Effects of Length on the Catchlike Property of Human Quadriceps Femoris Muscle

Background and Purpose. Recent reports have suggested that electrical stimulation trains that take advantage of the catchlike property of skeletal muscle can produce higher forces from skeletal muscle than traditionally used constant-frequency trains. This study investigated the effects of catchlike-inducing trains on human quadriceps femoris muscles while the knee joint was held at 15 degrees of flexion. Subjects and Methods. Subjects (N=12) were tested with constant-frequency trains that had interpulse intervals ranging from 10 to 160 milliseconds and comparable catchlike-inducing trains. Data were collected during the control condition (1 train every 10 seconds) and during repetitive contractions (1 train per second). Results. During control and repetitive activation conditions, catchlike-inducing trains produced approximately 5% to 110% greater peak forces than comparable constant-frequency trains, depending on the frequencies being compared. Total forces produced (ie, force-time integrals) were increased up to 59% and 49% during the control and repetitive activation conditions, respectively. Conclusion and Discussion. These results support earlier findings that catchlike-inducing trains may be advantageous in functional electrical stimulation applications. [Lee SCK, Gerdom ML, Binder-Macleod SA. Effects of length on the catchlike property of human quadriceps femoris muscle. *Phys Ther.* 1999;79:738–748.]

Key Words: *Catchlike property, Fatigue, Functional electrical stimulation, Human quadriceps femoris muscle, Muscle length.*

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Functional electrical stimulation (FES) to assist individuals with central nervous system damage to ambulate requires repetitive activation of paralyzed muscles. One primary limitation to the widespread implementation of FES is muscle fatigue,[1,2] which is the decrease in the force-generating ability of a muscle resulting from recent activation.[3,4] Most improvements in FES applications involve technological advances in system design and implementation, but few systematic investigations of the most appropriate stimulation frequencies or patterns for activating muscles have been performed.[5] Stimulation frequency affects the force production of muscle[6,7] and influences fatigue.[8–10] High stimulation frequencies are associated with higher forces and greater fatigue than are associated with lower frequencies of stimulation.[8–10] Using low frequencies may reduce the rate of fatigue, but it may not lead to the development of sufficient forces for all FES applications. Optimal stimulation patterns, therefore, need to be identified.

Recent work suggests that optimal stimulation may consist of a train of pulses containing more than one instantaneous frequency.[11] By using catchlike-inducing trains that exploit the catchlike-property of skeletal muscle, higher forces can be elicited than if traditional constant-frequency stimulation trains with comparable frequencies are used.[11–14] 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.[13,15–17] The catchlike property is a fundamental property of muscle that is not due to properties of the motor axon or the neuromuscular junction.[13,14,18]

In our previous investigations of the human quadriceps femoris muscle, we found that, during isometric contractions with the knee in 90 degrees of flexion, catchlike-inducing trains were highly effective in augmenting forces of fatigued muscle compared with comparable constant-frequency trains.[11,12,19] As much as 72% augmentation in peak force and 52% augmentation in force-time integrals (ie, the area of the force curve produced in response to stimulation) with respect to

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Lee, Gerdom, and Binder-Macleod provided the concept and research design, wrote the manuscript, and, with the assistance of Todd Moore and Cara Becker, collected and analyzed the data. Project management and fund procurement were provided by Lee and Binder-Macleod.

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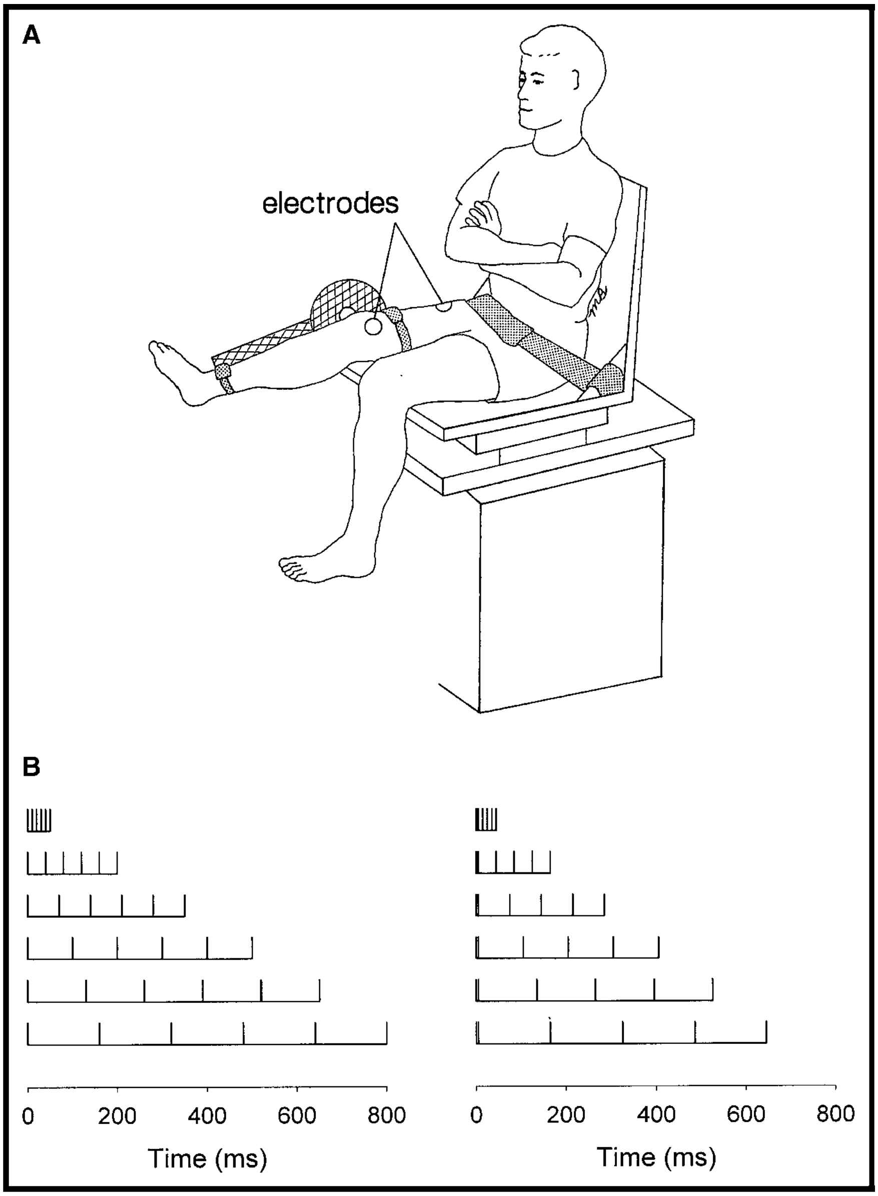

Figure 1.
Schematic representation of the experimental setup and stimulation trains used during the study. (A) Schematic drawing of the experimental setup used to test the right quadriceps femoris muscle. For the main study, the knee was positioned in 15 degrees of flexion. For additional testing on a subset of subjects, the knee was positioned in 15 and 90 degrees of flexion. (B) Schematic representation of 6 of the 16 constant-frequency trains (CFTs) (left panel) and 6 comparable catchlike-inducing trains (CITs) (right panel) used during the study. Vertical lines represent each stimulation pulse used within a train. Traces shown are examples of 6-pulse CFTs (left panel) with interpulse intervals of 10, 40, 70, 100, 130, and 160 milliseconds (top to bottom) and comparable CITs (right panel). All CITs have an initial interpulse interval of 5 milliseconds.

comparable, subtetanic, constant-frequency trains have been observed.[12] Additionally, we recently showed that catchlike-inducing trains not only augment force compared with subtetanic, constant-frequency trains but also produce 25% greater force-time integrals than even the best constant-frequency train in fatigued human quadriceps femoris muscle.[11] When the muscle is not fatigued, however, catchlike-inducing trains generally produce about the same force as comparable constant-frequency trains, with the only added advantage of producing faster rates of rise of force.[11,12]

In our previous studies, we activated the human quadriceps femoris muscle at the muscle length that produced near-maximum force, corresponding to a knee joint angle of about 90 degrees. Functional electrical stimulation requires quadriceps femoris muscle activation at or near full knee extension to produce standing and ambulation. The force-frequency characteristics of skeletal muscle are known to be altered in the shortened position.[20,21] Higher frequencies of activation are required to produce forces at short muscle lengths than what occurs with optimal muscle lengths (ie, a rightward shift in the force-frequency relationship).[20,21] Because of this difference, the purpose of this study was to investigate force production as a function of stimulus frequency using both constant and catchlike-inducing trains prior to and during repetitive activation of the human quadriceps femoris muscle while the knee joint angle was held at 15 degrees of flexion. Relatively simple, doublet-initiated (5-millisecond initial interpulse interval), catchlike-inducing trains were used because they have been shown to be effective in augmenting force from human quadriceps femoris muscle.[12] A preliminary report of this work has been presented elsewhere.[22]

Method

Subjects

Data were obtained from 12 volunteers (6 male, 6 female) ranging in age from 19 to 31 years ($\bar{X}$=23.3, SD=3.89). The subjects had no history of lower-extremity orthopedic problems. All subjects signed informed consent forms prior to participation in the study.

Experimental Setup

Subjects were seated at a computer-controlled force dynamometer with their hips flexed to about 75 degrees and the knee positioned in 15 degrees of flexion (Fig. 1).

We used a KIN-COM II dynamometer* for 8 subjects and a KIN-COM III dynamometer* for 4 subjects. The dynamometer axis was aligned with the knee joint axis, and the force transducer pad was positioned against the anterior surface of the leg about 3 cm proximal to the lateral malleolus. The right quadriceps femoris muscle was stimulated using a Grass S8800 stimulator† with a SIU8T stimulus isolation unit.† All stimulation pulses were 600 microseconds in duration. Two self-adhesive, 7.6- × 12.7-cm (3- × 5-in) electrodes were used to electrically stimulate the muscle. The anode was placed proximally, over the motor point of the rectus femoris muscle, and the cathode was placed distally, over the motor point of the vastus medialis muscle. The stimulator was driven by a personal computer that controlled all timing parameters of each stimulation protocol. All force data were digitized on-line at a rate of 200 samples per second and stored for subsequent analysis.

All subjects were instructed to refrain from strenuous activity for at least 24 hours prior to testing. Prior to the commencement of the experimental protocol, all subjects were familiarized with the experimental protocol, trained to relax their muscles during stimulation of their quadriceps femoris muscle, and tested for their maximal voluntary isometric contraction (MVIC) with the knee in 15 degrees of flexion (which we believe results in a short muscle length). For each subject, the MVIC was determined by using a burst superimposition technique,[23] during which a 100-Hz, 10-pulse train at supramaximal intensity was delivered to the quadriceps femoris muscle during an attempted maximal volitional contraction. If the stimulation produced less than a 5% increase in force above the subject's volitionally produced force, the force produced by the subject was determined to be the subject's MVIC. If the stimulation produced more than a 5% increase in force, the subject rested for 5 minutes and the testing was then repeated. All subjects produced MVICs within 3 trials.

After completing the training protocol, subjects rested a minimum of 5 minutes before we started the experimental protocol, which consisted of a control and a repetitive activation sequence. All stimulation trains contained 6 pulses (5 interpulse intervals). The constant-frequency trains had equal interpulse intervals from 10 milliseconds and increased by 10-millisecond intervals up to 160 milliseconds (total of 16 constant-frequency trains; see Fig. 1B, left panel). Because of the reciprocal relationship between interpulse interval and frequency, these trains had frequencies ranging from 100 to 6.25 pulses per second. The catchlike-inducing trains used to elicit the catchlike response, had one initial, brief interpulse interval equal to 5 milliseconds, followed by a constant-frequency portion containing interpulse intervals comparable to the 16 constant-frequency trains (4 equal interpulse intervals ranging from 10 to 160 milliseconds, for a total of 16 catchlike-inducing trains; see Fig. 1B, right panel).

To set the "stimulus intensity," the output of the stimulator was adjusted until it elicited a force equal to about 20% of the MVIC of the subject's quadriceps femoris muscle when stimulated with a 6-pulse constant-frequency train with 10-millisecond interpulse intervals. The stimulation was then delivered once every 5 seconds until the muscle was potentiated (ie, force did not increase with 3 successive trains). Potentiation required 5 to 10 trains. Stimulation was continued to allow the stimulation intensity to be readjusted to elicit 20% of the MVIC from the potentiated muscle. Stimulation was then stopped, and the intensity was not changed for the remainder of the session. All force measurements were gravity corrected for the weight of the subject's limb in 15 degrees of knee flexion.

Control sequence. Within 5 seconds of adjustment of the stimulation intensity, the control sequence began. This sequence consisted of the 16 constant-frequency and 16 catchlike-inducing trains first presented in a random order and then repeated in reverse order (total of 64 trains). One train was delivered every 10 seconds to avoid fatiguing the muscle. The same random order was used for each subject.

Repetitive activation sequence. Ten minutes after completion of the control sequence, the muscle was repotentiated using the same methods outlined earlier and the repetitive activation sequence commenced. Repetitive activation consisted of 192 trains, delivered once per second. The 192 trains were composed of 2 different random sequences of the 16 constant-frequency and 16 catchlike-inducing trains (the first random order was the same as that used in the control protocol). The 2 random sequences formed a block of 64 stimulus trains, which were repeated 3 times to form the 192-train sequence (Fig. 2). The same repetitive activation sequence was used for each subject to allow train-by-train comparisons across subjects.

Data Management

The dependent variables we examined were the force-time integral and peak force in response to each train of pulses. Because the responses to each of the 16 constant-frequency and 16 catchlike-inducing trains occurred twice during the control protocol, the responses of the 2 like trains were averaged and then analyzed. Similarly, the last 64 contractions of the 192-contraction repetitive

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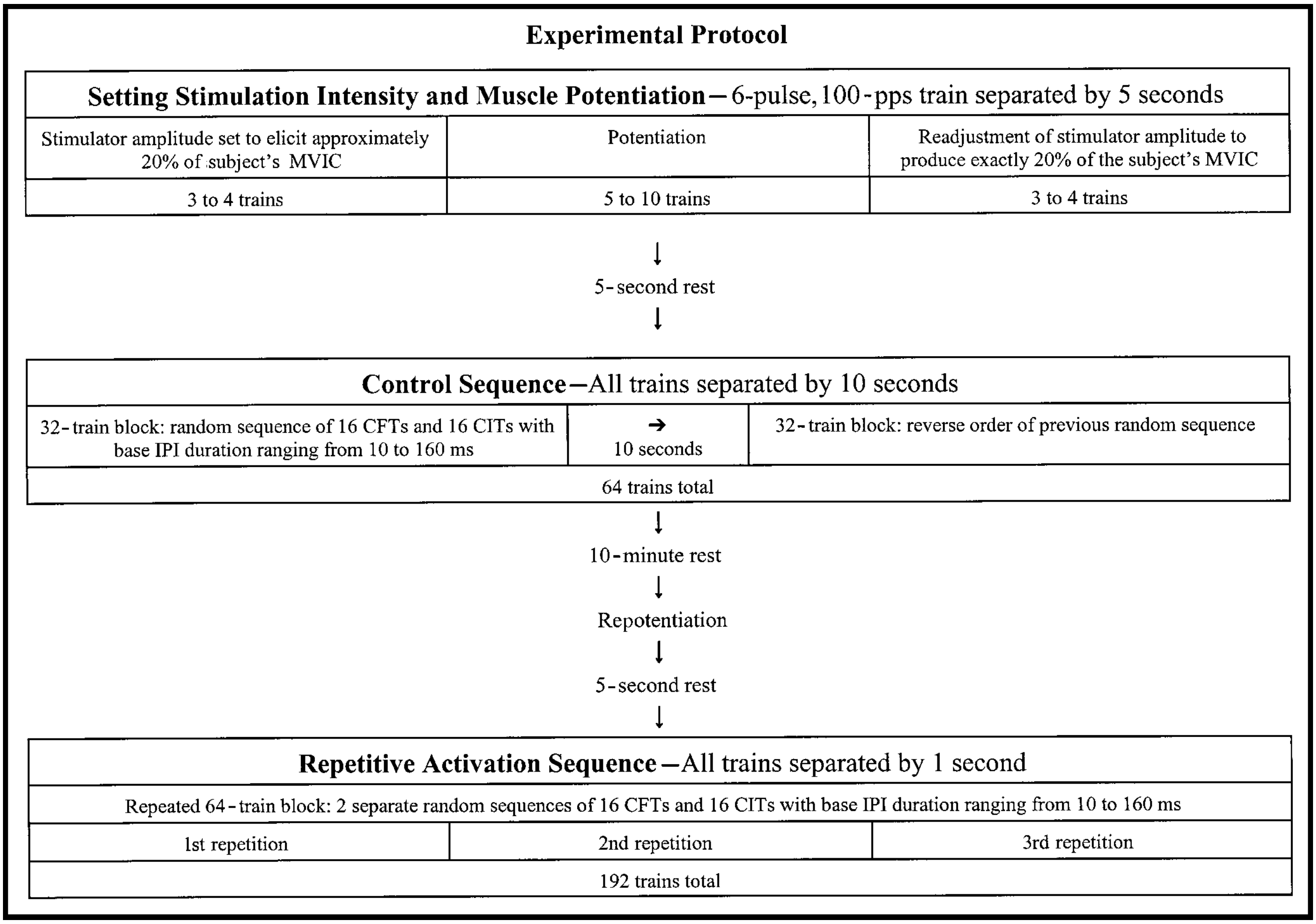

Experimental Protocol

Setting Stimulation Intensity and Muscle Potentiation—6-pulse, 100-pps train separated by 5 seconds

Stimulator amplitude set to elicit approximately 20% of subject's MVIC	Potentiation	Readjustment of stimulator amplitude to produce exactly 20% of the subject's MVIC
3 to 4 trains	5 to 10 trains	3 to 4 trains

↓
5-second rest
↓

Control Sequence—All trains separated by 10 seconds

32-train block: random sequence of 16 CFTs and 16 CITs with base IPI duration ranging from 10 to 160 ms	→ 10 seconds	32-train block: reverse order of previous random sequence
64 trains total		

↓
10-minute rest
↓
Repotentiation
↓
5-second rest
↓

Repetitive Activation Sequence—All trains separated by 1 second

Repeated 64-train block: 2 separate random sequences of 16 CFTs and 16 CITs with base IPI duration ranging from 10 to 160 ms

1st repetition	2nd repetition	3rd repetition
192 trains total		

Figure 2.
Flow sheet illustrating the protocol used during experimental sessions. Stimulator amplitude was adjusted to elicit 20% of the subject's maximal voluntary isometric contraction (MVIC) using a 6-pulse, 100-pulse per second train from fully potentiated muscle. To avoid fatigue, trains were separated by 10 seconds in the control condition, whereas trains were separated by 1 second in the repetitive activation condition. CFT=constant-frequency train, CIT=catchlike-inducing train, IPI=interpulse interval.

activation sequence were used to examine changes in responses due to repetitive activation. This block of 64 trains contained 2 occurrences of each train tested, which were also averaged.

Data Analysis

Two-way, within-subjects, factorial analyses of variance (ANOVAs) were performed to test the effects of train type (constant-frequency versus catchlike-inducing trains) and interpulse interval on the force data. Separate ANOVAs were used to test the control and repetitive activation conditions. Furthermore, within each activation condition, peak force and force-time integral data were analyzed separately. If significant effects were observed, Holm's sequentially rejective, Bonferroni-corrected, *post hoc*, 2-tailed paired *t* tests[24] were used to compare the responses of the constant-frequency trains with the responses of catchlike-inducing trains at each interpulse interval. Finally, for both control and repetitive activation data, 2-tailed paired *t* tests were performed to compare the greatest or "best" constant-frequency train response with the best catchlike-inducing train response (eg, for repetitive activation force-time integral in Fig. 5D, the 60-millisecond interpulse interval constant-frequency train with the 80-millisecond interpulse interval catchlike-inducing train) for each of the 2 force measures (peak force and force-time integral) to determine which stimulus pattern produced the best overall performance. For all group data, means (± standard error) are presented. An observation was significant if $P \leq .05$.

Additional testing. Because the repetitive activation sequence produced little fatigue compared with results using a similar protocol performed in 90 degrees of knee flexion,[11] a subset of 4 subjects (2 male, 2 female) selected as a sample of convenience underwent additional testing. One difference between the 2 protocols was that the present protocol tested interpulse interval durations up to 160 milliseconds, whereas the previously published study[11] tested only interpulse interval durations to 120 milliseconds. Thus, to investigate the possibility that the longer interpulse interval durations con-

Table.
Results of Analysis of Variance (ANOVA) (N=12)

Force Measurement	Test	Fatigue State	Interpulse Interval	Train Type	Interaction
Peak	2-way ANOVA	Control	F=78.068, *P*<.001	F=42.957, *P*<.001	F=29.554, *P*<.001
Peak	2-way ANOVA	Repetitive activation	F=74.526, *P*<.001	F=49.255, *P*<.001	F=32.938, *P*<.001
Force-time integral	2-way ANOVA	Control	F=41.446, *P*<.001	F=19.740, *P*<.001	F=18.506, *P*<.001
Force-time integral	2-way ANOVA	Repetitive activation	F=23.880, *P*<.001	F=59.243, *P*<.001	F=27.316, *P*<.001

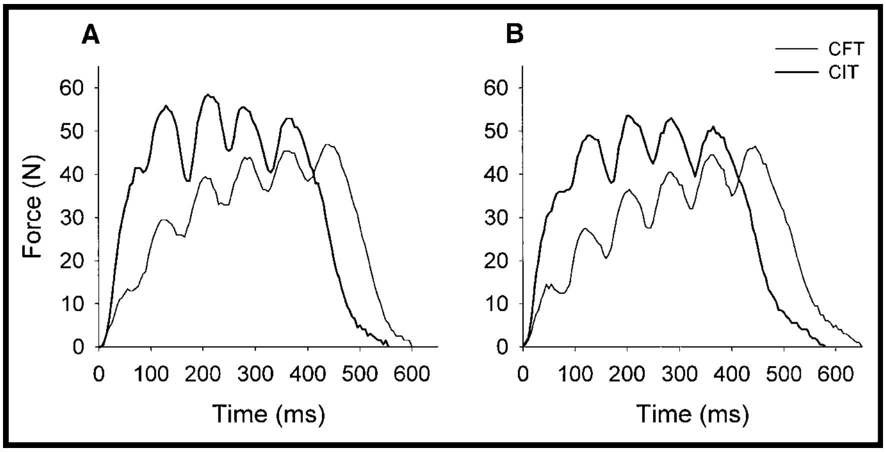

Figure 3.
Force responses from a representative subject. (A) Responses to a constant-frequency train (CFT) with an 80-millisecond interpulse interval and a comparable catchlike-inducing train (CIT) during the control sequence. (B) Responses to the last presentation of the trains with 80-millisecond interpulse intervals during repetitive activation. Note the more rapid rate of rise of force produced in response to CITs (thick lines) than to CFTs (thin lines). Little fatigue was noted following repetitive activation.

tributed to the lower amount of fatigue we observed, each of the 4 subjects participated in 4 additional testing sessions. Each session tested 1 of 4 conditions: (1) 15 degrees of knee flexion using the present protocol (10 to 160-millisecond interpulse intervals), (2) 90 degrees of knee flexion using the present protocol, (3) 15 degrees of knee flexion using the previous protocol (10 to 120-millisecond interpulse intervals), or (4) 90 degrees of knee flexion using the previous protocol. For testing at 15 degrees of knee flexion, the force used was set as described earlier (ie, 20% of the subject's MVIC generated at 15°). At 90 degrees of knee flexion, the force was set using 20% of the subject's MVIC generated at 90 degrees. Thus, the same relative force was used at the 2 joint angles. The order of the sessions was randomized for each subject, and each session was separated by a minimum of 48 hours.

Results

Complete data sets were collected for all 12 subjects and for all 4 subjects selected to undergo the additional testing. The results of the ANOVA are summarized in the Table. Figure 3 shows typical force responses to stimulation with constant-frequency and catchlike-inducing trains when the knee was held in 15 degrees of flexion before and after repetitive activation. The catchlike-inducing trains produced greater rates of rise of force both before and after repetitive activation. For this subject and for the group, the catchlike-inducing train produced greater peak force and force-time integrals than the comparable subtetanic constant-frequency train produced, both before and after repetitive activation.

Plots of the peak forces and force-time integrals in response to each train of the repetitive activation sequence showed little fatigue (Fig. 4). For peak force, the 20-millisecond constant-frequency and catchlike-inducing trains produced the greatest peak forces following repetitive activation and declined about 9% and 6%, respectively, from their control values (Fig. 5). Similarly, the 60-millisecond constant-frequency and 80-millisecond catchlike-inducing trains produced the greatest force-time integrals following repetitive activation and declined by about 10% and 8%, respectively, from their control values.

Comparison of Constant-Frequency and Catchlike-Inducing Train Stimulation

Peak forces. Catchlike-inducing trains produced greater peak forces than comparable constant-frequency trains for all interpulse intervals of ≥50 milliseconds in the control condition and for all interpulse intervals of ≥30 milliseconds following repetitive activation (Fig. 5). For both conditions, the augmentation in peak force by catchlike-inducing trains generally increased as interpulse intervals of longer duration were used. The augmentation ranged from about 6% at 50 milliseconds to about 117% at 160 milliseconds in the control condition

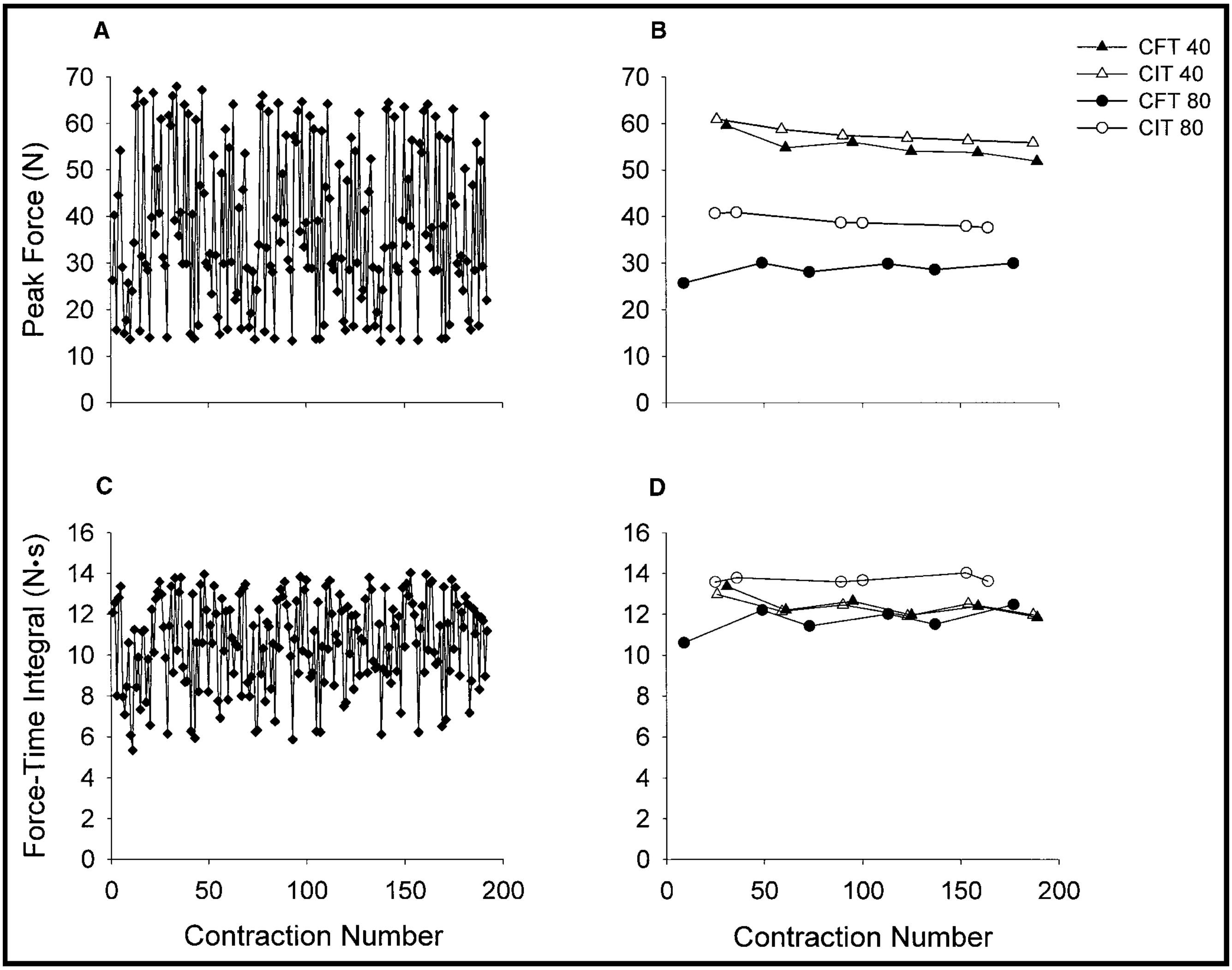

Figure 4.
Averaged group peak force and force-time integral responses (N=12) during the repetitive activation sequence. (A and C) Peak force and force-time integral responses, respectively, to each of the 192 trains of the repetitive activation sequence. (B and D) Peak force and force-time integral responses to stimulation trains with 40-millisecond interpulse intervals (triangles) and 80-millisecond interpulse intervals (circles) during the 192-train repetitive activation sequence. Closed symbols are constant-frequency trains (CFTs), and open symbols are catchlike-inducing trains (CITs). Relatively little fatigue occurred in response to repetitive activation.

and from about 4% at 30 milliseconds to about 110% at 160 milliseconds following repetitive activation. The 20-millisecond interpulse interval produced the greatest peak force for both constant-frequency and catchlike-inducing trains both before and after repetitive activation.

Force-time integrals. For the control condition, catchlike-inducing trains produced greater force-time integrals than the constant-frequency trains produced for all interpulse intervals of ≥80 milliseconds (Fig. 5). Although the 20-millisecond constant-frequency train produced greater force-time integrals than its comparable catchlike-inducing train, the difference was small (about 5%). Following repetitive activation, catchlike-inducing trains with interpulse intervals of ≥70 milliseconds produced greater force-time integrals than their comparable constant-frequency trains produced. For both conditions, the augmentation in force-time integral by catchlike-inducing trains generally increased as interpulse intervals of longer duration were used. The augmentation ranged from about 18% at 80 milliseconds to about 59% at 160 milliseconds in the control condition and from about 9% at 70 milliseconds to about 49% at 150 milliseconds following repetitive activation. There was no difference in the force-time integrals produced by the best constant-frequency train (60 milliseconds) and the best catchlike-inducing train (60 milliseconds) when the muscle was in the control condition. Following repetitive activation, however, the best catchlike-inducing train (80 milliseconds) produced a 6.2% greater force-time integral than the optimal constant-frequency train (60 milliseconds) produced and a 15.3% greater force-time integral than its comparable constant-frequency train produced.

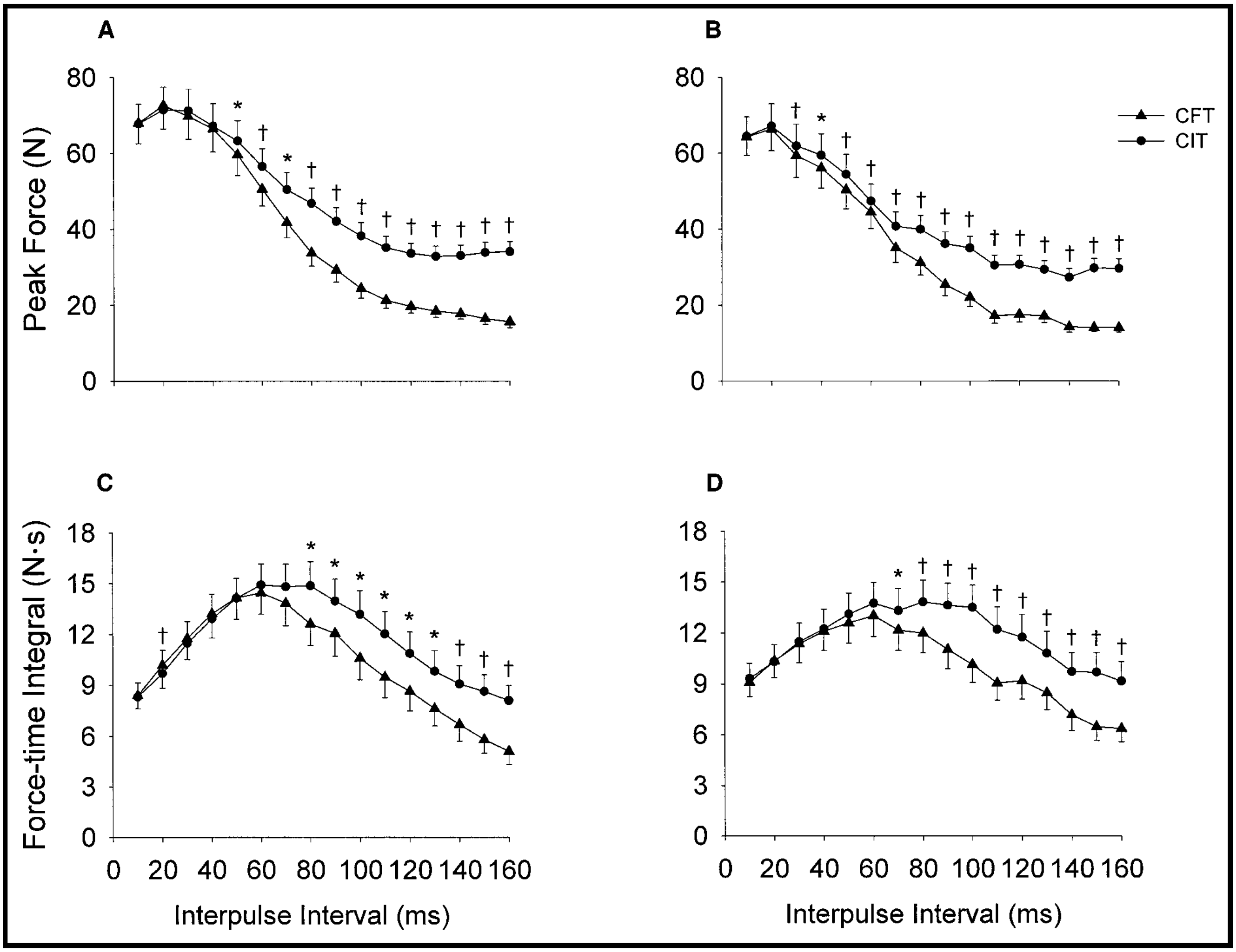

Figure 5.
Averaged group (N=12) peak forces and force-time integrals in response to constant-frequency train (CFT) and catchlike-inducing train (CIT) stimulation during control and repetitive activation conditions. Peak forces during control conditions (A) and peak forces from repetitively activated muscles (B) plotted as a function of interpulse interval. Force-time integrals during control conditions (C) and force-time integrals from repetitively activated muscles (D) plotted as a function of interpulse interval. For the peak force responses, comparison of the best CFT and CIT responses within each condition demonstrates no differences between the 20-millisecond CFTs and the 20-millisecond CITs. For force-time integral responses, the best CIT (80 milliseconds) produced 6.2% greater force than the best CFT (60 milliseconds) following repetitive activation. This 80-millisecond CIT also produced a 15.3% greater force-time integral than its comparable 80-millisecond CFT. Holm's sequentially rejective, Bonferroni-corrected, 2-tailed, paired *t* tests were used to compare force responses to CFTs and CITs at each interpulse interval. Asterisk (*) indicates $P \leq .05$; dagger (†) indicates $P \leq .01$.

Additional testing at long and short muscle lengths. Force-time integral data from the 4 subjects tested at 15 and 90 degrees of knee flexion (short and long muscle lengths, respectively) with both the present protocol (10–160 milliseconds) and the previous protocol (10–120 milliseconds) showed that, regardless of protocol, less fatigue occurred at short muscle lengths than at long muscle lengths (Fig. 6). Averaged across interpulse intervals and train types, the present protocol (10–160 milliseconds) produced about 11% and 33% declines in force at short and long muscle lengths, respectively. The previous protocol (10–120 milliseconds) produced an increase in force of about 9% and a decrease in force of about 46% at short and long muscle lengths, respectively.

Discussion

Our major finding was that catchlike-inducing trains augmented force compared with constant-frequency trains both before and following repetitive activation when the muscle was held at a shortened length. Our previous work using the human quadriceps femoris muscle held at a longer length than we used in this study showed augmentation in the force-time integral for catchlike-inducing trains only when the muscle was fatigued.[11,12,19] Thus, the use of catchlike-inducing trains augmented force compared with constant-frequency trains when activating muscles at shorter lengths, regardless whether the muscles were activated in the control condition or whether the muscles had been modestly

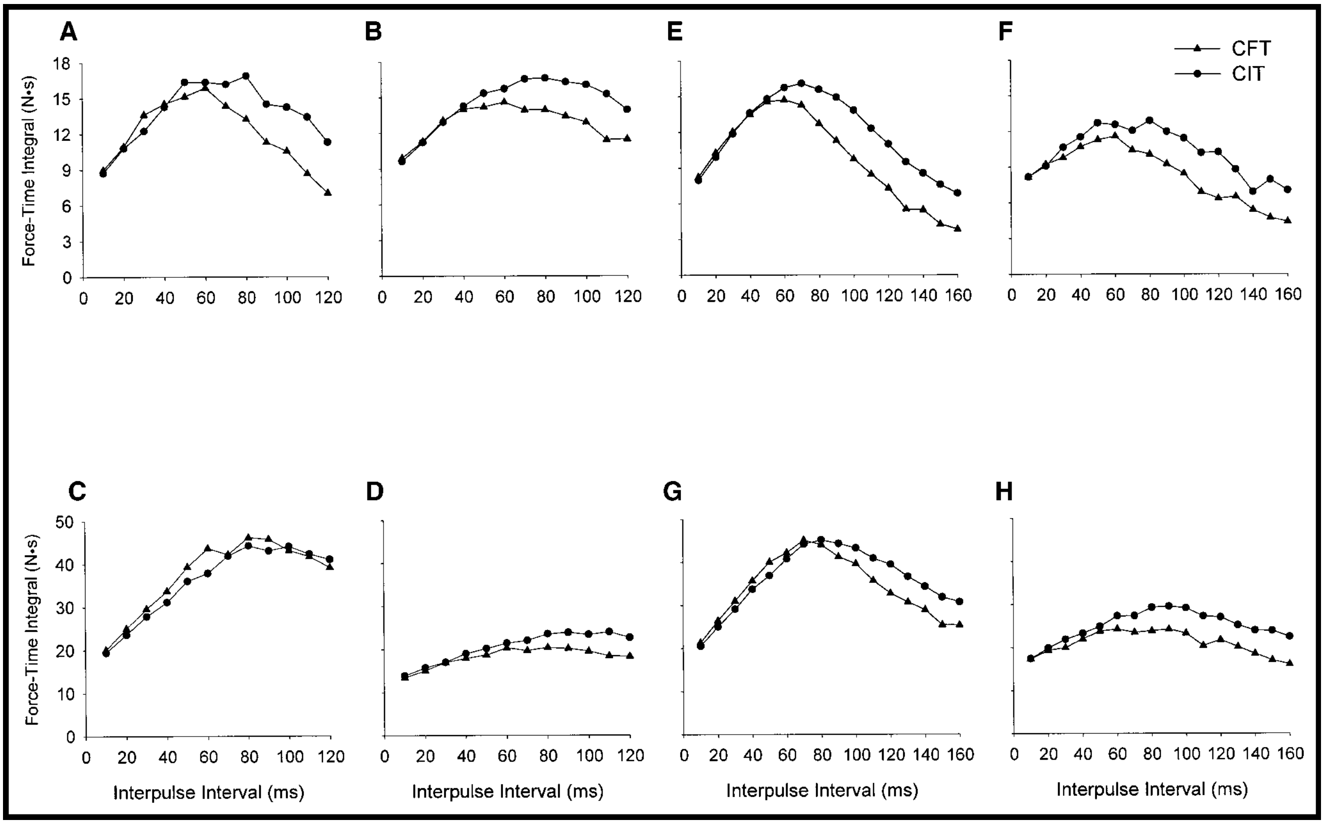

Figure 6.
Averaged force-time integrals from a subset (n=4) of subjects in response to constant-frequency train (CFT) and catchlike-inducing train (CIT) stimulation during control and repetitive activation conditions. Testing was performed at short (A, B, E, and F) and long (C, D, G, and H) muscle lengths corresponding to 15 and 90 degrees of knee flexion, respectively. Control (A and C) and repetitively activated (B and D) responses using interpulse interval durations ranging from 10 to 120 milliseconds. Control (E and F) and repetitively activated (G and H) responses using interpulse interval durations ranging from 10 to 160 milliseconds. Regardless of the protocol used, greater fatigue occurred at long muscle lengths than at short muscle lengths.

fatigued due to repetitive activation. Because all trains contained 6 pulses, the catchlike-inducing train response always ended sooner than the response of the comparable constant-frequency train. Thus, for a catchlike-inducing train to show a greater force-time integral, any increase in force produced at the onset of stimulation must be greater than the area "lost" due to the use of a briefer train.

We found a small amount of fatigue produced by repetitive activation. In general, constant-frequency and catchlike-inducing train force-time integral responses declined about 2% and peak force responses declined about 12% when averaged across all interpulse intervals. Previous work[25,26] has demonstrated less fatigability of human skeletal muscle at shorter lengths, but the profound lack of fatigue we found was somewhat surprising. In a previous study investigating fatigue as a function of muscle length, we observed a 40% decline in peak force at short muscle length (15° of knee flexion) compared with a 53% decline at long muscle length (90° of knee flexion).[25] In that study, we used a single 25-millisecond interpulse interval constant-frequency train to activate the muscle repetitively. In another of our previous studies,[11] which tested constant-frequency trains with interpulse intervals of 10 to 120 milliseconds and comparable catchlike-inducing trains, a 48% decline in force-time integral and a 47% decline in peak force were observed when the human quadriceps femoris muscle was held at a long length (90° of knee flexion). Because we used multiple frequencies in the present study, including frequencies that produced lower forces than the 120-millisecond interpulse interval train (Fig. 5), the inclusion of these lower frequencies (longer interpulse intervals) may have contributed to the lower amount of fatigue we observed. Our study of the subset of 4 subjects was used to investigate this possibility. We found that, independent of activating sequence, little fatigue was produced when the muscle was held at the shorter length. It appears, therefore, that our findings are consistent with previous findings that less fatigue occurs at shorter muscle lengths than at longer muscle lengths.

The ability to augment force during the control sequence at short muscle lengths may be due to the selective attenuation of force produced at low frequencies when muscles are held at short lengths.[20,21] This attenuation is consistent with observations that Ca^{2+} release per pulse[27,28] or Ca^{2+} sensitivity of the myofibrils[29–31] is diminished at short muscle lengths compared with long muscle lengths. Duchateau and Hainaut[32] demonstrated that one mechanism by which catchlike-inducing trains augment force is through the increased Ca^{2+} release from the sarcoplasmic reticulum by the initial high-frequency burst. Thus, greater Ca^{2+} release by catchlike-inducing trains could partially compensate for the decreased Ca^{2+} release or sensitivity when the muscle is held at short lengths.

Overall, the augmentations by catchlike-inducing trains following repetitive activation were substantially less than those observed at longer muscle lengths. Optimal catchlike-inducing trains (80-millisecond interpulse intervals) produced approximately 15% greater force-time integrals than comparable constant-frequency trains and approximately 6% greater force-time integrals than optimal constant-frequency trains (60-millisecond interpulse intervals). In a similar study,[11] at longer muscle lengths, optimal catchlike-inducing trains produced approximately 31% greater force-time integrals than comparable constant-frequency trains and approximately 25% greater force-time integrals than optimal constant-frequency trains. The relative lack of augmentation is probably due to the relatively small amount of fatigue produced in the present study. Nonetheless, catchlike-inducing trains appear to be effective in producing force augmentation in muscles at various lengths. Thus, train pattern is a variable that should be considered when attempting to optimize force.

Use of Short-Duration Stimulation Trains

We used short-duration stimulation trains in this study because short bursts of activity typify activation patterns needed to produce functional movements. Hennig and Lømo[33] found that motor unit discharge patterns in awake and freely behaving animals typically involved ≤6 action potentials. Additionally, because functional human movements typically require brief periods of activation of each muscle (eg, walking, eating), we anticipate that electrical stimulators designed to perform FES will require brief trains of activation to mimic natural movements. Lastly, all stimulators used in cardiomyoplasty, a procedure in which a skeletal muscle is wrapped around the heart and stimulated to assist systole, use 6-pulse trains.[34]

Clinical Implications

We attempted to define the boundary conditions for force augmentation by catchlike-inducing train stimulation. The optimal catchlike-inducing train produced more force than any constant-frequency train at short muscle lengths during both control and repetitive activation conditions. Because catchlike-inducing trains produce greater forces during these conditions, they may improve FES applications that require muscle activation at short lengths. Catchlike-inducing trains produce more rapid rates of rise of force than constant-frequency trains.[18,35] Therefore, faster FES-induced ambulation speeds, which have been reported to diminish the metabolic demand during FES by improving ambulation efficiency,[2] may be attained. Our results are consistent with our previous findings,[11] and they show maximal force-time integral production using interpulse interval durations of about 60 to 80 milliseconds (16.7–12.5 pulses per second). These frequencies are similar to the frequencies observed during physiological activation of motor units during maximal voluntary efforts.[36] Stimulation at interpulse interval durations of about 60 to 80 milliseconds produced forces that were subtetanic (ie, force production and relaxation are seen in response to each pulse within the train). The influence that these subtetanic trains may have on the smoothness of the movement produced during FES has yet to be determined.

Conclusions

This study shows that stimulation trains that exploit the catchlike property of skeletal muscle can augment forces from the human quadriceps femoris muscles held at short lengths in both control and repetitive activation muscle conditions. The human quadriceps femoris muscle demonstrated remarkable fatigue resistance to the repetitive activation sequence used in this study. This study is important in defining boundary conditions for the force augmentation seen with the use of catchlike-inducing trains. Finally, this study suggests the use of catchlike-inducing trains may be advantageous during FES. Clinical studies testing this hypothesis are needed.

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