Sustained contraction at very low forces produces prominent supraspinal fatigue in human elbow flexor muscles

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METHODS
Subjects. Eight normal subjects (23–51 yr old; 4 women) took part in the study. Some subjects participated in more than one experiment. All subjects gave their informed consent, and all experimental procedures were approved by the local ethics committee and were conducted according to the Declaration of Helsinki.

Experimental setup. Subjects sat with the right arm flexed at 90° in an isometric myograph that measured elbow flexion torque (transducer linear to 2kN, X-tran, Melbourne Australia; see Ref. 2 for details). The forearm was vertical and supinated and strapped to the myograph proximal to the wrist. Feedback of torque was provided to the subject by an LED display and by an oscilloscope showing a 5% MVC target as well as two lines marking a deviation of ±10% of the target torque. The subject was encouraged to keep the torque between the lines.

Surface EMGs were recorded with electrodes (Ag/AgCl, 10 mm diameter) overlaying the muscle bellies of biceps brachii, brachioradialis, and triceps brachii. Signals were amplified and filtered (16–1,000 Hz). Torque and EMG signals were sampled at 2,000 Hz for offline analysis (CED 1401 interface; Cambridge Electronic Design, Cambridge, UK).

Rating of subjective effort and pain. During the prolonged contraction and recovery, subjects were asked regularly to score the effort.

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FATIGUE IS DEFINED AS an exercise-induced decrease in the capacity to produce force and can be conceptualized as a continuous decline, rather than as an instantaneous event (7, 15). Fatigue can be produced by maximal or submaximal contractions; thus the ability to produce force in maximal contractions can be affected, even if a submaximal task can still be performed. Rohmert (34) has shown that endurance time increases exponentially as contraction strength decreases, and Bigland-Ritchie and Woods (7) suggested that contractions of <15% of maximal voluntary contraction (MVC) might be sustained “indeﬁnitely” (more than 45 min).

Muscles often contract at low levels for long periods to maintain posture or speciﬁc tasks. Neural drive in this type of contraction may differ from that in strong contractions. Activity switched between some of the synergists when subjects performed a prolonged contraction of the knee extensors below 5% MVC (21), whereas this was not seen in stronger contractions (23). Despite this changing muscle recruitment strategy, fatigue can develop during low-level contractions as shown by a fall in maximal voluntary force at the end of the contractions (22). It is not known whether this fatigue occurs peripherally (in the muscle) or centrally (in the nervous system), although it is likely that both contribute. After a 10-min contraction of 10% maximal force of the wrist extensors, although there is no decrease in maximal voluntary force, fatigue affecting the contractile apparatus of the muscle is indicated by a decrease in twitch force lasting >2 h (8). In a longer duration 15% MVC elbow ﬂexion contraction sustained for 43 min, both peripheral fatigue and central fatigue were observed (39). To our knowledge, the development of central fatigue has not been studied with sustained contractions of <15% MVC. Therefore, in the present study, we asked subjects to maintain a 5% MVC of the elbow ﬂexion muscles for 70 min. Brief MVCs were performed intermittently to measure maximal voluntary force and voluntary activation by the use of superimposed twitches elicited by motor point and motor cortex stimulation (16, 39, 46). EMG responses evoked by motor cortex stimulation were assessed throughout the low-force contraction and during the MVCs to look for changes associated with fatigue. We hypothesized that fatigue would develop progressively during a very weak contraction of the elbow ﬂexors and that part of the decrease in voluntary force would be due to central fatigue.
required to produce the target torque, and the amount of pain in their muscle, on a modified Borg (11) scale from 0 ("nothing") to 10 ("maximal").

Motor-point stimulation. Electrical stimuli were delivered to intramuscular nerve fibers of the biceps via an anode over the bicipital tendon and a cathode located over the motor point (midway between the anterior edge of the deltoid and the proximal elbow crease). The intensity of stimulation was selected by increasing single stimulus intensity until no further increase in twitch force was evoked by the stimulus at rest (100-μs duration, constant current, Digitimer DS7AH; Welwyn, Garden City, UK). During and after brief MVCs, pairs of electrical stimuli were delivered 10 ms apart. Single stimuli were also delivered at rest after MVCs during control contractions and recovery. The intensities used ranged from 130 to 330 mA.

Brachial plexus stimulation. Electrical stimuli were delivered to the brachial plexus via a cathode in the supraclavicular fossa and an anode on the acromion (100-μs duration, Digitimer DS7AH). Stimulus intensity was increased until no further increase was observed in the resting compound muscle action potential (M wave) of biceps, brachioradialis, and triceps muscles. Stimulus intensity was set at 50% above this level and ranged between 75 and 225 mA. The average amplitude of the resting maximal M wave (Mmax) was 17.1 ± 8.2 mV for biceps, 9.5 ± 5.5 mV for brachioradialis, and 8.1 ± 3.8 mV for triceps.

Motor cortical stimulation. Transcranial magnetic stimulation (Magstim 200; Magstim, Dyfed, UK) was used to stimulate the motor cortex. A circular coil (13.5 cm outside diameter) positioned over the vertex and oriented to preferentially activate the left motor cortex elicited motor-evoked potentials (MEPs) in biceps, brachioradialis, and triceps. Stimulator output (50–90% maximum) was set during brief MVCs to obtain a large MEP in the biceps (>60% Mmax) and a small MEP in the triceps (<20% Mmax). Stimulus intensity remained constant throughout the protocol.

Experimental protocol. The protocol consisted of initial control measurements, a prolonged contraction (70 min at 5% MVC), and recovery (29 min). After stimulus intensities were set, six brief control MVCs were performed with at least 1 min of rest between them. During three contractions, pairs of stimuli were delivered to the motor point, followed 5 s later by another paired stimulus at rest. During the other MVCs, motor cortical stimulation was followed 1 s later by brachial plexus stimulation. After each of these MVCs, contractions to 75% and 50% MVC were performed, with cortical and brachial plexus stimulation 1 s apart. These contractions were necessary for the calculation of voluntary activation (see Data analysis below). A single stimulus was also delivered to the motor point at rest just after each MVC. The peak MVC torque in six control efforts was used to calculate the target torque of 5% MVC. Five contractions to this target torque were performed to provide prefatigue control measures, with motor cortical and brachial plexus stimulation delivered 1 s apart during the contraction.

The prolonged contraction consisted of 70 min of isometric elbow flexion at 5% MVC. After 1 min of contraction and then at 3-min intervals, the subject performed a brief MVC (Fig. 1A). Minimal fatigue is caused by repeated MVCs when a substantial rest period is allowed. On the first set, and every second set thereafter, subjects received motor cortical and brachial plexus stimulation during the MVC, as well as during subsequent contractions to 75% and 50% MVC. Between these contractions, participants did not rest but maintained the target 5% torque. On alternate sets, participants received paired motor point stimulation during the MVC and at rest, before

Fig. 1. Diagram of the experimental and recovery protocols. A: experimental protocol. The fatiguing exercise consisted of 70 min of sustained contraction at 5% initial maximal voluntary contraction (MVC), with MVCs every 3 min. Contraction sets (100%, 75%, and 50% MVC) were performed with or without paired motor point and brachial plexus stimulation alternated with maximal contractions followed by rest with paired motor point stimulation. Between MVCs, subjects maintained the target 5% MVC contraction, with regular motor cortical and brachial plexus stimulation, and effort and pain ratings. B: recovery protocol. Subjects received motor cortical and brachial plexus stimulation at 5%, 100%, 75%, and 50% of MVC with a single motor point stimulus after the 100% MVC. Subjects then rated effort and muscle pain at the target torque, followed by maximal contraction with paired motor point stimulation during and after the contraction. Subjects completed 14 such sets during the 29-min recovery period.
returning to the target 5% torque. During the 70-min contraction, motor cortical and brachial plexus stimuli were delivered at 30-s intervals while the subjects maintained the target torque. At 30 s before each MVC, no stimulation was given, but subjects rated their perceived effort for the task and muscle pain. Throughout the prolonged 5% contraction, subjects were encouraged to maintain a steady target torque and to regain the target torque as fast as possible after each stimulus. During the brief MVCs, subjects were urged to produce a maximal effort and to pull up hard and fast after the stimulation. Because the myograph strap caused discomfort at the wrist during the prolonged contraction, it was loosened for 2 min between MVCs at 22 and 46 min of contraction. During these periods, subjects generated the target torque through a handheld strap, but stimulation and perceptual ratings were suspended.

Recovery was followed for 29 min. After the last MVC of the prolonged contraction, subjects relaxed completely for a single motor point stimulus before the recovery sets began. Fourteen sets of brief contractions were performed according to the timing shown in Fig. 1B. Participants performed brief contractions of the target, MVC, 75% MVC, and 50% MVC torques, with motor cortical and brachial plexus stimulations during each contraction. Between contractions, participants relaxed completely, with a single motor point stimulus delivered after the MVC. Participants then made a contraction to the target for ratings of perceived effort and pain. Finally, they performed a brief MVC with paired motor point stimulation, followed by another paired stimulus at rest.

Two extra studies were performed. The first extra study was performed because recovery of the MVC was poor, which may have been because of the large number of contractions in the first part of the recovery period with little rest between them. In this control experiment, the schedule of MVCs during the 70-min contraction was identical, but contractions were more spaced during the recovery period (one MVC every 2 min, with alternation of the cortical and Mmax stimulation sets with the motor point sets). Four subjects completed this extra experiment (3 of whom had completed the main experiment).

The second extra study was performed because intensities for motor cortical stimulation were set to optimize the measurement of

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<th>End Recovery</th>
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*Data are from additional experiment using high-intensity cortical stimulation. Significance values: †P < 0.01; ‡P < 0.001; §P < 0.05.

Table 1. Changes during the sustained contraction and recovery in measurements during 5% MVC contractions

Table 2. Changes in brief MVCs during the sustained contraction at 5% MVC and recovery
voluntary activation (46, 47), resulting in a relatively short silent period evoked by cortical stimulation (~80 ms for biceps during control MVCs). With such short silent periods, it is not clear whether inhibition at the spinal cord or the cortical level determines the end of the silent period (e.g., Ref. 18). Therefore, six subjects performed a fatigue and recovery protocol identical to the above control experiment (i.e., the more spaced recovery period). Here, intensities for cortical stimulation were selected that elicited silent periods of at least 150 ms in the biceps during control MVCs. This long duration means that termination of the silent period reflects recovery of cortical drive rather than motoneuronal excitability (18, 41). All silent period data reported are from this experiment.

Data analysis. Mean elbow flexion torque was calculated over 200 ms before each stimulus, to measure performance of the sustained 5% contraction and changes in the MVC. Increments in torque evoked by motor point stimulation were measured during the brief MVCs (superimposed twitch) and the subsequent brief rests (resting twitch). Voluntary activation was calculated by comparing the amplitude of the superimposed twitch to the amplitude of the resting twitch, expressed as a percentage by the formula: \( \frac{1 - \text{superimposed twitch}}{\text{resting twitch}} \times 100 \). This method has been used extensively with motor point stimulation (e.g., Refs. 3, 31). Increments in torque evoked by motor cortical stimulation were measured during the sustained 5% MVC and during the brief contractions at 100% MVC, 75% MVC, and 50% MVC. The formula for voluntary activation has to be adjusted for motor cortical stimulation, because the motoneuronal output evoked by motor cortical stimulation at rest differs from that during a contraction. That is, at low contraction strengths, there is a nonlinear relationship between voluntary torque and the twitch evoked by motor cortical stimulation (e.g., Ref. 17). However, Todd et al. (46, 47) developed a method to estimate the resting twitch for all elbow flexors from cortical stimulation during strong contractions. The method involves calculating the y-intercept of voluntary contractions of varying strength with the superimposed twitch during the contractions. Three contractions at 100% MVC, 75% MVC, and 50% MVC are sufficient to give a reliable estimate of the resting twitch (47). Voluntary activation (as a percentage) measured by cortical stimulation is then given by \( \frac{1 - \text{superimposed twitch}}{\text{estimated resting twitch}} \times 100 \).

For each muscle, the size of MEPs after motor cortical stimulation and the Mmax evoked by brachial plexus stimulation were measured as the area under the curve between set cursors. The cursors encompassed a region from the initial deflection from baseline to the second crossing of the horizontal axis. The area of the MEP in each muscle was normalized to the area of Mmax elicited in the same contraction. The silent period after cortical stimulation was measured as the time from the stimulus to the resumption of voluntary EMG, and the differences from control contractions at 5% and 100% MVC were calculated.

Root mean square EMG activity (EMGrms) was measured over 200 ms before cortical stimuli for 5% MVC and 100% MVC contractions during the fatigue protocol and during recovery. For
5% MVC and 100% MVC contractions, and for each muscle, EMGrms was expressed as a percentage of EMGrms during the brief control MVCs.

Statistical analysis. To reduce the data from 5% contractions, averages of the three stimuli between MVCs were calculated and used in analyses over time. The first two data points (in the first minute) of contraction were not used because inspection of the graphs revealed abrupt changes after the initial MVC. These changes were most likely from potentiation of the muscle by the MVC. Group averages over time were entered into a linear regression for the sustained contraction for each measure, to assess whether reliable changes in those measures occurred over time (“contraction regression” in Tables 1 and 2). Furthermore, paired t-tests compared values from the start and end of the sustained contraction (“contraction t-test” in Tables 1 and 2). Because of the nonlinear recovery of many variables, only paired t-tests were used in recovery, comparing values from the end of the sustained contraction and the end of recovery (“recovery t-test” in Tables 1 and 2). Data reported in Tables 1 and 2 are presented as means and SD, and data in Figs. 1–5 are presented as means ± SE.

RESULTS

Changes during the sustained contraction at 5% MVC. All subjects were able to sustain the 5% MVC for the full 70 min of prolonged contraction. Regression showed that subjects’ ratings of perceived effort increased linearly [Fig. 2A and Table 1 (summary of results)]. The final MVC of the sustained contraction (as a percentage of initial MVC torque) was strongly correlated with the final effort rating for the 5% contraction ($r = -0.87, P < 0.05$), such that subjects who had fatigued most reported that more effort was needed to generate the 5% target torque. However, there was no correlation ($r = -0.15$) between subjects’ absolute target torque and their perceived effort at the final rating period, suggesting that variability in ratings of effort are not due to initial strength and/or intramuscular pressure. Regression and t-tests showed that subjective ratings of muscle pain also increased progressively over the sustained contraction (Table 1).

Voluntary EMG, as a percentage of EMG for each muscle during a maximal elbow flexion effort, increased linearly over the sustained 5% MVC for biceps and brachioradialis (Fig. 2B). Mmax area (expressed as a percentage of control values) did not change over the sustained contraction for biceps and brachioradialis (either in regression or t-test analyses; Table 1). To account for peripheral changes that may affect the size of the evoked potential to cortical stimulation, MEP area was normalized to Mmax area obtained closest in time. Regression and t-tests showed progressive increases in both muscles (Fig. 2C and Table 1). The silent period after high-intensity cortical stimulation (additional experiment; see METHODS) showed a significant increase in both muscles (Fig. 2D).

Changes in brief MVCs during the sustained contraction at 5% MVC. During the sustained contraction, the torque in brief MVCs dropped substantially to 71.7 ± 13.3% of initial MVC (Fig. 3A and Table 2), indicating that the sustained 5% contraction caused considerable fatigue. Regression showed that the resting twitch evoked by paired motor point stimulation in the muscle potentiated by a prior MVC steadily declined, as did the estimated resting twitch (Fig. 3B; Table 2). The declines in the resting twitch and estimated resting twitch indicate peripheral fatigue. Voluntary activation measured with both motor cortical and motor point stimulation declined over the prolonged contraction (Fig. 3C; Table 2). Voluntary EMG for maximal contractions (expressed as a percentage of control values) also declined significantly in regression analyses.

![Fig. 3. Changes in MVC torque, the superimposed twitch, the (estimated) resting twitch, and voluntary activation over the experimental protocol. ● Data obtained with motor cortical stimulation; ▽ data obtained with motor point stimulation. A: mean prestimulus MVC torque as a percentage of control MVC. B: estimated resting twitch evoked from motor cortical stimulation and resting twitch evoked from the potentiated muscle with paired motor point stimulation, expressed as a percentage of the initial MVC force. C: voluntary activation during the contraction.](http://jap.physiology.org/)
Regression analyses showed that the silent period after high-intensity cortical stimulation increased slightly over the 70-min fatigue protocol (Fig. 4C; Table 2).

Changes during recovery from the sustained contraction at 5% MVC. Subjective ratings of both effort and pain dropped immediately as the recovery period began and continued to decline thereafter (Table 1 and Fig. 2). The voluntary EMG required to achieve the target torque also declined in biceps, although the decrement in brachioradialis did not reach significance in a t-test (Table 1). The EMG responses to stimulation during contractions to the 5% MVC target torque did not change greatly over the recovery period. Mmax area increased in biceps, but there were no other changes in Mmax area in brachioradialis or in the normalized MEP in either elbow flexor (Table 1). The duration of the silent period did not return to control values.

The torque produced in brief MVCs increased progressively in the first 14 min of recovery (Table 2 and Fig. 3). However, no further increase in the MVC torque was seen beyond this time. Neither the resting twitches nor voluntary activation showed significant recovery with a t-test (Table 2).

The return of voluntary torque was accompanied by a slight increase in voluntary EMG; however, this was not statistically significant because of large variability between subjects (Table 2 and Fig. 4). The evoked EMG responses to stimulation during brief MVCs did not change significantly over the recovery period. The area of Mmax and the normalized MEP did not change for either elbow flexor, and the silent period duration did not recover to control values (Table 2).

DISCUSSION

The aim of the present study was to determine whether a sustained contraction at 5% MVC produced central fatigue. Considerable loss of force was observed with the decline of torque in the occasional brief MVCs to 72% of initial control values by the end of the fatigue protocol. Part of this loss of force is due to peripheral factors, as there was a decrease in the resting twitch over time. However, the steady decrease in voluntary activation measured by motor point stimulation indicates a central component to the fatigue. Furthermore, a component of the central fatigue is due to supraspinal factors, as voluntary activation measured by cortical stimulation also decreased over 70 min of sustained weak contraction.

Subjects performed brief, strong contractions every 3 min during the prolonged weak contraction, and this might have influenced the development of fatigue. In the first set of experiments, there was very little recovery of MVC torque and no significant recovery of twitch force or voluntary activation when the sustained weak contraction ended. However, in these experiments, subjects performed brief MVCs and other contractions frequently after the sustained contraction, and this may have hindered recovery. When the main experiment was repeated with less frequent contractions in the recovery period (2 min apart), MVC torque, EMGrms, and voluntary activation recovered within ~12 min, but twitch torque still showed no recovery (Fig. 5). That is, MVC torque increased during the recovery period despite more frequent performance of MVCs; thus the 28% loss of MVC torque during the fatigue protocol was not recovered. Nonetheless, there was a significant decrease in voluntary activation measured by cortical stimulation, indicating a central component to the fatigue.
can be attributed to the 5% contraction, rather than to the frequency of MVCs.

The increase in the EMG required to maintain the 5% contraction over time (from 5% to 8% of initial flexion MVC EMG in biceps and from 3% to 5% in brachioradialis) is also consistent with fatigue produced by the sustained 5% contraction and not the intermittent brief MVCs. MVCs would be expected to fatigue the high-threshold fast-fatigable muscle fibers rather than the fibers in the motor units active in the weak contraction. Because changes in Mmax were minimal in biceps and brachioradialis, the increased EMG is unlikely to be due to changes in muscle fiber action potentials. Rather, it suggests peripheral fatigue, such that, as muscle fibers become fatigued, firing frequencies or the number of active motor units was increased to maintain the target torque (e.g., Refs. 1, 6, 14, 25, 26). The presence of peripheral fatigue is confirmed by a decrease in the amplitude of the resting twitch over the fatigue protocol (20% for motor point stimulation, 25% for cortical stimulation).

The progressive inability of subjects to drive the elbow flexor muscles maximally during the occasional brief MVCs indicates that central fatigue developed at the same time as peripheral fatigue. The increase in the superimposed twitch elicited by motor point stimulation demonstrates failure of drive somewhere in the nervous system above the site of stimulation of the motor axons (4, 16, 32). The presence of peripheral fatigue is confirmed by a decrease in the amplitude of the resting twitch over the fatigue protocol (~20% for motor point stimulation, ~25% for cortical stimulation).

The progressive inability of subjects to drive the elbow flexor muscles maximally during the occasional brief MVCs indicates that central fatigue developed at the same time as peripheral fatigue. The increase in the superimposed twitch elicited by motor point stimulation demonstrates failure of drive somewhere in the nervous system above the site of stimulation of the motor axons (4, 16, 32). The increase in the superimposed twitch elicited by motor point stimulation indicates a supraspinal component to the central fatigue. That is, inadequate descending drive contributed to the failure to drive the motoneurons and muscles maximally (e.g., Refs. 16, 46). As the relationship between voluntary force and activation measured via cortical stimulation remains linear with fatigue (46), it is possible to estimate the final torque if voluntary activation had remained unchanged. A comparison with the actual torque loss gives an estimate of the proportion of the total torque loss, which can be attributed to supraspinal mechanisms. The MVC decreased from ~90% to 72% of control values during the 5% contraction, whereas voluntary activation measured with motor cortex stimulation decreased from ~94% to 80%. If voluntary activation had remained at 94%, then the MVC would only have dropped to 84%. Thus the remainder of the fall to 72% is due to reduced voluntary activation; i.e., supraspinal fatigue accounts for ~66% of the 18% drop in MVC torque from the beginning to the end of the fatiguing protocol. By comparison, with the use of similar calculations, at the end of a 2-min sustained MVC, supraspinal fatigue accounted for ~25% of the total loss of force. Similarly, at the end of a 43-min 15% MVC when voluntary activation dropped to 77%, supraspinal fatigue accounted for ~40% of the force loss (39, 44, 45). Thus the proportion of fatigue due to supraspinal mechanisms is greater with the more prolonged weaker contraction, even though voluntary activation does not necessarily fall as low.

Although central fatigue can be quantified in maximal efforts by a fall in voluntary activation, the influence of central fatigue on performance of submaximal contractions is not clear. In the present study, the EMG required to maintain the target torque approximately doubled during the prolonged weak contraction. At the same time, MEPs increased in size. This is consistent with increased cortical excitability associated with additional cortical drive to the motoneurons (13, 42, 48). By comparison, subjects’ perceived effort increased eightfold. Near the end of the prolonged contraction, subjects rated the effort required to maintain the torque as “considerable.”

Fig. 5. MVC torque and voluntary activation during the control experiment. The schedule for MVCs was identical for the 70 min of long contraction, but MVCs were 2 min apart during recovery. A: mean prestimulus MVC torque as a percentage of control MVC. B: estimated resting twitch evoked from motor cortical stimulation and resting twitch evoked from the potentiated muscle with motor point stimulation, expressed as a percentage of the initial MVC force. C: voluntary activation during the contraction. For B and C, •, cortex; ▼, motor point.
Whereas in an unfatigued subject, this rating might be given for a contraction of 30–40% MVC, the EMG in the fatigued subjects was only 8% of that in the initial MVCs or 11% of the final fatigued MVC. This disproportionate increase in effort compared with the level of EMG may be related to the central fatigue. Søgaard et al. (39) reported a similar mismatch of high or even maximal effort at the end of a sustained 15% MVC, when the target torque had reached 25–50% of the ongoing maximal torque. A change in the relationship between descending drive and EMG output could contribute to the mismatch. This would occur if the active motoneurons became harder to drive at fast rates through changes in their intrinsic properties brought about by repetitive activation (19, 20). Altered afferent input to the motoneurons could also be a factor. In particular, muscle spindle firing rates decline during fatiguing contractions and thus reduce facilitation to motoneurons (10, 28). Inhibition of motoneurons during fatigue by small-diameter muscle afferents has been proposed but is unlikely to be relevant here because a recent study shows that such input facilitates elbow flexor motoneurons in humans (29). At a supraspinal level, the lengthening of the silent period suggests extra intracortical inhibition, which might change the input-output relationship of the motor cortex. However, comparisons of sustained submaximal contractions in control subjects and patients with chronic fatigue showed higher perception of effort but less lengthening of the silent period in the patients (37). Furthermore, studies of intracortical inhibition with the use of paired-pulse cortical stimulation suggest that inhibition in the motor cortex may decrease during fatiguing exercise (5). An alternative possibility is that the interpretation of the signal that is perceived as effort is altered such that the same central signal associated with the same motor command is perceived as more effortful.

Because the prolonged 5% MVC is likely to use a relatively small number of low-threshold motor units, it is difficult to see how a decrease in the force-generating capacity of just these active units (either through peripheral fatigue or through changes of their motoneuron properties) can cause ~20% fall in maximal force production. One possibility is that the activity of fatigue-sensitive small-diameter muscle afferents, which the subjects report as muscle pain, plays a role in the impairment of voluntary activation and development of supraspinal fatigue. Overall, restriction of blood flow to the muscle from increased intramuscular pressure is unlikely with such a weak contraction (8), and there was no correlation between subjects’ final pain ratings and absolute target torque results ($r = 0.05$). However, localized areas of changing intramuscular pressure and blood flow with low-level contractions have been linked to muscle fatigue and changing muscle activity in the knee extensors (24, 38). Furthermore, localized concentrations of potassium and other algesic substances can increase even with low-level activity (35, 36), and muscle pain increased steadily throughout the sustained contraction. With hand muscles at rest, experimental muscle pain induced by injection of hypertonic saline causes decreased motor cortical excitability (27). Furthermore, when the firing of small-diameter muscle afferents is maintained post-fatigue by occlusion of blood flow with an inflatable cuff, MVC torque and voluntary activation do not recover (16). As MEP area and silent period duration both return to control values quickly under these conditions, and the firing of fatigue-sensitive muscle afferents does not inhibit the motoneurons of the elbow flexors in humans (12, 29, 43), it is unlikely that exercise-related muscle pain impairs muscle performance by direct action on the motoneurons or on the output cells of the motor cortex. However, it may influence circuits that generate motor cortical output and thus lead to increased effort and supraspinal fatigue.

One unexpected finding was that the silent period, which lengthened with fatigue during both weak contractions and MVCs, showed no recovery to control values when the sustained contraction stopped. Although there is a contribution of spinal mechanisms to the initial part of the silent period, the latter part represents inhibition of voluntary cortical output (18). Thus an increased duration of the silent period is thought to reflect increased inhibition within the motor cortex. Progressive lengthening of the silent period is a common result during fatiguing exercise, but the silent period usually recovers quickly, within 1 min of the cessation of the fatiguing contraction (39–41). Only one previous study has reported a lack of recovery during weak contractions (30). A major difference between the present study and previous studies is the duration of the sustained exercise. We propose that the sustained cortical activity may have resulted in long-lasting changes in cortical circuits, whereas briefer periods of activity do not show this same result. Nevertheless, despite the continued long-duration silent period, perceived effort recovered after the sustained contraction was stopped.

The present study demonstrates that sustained voluntary contractions at very low force levels cause progressive fatigue in the elbow flexor muscles. About two-thirds of the decrease in maximal voluntary torque can be attributed to a failure of the motor cortex to generate sufficient output to drive the muscle optimally. The disproportionate increase in effort required to produce a weak contraction during fatigue indicates that supraspinal fatigue is important in submaximal, as well as maximal, voluntary contractions. Parallel changes in muscle pain and perceived effort suggest a role for small-diameter muscle afferents in the increasing effort.

**GRANTS**

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**REFERENCES**


