min Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30% MVC</td>
<td>45% MVC</td>
</tr>
<tr>
<td>MRR, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twitch</td>
<td>171±15</td>
<td>169±8</td>
</tr>
<tr>
<td>10 Hz</td>
<td>268±24</td>
<td>261±25</td>
</tr>
<tr>
<td>15 Hz</td>
<td>175±17</td>
<td>142±16</td>
</tr>
<tr>
<td>20 Hz</td>
<td>149±6</td>
<td>116±8</td>
</tr>
<tr>
<td>50 Hz</td>
<td>151±15</td>
<td>123±15</td>
</tr>
<tr>
<td>MCR, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twitch</td>
<td>119±5</td>
<td>119±6</td>
</tr>
<tr>
<td>50 Hz</td>
<td>118±8</td>
<td>109±6</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 7 subjects. Data given as %preexercise control values in experiments consisting of repetitive isometric contractions at 30, 45, and 60% MVC.
shifted from values longer than preexercise control values to shorter values (e.g., 50-Hz stimulation after 60% MVC exercise). The end points for RT_{1/2} were thus remarkably similar among the three target force levels. A similar convergence in the recovery period was also observed for the ΔF/FF_{m} ratio. There was a close and inverse relationship between ΔF/FF_{m} and RT_{1/2} under all conditions.

The methods used in this study to determine the contractile speed have been validated in numerous other studies that showed contractile slowing with fatigue of both human and animal muscle (5, 8, 12, 19). Here consistent measurements were made of both time measurements (RT_{1/2} and CT) as well as rate measurements (MRR and MCR) in response to a wide range of stimulus frequencies. All seven subjects showed a gradual decline in RT_{1/2} in response to five different stimulation regimes in each of two experiments carried out on separate days at different target force levels (30 and 45% MVC). Similar values were obtained from unfatigued muscle of each subject in three separate experiments on different days (Table 1), and when the subjects sat resting in the chair for 60–90 min. It is, therefore, reasonable to assume that both the constancy of CT as well as the marked changes in RT_{1/2} values reflect the real mechanical properties of the muscle-tendon unit.

Mechanical responses in relation to muscle chemistry. Fatigue in human muscle in vivo is mostly studied by experimental protocols allowing a precise determination of the excitation pattern (electrical stimulation) or in situations where the excitation pattern is well known (MVCs). The results from these studies, together with data extrapolated from fatigue induced by electrical stimulation in vitro, almost unequivocally associate fatigue with a slowing of relaxation [see review by Fitts (16)]. This slowing is usually attributed to the large changes in high-energy substrate and metabolite concentrations (5, 9, 12, 18).

It was previously demonstrated that only moderate initial changes in high-energy P_{i}, lactate, and H^{+} levels occur during repetitive isometric exercise at 30% MVC (27, 35). Furthermore, we have previously estimated...
that the rate of ATP turnover during this type of exercise is well below the limits for aerobic metabolism (29, 36). The low amounts of lactate production support the opinion that the ATP demand during this type of exercise is adequately met by oxidative ATP resynthesis (27, 36). The absence of large changes in substrate and metabolite levels may explain why contractile slowing was not found during repetitive isometric exercise at the two lowest force levels. Even though we have no direct evidence of changes in metabolites in the present study, it is reasonable to assume that the 60% MVC repetitive isometric exercise may have induced larger changes in high-energy P, and other metabolites compared with the 30 and 45% MVC exercise. These chemical changes may have caused the slowing of relaxation demonstrated for the tetanic contractions during the 60% MVC exercise. The slowing of relaxation was reversed with a time course similar to recovery of metabolite changes after exercise (17, 30). However, no known metabolic factors can explain why RT1/2 values decreased during the low-force contractions or in the recovery period.

A recent paper by Ferrington and coworkers (15) demonstrated that prolonged exercise in rats induced an increased proportion of functional Ca2+ pumps at the sarcoplasmic reticulum (SR) membrane. If this response occurs also in our human model involving isometric contractions, faster relaxation is predicted. Analysis of functional Ca2+ pumps during repetitive isometric exercise may thus be an important step toward understanding the mechanisms behind the increased contractile speed.

Changes in muscle fiber activation pattern. The sequence in which motor units are recruited may influence the contractile properties of muscle during voluntary contractions executed at different intensities (25, 40). It has previously been shown that low-force contractions involve only a fraction of the motor-unit pool and that these are predominantly type I fibers (2, 24). As exercise progresses, these fibers fatigue and thus produce less force when a given electrical stimulation is applied. Thus an increasing fraction of the force response elicited by external stimulation will be generated by the faster type II fibers. The muscle as a whole will thus appear with faster contractile properties, even in the absence of changes at the cellular level.

At higher target forces, the initially recruited fraction of type II fibers increases. The greater twitch potentiation after the first 45% compared with the first 30% contraction indicates that a substantially larger number of type II fibers were recruited initially during this more intense exercise regime (11). Thus, at the higher target force, fatigue will develop simultaneously in both type I and in the active type II fibers, and the dominance of un-fatigued type II fibers on contractile speed will be decreased. In consequence, the temporal changes in muscle activation pattern would predict a lesser decline in RT1/2 during exercise at higher target force. We did not observe this. Furthermore, one would expect that RT1/2 and CT would be altered in a similar manner, as they are both heavily dependent on the fiber type (1, 20, 40). The lack of changes in CT, apart from an initial change, indicates that the changes in contractile speed observed in these experiments were not primarily due to selective fatigue of type I fibers. This interpretation is in keeping with a small decline in twitch time recorded when 10-s maximal contractions with the elbow flexors were repeated every 100 or 200 s (22). Therefore, we conclude that the gradual fall in RT1/2 reflects a change in mechanical properties at the cellular level.

Muscle temperature. The contractile speed of skeletal muscle is sensitive to temperature, exhibiting a Q10 of ~2 above 25°C (33, 39). We have recently reported a 3–4°C increase in muscle temperature during 30% MVC repetitive isometric exercise to exhaustion (29), and a similar increase has been seen during 60% MVC repetitive isometric exercise (unpublished observations). The expected increase in contractile speed due to increasing muscle temperature would then be ~30%. The relaxation rates increased by 50–170% (cf. Table 3), and, hence, part of this rise could possibly be a temperature effect. However, temperature changes are shown to affect CT and RT1/2 equally (5, 33). In addition, muscle temperature falls linearly in the recovery period (29), predicting a linear rise in RT1/2. Therefore, the constancy of CT presently observed while RT1/2 decreased markedly during exercise, with only little normalization in the postexercise recovery period, does not indicate that the changes in RT1/2 primarily are a consequence of the changes in muscle temperature.

Contractile changes and muscle energetics. At the cellular level, the relaxation process is regulated by enzymes controlling the rate of Ca2+ reuptake in the SR and, possibly, also the rate of cross-bridge detachment (12, 16). Hence, the decline in RT1/2 during the 30 and 45% MVC exercise is expected to coincide with an increase in the rate of ATP utilization. This contention agrees well with the observed increase in energy cost during 30% MVC repetitive isometric exercise, seen as a twofold increase in oxygen uptake in the working muscle (27, 36), and a 75% increase in metabolic heat production during contraction (29). Furthermore, the decrease in RT1/2 and increase in energy turnover follow similar time courses during exercise and show a similar slow return toward control values during postexercise recovery. The present data, therefore, strongly indicate that the decline in RT1/2 seen during the 30 and 45% MVC exercise is caused by a higher rate of ATP utilization either at the cross bridges or at the membrane of the SR.

The changes in RT1/2 during the 60% MVC exercise clearly differ from those seen at the lower exercise intensities in the respect that RT1/2 increased initially from all stimulation regimes and remained elevated for the higher frequencies throughout the exercise. At exhaustion, the change in RT1/2 seemed to be “dose” dependent, with the slowest relaxation seen from the 50-Hz stimulation. The short endurance may indicate that the energy turnover during the 60% MVC exercise is at or beyond the limit for aerobic ATP replenishment during the hyperaemic rest period between contrac-
Consequences of faster relaxation. Relaxation rate is an important factor in determining the contractile response of the muscle fibers during isometric contraction. It was previously documented that the motor unit discharge rate is in the order of 10–15 Hz during submaximal voluntary contractions in humans (2, 25). As shown in Fig. 4 for unfused tetanic contraction of the whole muscle during electrical stimulation, these slow excitation rates result in large oscillations of the force output. The $\Delta F$, together with $F_m$, is expected to be influenced by any changes in relaxation rate, as shown for the $\Delta F/F_m$ ratio and $RT_{1/2}$ in Fig. 6. The same relationship between these indicators of mechanical behavior was observed independent of fatigue and target force level, despite quite different changes in $RT_{1/2}$ and $\Delta F/F_m$ ratio during repetitive isometric exercise at 60% MVC compared with 30 and 45% MVC (cf. Figs. 3 and 5).

Oscillation of isometric tension is associated with a higher cross-bridge cycling rate than during a fully fused isometric contraction, in which cross-bridge turnover is relatively slow (41). The energy cost of contraction, expressed as the ratio between the rate of ATP turnover and force, is thus expected to be higher in unfused compared with fully fused isometric contractions. In keeping with this, Wiles and Edwards (38) found that when the unfatigued human adductor pollicis muscle was stimulated at a wide range of frequencies, the energy cost of contraction was linearly and closely correlated to the $\Delta F/F_m$ ratio. In fact, at the lowest stimulation frequencies in which the highest values for both energy cost and $\Delta F/F_m$ were found, the energy cost of contractions was six times higher than that observed during maximal stimulation. We have recently reported a similar sixfold difference in energy cost between submaximal (10% MVC) and MVC in the vastus lateralis muscle (28). The increase in energy cost during and after the repetitive isometric contractions may thus involve a two-step process. An enhanced rate of ATP turnover at the Ca$^{2+}$-adenosinetriphosphatase (ATPase) causes a faster relaxation. Consequently, larger tension and possibly also length adjustments consequent to the faster contractile speed occur, and this altered mechanical behavior causes a larger rate of ATP turnover at the myosin ATPase.

In conclusion, our results indicate that repetitive low-force isometric contractions induce a gradual fall in the $RT_{1/2}$ while the CT is unaltered. With higher target force levels, the faster relaxation may be masked during exercise, probably by the slowing effect of anaerobic metabolites. Our data further suggest that the reduced $RT_{1/2}$ occurs at the cellular level and is not primarily caused by temperature rise or selective muscle fiber recruitment and fatigue. The most likely cause is an increased turnover rate of the SR Ca$^{2+}$-ATPase or the myosin ATPase. We argue that voluntary submaximal isometric contractions are associated with low motor-unit excitation rates and corresponding oscillations in force output. The faster relaxation may thus induce increased amplitudes of force oscillations in the active motor units and thereby increase the energy cost of contraction.
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