Estimation of critical torque using intermittent isometric maximal voluntary contractions of the quadriceps in humans

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Burnley M. Estimation of critical torque using intermittent isometric maximal voluntary contractions of the quadriceps in humans. J Appl Physiol 106: 975–983, 2009. First published January 15, 2009; doi:10.1152/japplphysiol.91474.2008.—To determine whether the asymptote of the torque-duration relationship (critical torque) could be estimated from the torque measured at the end of a series of maximal voluntary contractions (MVCs) of the quadriceps, eight healthy men performed eight laboratory tests. Following familiarization, subjects performed two tests in which they were required to perform 60 isometric MVCs over a period of 5 min (3 s contraction, 2 s rest), and five tests involving intermittent isometric contractions at ~35–60% MVC, each performed to task failure. Critical torque was determined using linear regression of the torque impulse and contraction time during the submaximal tests, and the end-test torque during the MVCs was calculated from the mean of the last six contractions of the test. During the MVCs voluntary torque declined from 263.9 ± 44.6 to 77.8 ± 17.8 N·m. The end-test torque was not different from the critical torque (77.9 ± 15.9 N·m; 95% paired-sample confidence interval, −6.5 to 6.2 N·m). The root mean squared error of the estimation of critical torque from the end-test torque was 7.1 N·m. Twitch interpolation showed that voluntary activation declined from 90.9 ± 6.5% to 66.9 ± 13.1% (P < 0.001), and the potentiated doublet response declined from 97.7 ± 23.0 to 46.9 ± 6.7 N·m (P < 0.001) during the MVCs, indicating the development of both central and peripheral fatigue. These data indicate that fatigue during 5 min of intermittent isometric MVCs of the quadriceps leads to an end-test torque that closely approximates the critical torque.

DURING MAXIMAL muscle contractions, fatigue results in a systematic decrease in muscle performance measured as a fall in force-, torque-, or power-generating capacity (9, 11, 23, 28, 32, 45). Similarly, during submaximal contractions sustained above a “critical” intensity, fatigue progresses until it is not possible to maintain the required force, torque, or power output (so-called task failure or exhaustion), with exhaustion occurring sooner at higher contraction intensities (8, 10, 14, 24, 36, 41). The relationship between intensity (e.g., power output) and time to exhaustion has been shown to be well-described by a hyperbolic function of the form:

\[ T_{lim} = W'/(P - CP) \]  

where \( T_{lim} \) is the time to exhaustion, \( P \) is the power output of the task, \( CP \) is the power asymptote referred to as the “critical power,” and \( W' \) is the curvature constant of the relationship and represents a finite amount of work that can be performed above the critical power (25, 36–38, 41). Linear forms of this relationship can be derived by plotting power against the inverse of time, or by plotting total work done as a function of time to exhaustion, giving

\[ P = (W'/T_{lim}) + CP \]  

and

\[ W = W' + T_{lim} \cdot CP \]

where \( W \) is work output. These linear formulations are more commonly used as they do not require nonlinear regression for computation of \( CP \) and \( W' \). When force, torque, or speed is used to quantify the intensity of exercise, these terms are substituted for power output (36, 38). Since the present study involves isometric contractions, the measure of interest is “critical torque.”

During cycle ergometry the critical power has been shown to approximate the highest work rate for which steady states in blood lactate, pH, and pulmonary oxygen uptake can be stabilized above the critical power (41), with their rate of change being greater at higher work rates (e.g., 12). Jones et al. (29) recently used \(^{31}\)P-magnetic resonance spectroscopy to demonstrate that knee-extension exercise below critical power resulted in steady-state muscle metabolic responses, whereas during exercise above critical power muscle phosphorylcreatine and pH systemically decreased until exhaustion. These findings are consistent with the concept that exercise performed above the critical power induces a progressive depletion of muscle high-energy phosphates and an accumulation of metabolites associated with peripheral fatigue (such as inorganic phosphate) (12, 17, 29).

Despite the physiological significance of the critical power concept, a significant practical shortcoming is that several bouts of exhaustive exercise are required to determine the critical power, usually performed on separate days (36, 48, 49). Recently, however, it has been demonstrated that the parameters of the power-duration relationship can be determined using a single exercise test (11, 48, 49). Vanhatalo et al. (49) demonstrated that a 3-min period of all-out cycling against a fixed resistance led to a stable power output in the last 30 s of the test (the “end-test power”), and this power output was equivalent to the conventional estimate of critical power. This is exciting because it provides perhaps the first evidence that maximal-intensity cycle exercise can be used to estimate a parameter of submaximal muscular endurance, although whether this is also true for other modes of exercise is not known. The demonstration of the same relationship between...
critical torque and the “end-test torque” during a prolonged period of maximal isometric contractions would be useful because muscle fatigue is most commonly studied using either MVCs (22, 23, 28, 45, 46) or submaximal contractions performed to task failure (8, 24, 26). Intermittent isometric contractions of the quadriceps are well-suited to the measurement of fatigue processes during high-intensity exercise (3, 30, 39). Using this exercise mode, percutaneous muscle stimulation can be employed to determine central and peripheral fatigue, since the mechanical response to the superimposition of supramaximal stimuli during MVCs can be compared with that in response to potentiated stimuli in a resting muscle to measure changes in voluntary activation (and therefore central fatigue; 21, 35), whereas a reduction in the response evoked by stimulation of the resting muscle can be used to estimate peripheral fatigue (47). Fatigue during maximal contractions is also accompanied by a reduction in the amplitude of the surface electromyogram (EMG; 9, 32), which may also indicate central fatigue (9).

Determining whether the knee extensor torque declines during a series of isometric MVCs to reach the independently measured critical torque should provide a stringent “proof of principle” for the results of Vanhatalo et al. (48, 49) because potential constraints placed on muscle performance by the force-velocity relationship (50) and the attainment of peak oxygen uptake (11) during fixed-resistance cycle ergometry are avoided using isometric contractions of the knee extensors. Moreover, although it is widely accepted that the relationship between force, torque, or power output and time to exhaustion is hyperbolic (10, 14, 15), critical torque is rarely used to demarcate exercise intensity in studies of muscle fatigue. The ability to estimate critical torque from a relatively short series of maximal contractions would allow this important parameter to be used routinely in addition to the MVC as a measure of the intensity of muscular contractions.

The hypothesis tested by the present study, therefore, is that a series of intermittent MVCs will instigate fatigue processes of both central and peripheral origin that will reduce maximal knee extensor torque until a plateau in torque is achieved, which will closely approximate the critical torque estimated by the performance of a series of submaximal tests performed to task failure.

METHODS

Subjects

Eight healthy men (mean ± SD: age 29 ± 6 yr, height 1.79 ± 0.09 m, body mass 77.3 ± 11.3 kg) gave written informed consent to participate in this study, which was approved by the Aberystwyth University Ethics Committee for Research Procedures, and which adhered to the Declaration of Helsinki. Subjects were instructed to arrive at the laboratory in a rested state (having performed no heavy exercise in the 24 h preceding the test) and to refrain from food and caffeinated beverages in the 3 h before arrival at the laboratory. Subjects attended the laboratory at the same time of day (±2 h) during each visit.

Experimental Design

Subjects were required to visit the laboratory on eight occasions within 3 wk to complete the experimentation. During the first visit, subjects were familiarized with all equipment and testing procedures. During the second visit, subjects performed a series of 60 intermittent isometric MVCs with muscle stimulation (the “5-min all-out test”; see below). Subjects performed a further six exercise tests on separate days. Five tests involved intermittent submaximal contractions (requiring ~35–60% MVC) performed to task failure on separate days to establish the critical torque, and the sixth test was another 5-min all-out test in which the surface EMG was recorded. These final six tests were randomly assigned.

Dynamometry

During all visits, subjects were seated in the chair of a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY), initialized and calibrated according to the manufacturer’s instructions. The right leg was attached to the lever arm of the dynamometer with the seating position adjusted to ensure that the lateral epicondylye of the right femur was centered with the axis of rotation of the lever arm. The subjects sat with relative hip and knee angles of 85° and 90°, respectively (full extension being 0°), determined using a goniometer. The lower leg was firmly attached to the lever arm above the ankle using a padded Velcro strap, and straps secured firmly across the waist and both shoulders prevented extraneous movement during the isometric contractions. The seating position was recorded during the first visit and replicated for all subsequent visits.

Protocol

All experiments followed a similar pattern of data acquisition and began with the instrumentation of the subjects, and the (re)establishment of the correct seating position and supramaximal potentiated doublet response (see Muscle stimulation). Subjects then performed three MVCs, each lasting 3 s and separated by 60 s rest. The second of these contractions was performed with muscle stimulation. Subjects were given a countdown followed by very strong verbal encouragement to maximize torque. At 1.5 s into the contraction a doublet was delivered, subjects were instructed to stop the contraction after 3 s, and a doublet was delivered 1 s after the end of the contraction (Fig. 1A). The third MVC was used to establish the maximal EMG signal, against which the subsequent EMG signal was normalized (see Data Analysis). Following the third MVC, subjects rested for 10 min. The contraction regime for all tests consisted of 3 s contraction and 2 s rest. In the 5-min all-out tests, 60 MVCs were performed. Pilot work showed that 4–5 min of this contraction regime would be necessary to confidently establish a plateau in torque in the final 60 s of the test. In the submaximal tests subjects were required to achieve a target torque during each 3-s contraction and continue matching the instantaneous torque with the target torque during each 3-s contraction for as long as possible.

Five-minute all-out tests. A 5 min all-out test with muscle stimulation was performed by all subjects during the familiarization visit, and two further all-out tests were conducted on separate occasions. The subjects were given feedback on their previous MVCs during the 10-min rest period and were encouraged to attempt to equal or exceed those values during the first 3–5 contractions. Subjects were also briefed to expect the torque to decline by more than 50% during the test but to produce a maximal effort during each contraction despite this occurrence. During the test the subjects were very strongly encouraged to maximize torque during each contraction but were not informed of the elapsed time or the number of contractions remaining. A green light on the projected display prompted the subjects to contract, and a red light prompted them to stop. However, subjects often chose to focus on the exercising leg rather than the screen, and so they were also verbally instructed to “push” and “stop.” The test was ended after the 60th contraction cycle was completed. During the first 5-min all-out test used for data analysis, the muscle stimulator was triggered on the second, sixth, and every sixth contraction thereafter (i.e., every 30 s). Stimuli were delivered 1.5 s into each of these contractions, and 1 s after each contraction. The second 5-min all-out test was conducted in exactly the same manner as the first,
superimposed, followed by a doublet after the subjects were instructed to stop (Fig. 1B).

Measurements

Muscle stimulation. Carbon rubber electrodes (12 × 10 cm, EMS Physio, Oxfordshire, UK) coated in conductive gel were placed on the anterior thigh and secured using elastic Velcro bandages. The cathode was placed on the midline of the thigh at ~30% of thigh length measured in the seated position from the anterior superior iliac spine to the superior border of the patella, while the anode was positioned 8 cm proximal to the superior border of the patella over the vastus medialis. A constant-current, variable-voltage stimulator (Digitimer DSTAH, Welwyn Garden City, UK) was used to deliver doublet stimuli (100-μs pulses, 10-ms interval) at 400 V. During the first visit, the current was increased in steps of 10 mA from 100 mA until no further increase in potentiated doublet torque occurred. The current was then increased by a further 10 mA (range utilized, 310–430 mA). These stimuli were tolerated without discomfort. One subject did not consent to muscle stimulation.

Surface EMG. The EMG of the vastus lateralis was sampled using bipolar Ag-AgCl electrodes (10-mm diameter, 30-mm center-to-center distance) following the shaving and cleaning of the skin. Electrodes were placed parallel to the muscle fibers on the belly of the muscle between the stimulating electrodes. A reference electrode was placed on prepared skin medial to the tibial tuberosity. The raw EMG signal was sampled at 1 kHz, amplified (gain 1,000; Dual Bioamp, ADI Instruments, Colorado Springs, CO), and band-pass filtered using a third-order Butterworth filter (20–500 Hz, LabVIEW 8.5, National Instruments, Austin, TX).

Data acquisition and subject interface. Data were acquired from all peripheral devices through BNC cables connected to a National Instruments BNC 2110 connector block (National Instruments) interfaced with a personal computer. All signals were sampled at 1 kHz. A 40-Hz low-pass filter was applied to the torque signal. Charts containing instantaneous torque, EMG, and a visual prompt to contract and relax were projected onto a large screen placed 3 m in front of the subject. A scale consisting of a thin blue line was superimposed on the torque chart so that the subject could match the instantaneous torque output from the dynamometer with the target torque during the submaximal contractions performed to task failure. Muscle stimuli were delivered at preprogrammed intervals during the 5-min all-out tests (see below) or manually at the end of the submaximal tests performed to task failure.

Data Analysis

Torque: 5-min all-out test. The torque data were analyzed using code written in MATLAB R2007a (The MathWorks), and peak torque and mean torque for each 3-s contraction were determined for all tests. The torque impulse was also calculated as the area under the torque-time curve. The potentiated doublet torque was calculated as the peak torque achieved following the doublet stimuli between contractions, and superimposed doublet torque was calculated as the increment in torque immediately following the stimuli during contraction. The end-test torque during the 5-min all-out tests was operationally defined as the mean of the last six contractions in the test (the last 30 s; cf. Ref. 49). Voluntary activation was determined using the twitch interpolation technique (4, 6), and was calculated as:

\[
\text{voluntary activation (\%)} = \frac{1}{(\text{superimposed doublet/potentiated doublet}) \cdot 100}
\]

where the superimposed doublet was that measured during the contraction of interest, and the potentiated doublet was measured 1 s after the contraction.

Torque: submaximal tests. The mean torque and torque impulse for each contraction during the submaximal tests were calculated and
were used to determine the mean torque during the test, the total torque impulse for the submaximal test, and the time to task failure. From these three variables, the critical torque was determined as described below. Calculation of time to task failure during intermittent contractions is somewhat more complicated than defining failure during sustained contractions. Invariably, the mean torque during successful targeted contractions was less than the target torque due to the rise and fall in torque at the on- and off-set of each contraction. Therefore, to establish the point of task failure the actual test torque had to be determined. This was operationally defined as the mean torque recorded in the first 12 contractions (i.e., the 1st minute of the test). Task failure was then deemed to have occurred when the mean torque recorded during three consecutive contractions was more than 5 N·m below the mean torque of the first 12 contractions, with the first of these contractions being considered the point (and time) of task failure. To provide a measure of average torque for the entire test, the mean torque of all contractions preceding task failure was calculated. Similarly, the torque impulse and total time spent contracting during the test were calculated by summing all contractions preceding task failure.

**Determination of critical torque.** The critical torque was determined from the five submaximal tests using the impulse-time model, which is analogous to the work-time model presented in Eq. 3 (36, 37). The torque impulse of each submaximal test in each subject was plotted against the total contraction time for that test, and linear regression was used to establish the critical torque and the curvature constant (W'), with critical torque being the slope and the W' being the intercept.

**EMG analysis.** The EMG signal for each contraction was full-wave rectified using MATLAB; average rectified EMG (aEMG) was then calculated, and this was normalized by expressing the aEMG as a fraction of the aEMG observed during the MVC preceding the test.

**Statistics.** A Student’s paired-samples t-test and 95% paired-samples confidence intervals were used to compare the critical torque estimated from the impulse-time model with the end-test torque from the 5-min all-out test. The same procedures were used to compare the W' with the impulse measured above the end-test torque during the 5-min all-out test. The relationship between the end-test torque and the critical torque was determined using linear regression and 95% limits of agreement. In addition, the root mean square error associated with the end-test torque vs. critical torque was calculated. The temporal profiles of mean torque, potentiated doublet torque, voluntary activation, and aEMG were analyzed using a one-way ANOVA with repeated measures, with contrasts between the end-test contraction and all other time points made using Bonferroni-adjusted 95% paired-samples confidence intervals. For all tests, results were considered statistically significant when P < 0.05. Throughout, values are presented as means ± SD.

**RESULTS**

The MVC recorded during the second laboratory visit was 272.3 ± 50.1 N·m, and the voluntary activation achieved during the preliminary MVCs was 92.8 ± 4.9%. There was no difference between the peak torque (264.5 ± 52.5 vs. 263.2 ± 39.2 N·m; \(t_7 = 0.16, P = 0.88\)) or torque achieved during the last six contractions (the end-test torque; 78.7 ± 17.8 vs. 76.9 ± 14.8 N·m; \(t_7 = 0.74, P = 0.49\)) between the first and second 5-min all-out tests. The end-test torque was also highly correlated between the tests (r = 0.93, P = 0.001). Consequently, the two torque profiles were ensemble averaged in each subject and used in further comparisons.

**5-Min Test Torque Profile**

The raw torque profile from a 5-min all-out test is shown in Fig. 1C, and the mean data for peak torque and mean torque during each contraction in all subjects are shown in Fig. 2. Torque declined from a peak of ~97% MVC during the first contraction to ~29% MVC during the last six contractions (Table 1, Fig. 2). Using six-contraction (30 s) bin averages for analysis revealed that all time bins were significantly different from the end-test torque, with the exception of the 240- to 270-s time bin \((F_{7,9} = 172.67, P < 0.001)\), indicating that the torque did not significantly change during the final minute of the test. In addition, linear regression showed that the slope of torque during the last 30 s of the all-out test was ~0.04 N·m/s, which was not significantly different from zero \((P = 0.65)\). These data indicate that a plateau in torque was achieved at the end of the test.

**Comparison with Critical Torque**

The end-test torque in the 5-min all-out test (77.8 ± 17.8 N·m) was not different from critical torque estimated using the impulse-time model (77.9 ± 15.1 N·m; \(t_7 = 0.07, P = 0.95\); Table 1), with the confidence intervals for the difference being −6.5 to 6.2 N·m. Figure 3A shows the derivation of critical torque and Fig. 3B the mean torque during each contraction in the 5-min all-out test in subject 2. The impulse-time model consistently provided an excellent linear fit to the submaximal test data \((r = 0.994–0.999, \text{Fig. 3A})\). Figure 4A shows the relationship and Fig. 4B the bias ± 95% limits of agreement between the end-test torque and the critical torque. The root mean squared error between the end-test torque and critical torque was 7.1 N·m, with the absolute error between the end-test torque and the critical torque being ~2% of the MVC (range, 0.1–4.8%) or ~6% of the critical torque (range 0.1–15.8%). The torque impulse accumulated above the end-test torque was significantly higher than the estimated curvature constant \((W') (t_7 = 5.75, P = 0.001; \text{Table 1}).

**Fig. 2.** Group peak and mean torque (±SD) during the 60 maximal contractions that comprised the 5-min all-out test. Peak torque refers to the highest measured torque during each contraction, whereas mean torque is the average torque calculated over the duration of the contraction. All contractions are normalized to a control MVC performed 10 min before the test commenced. Note that torque falls over the first ~150 s before reaching stable values between 240 and 300 s (the end-test torque).
Central and Peripheral Fatigue

The potentiated doublet responses decreased as the 5-min all-out test progressed (Fig. 5A), from $97.7 \pm 23.0$ to $45.9 \pm 6.7$ N·m ($F_{6,10} = 43.46, P < 0.001$), indicating the presence of peripheral fatigue. As the test progressed, voluntary activation fell from $90.9 \pm 6.5\%$ to $66.9 \pm 13.1\%$ ($F_{6,10} = 10.66, P < 0.001$), providing evidence of central fatigue (Fig. 5B). In addition, the aEMG (normalized to a fresh MVC) decreased from $99.4 \pm 3.9\%$ (first contraction) to $71.0 \pm 14.4\%$ (last contraction; $F_{7,10} = 23.58, P < 0.001$; Fig. 5C).

Submaximal Tests

The time to task failure during the submaximal tests ranged from $625.0 \pm 209.9$ to $124 \pm 28.6$ s for the tests with the lowest and highest target torque, respectively. The torque achieved during the MVC in the final contraction of each test did not exceed the target torque (e.g., Fig. 1B), and was significantly lower than the target torque for the all but the test with the lowest target torque (Fig. 6A), indicating that the subjects were not able to achieve the required torque at the end of the test despite producing a maximal effort. In addition, in all trials the potentiated doublet responses produced by muscle stimulation declined significantly, falling from $95$ N·m following the control MVC to $45$ N·m following the end-exercise MVC (Fig. 6B). Technical difficulties meant that the manual delivery of a superimposed twitch on the end-exercise MVC was not always possible, or was delivered while voluntary torque was clearly in decline. Therefore voluntary activation during the end-exercise MVC could not be calculated.

DISCUSSION

The present study demonstrated that during repeated maximal isometric contractions of the quadriceps, torque declined to reach values of $25–35\%$ MVC, which was not different from the independently measured critical torque. The decline in torque was associated with significant central and peripheral fatigue, as evidenced by a decrease in voluntary activation and potentiated doublet response amplitude, respectively. The surface EMG recorded from the vastus lateralis also declined as the contractions progressed, providing additional evidence of central fatigue. These results provide the first evidence that fatigue processes occurring during repeated maximal contractions reduce muscle torque-generating capacity until the critical torque is achieved.

It has long been appreciated that the maximum sustainable force or power output during rhythmic or intermittent exercise is approximately one-third of peak force or power output (15, Table 1. Parameters of the 5-min all-out test and the critical torque derived from the submaximal tests

<table>
<thead>
<tr>
<th>Subject</th>
<th>Peak Torque N·m</th>
<th>% MVC</th>
<th>End-test Torque N·m</th>
<th>% MVC</th>
<th>Impulse Above End-test Torque, N·m·s</th>
<th>Critical Torque, N·m</th>
<th>Curvature Constant (W·s), N·m·s(^{-1})</th>
<th>% MVC</th>
<th>Critical Torque, N·m</th>
<th>% MVC</th>
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<td>88.9</td>
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<td>8</td>
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<td>62.2</td>
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<td>Mean</td>
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<td>77.8</td>
<td>28.7</td>
<td>7,617.4</td>
<td>77.9</td>
<td>5,357.9*</td>
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<td>SD</td>
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<td>4.6</td>
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<td>15.1</td>
<td>1,873.2</td>
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</table>

MVC, maximal voluntary contraction; peak torque, highest torque measured during the test; end-test torque, mean torque measured in the last 6 contractions of the 5-min all-out test. *Significantly different from 5-min all-out test ($P < 0.05$).
In practice, this exercise intensity has been estimated by establishing the maximal steady state (7, 11) or the critical power (29, 41, 42). When exercise is performed below the critical power, stable profiles of oxygen uptake, arterial pH, and [lactate] are attainable, whereas each change progressively above the critical power (12, 14, 17, 41, 42). In addition, it has been demonstrated that progressive derangements of the muscle metabolic profile occur when the work rate exceeds the critical power during knee extension exercise (29). Vanhatalo and colleagues (11, 48, 49) recently demonstrated that during prolonged all-out cycle ergometry power output falls to about one-third of the peak power output, and this “end-test” power closely approximates the critical power. The present study was designed to advance these findings by testing the hypothesis that the torque during repeated MVCs would decline until critical torque was achieved. To this end, 60 isometric MVCs of the quadriceps (3 s contraction, 2 s rest) were performed, and as the tests progressed torque fell until the final minute, whereupon it reached stable values at ~25–35% MVC (Figs. 1C, 2, and 3B). These data are strikingly similar to studies showing that during prolonged maximal isometric contractions (sustained or repeated) the force or torque appears to decline and reach a plateau if the effort is sustained for a sufficient duration (22, 23, 28, 30, 45, 46). The degree to which the force or torque declines varies considerably between studies (5, 10, 35), but it is commonly reduced to less than 50% of the initial MVC (22, 27, 32, 46; i.e., approaching the fraction of MVC associated with critical force or torque; 5, 10, 36).

The crucial original finding of the present investigation is that the plateau in torque that occurred during prolonged

![Graph](image-url)
were significantly reduced following exhaustive exercise. 

![Graph A](image)

Fig. 6. Torque responses during and at the termination of submaximal exercise. The submaximal tests are labeled 1–5, with test 1 being the lowest target each subject attempted, and test 5 being the highest. A shows the mean torque achieved before task failure, and the mean torque achieved during the final contraction of the test (the end-test MVC). B shows the potentiated doublet responses produced by percutaneous muscle stimulation before the test and immediately after the end-exercise MVC. Error bars represent SD. *Significantly lower than mean torque (P < 0.05). All potentiated doublet responses were significantly reduced following exhaustive exercise.

intermittent maximal contractions closely approximated the critical torque measured using submaximal contractions performed to task failure (Figs. 3 and 4). Although the sample sizes used in the present study and those of Vanhatalo et al. (48, 49) are too small to generalize to a wider population, they do provide evidence that critical torque (present study) and critical power (48, 49) can in principle be attained (and therefore estimated) using all-out exercise tests. Since the original presentation of the critical power concept by Monod and Scherrer (36) this was not thought to be possible. The results of the present study therefore provide further evidence that the asymptote of what has been referred to as the power-duration relationship (14, 17, 20), the force-fatigability relationship (16), or the endurance-time relationship (10) and the end-test power or torque measured following repeated maximal contractions may represent the same physiological parameter. From a practical perspective, the performance of a prolonged series of maximal contractions is useful as it provides a means of estimating the MVC and the critical torque in a single exercise testing session, which could then be used to normalize the metabolic stress (and likely fatigue mechanisms) of subsequent tests across a subject sample (see below).

The present study was also designed to quantify the degree of central and peripheral fatigue that occurred during the 5-min all-out test. The data indicated that both central and peripheral fatigue occurred: at the end of the 5-min test the ~71% decrease in voluntary torque was associated with reductions of ~53% in potentiated doublet torque, ~26% in voluntary activation, and ~29% in aEMG (Fig. 5). The data of the present study suggest that a significant component of the loss of torque observed may be explained by events at or distal to the neuromuscular junction, although the data cannot determine the precise location or mechanism. This peripheral fatigue may be the result of a number of derangements occurring within the muscle fibers (for reviews, see 2, 18, 19, 40). For example, exhaustion during dynamic exercise above the critical power has been associated with the depletion of phosphocreatine and/or accumulation of inorganic phosphate and protons (29, 41). Whether the attainment of the end-test torque in the 5-min all-out test correlates with similar changes in muscle metabolic profile (cf. Ref. 32) requires further work.

Central fatigue was also observed during the 5-min all-out test. Although the decline in torque may be attributed primarily to events occurring within the muscle, the finding that voluntary activation declined to ~67% demonstrates that the descending drive to the muscle was suboptimal (21, 47), which was confirmed by the reduced aEMG. During fatigue during submaximal contractions, an increase in EMG amplitude may indicate increased motor unit recruitment and/or firing frequency (1, 26, 27, 33), and it is tempting to offer the converse explanation to account for the observed reduction in aEMG during repeated maximal contractions. However, this interpretation is confounded by amplitude cancellation (31) and cannot distinguish between reduced EMG amplitude consequent to, for example, reduced motor cortex output (46) or reflex inhibition leading to decreased motoneurone excitability (13, 34). Thus further work is also necessary to determine the contribution of spinal and/or supraspinal mechanisms to the fall in voluntary activation during the 5-min all-out test (cf. 22, 27, 33).

The data from both the 5-min all-out test and the submaximal trials performed to task failure support the concept that exercise performed above the critical torque or power results in a systematic decline in muscle torque- or power-generating capacity (8, 40). During maximal intermittent contractions, torque continues to decline and should ultimately attain the critical torque (Fig. 3B), whereas during submaximal contractions performed above critical torque fatigue progresses until task failure occurs, at which point an MVC is required to attain the target torque (Fig. 6A). It is important to stress, however, that the fatigue processes discussed above pertain only to intermittent contractions sustained above the critical torque. It is likely that the mechanisms of fatigue are profoundly different during exercise performed below the critical torque, consistent with the smaller metabolic perturbations that attend such exercise (29). Indeed, it has been suggested that central fatigue is prominent during sustained contractions lower than ~30%
MVC (40, 43, 44). In addition, the peripheral fatigue that attends sustained contractions at 5–15% MVC demonstrates a recovery time course much slower than that of intramuscular metabolites (44), suggesting that factors other than the depletion and/or accumulation of metabolites are involved. Therefore, it could be suggested that critical torque represents a boundary below which the fatigue processes are predominantly central in origin, and above which they are predominantly peripheral (cf. 29, 40), although this hypothesis remains to be tested.

An unexpected finding of the present study was that the impulse accumulated above the end-test torque during the 5-min all-out test was significantly larger than the \( W' \) (i.e., the impulse accumulated above critical torque before task failure in the sub-maximal trials, Table 1). Previous data from cycle ergometry demonstrated that the analogous parameter to the impulse above end-test torque (work done above the end-test power) was not significantly different from \( W' \) (work done above critical power; 48, 49), although it tended to underestimate \( W' \) in one study (49) and responded differently to training in the other (48). Although these parameters share the same unit of measurement, and are of the same order of magnitude for both isometric contractions (present study) and cycling (48, 49), the results of the present study suggest that the impulse accumulated above the end-test torque and the \( W' \) do not represent the same physiological quantity.

In summary, the performance of 60 isometric MVCs of the quadriceps resulted in a decline in voluntary torque until a plateau was attained at \( \sim 25–35\% \) MVC. This end-test torque was not significantly different from, and correlated with, the independently estimated critical torque. The decline in torque was associated with reductions in voluntary activation (of \( \sim 26\% \)) and the potentiated doublet response (of \( \sim 53\% \)), indicating the development of central and peripheral fatigue, respectively. These results provide evidence that during MVCs, muscle fatigue reduces knee extensor torque until the critical torque is attained. Analogous results have been presented previously for cycling (48, 49). These results may, therefore, reflect a fundamental but underappreciated relationship between neuromuscular fatigue and critical torque or power that is evident during both isometric dynamometry and cycle ergometry.

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REFERENCES


