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Activation of human quadriceps femoris muscle during dynamic contractions: effects of load on fatigue

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Lee, Samuel C. K., Cara N. Becker, and Stuart A. Binder-Macleod. Activation of human quadriceps femoris muscle during dynamic contractions: effects of load on fatigue. *J Appl Physiol* 89: 926–936, 2000.—Muscle fatigue is both multifactorial and task dependent. Electrical stimulation may assist individuals with paralysis to perform functional activities [functional electrical stimulation (FES), e.g., standing or walking], but muscle fatigue is a limiting factor. One method of optimizing force is to use stimulation patterns that exploit the catchlike property of skeletal muscle [catchlike-inducing trains (CITs)]. Although nonisometric (dynamic) contractions are important parts of both normal physiological activation of skeletal muscles and FES, no previous studies have attempted to identify the effect that the load being lifted by a muscle has on the fatigue produced. This study examined the effects of load on fatigue during dynamic contractions and the augmentation produced by CITs as a function of load. Knee extension in healthy subjects was electrically elicited against three different loads. The highest load produced the least excursion, work, and average power, but it produced the greatest fatigue. CIT augmentation was greatest at the highest load and increased with fatigue. Because CITs were effective during shortening contractions for a variety of loads, they may be of benefit during FES applications.

catchlike property; shortening; functional electrical stimulation

MUSCLE FATIGUE IS THE DECREASE in force-generating ability of a muscle as a result of recent activation (6, 28). The mechanisms for the production of fatigue are not well understood, are complex, and most likely involve multiple sites (for reviews, see Refs. 26 and 28). Potential sites for fatigue may include the neuromuscular junction, propagation of the action potential along the muscle membrane, events associated with excitation-contraction coupling, events associated with cross-bridge interaction, and calcium uptake by the sarcoplasmic reticulum. Additionally, an inhibition or lack of central drive may play a role during voluntary contractions (26). Finally, fatigue is described as task dependent (7). That is, the mechanisms for fatigue may differ, depending on the type of activity performed.

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Electrical stimulation can be used to assist individuals with central nervous system dysfunctions to perform functional movements (functional electrical stimulation). For example, in patients with paralysis, functional electrical stimulation may be used to produce standing and walking (1, 35, 40, 41), which are complex tasks requiring sustained or repetitive activation of muscles during isometric and dynamic contractions. Muscle fatigue, however, is a major limiting factor in functional electrical stimulation applications (34, 35, 42). Thus methods of optimizing force and minimizing fatigue during functional electrical stimulation are needed.

Recent reports (10, 12) suggest that one method for optimizing force from each active motor unit is to use stimulation patterns that exploit the catchlike property of skeletal muscle (i.e., catchlike-inducing trains). The catchlike property of skeletal muscle is the tension enhancement produced when an initial brief high-frequency burst of pulses (2–4 pulses) is used at the onset of a subtetanic constant-frequency train to activate the muscle (8, 9, 17, 18) and is a fundamental property of muscle (5, 17, 34). Catchlike-inducing trains augment force and rates of rise of force from human skeletal muscles vs. traditionally used constant-frequency trains during isometric contractions (11–13, 39), particularly when muscles are fatigued. In addition, we have recently shown that catchlike-inducing trains also enhance muscle performance during nonisometric contractions (10, 38).

Interestingly, although nonisometric contractions are important parts of both normal physiological activation of skeletal muscles and functional electrical stimulation, no previous studies have attempted to identify the effect that the load being lifted by a muscle has on the fatigue produced. This information could have important implications for understanding the causes of fatigue during dynamic contractions and for designing strategies for optimizing muscle performance during functional electrical stimulation. The purpose of this study is to investigate the effects of load on fatigue during shortening contractions. In addition, because of this laboratory's interest in using catchlike-

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inducing trains to enhance muscle performance, this study also examines the augmentation produced by catchlike-inducing trains as a function of load and fatigue.

METHODS

Subjects

Data were obtained from 11 healthy volunteer subjects (6 men, 5 women) ranging in age from 19 to 31 yr old [mean 22.64 ± 4.08 (SD) yr], with no history of lower extremity orthopedic problems. This study was approved by the University of Delaware Human Subjects Review Board, and all subjects signed informed consent forms.

Experimental Setup

Details of the experimental setup have been previously described (38). Briefly, subjects were seated on a computer-controlled dynamometer (KinCom III, Chattecx, Chattanooga, TN) with hips flexed to $\sim 75^\circ$ (Fig. 1). The dynamometer axis was aligned with the knee joint axis, and force was measured with the force transducer pad positioned ~ 3 cm proximal to the lateral malleolus. The left quadriceps femoris muscle was stimulated by using a Grass S8800 stimulator

with an SIU8T stimulus isolation unit. All stimulation pulses were $600 \mu\text{s}$ in duration. Two self-adhesive, 3×5 -in. electrodes were used to stimulate the muscle. The stimulator was driven by a personal computer that controlled all timing parameters of each stimulation protocol. Force, angle, and velocity data were digitized on-line at a rate of 200/s and stored for subsequent analysis.

Training Sessions

Before the commencement of the experimental sessions, all subjects participated in one training session. Subjects were familiarized with the experimental protocol and trained to relax during stimulation of their quadriceps muscle during both isometric and nonisometric contractions. For each subject, the maximum voluntary isometric contraction (MVIC) was determined by using a burst superimposition technique that has been previously described (48).

Experimental Sessions

All subjects were instructed to refrain from strenuous activity for at least 24 h before each testing session. Each of the 11 subjects participated in three experimental sessions; each session consisted of a pre-fatigue-testing sequence, a fatigue-producing sequence, and a fatigue-testing sequence

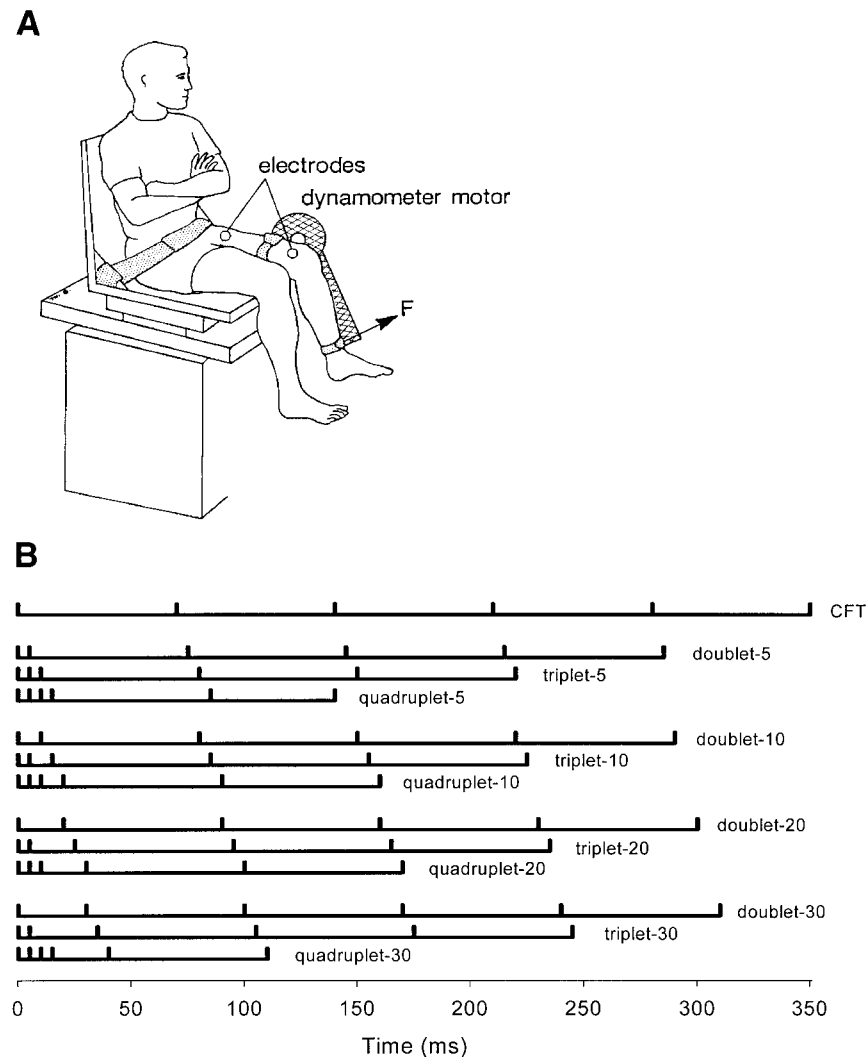


Fig. 1. A: experimental setup showing a subject seated on the computer-controlled dynamometer. Self-adhesive electrodes were placed over the rectus femoris (anode) and the vastus medialis (cathode) portions of the left quadriceps femoris muscle (see text for details). B: schematic representation of each stimulus train. Vertical lines represent each stimulation pulse within each train. Each train contained 6 pulses. Constant-frequency trains (CFTs) had all interpulse intervals equal to 70 ms. Each of the 12 catchlike-inducing trains (CITs) had an initial burst that contained 2, 3, or 4 pulses (doublets, triplets, and quadruplets, respectively). For the doublet CIT, the initial interpulse interval was varied from 5 to 30 ms (designated as doublet-5, doublet-10, doublet-20, and doublet-30, respectively). For the triplet and quadruplet CITs, the first 1 interpulse interval and first 2 interpulse intervals, respectively, were 5 ms, whereas the last interpulse interval of the initial burst varied from 5 to 30 ms (designated as triplet-5, triplet-10, triplet-20, and triplet-30 and as quadruplet-5, quadruplet-10, quadruplet-20, and quadruplet-30). For all CITs, the interpulse intervals after the initial burst of pulses were 70 ms.

Experimental Protocol

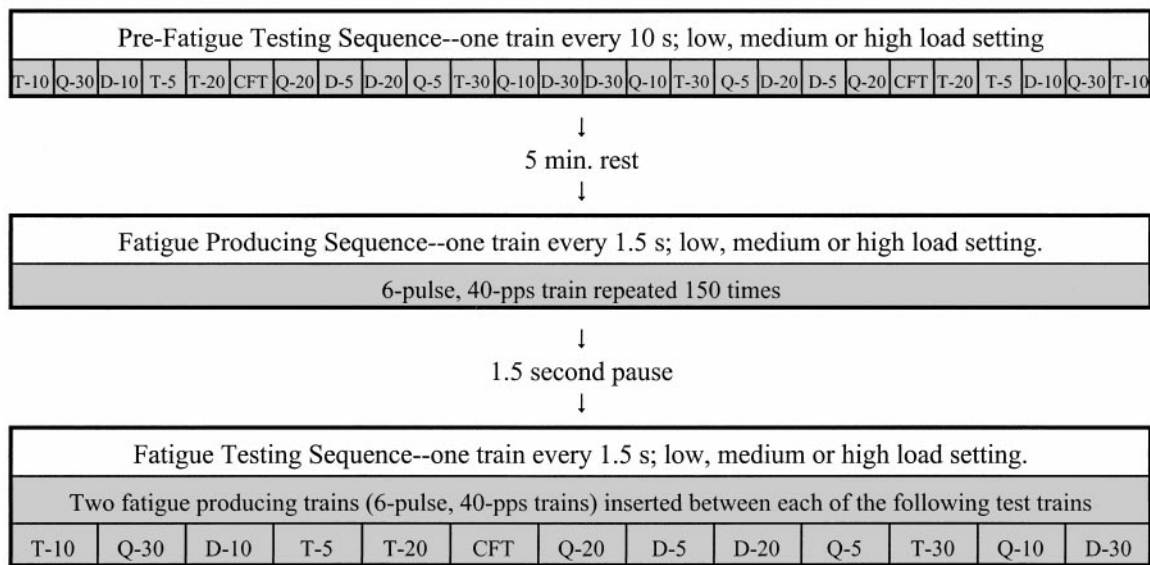


Fig. 2. Flow sheet illustrating prefatigue-testing, fatigue-producing, and fatigue-testing sequences that comprised the experimental protocol. During the testing sequences, subjects were stimulated with a random order of trains that included the CFT and the 12 different CITs (see Fig. 1 for details). D, doublet CIT; T, triplet CIT; Q, quadruplet CIT; pps, pulses/s. Train order for an individual subject is shown. All subjects were tested at a low, medium, and high load. Each subject received his or her own random sequence for testing each load condition. All sessions were separated by a minimum of 48 h. See text for additional details.

(Fig. 2) and tested one of three different load conditions (see below). Sessions were separated by at least 48 h, and the order of load conditions tested was randomly assigned for each subject.

Before each experimental session, MVIC testing was conducted. The session was conducted only if the subject performed an MVIC that was $\geq 95\%$ of the MVIC produced during the training session. If a subject was unable to meet this MVIC standard within four attempts, the experimental session was rescheduled for another day.

For gravity-correction purposes, the subject's leg was positioned at 0, 30, 45, and 60° of knee flexion. For each knee joint angle, the weight of the limb was determined by using a cosine function that reflected the angle of the leg with respect to the ground. All four estimates of the limb's weight were averaged and used for gravity correction during data analysis.

Next, with the knee positioned at 90°, 6-pulse, 100 pulses/s (pps) trains were delivered to the muscle once every 5 s, first to potentiate the muscle and then to set the stimulation intensity. Stimulation intensity initially was adjusted to elicit an isometric force $\cong 20\%$ of the subject's MVIC. Stimulation was continued until the force did not increase over three successive trains, which usually required ~ 10 stimulation trains. After force potentiation, the intensity was re-adjusted to produce a force equal to 20% of the subject's MVIC. The intensity was then kept constant throughout the remainder of the session in an attempt to recruit a consistent population of motor units from each subject's muscle.

After the stimulation intensity was set, the dynamometer was set in the isotonic mode by using the maximum available velocity setting (250°/s). This setting allowed the velocity of movement to vary up to a maximum of 250°/s. The dynamometer settings were adjusted to begin all movement at 90° of knee flexion and to provide the appropriate resistance to

knee extension. Resistance was either 5 N (low load), 25% of the stimulated tetanic force (medium load; i.e., 5% of the subject's MVIC), or 50% of the stimulated tetanic force (high load; i.e., 10% of the subject's MVIC). The dynamometer has three available accelerations "low," "medium," and "high." The medium setting was used as a tradeoff to reduce the dampening effects while maintaining system stability.

Prefatigue-Testing Sequence

Before the prefatigue-testing sequence, the muscle was repotentiated isometrically by using ten, 6-pulse, 100 pps trains. One train was delivered every 5 s. Within 5 s of the last potentiating train, the dynamometer's isotonic mode was enabled and the prefatigue-testing sequence commenced. The prefatigue-testing sequence consisted of a 70-ms inter-pulse interval constant-frequency train and 12 different catchlike-inducing trains (Fig. 1B). The 12 catchlike-inducing trains had an initial burst that contained 2, 3, or 4 pulses (i.e., a doublet, triplet, or quadruplet, respectively). For the doublet catchlike-inducing trains, the initial inter-pulse intervals were 5, 10, 20, or 30 ms. For triplet and quadruplet trains, the first one and first two inter-pulse intervals, respectively, were 5 ms, and the last inter-pulse interval in the burst was 5, 10, 20, or 30 ms. The inter-pulse interval for all the pulses of the catchlike-inducing trains after the initial doublet, triplet, or quadruplet was 70 ms (see Fig. 1B for additional details). One train was delivered every 10 s to prevent muscle fatigue. The order of the 13 trains was randomized for each subject and repeated in reverse order, for a total of 26 trains (Fig. 2).

Fatigue-Producing Sequence

The fatigue-producing protocol followed 5 min after the prefatigue-testing protocol was completed. Before the fa-

tigue-producing protocol was begun, the muscle was repotenti-ated isometrically, and then the isotonic mode was enabled. Six-pulse, 40 pps trains were delivered to the muscle once every 1.5 s for a total of 150 dynamic contractions to fatigue the muscle. Six-pulse trains, which lasted 125 ms, were used to allow the stimulation to end before the knee reached full extension. The 1.5-s period allowed sufficient time for the leg to return to the start position. Additionally, brief trains were used because short bursts of activity typify activation patterns used to produce functional movements (29). Additionally, stimulators used in cardiomyoplasty, a procedure in which a skeletal muscle is wrapped around the heart and stimulated to assist systole, all use 6-pulse trains (19) because this functional electrical stimulation application is constrained by the cadence of the heartbeat.

Fatigue-Testing Sequence

Fatigue testing began immediately (1.5 s) after the last fatigue-producing train was delivered. All trains continued to be delivered in 1.5-s intervals. The subject's same prefatigue sequence (13 testing trains) was delivered with the exception that two fatigue-producing stimulation trains (6-pulse, 40 pps) were delivered before the presentation of each testing train (see Fig. 2). This was done to control for prior activation history and to ensure a stable level of fatigue during the fatigue-testing sequence.

Data Management

All force responses were gravity corrected, and the three dependent variables were calculated by using custom-written software (Labview 4.0). The dependent measures of muscle performance were joint excursion, work, and average power produced during the shortening portion of each contraction. All performance measures were calculated by using the force, angle, and velocity data from the dynamometer during the period between force onset and maximum shortening (Figs. 3 and 4). Excursion was calculated as the maximum knee joint displacement in degrees; work was calculated as the numerical integration (trapezoidal method) of force times the arc of movement (knee joint displacement in radians times the

transducer lever arm) divided by the time interval from force onset to the time of maximum knee extension (muscle shortening), and average power was calculated by dividing the work by the time interval from force onset to maximum knee extension (Figs. 3 and 4). The prefatigue data analysis used the responses of the constant-frequency train and 12 catchlike-inducing trains collected during the prefatigue-testing protocol. The two occurrences of each train were averaged to help to control for previous muscle activation history. The responses to each train in the fatigue-producing sequence were recorded, and the percent decline for each dependant measure of muscle performance was calculated from the maximum response and the average response of the last three fatiguing trains. The fatigue data analysis used the responses of the 70-ms constant-frequency train and each catchlike-inducing train during the fatigue-testing sequence.

Data Analysis

Fatigue-producing sequence. One-way repeated-measures ANOVAs were used to determine the effect of load condition (low, medium, high) on the decline in muscle performance resulting from repetitive activation during the fatigue-producing sequence. Separate analyses were performed for each dependent measure (excursion, work, average power). If the ANOVA was significant, post hoc paired *t*-tests were used to compare the three load conditions.

Prefatigue- and fatigue-testing sequences. For testing trains, separate analyses were performed for each dependent measure and for fresh and fatigued responses. Recent findings during dynamic contractions (38) and isometric contractions (11) found that 5 ms was the optimal interpulse interval for the burst portion of catchlike-inducing trains when activating the human quadriceps femoris muscle. Visual inspection of the data confirmed that the 5-ms initial interpulse intervals generally produced greater performance than other intervals (10, 20, and 30 ms) for all performance measures and across load conditions. Thus only data for the 5-ms interval catchlike-inducing trains (i.e., doublet, triplet, or quadruplet) are presented.

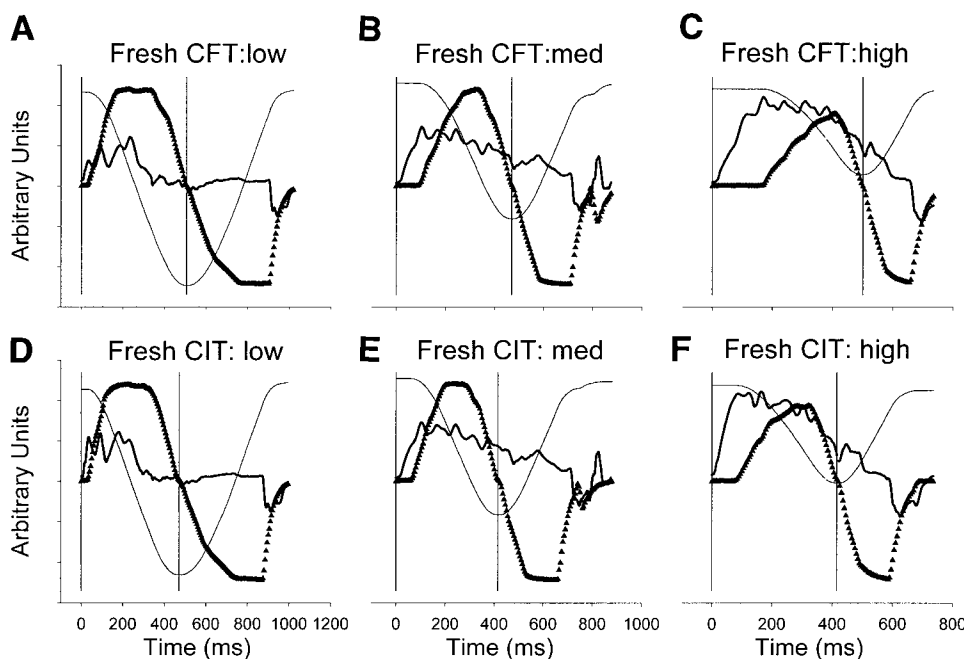


Fig. 3. Prefatigue raw data traces from a subject showing velocity-limited data. Gravity-corrected force (thick lines), angle (thin lines), and velocity (\blacktriangle) data in response to CFTs (A–C) and CITs (D–F). low, Low load; med, medium load; high, high load. CITs had 1 brief initial interpulse interval (doublet) equal to 5 ms. Excursion, work, and average power were calculated by using the period from force onset to maximum shortening of the muscle (between vertical lines). Relative scales for force, excursion, and velocity are the same across all panels. Note that the CITs produced peak excursions before CFTs.

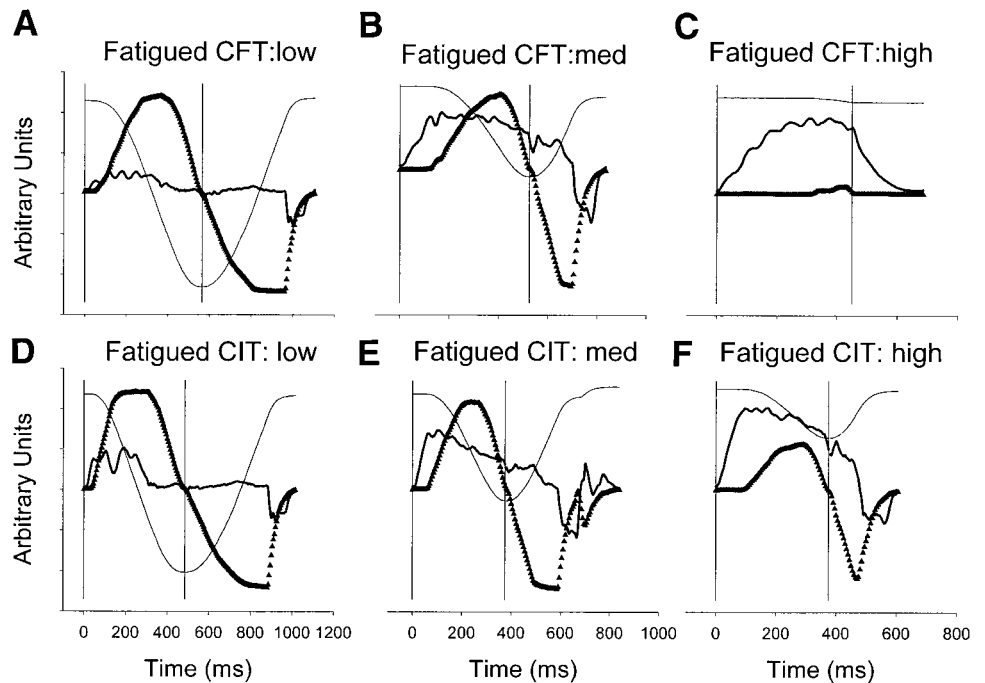


Fig. 4. Fatigued raw data traces from the same subject as in Fig. 3. Gravity-corrected force (thick lines), angle (thin lines), and velocity (\blacktriangle) data in response to CFTs (A–C) and CITs (D–F). CITs had 2 brief initial interpulse intervals (triplet) equal to 5 ms. Excursion, work, and average power were calculated by using the period from force onset to maximum shortening of the muscle (between vertical lines). Relative scales for force, excursion, and velocity are the same across all panels. Note that CITs produced peak excursions before CFTs and that they were able to maintain the rate of rise of force when fatigued (see Fig. 3).

Paired *t*-tests were used to compare the constant-frequency responses with each of the three cathchlike-inducing trains (i.e., doublet-, triplet-, and quadruplet-burst trains) responses for each load condition. If only one catchlike-inducing train was significantly greater than the constant-frequency train, then that catchlike-inducing train was designated the optimum train for that load condition. If more than one catchlike-inducing train produced significantly greater responses than the constant-frequency train, then paired *t*-tests were used to determine the best overall catchlike-inducing train. Paired *t*-tests were also used to compare responses of the different load conditions within each train type. For all analyses, an observation was significant at $P \leq 0.05$.

RESULTS

Fatigue-Producing Sequence

Complete data sets were collected for all 11 subjects. All three muscle performance measures for all three loads showed potentiation from the onset of the fatiguing protocol until approximately the 15–20th contraction (see Fig. 5). Maximum peak forces observed during these initial contractions were 120.6 ± 42.2 , 125.2 ± 39.8 , and 162.7 ± 55.1 N for the low, medium, and high loads, respectively. After the 20th contraction, a steady decline in performance was observed until approximately the 80th contraction. After the 80th contraction, each measure was relatively stable. The decline in excursion from the maximum response for the high-load condition ($\sim 55\%$) was significantly greater than the medium- ($\sim 27\%$) and low-load ($\sim 9\%$) conditions (see Fig. 6). Additionally, the decline in excursion for the medium load was significantly greater than for the low-load condition. For work, the low and medium loads produced about the same amount of fatigue (~ 33 and $\sim 34\%$, respectively), and the high-load condition

produced a significantly greater decline ($\sim 58\%$) than either the low or medium loads. Similarly, average power fatigued about same amounts for the low- and medium-load conditions ($\sim 37\%$), and the fatigue for the high-load condition ($\sim 58\%$) was significantly greater than either of the lower load conditions.

Prefatigue Testing

When muscles were fresh, the lighter the load the greater the excursion for all train types tested (Fig. 7). The catchlike-inducing trains did not significantly augment excursion in the low- or medium-load condition (see Fig. 7). For the high-load condition, only the doublet catchlike-inducing trains significantly augmented excursion ($\sim 17\%$). The effects of load were much less marked for work than for excursion. The doublet catchlike-inducing trains only produced significant augmentation in the low- ($\sim 9\%$) and high-load ($\sim 21\%$) conditions. Neither the triplet nor quadruplet trains produced any augmentation in work.

The average power produced was similar for all three load conditions. All catchlike-inducing trains augmented average power in the low-load condition (doublet: $\sim 16\%$, triplet: $\sim 15\%$, quadruplet: $\sim 11\%$), and none was significantly different from each other. No significant augmentations by catchlike-inducing trains were observed in the medium-load condition. For the high-load condition, only the doublet and triplet catchlike-inducing trains produced significant augmentation (~ 38 and $\sim 40\%$, respectively), and no significant differences were noted between them.

Fatigue Testing

The effects of load on excursion were similar in the fresh and fatigued states. When the muscles were

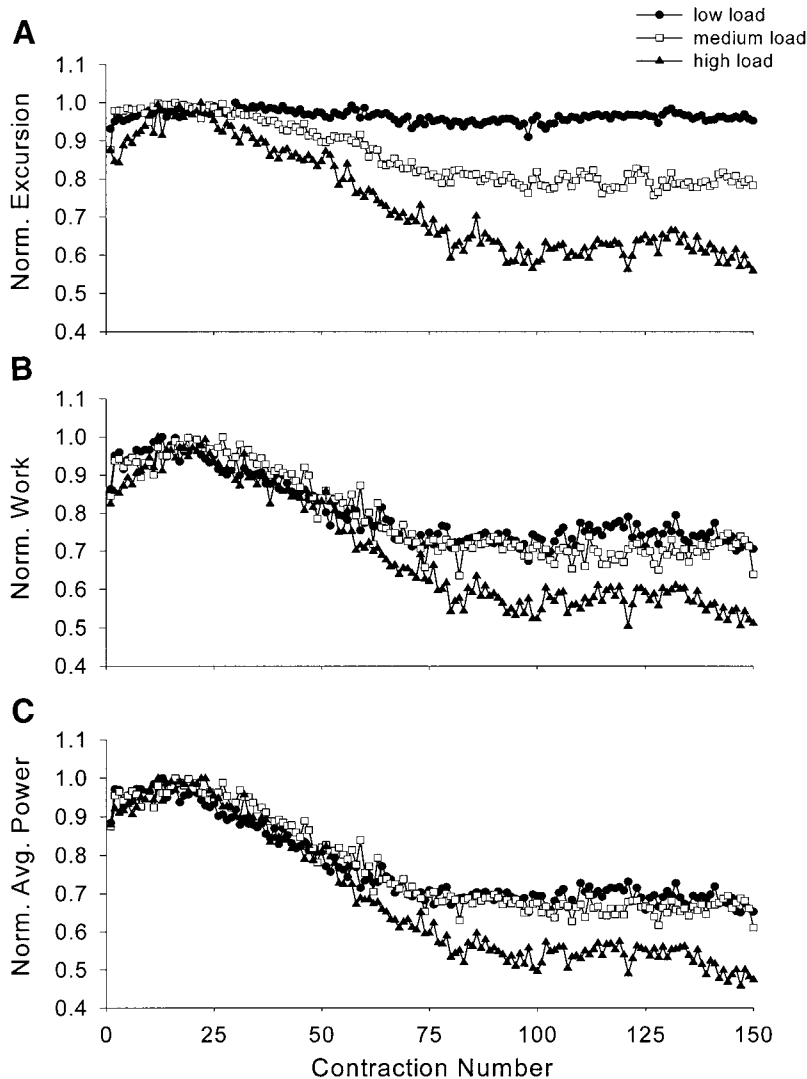


Fig. 5. Normalized (Norm) group excursion (A), work (B), and average (Avg) power (C) in response to each train of the fatigue-producing sequence. To produce fatigue, quadriceps femoris muscle was repetitively activated 150 times at a rate of 1 train/1.5 s by using 6-pulse, 40 pps trains during 3 different load conditions. Resistance was either 5 N (low load), 25% of the stimulated tetanic force (medium load; i.e., 5% of the subject's maximum voluntary isometric contraction), or 50% of the stimulated tetanic force (high load; i.e., 10% of the subject's maximum voluntary isometric contraction). $n = 11$ Subjects. See text for additional details.

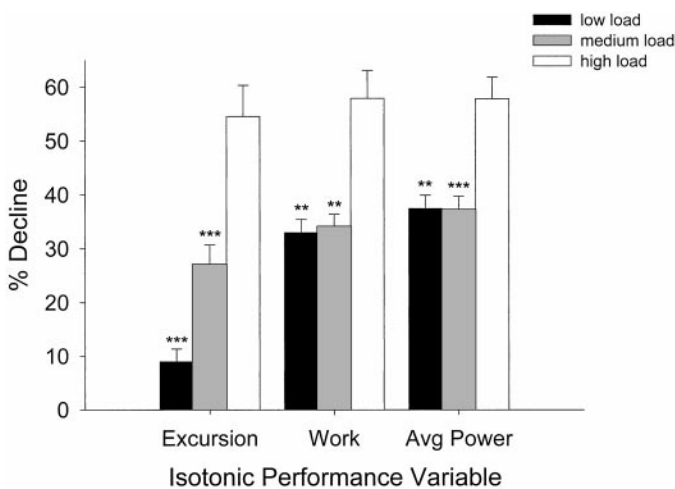


Fig. 6. Group percent decline of excursion, work, and average power in response to the fatigue-producing sequence for each load condition. Values are means \pm SE; $n = 11$ subjects. For all performance measures, one-way repeated-measures ANOVA showed a main effect for load condition (excursion: $F = 40.777$, $P < 0.001$; work: $F = 13.401$, $P < 0.001$; average power: $F = 14.407$, $P < 0.001$). Comparisons with the high-load condition within each dependent variable: ** $P \leq 0.01$, *** $P \leq 0.001$. See text for additional details.

fatigued, the lighter the load the greater the excursion (see Fig. 8). Similarly, no significant augmentations in excursion by catchlike-inducing trains were noted for either the low- or medium-load conditions; for the high-load condition, only the triplet and quadruplet catchlike-inducing trains produced significant augmentation (~67 and ~61%, respectively). Responses to the triplet and quadruplet catchlike-inducing trains were not significantly different. The effects of load were less marked for work than for excursion. All catchlike-inducing trains produced significant augmentation over the constant-frequency trains in the low-load condition (~18, ~24, and ~24% for the doublet, triplet, and quadruplet trains, respectively), and none was significantly different from each other. No significant augmentation by catchlike-inducing trains was noted for the medium-load condition. For the high-load condition, only the triplet and quadruplet catchlike-inducing trains augmented work (~91 and ~86%, respectively), and no significant differences were noted between them. Unlike the fresh muscle condition in which the average power produced was similar for all three load conditions, differences in average power

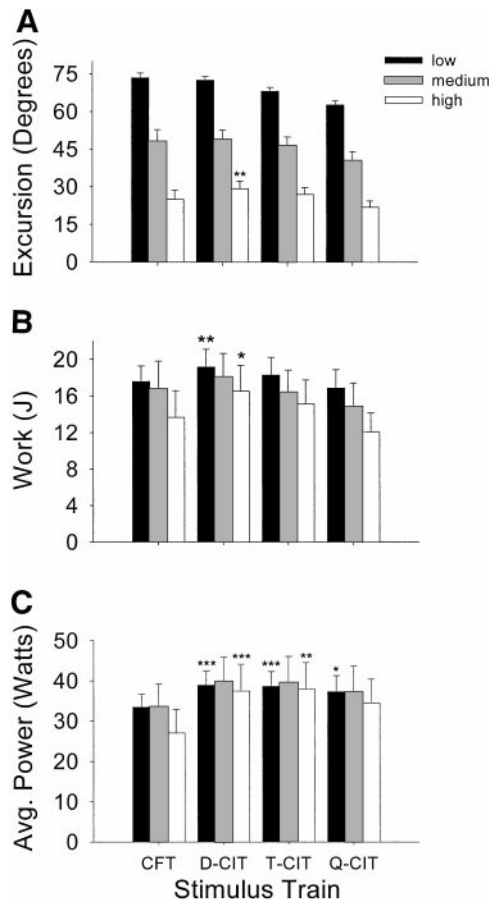


Fig. 7. Group prefatigue excursion (A), work (B), and average power (C) in response to CFT and CITs. Values are means \pm SE; $n = 11$ subjects. CITs had 1, 2, or 3 brief initial interpulse intervals [designated as doublet CIT (D-CIT), triplet CIT (T-CIT), or quadruplet CIT (Q-CIT), respectively]. Paired t -tests were used to compare the CFT responses to each CIT response within each load condition only if the CITs were producing greater values than the CFT. If >1 CIT produced significantly greater responses than the CFT, then additional paired t -tests were used to determine the best overall CIT. Comparisons of CFT to each CIT within each load condition: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$. See text for additional details.

were noted as a function of load with the greatest average powers produced at the lowest loads. The doublet, triplet, and quadruplet catchlike-inducing trains produced significant augmentation over the constant-frequency trains in the low-load condition (~ 28 , ~ 40 , and $\sim 45\%$, respectively), with the quadruplet catchlike-inducing trains producing significantly greater responses than the doublet catchlike-inducing trains. No significant difference was noted between the triplet and quadruplet trains. For the medium-load condition, only the doublet and quadruplet trains produced significant augmentation (~ 33 and 66% , respectively), and they were not significantly different from each other. Similarly, for high loads, only the triplet and quadruplet trains produced significant augmentation (173 and 187% , respectively) in average power over the constant-frequency trains, but no significant difference was noted between them.

DISCUSSION

This is the first study to investigate the effect of load on the fatigue resulting from repetitive electrically elicited nonisometric contractions. Although higher loads produced the least excursion, work, and average power, they produced the greatest fatigue of these measures. Additionally, this is the first study to investigate the amount of augmentation produced by catchlike-inducing trains over constant-frequency trains as a function of load. Augmentation of muscle performance by catchlike-inducing trains was greatest at the highest load tested and increased with fatigue. In general, for fresh muscles the optimum burst for the catchlike-inducing trains was an initial doublet. For fatigued muscles, the optimum burst was an initial triplet or quadruplet.

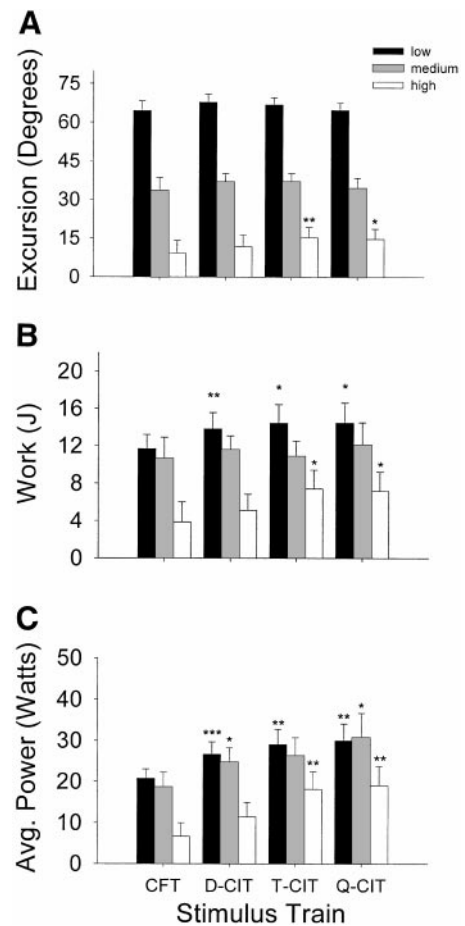


Fig. 8. Group fatigued excursion (A), work (B), and average power (C) in response to CFT and CITs. Values are means \pm SE; $n = 11$ subjects. CITs had 1, 2, or 3 brief initial interpulse intervals (designated as D-CIT, T-CIT, or Q-CIT, respectively). Paired t -tests were used to compare the CFT responses to each CIT response within each load condition only if the CITs were producing greater values than the CFT. If >1 CIT produced significantly greater responses than the CFT, then additional paired t -tests were used to determine the best overall CIT. Comparisons of CFT to each CIT within each load condition: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$. See text for additional details.

Muscle Performance as a Function of Load

Power can be expressed either as a function of velocity or as a function of load; both relationships are parabolic (for reviews see Refs. 33 and 46). The classic work of Hill (31), which was subsequently verified by others (47), suggests that a load equal to $\sim 30\%$ of the maximum isometric force generated from a muscle produces maximum values for power. Our results show greater work and average power were generated by contractions elicited at the low-load condition vs. higher loads. These observations are due to the relatively greater excursions and velocities generated during the low-load condition than at higher loads. Our results suggest that, because both low- and medium-load conditions produce approximately equal power, they must both lie near the peak, or straddle the peak, of the power-load relationship. Similarly, because the high load produced the least power, it must be working at loads greater than optimal for the production of power.

We attempted to emulate physiological shortening contractions by using a hydraulic dynamometer. The maximum velocity setting of the dynamometer was set to the limit of the machine ($250^\circ/\text{s}$). Some individuals, however, reached the dynamometer's maximum velocity during activation at the low- and medium-load conditions. Thus our shortening contractions included isometric, isotonic, and isovelocity portions for some individuals (see low- and medium-load data in Figs. 3 and 4). Some individuals, however, demonstrated isovelocity portions during contractions at the low- and medium-load conditions without reaching the dynamometer's maximum velocity, whereas others did not show isovelocity portions. None of the high-load condition data appeared to be velocity limited. For contractions limited by the dynamometer's maximum velocity, both excursion and velocity would be less than what the muscle is capable of producing for the load being tested. Such underestimations would lead to underestimated values for work and average power. Additionally, attainment of the maximum velocity of the dynamometer can result in forces greater than would be produced during "purely" isotonic contractions. Maximum dynamometer velocity was attained most frequently for the low-load condition, which may explain why initial maximum peak forces during the fatigue-producing sequence were not substantially different for the low- (120.6 ± 42.2 N) and medium- (125.2 ± 39.8 N) load conditions. In contrast, for the high-load condition, the maximum peak forces were 162.7 ± 55.1 N.

Our method of calculating work and power is different from traditional investigations measuring work and power resulting from dynamic contractions (20, 21; for review see Ref. 33). Traditional investigations have used isotonic or isovelocity releases, in which maximum isometric force is allowed to develop before the muscle is allowed to shorten either against a preset load or at a preset velocity (32). Isotonic releases are often used to derive the force-velocity relationship. In this case, the distance and velocity are measured while

the muscle shortens against a given load. Work is calculated as the product of the load (not necessarily muscle force) and the distance the load was moved during the shortening movement. Similarly, power is calculated as the product of the load and the maximum instantaneous velocity. For isovelocity releases, the muscle shortens at a preset velocity and power is calculated by using the velocity of shortening and the maximum force during the shortening or the force at a discrete point in the range of movement (cf. Refs. 14–16). Our approach results in values for work and power that reflect the overall performance of the muscle during the force generation and shortening phase rather than an instantaneous measurement occurring during the range of movement. Thus our measures of performance are more representative of the functional movements we are attempting to emulate than traditional approaches that have used isotonic or isovelocity releases.

Fatigue of Muscle Performance as a Function of Load

No previous study has reported the effects of load on fatigue. Traditionally, others have examined the effect of fatigue on isotonic performance measures rather than the reverse (4, 50). It has been reported anecdotally, however, that loads corresponding to maximum power generation produce the greatest fatigue (47). Chemical energetic studies have shown that maximum ATP utilization coincides with maximum power output (37). Furthermore, Baratta et al. (3) found that the kinetic energy efficiency of load-moving muscles of the cat were the least efficient at low loads. Lower efficiency at lower loads than at higher loads suggests that lower loads would generate greater fatigue. One may, therefore, infer that contractions producing the greatest power (low and medium loads) should produce the greatest fatigue. This was not observed in the present study. In contrast, the present study showed that, although the greatest load condition produced the least excursion, work and power, it produced the most fatigue of these measures after repetitive activation.

It is not clear why the high-load condition produced the greatest fatigue. The present results suggest that the force or strain produced during the contraction, rather than excursion, work, or power, may determine the amount of fatigue produced. This would suggest, however, that isometric contractions, which have the muscle contracting against an infinite load and produce greater forces and strains than shortening contractions, should produce greater fatigue than the shortening contractions. Shortening contractions, however, have been found to be more fatiguing than isometric (maximum-load) contractions (43, 44, 47). Fenn (27) was the first to show that shortening contractions release more heat than isometric contractions (Fenn effect), which implied greater metabolic costs by shortening contractions than isometric ones. Greater fatigue (44, 47) and metabolic cost during shortening contractions (37, 43) than isometric contractions have been substantiated in more contemporary studies. The spe-

cific mechanisms for the present results, therefore, need further investigation.

Augmentation With Catchlike-Inducing Trains

Our first report of the use of catchlike-inducing trains to produce dynamic contractions only examined loads comparable to the heavy load condition (38). This report found modest augmentations in excursion, work, peak power, and average power when the muscle was in the fresh state and marked augmentation of these same measures when fatigued. The present work extends this initial report and examines augmentation as a function of load. As was typical in previous work in isometric contractions (11–13) and isovelocity movements (10), augmentations by catchlike-inducing trains increased when the muscle was fatigued during dynamic contractions. The present results showed the greatest augmentations in muscle performance measures produced by catchlike-inducing trains at the highest load tested during both fresh and fatigued conditions.

Consistent with our previous report on dynamic contractions, the burst characteristics of the optimum catchlike-inducing trains contained an initial doublet when the muscle was fresh, and an initial triplet or quadruplet when fatigued, regardless of load condition (38). Similar optimum burst characteristics, consisting of initial doublets or triplets of pulses with 5-ms inter-pulse intervals are consistent with human quadriceps femoris data during isometric contractions at long (11) and short (39) muscle lengths as well as data from isovelocity shortening and lengthening movements (10). Similarly, similar optimum burst characteristics are consistent across species (5, 8, 11, 49, 50).

The appearance of doublets or other trains of motor unit activity that resemble our catchlike-inducing trains occur during volitional contractions (22, 30, 36). Additionally, in a denervation and cross-innervation study, Eken and Gundersen (24) demonstrated that “native stimulation patterns” consisting of a short-duration train including an initial triplet of pulses could maintain normal contractile speeds in both denervated rat extensor digitorum longus and soleus muscles and could maintain normal isotonic shortening velocity in the denervated extensor digitorum longus. Thus catchlike-inducing trains appear to have physiological importance.

Potential Fatigue Mechanisms

We found that the greater the load, the greater the fatigue and thus the greater the augmentation produced by catchlike-inducing trains. Slowing of cross-bridge cycling has been suggested as the primary fatigue mechanism for the loss of power resulting from fatigue during isotonic contractions (21). Slowing of cross-bridge cycling causes a decrease in the shortening velocity and thus a decrease in power. Slowing of force generation, possibly due to cross-bridge cycling mechanics, is evident in the constant-frequency trains responses in Figs. 3 and 4. When fresh, the time of

force onset to the onset of movement was 25, 90, and 165 ms for the low, medium, and high loads, respectively (Fig. 3). The rate of rise of force slowed when the muscles fatigued, requiring 40, 110, and 320 ms for the constant-frequency trains to initiate movements for the same respective load conditions (Fig. 4). This slowing of force development and time to the onset of movement is accompanied by a decrease in the slope of the velocity trace for the constant-frequency trains during all load conditions. Thus the changes in constant-frequency trains responses with fatigue supports the suggestion that slowing in cross-bridge cycling contributes to declines in dynamic performance.

In contrast to constant-frequency trains, the catchlike-inducing trains retained their rate of force production when fatigued (Figs. 3 and 4) (also see Refs. 11–13). When the muscles were fresh, the times from force onset to the onset of movement produced by catchlike-inducing trains were 25, 55, and 75 ms for the low, medium, and high loads, respectively. During fatigue, these times only increased slightly for the high-load condition (85 ms) and remained the same for the low and medium loads. Additionally, the only notable decline in the slope of the velocity trace occurred for catchlike-inducing trains in the high-load condition. Thus contractile slowing, evident in the fatigue of constant-frequency trains responses, cannot be the only mechanism contributing to fatigue during dynamic contractions because the rates of force production in response to catchlike-inducing trains were relatively unchanged.

Recent work (45) suggests that augmentation by catchlike-inducing trains over constant-frequency trains parallels the development of low-frequency fatigue. Because catchlike-inducing trains augment calcium release from the sarcoplasmic reticulum (23), they are less susceptible to impairments in excitation-contraction coupling associated with low-frequency fatigue than are constant-frequency trains (45). Thus the observation that catchlike-inducing trains did not show the same decline in force and velocity generation as constant-frequency trains and were able to augment performance suggests that problems in excitation-contraction coupling were also mechanisms contributing to the fatigue of dynamic contractions.

Clinical Implications

Because catchlike-inducing trains produce greater dynamic performance than constant-frequency trains regardless of fatigue condition and load imposed on the muscle, they may help to improve functional electrical stimulation applications that require limb movements. When accounting for lever arm length, the average peak torques generated during the high-load condition was $\sim 55 \text{ N} \cdot \text{m}$, which is within the estimated range of torques required from the quadriceps to stand up from a seated position (2, 25). This study, however, only compared catchlike-inducing trains, which had long interpulse intervals of 70 ms. Future studies need to look at a wider range of frequencies to determine which

stimulation pattern is best for producing dynamic contractions. Last, future study in different patient populations is warranted because fatigue characteristics and individual responses undoubtedly will vary between healthy individuals and those who may use functional electrical stimulation.

Conclusions

Generally, an inverse relationship between load and the development of excursion, work, and average power was observed for the quadriceps femoris muscle. Surprisingly, although the heavy-load condition produced the least excursion, work, and average power, it produced the greatest fatigue of these measures. Catchlike-inducing trains were effective in improving shortening contractions, and their efficacy increases with load and the amount of fatigue. When the muscle was fresh, doublet-initiated catchlike-inducing trains produced the greatest performance, whereas triplet-initiated catchlike-inducing trains were optimal when the muscle was fatigued. The ability of catchlike-inducing trains to retain their rates of force development and their ability to retain their velocities of shortening when fatigued caused the enhanced augmentation over constant-frequency trains in producing dynamic muscle performance. This enhancement in performance may be due to catchlike-inducing trains being less susceptible than constant-frequency trains to impairments in excitation-contraction coupling. Because catchlike-inducing trains were effective during shortening contractions for a variety of loads, they may be of benefit during functional electrical stimulation applications.

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