# Reduction of the Fatigue-Induced Force Decline in Human Skeletal Muscle by Optimized Stimulation Trains

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ABSTRACT. Binder-Macleod SA, Lee SCK, Baadte SA. Reduction of the fatigue-induced force decline in human skeletal muscle by optimized stimulation trains. Arch Phys Med Rehabil 1997;78:1129-37.

**Objective:** To identify the stimulation pattern that optimizes the force-time integral produced during isometric contractions of fatigued human skeletal muscle.

**Design:** Twelve healthy subjects with no history of lower extremity orthopedic problems voluntarily participated.

**Results:** The primary findings were that (1) the optimized trains showed augmentation only from fatigued muscles and (2) a simple stimulation pattern, containing one brief (5msec) initial interpulse interval, produced the greatest force-time integrals and rates of rise of force. With muscle fatigue, the rate of rise of force of the constant-frequency train slowed, whereas the rate of rise of force of the optimized trains remained unchanged. This difference in the rate of rise of force may explain why the optimized trains, which take advantage of the catchlike property of skeletal muscle, are able to augment forces from fatigued muscles when compared with the constant-frequency train.

**Conclusions:** These results may have important clinical implications when using brief trains of electric stimulation to aid patients in performing functional movements and contribute to our understanding of the relationship between the activation pattern of a muscle and the force output produced.

IT HAS LONG BEEN KNOWN that during physiologic contractions the activation rate of each active motor unit affects the force output of the muscle.[1] Traditionally, the force-frequency relationship has been determined by using the responses of a muscle to a series of stimulus trains, with each train testing a different stimulation frequency. Recently, however, it has been shown that a muscle does not have a unique force-frequency relationship; rather, the force-frequency relationship is dynamic and depends on the activation history of the muscle.[2-4]

Many investigators have attempted to identify the optimal activation pattern for skeletal muscle. Stimulation trains that take advantage of the catchlike property of skeletal muscle have been shown to maximize muscle forces.[5-7] The catchlike property of skeletal muscle is the tension enhancement seen when a brief burst of pulses is added to the beginning of a subtetanic train of pulses.[3,5,8] A catchlike property has been observed in single motor units[7-9] and in whole human[10] and animal muscles.[5] This catchlike property has been suggested to be of possible benefit during physiologic activation by producing a predictable force-frequency relationship[3] and by augmenting force compared with constant-frequency stimulation.[10,11] During volitional contractions motor units have often been observed to fire with nonrepetitive discharge patterns that can take advantage of this catchlike property.[12-17]

The force augmentation seen because of the catchlike property varies as a function of the prior activity of the muscle, the type of motor unit being studied, and the specific pattern of stimulation used. The augmentation seen in fast-twitch and slow-twitch motor units with stimulation trains that produce a catchlike effect (henceforth called catchlike-inducing trains [CITs]) declines as the muscle becomes potentiated.[9,11] If repetitive activation of fast-twitch motor units continues following potentiation, the augmentation increases as the muscle fatigues.[11] Similarly, stimulation of whole muscles composed primarily of fast-twitch fibers with CITs produces much greater augmentation when the muscle is fatigued than when it is fresh but highly potentiated.[10,18] Burke and colleagues[9] showed that slow-twitch motor units exhibited greater augmentation than fast-twitch units when the muscles were potentiated but not fatigued. Similar differences have been observed between whole muscle composed primarily of fast- or slow-twitch motor units. The slow-twitch soleus muscle of the rat demonstrated significant force augmentation with CIT stimulation[5] but the predominantly fast-twitch rat gastrocnemius muscle exhibited little augmentation before the onset of fatigue.[19] Thus, although slow-twitch muscle appears to display augmentation from the onset of stimulation (ie, not fatigued), fast-twitch fatiguable motor units primarily exhibit augmentation with CITs when the muscle is either unpotentiated or fatigued.

The activation pattern that optimizes forces from nonfatigued cat single motor units[7] and rat whole muscles[5,6] has been shown to contain one or two brief (5 to 10msec) interpulse intervals (IPIs) at the onset of the stimulation train. To date, no studies have identified the optimal stimulation activation pattern for fatigued skeletal muscle. Thus, the purpose of this study was to identify the stimulation pattern that optimizes the force-time integral produced by fatigued human skeletal muscle. Preliminary results have been reported in abstract form.[20]

## METHODS

### Subjects

Twelve healthy subjects (eight men, four women) ranging in age from 20 to 26 years (mean = 21.7, SD = 1.8 years), with no history of lower extremity orthopedic problems, voluntarily participated in this study and signed informed consent agreements. This study was approved by our university's Human Subjects Review Board.

### Instrumentation and Procedures

Subjects were seated on a force dynamometer (fig 1) with their hips flexed to approximately 75° and their knees flexed to

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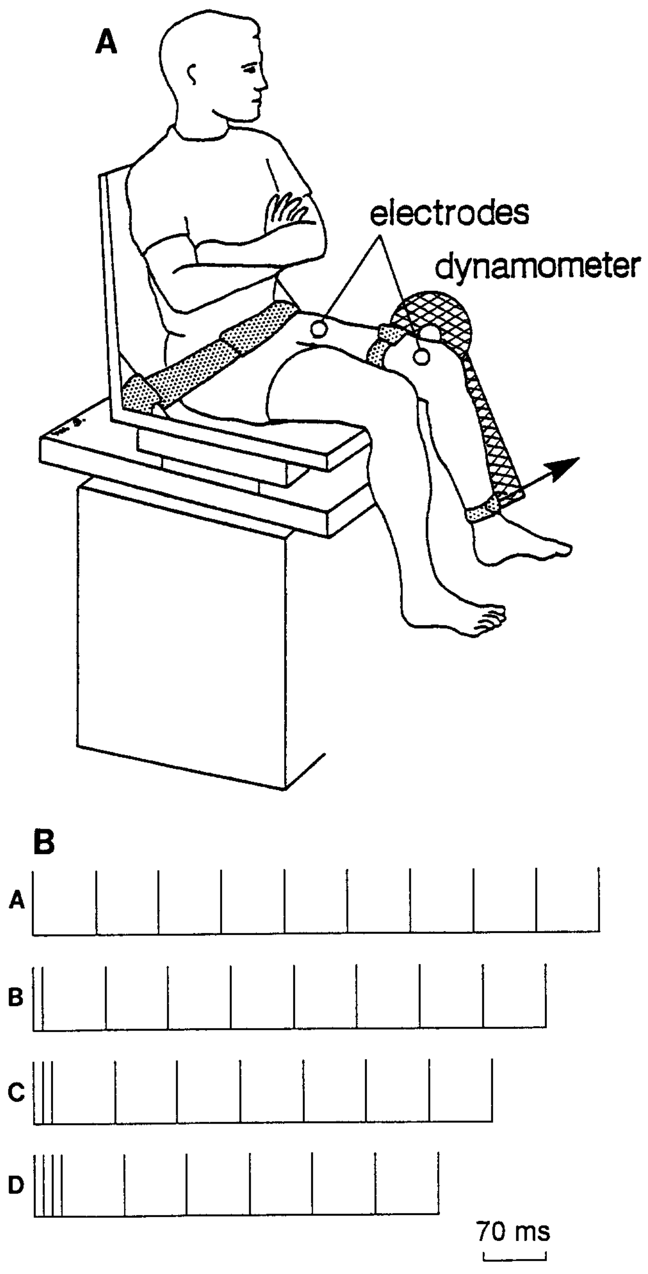

**Fig 1. (A) Schematic representation of the experimental setup used to test the left quadriceps femoris muscle and (B) stimulation trains used in the study. Trace A is the 10-pulse, 70-msec IPI, constant-frequency train. Each pulse within a train is represented by a vertical line. Trains B through D are examples of 10-pulse CITs with one, two, and three brief IPIs, respectively.**

95°. The left quadriceps femoris muscles were tested. The axis of the dynamometer was aligned with the axis of the knee joint, and the bottom of the force transducer pad was positioned against the anterior aspect of the leg approximately 4cm proximal to the lateral malleolus. The lower leg, thigh, and pelvis were stabilized using inelastic straps with Velcro closures. All contractions were isometric.

Two round, 7.5-cm-diameter carbon-rubber electrodes were secured to the thigh using elastic straps with Velcro closures that wrapped around the thigh. A 1.5-cm-thick sponge was placed under each electrode and saturated with tap water to ensure good electric conductivity. The anode was placed over the motor point of the rectus femoris and the cathode was placed over the motor point of the vastus medialis. A Grass S8800 stimulator with a Grass Model SIU8T stimulus isolation unit[a] was used to deliver 600-μsec pulses. The stimulator was driven by a personal computer that used customized software to control the timing parameters of each stimulation protocol. Data were digitized at 200 samples per second.

### Training Session

During training sessions, subjects were trained to perform two tasks. First, subjects were trained to perform maximum voluntary isometric contractions (MVICs) of their quadriceps femoris muscles. One-hundred-hertz, 10-pulse constant-frequency trains at a supramaximal intensity were delivered to the muscles during the voluntary contractions to determine if subjects were performing true MVICs.[21] If, during the voluntary contraction, the forces decreased or remained unchanged when the stimulation train was administered, the forces produced by the subjects were considered maximal. If the forces increased with stimulation, subjects rested approximately five minutes before attempting to perform another MVIC. Second, subjects were trained to relax their quadriceps femoris muscles during trains of electric stimulation similar to those used during testing. Relaxation was indicated by a smooth force baseline before stimulation, no evidence of volitional contraction during stimulation, and a rapid return to the baseline after stimulation. Verbal encouragement and visual feedback were used to train the subjects both to achieve an MVIC and to relax during electric stimulation. All subjects could perform an MVIC and relax during electric stimulation by the completion of the training session.

### Testing Sessions

The first testing session was separated from the training session by at least 48 hours, and successive testing sessions were separated by at least 72 hours. Subjects were asked to refrain from strenuous exercise 24 hours before each session. Data were collected at a stimulation intensity that produced peak forces equal to 20% of each subject's MVIC when using a 10-pulse, 70-msec IPI (14.3-Hz) constant-frequency train. Pilot work determined that this force level was the maximum that was tolerated well by all subjects during stimulation with a 70-msec IPI constant-frequency train. A constant-frequency train with a 70-msec IPI was used for testing because pilot testing showed that it produced a subtetanic response for all subjects (thus, should show a catchlike response) and because it produced a force-time integral that was greater than or equal to that produced by all other constant-frequency trains.

***First testing session.*** The muscle was potentiated with the 10-pulse, 70-msec IPI constant-frequency train delivered once every 5 seconds. The muscle was considered potentiated if the peak force output did not increase in response to three consecutive trains. As soon as the muscle was potentiated, which required between 5 and 10 stimulation trains, testing with a protocol that allowed a 10-sec rest between stimulation trains (nonfatiguing protocol) was begun (fig 2A). The protocol tested six stimulation patterns, the 10-pulse constant-frequency train with a 70-msec IPI and five 10-pulse CITs whose first IPI was either 5, 10, 15, 20, or 30msec and the remaining eight IPIs were 70msec. Stimulation began with the constant-frequency train and was followed by a random sequence of the five CITs, another constant-frequency train, the reverse order of the random sequence of CITs, and a final constant-frequency train. The CITs were presented randomly to remove any bias resulting

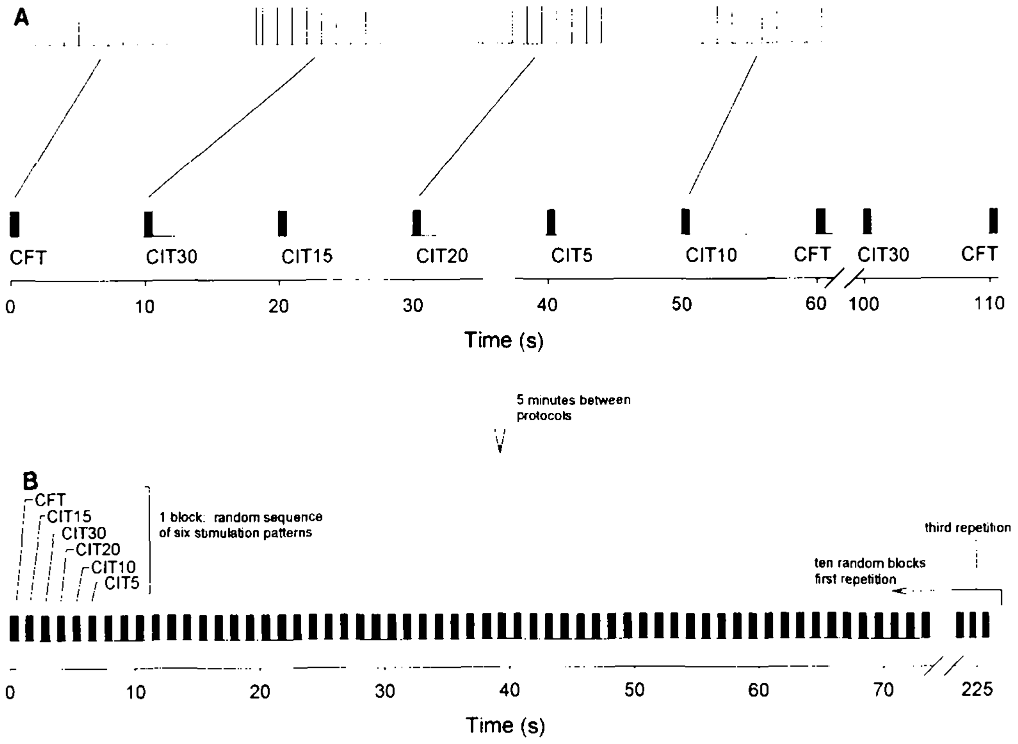

**Fig 2. Schematic representation of the stimulation protocol used during the first testing session: (A) nonfatiguing protocol; (B) fatiguing protocol.**

from differences in frequency and duration of the previous stimulation train. A different random order of CITs was used for each subject.

Five minutes after the nonfatiguing protocol the muscle was again potentiated and the fatiguing protocol commenced (fig 2B). The fatiguing protocol consisted of 180 trains with one train delivered every 1.26sec. Because the longest train (the constant-frequency train) lasted 630msec, the 1.26-sec train period produced a maximum duty cycle of 50%. The 180 trains were delivered in a pseudorandom sequence. To construct the fatiguing protocol, ten blocks of the six stimulation patterns being tested (ie, the constant-frequency train and five CITs previously identified) were used. Each block contained a different random sequence of the six stimulation patterns. These 60 trains were repeated three times to produce the 180 trains used to fatigue the muscles. Because we wanted to average the responses to each contraction within the fatigue test across subjects, the same sequence of trains was used for all subjects. The duration of the first IPI of the CIT that produced the greatest force-time integral when the muscle was fatigued was identified as the optimal first IPI for each subject.

***Second and third testing sessions.*** For the second testing session, the nonfatiguing and fatiguing protocols were similar to those used during the first testing session. However, all the CITs contained the optimal first IPI for each subject (which was identified during the previous testing session), and the second IPI was varied in the manner just described. The second IPI of the train that produced the greatest force-time integral when the muscle was fatigued was identified as the optimal second IPI. For the third testing session, nonfatiguing and fatiguing protocols tested CITs containing the optimal first and second IPIs for each subject and the third IPI was varied. Results from the fatigue test were used to identify the optimal third IPI.

## Data Management

The dependent variables analyzed were the force-time integral, peak force, and time needed to reach 80% of peak force (T80). The force-time integral, the area under the force trace, is a measure of the total force output of the muscle and was used to identify the optimal stimulation train.[7,22] Peak force, the highest value relative to the baseline force occurring within the force trace, was also used as a measure of force production. T80, the time from the onset of force to the first time force reached 80% of peak force, is a measure of the rate of tension production.[5] Linear interpolation between data points was used to estimate T80.

Nonfatigue data were the averages of responses to the three constant-frequency trains and the two CITs at each of the five IPI durations tested. Only a +0.8% (SD = .05%) change in the force-time integral and a +5.4% (SD = .56%) change in the peak force were noted between the first and last trains, which were both constant-frequency trains, indicating that the data were obtained from nonfatigued muscles. The averaged responses of the ten replicated trains of each of the six stimulation patterns tested during the last 60 contractions of the fatigue protocol were used to represent the fatigued data. This averaging of ten responses to each stimulation train served to minimize the effects of the differences in the activation history (ie, frequency and duration of the previous train) among the stimulation patterns tested.

## Data Analysis

The nonfatigued and fatigued data were analyzed independently. A two-way repeated-measure analysis of variance (ANOVA), including only the responses to the CITs, was performed with IPI duration (ie, 5, 10, 15, 20, and 30msec) and IPI number (ie, first, second, or third IPIs varied) as factors (fig 3). If there were a significant main effect for IPI durations and a significant interaction effect, one-way repeated-measures ANOVAs were used to determine for which of the three IPI numbers (ie, first, second, or third intervals) did varying the duration have an effect. To do this, the responses using only the five CITs when the first IPI duration was varied were analyzed separately; similar analyses were performed when the second and third IPIs

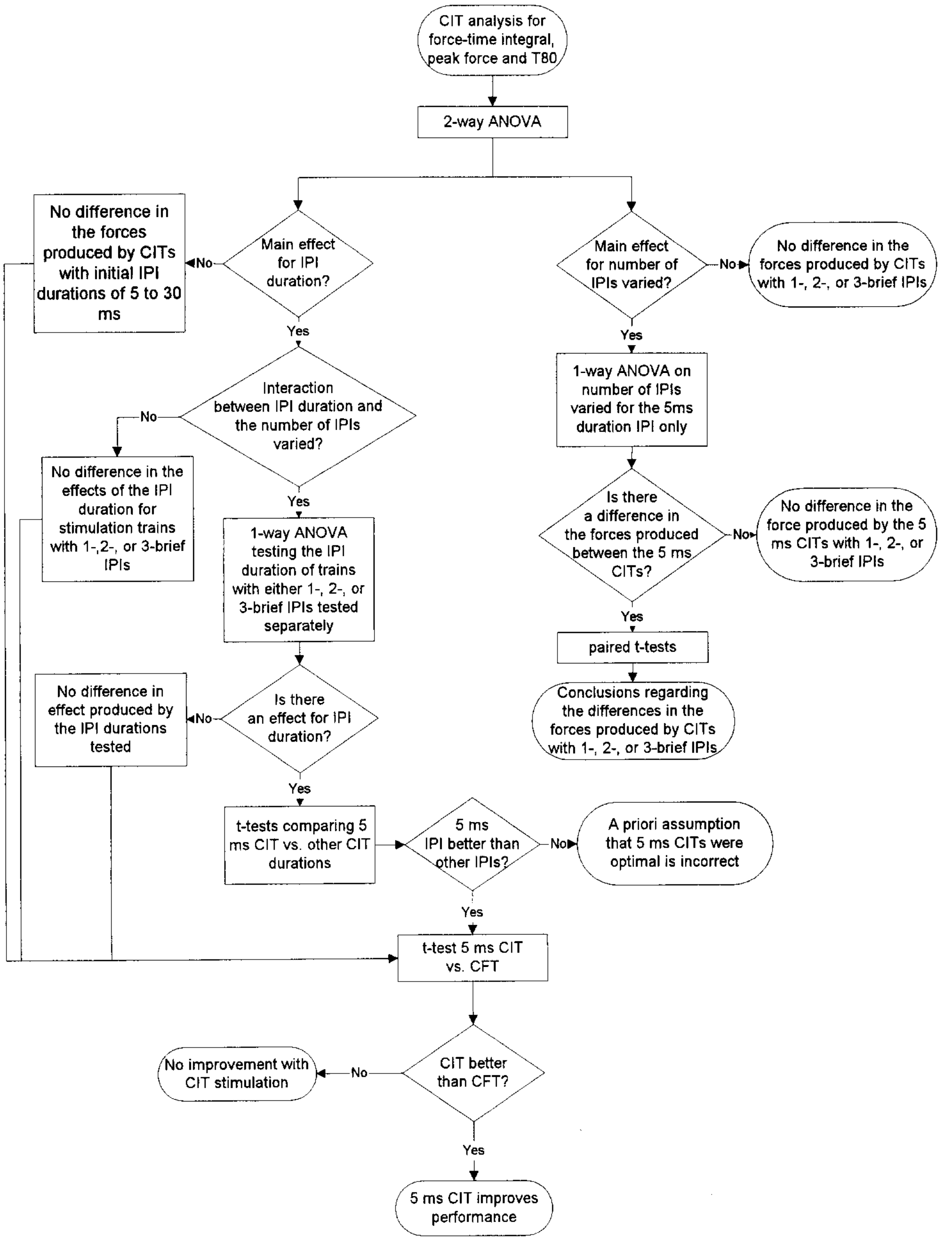

**Fig 3. Flowsheet outlining the statistical approach used to analyze the data.**

were tested. If no interaction was observed, these one-way ANOVAs were not performed. Because previous investigations and pilot data suggested that the CITs with the 5-msec IPI durations would produce the best responses,[23,24] paired *t* tests were used to compare the 5-msec CITs with the other CITs. This post hoc testing was only performed if varying the IPI duration had an effect. Next, because no CITs were better than the 5-msec CITs, the 5-msec CITs were compared with the constant-frequency trains using paired *t* tests. Finally, if the two-way ANOVA showed a significant main effect for the IPI number, a one-way repeated-measures ANOVA was performed to compare the 5-msec CITs when the first, second, and third IPIs were varied. If there was a significant difference among the three trains, paired *t* tests were used to compare the responses for the three stimulation trains. For all analyses, an observation was significant if $p \leq .05$.

## RESULTS

Figure 4 shows the nonfatigued and fatigued responses of a representative subject to stimulation with the 70-msec IPI constant-frequency train and optimized trains with one, two, or three brief interpulse intervals. It should be noted that, because all trains contained ten pulses, increasing the number of brief IPIs caused the optimized trains to end progressively sooner than the constant-frequency trains. In addition, as was typical for the group data, in the nonfatigued state there were small differences in the peak forces produced by the constant-frequency train and any of the optimized trains. In contrast, when the muscle was fatigued, the optimized trains markedly augmented the peak forces. Similarly, the optimized trains produced a much greater rate of rise of force when the muscle was fatigued than when the muscle was in the nonfatigued state.

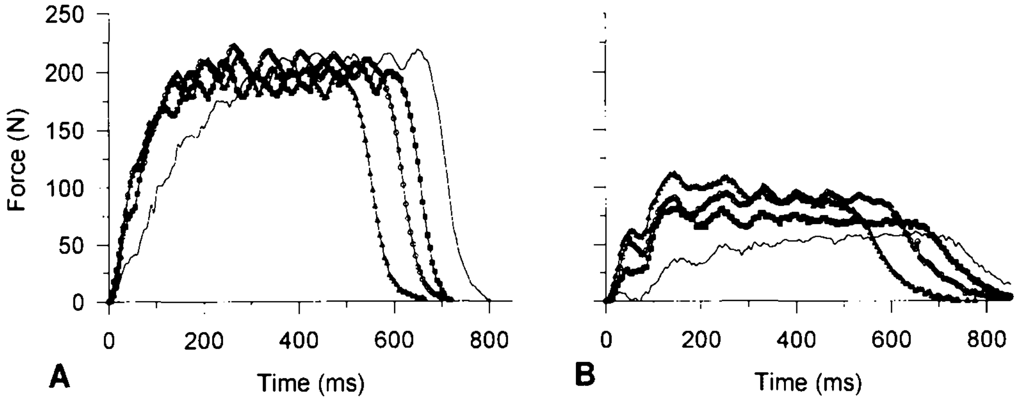

**Fig 4. (A) Nonfatigued and (B) fatigued force responses to stimulation from a representative subject:—, CFT; ■, one brief IPI; ○, two brief IPIs; ▲, three brief IPIs.**

## Force-Time Integral

In the control condition, when the muscle was potentiated and not fatigued, the force-time integrals produced during stimulation with optimized trains progressively decreased as the number of brief IPIs increased (fig 5A). The 5-msec optimized trains with one, two, and three brief IPIs produced approximately 3%, 10%, and 17% decreases in force-time integrals, respectively (T = 4.03, 6.50, and 11.02, all $p < .01$). Because the nonfatigued muscles produced greater force-time integrals in response to constant-frequency train stimulation than in response to the optimized trains, no further analysis of the nonfatigued muscle responses was conducted.

Although the constant-frequency trains produced greater force-time integrals from the nonfatigued muscles than the CITs, by about the 40th contraction of the fatigue test the optimized and constant-frequency trains were producing comparable force-time integrals (fig 6). However, by the end of the fatigue test the optimized trains with one, two, and three brief IPIs all produced significantly greater force-time integrals than the constant-frequency trains (fig 5B). The 5-msec optimized trains with one, two, and three brief IPIs produced approximately 36%, 52%, and 35% greater force-time integrals than their respective constant-frequency trains (T = 8.98, 6.81, 5.72, all $p < .001$). Varying the interpulse interval duration of the optimized trains only had a significant effect for trains with one or two brief IPIs (F = 51.53, 6.26, both $p < .001$). For trains with one brief IPI, the 5-msec optimized trains produced significantly greater force-time integrals than all other optimized trains. For trains with two brief IPIs, although no trains produced greater forces than the 5-msec optimized trains, the 5-msec optimized trains only produced significantly greater force-time integrals than the 20- and 30-msec optimized trains. Interestingly, there were no significant differences in the force-time integrals produced by the fatigued muscles in response to the optimized trains with one, two, or three brief IPIs.

## Peak Force

In nonfatigued muscles, the 5-msec optimized trains with one, two, and three brief IPIs produced approximately 9%, 3%, and 5% greater peak forces than their respective constant-frequency trains. The improvements, however, were only significant for the optimized trains with two and three brief interpulse intervals (fig 7A) (T = 2.91, 2.70, both $p < .05$; nb for 5-msec optimized trains with 1 brief IPI; T = 2.07, $p = .06$). There were no significant differences in the peak forces produced by the optimized trains as the duration or number of brief IPIs was varied.

The optimized trains produced greater augmentation of peak forces when the muscles were fatigued than was observed in the nonfatigued state (fig 7B). The duration of the initial IPIs significantly affected the peak forces for trains with one, two, and three brief intervals (F = 42.14, 18.51, 8.97; all $p < .001$). For trains with one-brief interpulse interval, the 5-msec optimized trains produced significantly greater peak forces than all other optimized trains. In contrast, although no optimized train produced greater forces than the 5-msec CIT, the 5-msec optimized train only produced significantly greater peak forces than the 20-msec and 30-msec optimized trains when the second IPI duration was varied, and the 30-msec optimized train when the third interpulse interval duration was varied. The 5-msec optimized trains with one, two, and three brief intervals produced about 48%, 72%, and 43% greater peak forces than their respective constant-frequency trains (T = 6.57, 8.12, 9.64; all $p < .001$). Comparisons of the three 5-msec optimized trains

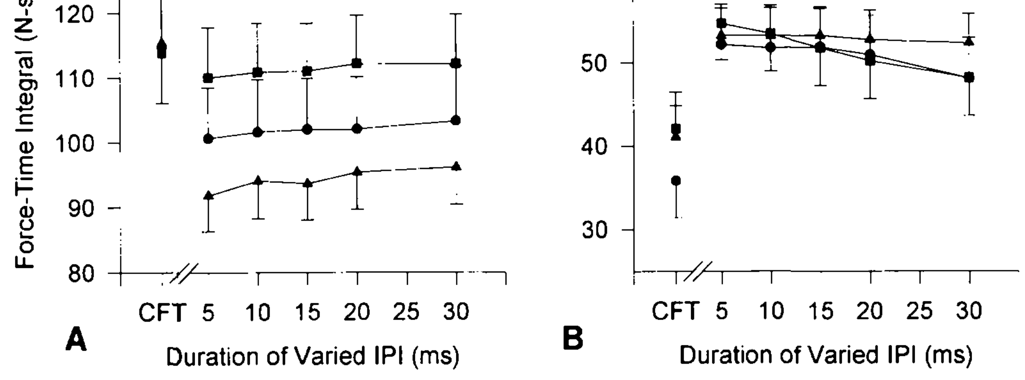

**Fig 5. Force-time integrals in a group of 12 subjects by (A) nonfatigued and (B) fatigued muscles in response to constant-frequency (CFT) and CIT stimulation with one (■), two (●), and three (▲) brief IPIs.**

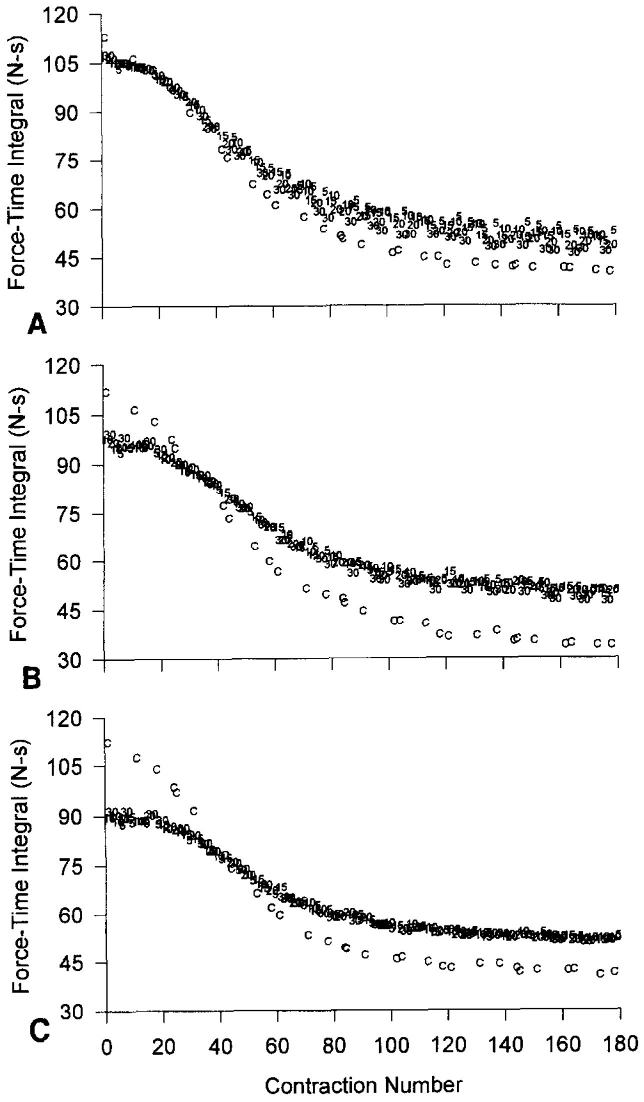

**Fig 6. Average force-time integrals ($n = 12$) to each of the 180 stimulation trains during the fatigue test when varying the (A) first, (B) second, and (C) third IPIs. The plotted letters "c" represent the responses to the constant-frequency trains; the numbers represent the duration (in milliseconds) of the IPI that was varied.**

showed the only significant difference was that the 5-msec optimized trains with three-brief interpulse intervals produced greater peak forces than the 5-msec optimized trains with one-brief IPI (T = 2.86, $p < .05$) (fig 7B).

### T80

In nonfatigued muscle, T80s were significantly shorter for the optimized trains with one, two, and three brief IPIs than the constant-frequency trains (T = 6.83, 5.55, 2.73, all $p < .05$) (fig 8A). The 5-msec optimized trains with one, two, and three brief IPIs needed 47, 68, and 32 fewer milliseconds than their respective constant-frequency trains to reach 80% of peak force. There were no significant differences in the T80s for the optimized trains as the duration or number of brief IPIs was varied.

The differences in T80 between the 5-msec optimized trains and constant-frequency trains became greater with fatigue (fig 8B). The 5-msec optimized trains with one, two, and three brief intervals needed 212, 214, and 157 fewer milliseconds than their respective constant-frequency trains to reach 80% of peak force (T = 9.00, 5.74, 4.49, all $p \leq .001$). The duration of the brief IPIs significantly affected T80 only for optimized trains with one brief interval (F = 5.43, $p = .001$). The 5-msec optimized trains produced significantly shorter T80s than all other optimized trains except the 10-msec optimized train. There was no significant difference in T80 for the optimized trains as a function of the number of brief IPIs contained within the train.

Figure 9 shows the normalized force responses averaged across all 12 subjects in response to stimulation with the constant-frequency train and the 5-msec optimized train with one brief IPI in the nonfatigued and fatigued states. Each train is normalized to the maximum force produced within that train. This figure shows that the normalized rate of rise of force of the constant-frequency trains declined with fatigue and that the normalized rate of rise of force produced by the optimized trains remained unchanged.

## DISCUSSION

This study was undertaken to identify the stimulation pattern that optimizes the force-time integral produced by fatigued human skeletal muscle. A relatively simple pattern, containing one brief (5msec) initial IPI, produced force-time integrals and rates of rise of force that were greater than the constant-frequency trains and greater than or equal to all other trains tested.

The present results, showing augmentation only during stimulation with the optimized trains when the muscles were fatigued, are consistent with previous reports for fast-twitch motor units from the hindlimbs of cats[9,11] and human whole muscle.[10] As

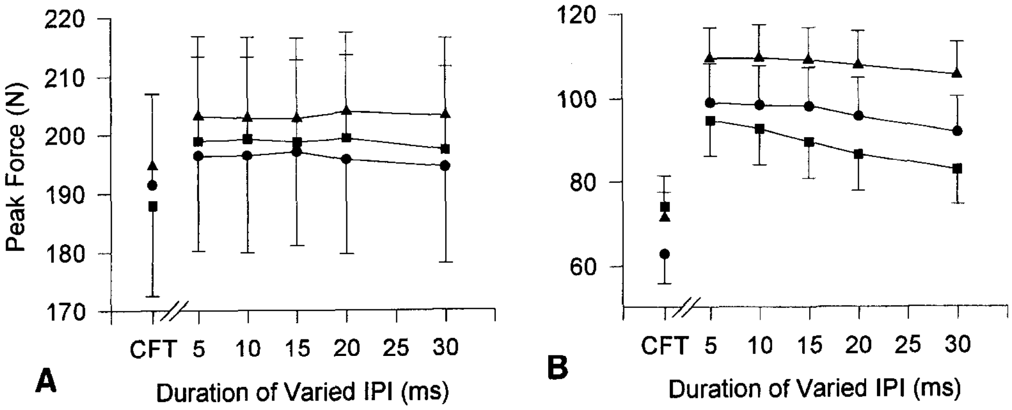

**Fig 7. Peak forces produced in 12 subjects by (A) nonfatigued and (B) fatigued muscles in response to constant-frequency (CFT) and CIT stimulation with one (■), two (●), and three (▲) brief IPIs.**

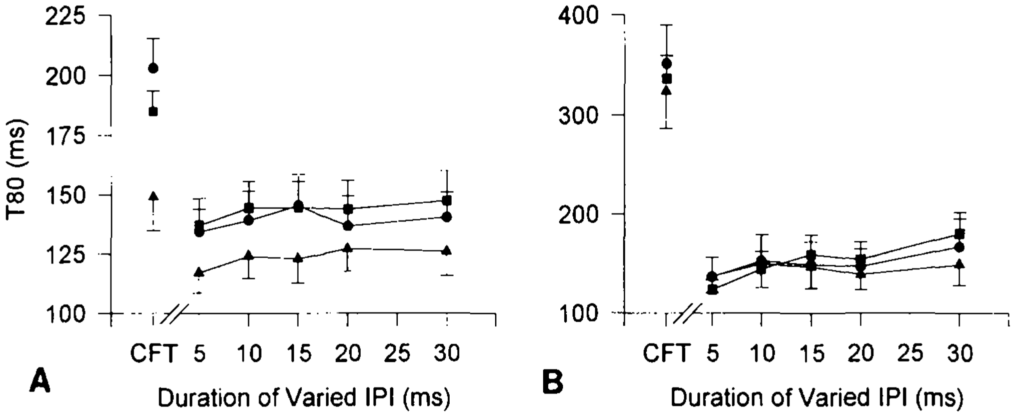

**Fig 8. T80s produced in 12 subjects by (A) nonfatigued and (B) fatigued muscles in response to constant-frequency (CFT) and CIT stimulation with one (■), two (●), and three (▲) brief IPIs.**

first reported by Burke and colleagues[8,9] and more recently confirmed by Bevan and colleagues,[11] although unpotentiated, fast-twitch motor units show force augmentation when stimulated with CITs, this augmentation disappears as the motor units become potentiated. This finding suggests that the catchlike property and force potentiation may share a common mechanism.[9] Bevan and colleagues[11] also showed that as the fast motor units fatigued, the CITs again markedly augmented the force. The muscle presently studied, the human quadriceps femoris muscle, has been reported to contain approximately 60% fast-twitch motor units.[25,26] Binder-Macleod and Barker[10] also showed for human quadriceps femoris muscle that augmentation with CITs was only seen from the highly potentiated muscle when the muscle was fatigued. Although the studies just cited showed augmentation in the fatigued state, none attempted to identify the optimal pattern for activation when it was fatigued. Similar to the present results for fatigued muscle, previous studies of nonfatigued mammalian skeletal muscle have found that the optimal initial IPI of the CIT is about 5 to 10msec and that only one or two brief initial IPIs are needed.[5-7,27,28]

The force augmentation observed in the present study when the muscle was stimulated with the optimized trains appears to be related to the rate of rise of force of the constant-frequency train. As can be seen in figure 4, the CIT responses always ended sooner than the responses to the constant-frequency stimulation trains because all the trains contained the same number of pulses. If stimulation with the CIT is to produce a greater force-time integral than stimulation with the constant-frequency train, any increase in force produced at the onset of stimulation must be greater than the area "lost" at the end of the train. In the nonfatigued state, the optimized train reached 80% of its maximum force only about 50msec sooner than the constant-frequency trains (fig 8A). Thus, in the nonfatigued state the greater forces produced at the onset of the train did not compensate for the force lost at the end of the train. In contrast, during fatigue, the T80 of the optimized train was more than 200msec sooner than for the constant-frequency train (fig 8B). This difference in the rate of rise of force was now sufficient to make up for any lost area at the end of the train resulting in the CITs producing greater force-time integrals than the constant-frequency trains when the muscle was fatigued.

As can be seen in figure 9, the increase in the difference in the T80 between the optimized train and the constant-frequency trains as the muscle became fatigued was due to slowing in the rate of rise of force for the constant-frequency trains with no change in the rate of rise of force in the CITs. Several mechanisms may account for this difference. The rate of rise of force from a muscle is directly dependent on the activation rate of the muscle. High-frequency stimulation produces a greater rate of rise of force than low-frequency stimulation. Fatigue of long duration is known to produce greater attenuation of forces at low frequencies of stimulation than at high frequencies and a drop in the twitch-to-tetanus ratio.[29,30] This attenuation of force to low-frequency stimulation may be the result of either decreased calcium release from the Sarcoplasmic reticulum or decreased Ca$^{2+}$ sensitivity of the myofilaments that accompany fatigue.[31] The attenuation of the response to low-frequency stimulation can be seen in figure 9 by comparing the normalized responses to the first pulse of the constant-frequency train when the muscle was not fatigued (right-pointing arrow) with the

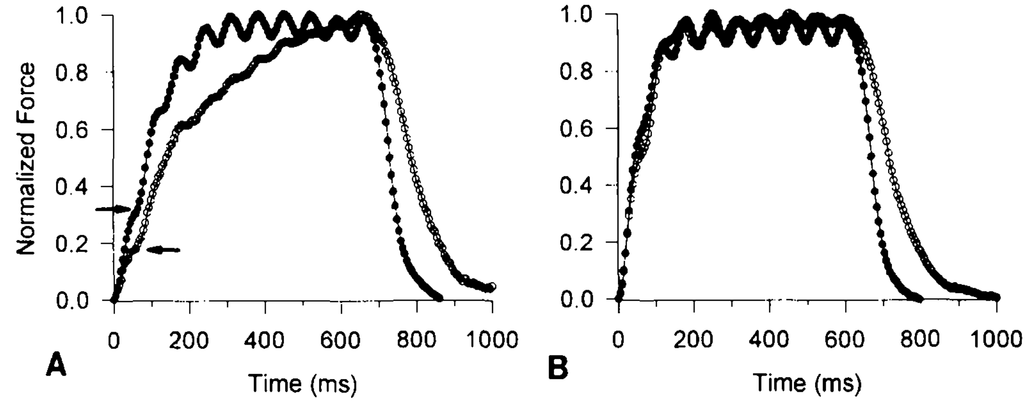

**Fig 9. Normalized group ($n = 12$) nonfatigued (●) and fatigued (○) force responses to (A) constant-frequency (CFT) and (B) CIT stimulation. Arrows identify the response to the first pulse of the CFT in the nonfatigued (→) and fatigued (←) states.**

response when the muscle was fatigued (left-pointing arrow). The normalized twitch response declines by approximately 50% with fatigue. The initial doublet can overcome this low-frequency attenuation, however, and produce a nearly identical force profile at the beginning and end of the fatigue protocol. Thus, the CITs by containing an initial high-frequency burst can eliminate the slowing in the rate of rise of force and, therefore, show less attenuation of force during fatigue than comparable constant-frequency trains.

### Implications of Present Findings

The present results may have important clinical implications when using electric stimulation to aid patients with lower extremity paralysis to stand or walk.[32-35] Current clinical protocols use about 30 to 60 pulse/sec constant-frequency trains to activate the muscles. A major limitation of this application, however, is the rapid muscle fatigue experienced during stimulation.[32,33,36] Using stimulation trains with lower frequencies could reduce the rate of fatigue[37]; however, lower-frequency trains produce lower rates of rise in force and lower peak forces than higher-frequency trains (eg, 30 to 60 pulse/sec). This study suggests that greater forces and more rapid rates of rise of force in fatigued muscle can be obtained with the use of CITs than with low-frequency constant-frequency trains. Future studies will need to compare the rates of rise of force, peak forces, force-time integrals, and fatigue rates between CITs and higher-frequency constant-frequency trains currently used in clinical practice.

This study also provides insight into understanding the relationship between the pattern of activation of skeletal muscle used by the central nervous system and the force output produced. Similar to previous studies that have shown that the force-frequency relationship of muscle changes as a muscle fatigues,[2,4,29,38-40] the present results demonstrate that the augmentation seen during activation of a muscle with stimulation patterns that take advantage of the catchlike property may vary with the fatigue state of a muscle. For the human quadriceps femoris muscle it appears that CITs are most effective in augmenting forces when the muscle is fatigued. It needs to be determined if this relationship is true for other muscles.

## CONCLUSION

The results show that a very simple stimulation pattern, containing one brief (5-msec) initial IPI, optimized the force-time integrals and rate of rise of force from the fatigued human quadriceps femoris muscle. It is interesting to note that for all muscles whose forces have been shown to be optimized with CITs that the optimal pattern is very similar to that presently observed for the human quadriceps femoris muscle. These results may have important clinical implications when using brief trains of electric stimulation to aid patients in performing functional movements and contributes to our understanding of the relationship between the activation pattern of a muscle and the force output produced.

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