

ABSTRACT: The purpose of this study was to determine the effect of three different stimulation patterns on repetitive knee movements. Each subject's quadriceps femoris was stimulated with: (1) a constant-frequency train (CFT) with an interpulse interval (IPI) of 50 ms; (2) a variable-frequency train (VFT)—similar to the CFT, except with an initial doublet with an IPI of 5 ms; and (3) a doublet-frequency train (DFT) with multiple doublets (doublet IPI 5 ms) separated by 50 ms, while the muscle was resisted by a load equal to 10% of the muscle's maximum voluntary isometric contraction. The muscle was stimulated while the knee moved through a 50° arc of motion (90° to 40° of flexion). Testing was stopped when the subject failed to reach the target three consecutive times. Results showed that DFTs reached the target (mean \pm SD) 36.4 \pm 14.4 times, followed by VFTs (25.4 \pm 17.9) and CFTs (17.4 \pm 11.9). The DFT was the best pattern for producing shortening contractions. The results suggest that DFTs may have significant benefits during clinical functional electrical stimulation.

© 2001 John Wiley & Sons, Inc. *Muscle Nerve* 24: 744–752, 2001

A NOVEL STIMULATION PATTERN IMPROVES PERFORMANCE DURING REPETITIVE DYNAMIC CONTRACTIONS

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Accepted 17 January 2001

Functional electrical stimulation (FES) is the coordinated electrical excitation of paralyzed or weak muscles in patients with upper motor neuron injuries to produce purposeful movements.^{26,32,35} Functional activities often demand repetitive contractions of the muscle being stimulated. Achieving such performance during FES applications, however, presents a great challenge due to muscle fatigue.^{17,19} Recent attempts to maximize muscle performance have focused on studying the effects of altering the frequency and pattern of the stimulation delivered to the muscle.^{8,11,17,19,34} Whole muscles^{2,13} and single motor units²¹ show a sigmoid relationship between stimulation frequency and peak force generated, with higher frequencies resulting in the great-

est forces. High-frequency stimulation, however, generally produces greater muscle fatigue than low-frequency stimulation.³

During FES applications, pulses within a stimulation train are traditionally delivered with consistent spacing between pulses, so that the entire train has a constant frequency. These trains are termed constant-frequency trains (CFTs).^{4,28,35} However, during volitional activation, motor units fire with varying frequencies, including short, high-frequency bursts.^{18,23,27} It has been suggested that the central nervous system uses these brief bursts of pulses to take advantage of the catchlike property of skeletal muscle.¹⁰ The catchlike property of skeletal muscle is the tension enhancement produced by a short high-frequency burst of pulses at the beginning of a lower frequency train of pulses.^{8,10} Traditionally used CFTs can be altered to take advantage of the catchlike property by adding a high-frequency burst (e.g., 100 Hz) at the beginning of the CFT. These trains, which have more than one frequency, have been termed variable-frequency trains (VFTs).^{7,8,17,19,34}

Abbreviations: ANOVA, analysis of variance; CFT, constant-frequency train; DFT, doublet-frequency train; FES, functional electrical stimulation; IPI, interpulse interval; MVIC, maximum voluntary isometric contraction; SR, sarcoplasmic reticulum; VFT, variable-frequency train

Key words: functional electrical stimulation; doublets; dynamic contractions; human quadriceps femoris muscle; stimulation patterns

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Compared to similar CFTs, VFTs produce faster rates of rise of force and higher average forces, peak forces, and force–time integrals during isometric contractions.^{2,4,7,8,37} During nonisometric contractions, VFTs augment average power, peak power, peak forces, and excursions when compared to similar CFTs.^{6,24,34} The augmentation in force with VFTs is greater when the muscle is fatigued than when fresh.^{2,6,7}

Recent studies have compared the fatigue produced by repetitive activation of a muscle with CFTs and VFTs. They have shown that, although VFTs are more fatiguing than CFTs, the VFTs produced greater forces than CFTs at the end of a fatiguing protocol (i.e., there was still augmentation with the VFTs).^{8,9} All studies that have compared the fatigue produced by CFTs and VFTs used isometric contractions. We believe that the use of shortening contractions, however, may be more appropriate to evaluate VFTs, because such contractions more closely approximate functional movements. All previous studies have controlled (fixed) the number of pulses within a train delivered to the muscle when comparing VFTs with CFTs and measured the muscle's performance after a controlled number of trains was delivered to the muscle. In contrast, functional activities are time- or task-dependent, without constraint on the number of pulses delivered to the muscle. The current study, therefore, compares CFTs with VFTs without dictating the number of pulses delivered to the muscle. Each stimulation train is terminated each time the knee joint reaches a target angle during repetitive knee extension.

We used two nontraditional stimulation trains (Fig. 1): VFTs containing an initial doublet, which have been studied previously^{2,8,24,34,37}; and a novel train, where each individual pulse within the train is replaced with a doublet (DFT). Doublets are pairs of closely spaced pulses, typically with a 5–10-ms interpulse interval. DFTs have not been extensively studied.^{19,29,30} Modeling work from our laboratory has shown that DFTs may have greater potential for augmenting forces than VFTs.^{5,14} The purpose of this study, therefore, was to determine whether there is a difference in the ability of CFTs, VFTs, and DFTs to perform dynamic repetitive (once every 2 s) contractions of the quadriceps femoris muscle.

METHODS

Eighteen healthy subjects (12 women and 6 men), ranging in age from 20 to 34 years (mean 25.3, SD 4.6), without history of orthopedic or neurological abnormality of the lower extremity, were studied. The study was approved by the University of Dela-

ware Human Subjects Review Board, and all subjects signed informed consent forms.

Experimental Setup. Subjects were seated on a computer-controlled dynamometer (KinCom III 500-11, Chattecx, Chattanooga, TN) with their hips flexed to $\sim 85^\circ$. The dynamometer axis was aligned with the knee joint axis, and the force transducer pad was positioned anteriorly against the tibia, ~ 4 cm proximal to the lateral malleolus. Two 3-in. \times 5-in. self-adhesive stimulating electrodes were used, with the anode placed proximally over the rectus femoris motor point, and the cathode placed distally over the vastus medialis motor point.¹ The cathode was applied with the knee at 15° of flexion to compensate for skin movement during knee extension. The trunk, pelvis, and thigh of the leg being tested (the dominant leg) were each stabilized with inelastic straps. A Grass S8800 stimulator with a SIU8T stimulus isolation unit (Grass Instruments, Quincy, MA) was used for stimulation.

Stimulation Trains. The three different types of trains used during experimental testing were constant-frequency trains with an interpulse interval (IPI) of 50 ms (CFTs), variable-frequency trains with an initial doublet (5 ms IPI) and all remaining IPIs equal to 50 ms (VFTs), and trains with doublets (5 ms IPI) separated by 50 ms (DFTs), as illustrated in Figure 1. The maximum number of pulses was 25 for the CFT and 26 each for the VFT and DFT. All pulses were 600 μ s in duration. A 5-ms IPI doublet was used because previous animal and human studies have shown that, to produce the greatest performance during isometric or shortening contractions, the initial bursts should have two to four pulses with an IPI of 5–10 ms, regardless of the contractile speed of the muscle.^{6,19,24,40} The 50-ms IPI was used for CFTs and VFTs, because a recent study investigating the effect of frequency on quadriceps muscle performance during shortening contractions showed that ~ 50 -ms IPIs produced maximum work, peak power, average power, and excursion for CFTs and VFTs when the muscles were fresh; slightly shorter IPIs were needed to produce maximum performance when the muscles were fatigued.²⁵

Experimental Testing. Before any stimulation was delivered to the muscle, all subjects were given the instruction, "relax as much as possible during stimulation, and do not assist the stimulation in moving the leg." Testing first involved determining the quadriceps muscle's maximum voluntary isometric contraction (MVIC) force with the knee at 90° of flex-

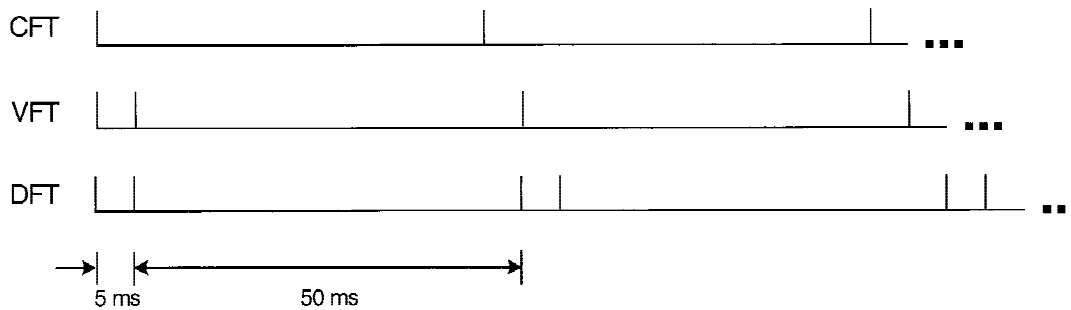


FIGURE 1. A schematic representation of the three types of stimulation trains used. Each vertical line represents a 600- μ s pulse. Top trace: constant-frequency train (CFT) with all interpulse intervals (IPIs) of 50-ms duration; middle trace: variable-frequency train (VFT) with the same IPIs as the CFT except for the initial doublet IPI of 5 ms; bottom trace: doublet-frequency train (DFT) with doublets throughout at interdoubt IPIs of 50-ms duration. The maximum allowable number of pulses was 25 for the CFT, and 26 each for the VFT and DFT.

ion. A burst superimposition technique was used to verify that a maximal contraction was being performed.³⁶ A supramaximal, 100-Hz, 10-pulse burst was used. Subjects were included in the study only if their voluntary effort was $\geq 95\%$ of their combined supramaximal stimulus and voluntarily elicited force. Next, the dynamometer's arm was rotated to hold the subject's leg at 15°, 30°, 45°, and 60° of knee flexion. At each angle, 10 s of force data were collected while the subject was instructed to relax their limb. For each angle, a cosine function was used to determine the weight of the leg. The average of the four values was used for gravity correction during data analysis.²⁵ The stimulation intensity was then set while the knee was held at 90° of flexion so that the 25-pulse CFT produced approximately 20% of the subject's MVIC force. The muscle was then repetitively stimulated (one train every 5 s) with the CFT to potentiate it. After the muscle was potentiated (i.e., the force did not increase between successive trains), which required three to five trains, the intensity was readjusted to produce 20% of the subject's MVIC. The intensity was not changed for the remainder of the experiment in an attempt to recruit a consistent population of motor units. The subject rested for 5 min before the muscle was repotentiated with 10, 7-pulse, 100-Hz trains (one train every 5 s). Within 5 s of repotentiating the muscle, testing began. The dynamometer was switched to the isotonic mode, which was previously set to provide a load equal to 50% of the subject's electrically elicited force (10% of the subject's MVIC force). The dynamometer was set so that the velocity of movement could vary to the dynamometer's maximum speed (250°/s). A custom-made hardware circuit terminated (truncated) the stimulation when the knee reached the 40° flexion target angle (i.e., a minimum of 50° of range of motion) and disarmed the stimulator until the leg returned to the starting po-

sition. The dynamometer was set so that the weight of the leg returned the leg and the dynamometer arm to the starting position. Stimulation was repeated every 2000 ms. If the knee failed to reach the target three consecutive times, testing was stopped and the subject rested for 10 min before the next stimulation pattern was tested.

Testing for all three different trains was performed in one session, with 10 min of rest between each test. Because ordering effects were likely, a counterbalanced repeated-measures design was used to control or account for the ordering (practice) effects.^{20,33} The three types of stimulation trains (CFT, VFT, and DFT) resulted in six possible combinations of systematically varied train-type sequences. The sequences were: (1) CFT-VFT-DFT; (2) CFT-DFT-VFT; (3) VFT-CFT-DFT; (4) VFT-DFT-CFT; (5) DFT-CFT-VFT; and (6) DFT-VFT-CFT. An equal number of subjects ($n = 3$) was randomly assigned to each sequence so that ordering effects were evenly spread across treatment conditions. Ordering effects are a common problem in repeated-measures designs, and counterbalancing ensures that the observed differences in the mean scores reflect differences in treatments, without contamination by practice effects.²⁰

Data Management. Force, angle, and velocity data were collected directly from the dynamometer at a sampling rate of 200 Hz. All force responses were gravity corrected for leg weight. The dependent variables studied were: (1) number of times the leg reached the target joint angle, which represented the primary outcome measurement; (2) time (milliseconds) required for the leg to move from the 90° starting position to the 40° target joint angle; (3) number of pulses needed for each train to reach the target; (4) total work (joules); (5) average power (watts); and (6) knee joint excursion (degrees). The

variables were calculated for each shortening contraction using custom-written software (LabView 4.0.1, National Instruments, Austin, TX). Work was calculated as the integral (trapezoid method) of force times the arc of the movement (joint displacement in radians times the force transducer's lever arm) from the time of force onset to the time of maximum excursion. Average power was calculated as work divided by the time interval from force onset to the target angle. Excursion was calculated as the maximum knee joint displacement. Although stimulation was stopped at the 40° target angle, excursions of >50° could be attained because of the momentum of the leg.

Data Analysis. The number of times the leg reached the target and, for the first and the last contractions that reached the target, the time, number of pulses, work, and average power required for the leg to reach the target were used for data analysis. Because the design was counterbalanced, and therefore there was no need to treat order as a second factor, a one-way repeated measures analysis of variance (ANOVA) was used to determine the effect of train type on each dependent variable. Paired *t*-tests with Holm's sequentially rejective Bonferroni correc-

tions were used for post hoc comparisons.²² Statistical significance was set at *P* = 0.05 for all tests.

RESULTS

Generally, DFTs produced the best performance (the number of times the target was reached, the time required to reach the target, work, average power, and the excursion produced in response to each train tested), followed by VFTs and CFTs. For a typical subject, plots of the time required for the knee to reach the target joint angle, work, average power, and the excursion produced in response to each train tested are shown in Figure 2. Only a slight improvement in performance (i.e., decrease in time required to reach the target, and increase in work, average power, and excursion) was seen when the VFT was compared to the CFT. In contrast, the DFT showed much greater improvement in these variables compared to the CFT or VFT. For the same subject, Figure 3 shows the knee joint angle plotted versus time for the three train types during the first and the last contractions that reached the target. Here, the last contraction for each train type produced less excursion and required more time (~400 ms, 450 ms, and 275 ms for CFTs, VFTs, and DFTs,

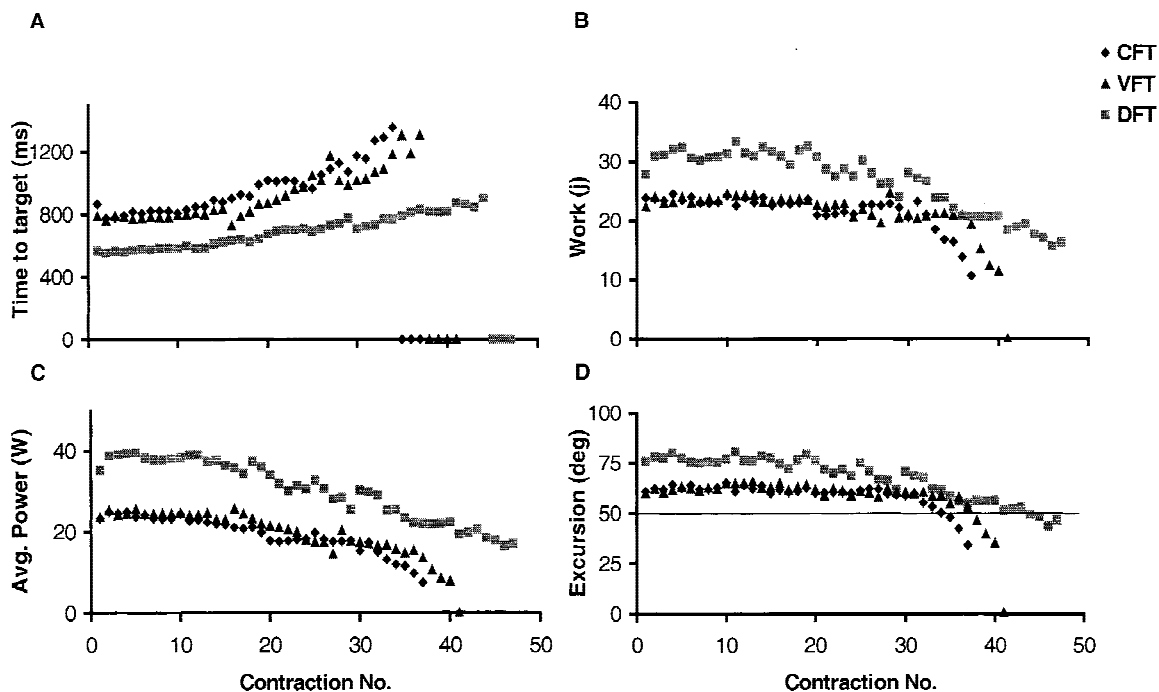


FIGURE 2. Time required to reach the target (A), work (B), average power (C), and excursion (D) for a typical subject. The testing train sequence for this subject was a constant-frequency train (CFT), followed by a variable-frequency train (VFT) and doublet-frequency train (DFT). The horizontal line in (D) represents the targeted excursion, and points above the line met the target. The number of times the target was met was 34, 37, and 44 for CFTs, VFTs, and DFTs, respectively. CFTs and VFTs produced initial excursions of ~60° and DFTs 75°–80°. Note that, although the targeted excursion was 50° (i.e., the stimulation was halted when the knee flexion joint angle was 40°), greater excursions were often produced because of the momentum of the leg.

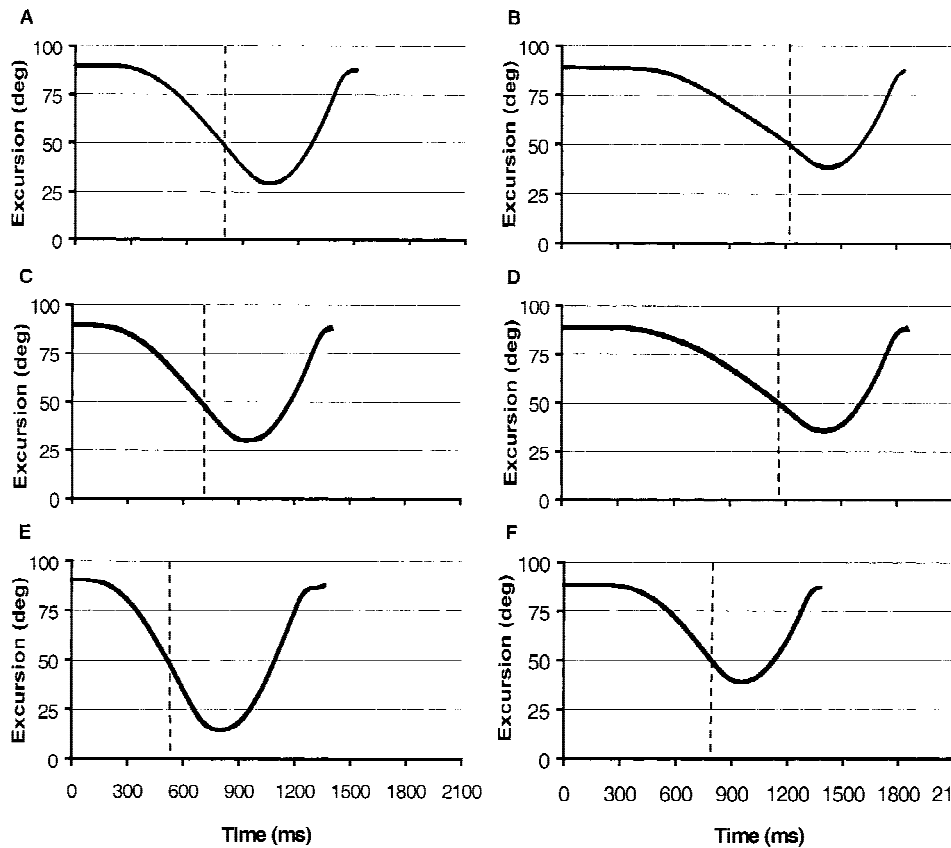


FIGURE 3. Excursion raw data for constant-frequency trains (CFTs) (A, B), variable-frequency trains (VFTs) (C, D), and doublet-frequency trains (DFTs) (E, F) for a typical subject. Initial contractions (A, C, E), and final contractions (B, D, F) that met or exceeded the target. Vertical dotted lines indicate the approximate time required to reach the target (i.e., where the excursion trace intersects 50° line). The time required to reach the target was always greatest for the CFTs and least for the DFTs. Data for the same subject as shown in Figure 2.

respectively) to reach the target angle than for the first contraction. Also, the time to reach the maximum excursion was shorter for the DFTs than for the CFTs or VFTs during both the initial and final contractions that met the target.

Except for work performed during the last contraction that reached the target, all ANOVAs were significant ($P = 0.001$; $F = 12.193$ – 100.16). Group data (means \pm standard deviations) show that the number of times the target joint angle was reached was greatest for DFTs (36.44 ± 14.39), followed by VFTs (24.89 ± 18.47) and CFTs (17.06 ± 12.08) (Fig. 4). DFTs produced a significantly greater number of target-meeting excursions than VFTs ($t = 2.64$, $P < 0.05$) and CFTs ($t = 4.95$, $P < 0.01$). VFTs produced a significantly greater number of target-meeting excursions than CFTs ($t = 2.24$, $P < 0.05$). For both the initial and final contractions, the DFT required the least time to reach the target and produced the greatest power (Fig. 5). No differences in time to target, work, or average power were noted between

the VFT and CFT for either the initial or final contractions. The DFT produced the greatest work for the initial contraction, but there was no difference during the final contraction among the work pro-

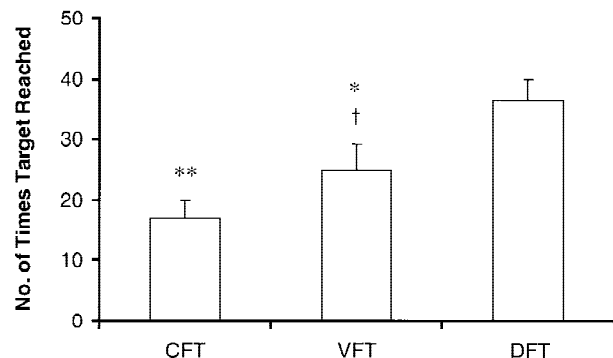


FIGURE 4. Number of times (means and SE) the target was reached within each train type. Doublet-frequency train (DFT) versus constant-frequency train (CFT) and variable-frequency train (VFT) (asterisk); VFT versus CFT (dagger). * $P = 0.05$; ** $P = 0.01$; † $P = 0.05$.

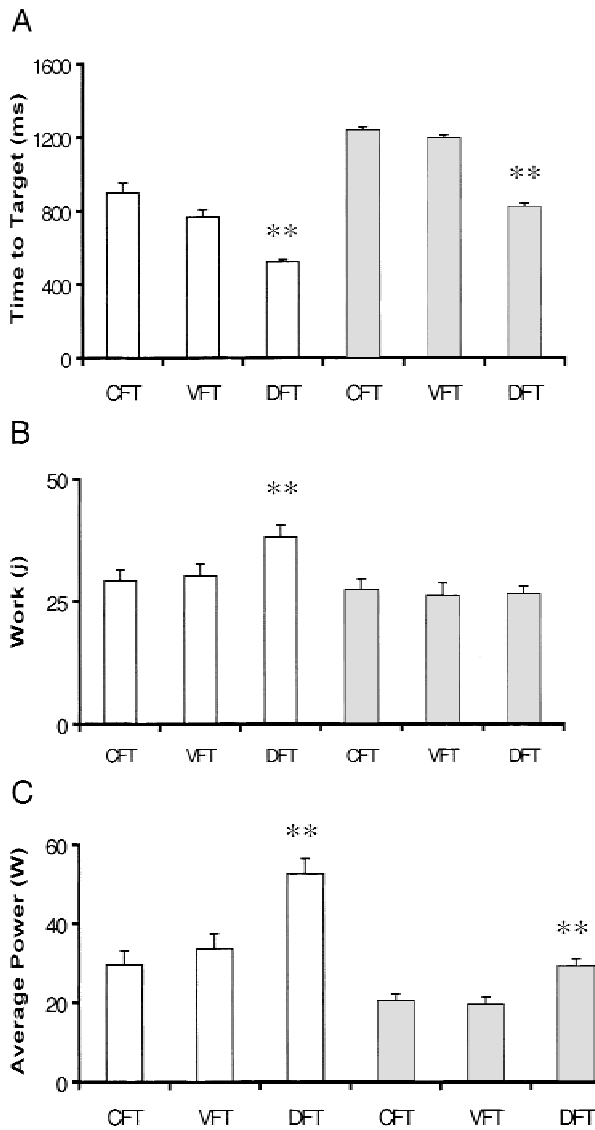


FIGURE 5. Group data ($N = 18$) of work (A), time to reach the target (B), and average power produced (C) in response to constant-frequency train (CFT), variable-frequency train (VFT), and doublet-frequency train (DFT) stimulation. Initial contraction (open bars) and final contraction (solid bars). DFT versus CFT and VFT (asterisk), $**P = 0.01$.

duced by the three testing trains. For the group, during the first contraction CFTs and VFTs each used 18 pulses, and DFTs used 24 pulses, to reach the target. All subjects used the maximum number of pulses by the 9th, 17th, and 11th contraction for CFTs, VFTs, and DFTs, respectively (i.e., well before failure).

Table 1 shows MVICs and the number of times the target was reached for each subject for each of the three testing trains. The boldface entries indicate trains that were tested first and the italicized entries indicate trains that were tested last for each

Table 1. MVICs and number of times the target was reached for each subject during constant-frequency train (CFT), variable-frequency train (VFT), and doublet-frequency train (DFT) stimulation.*

Subject	No. of times target reached			MVIC (N)
	CFT	VFT	DFT	
1	16	53	27	565
2	0	25	61	470
3	0	2	57	627
4	32	29	33	783
5	31	40	43	599
6	20	7	31	760
7	34	37	44	521
8	4	18	28	1165
9	14	0	42	681
10	15	13	22	861
11	21	27	30	576
12	30	66	62	1029
13	24	26	42	636
14	24	42	42	569
15	30	34	39	1233
16	3	9	9	613
17	0	20	25	645
18	9	0	19	796

*Bold entries represent trains tested first, and italicized entries represent trains tested last.

subject. In general, although DFTs performed better than either CFTs or VFTs, there was great variability in the number of times the target was reached. Table 1 also shows that CFTs and VFTs tended to perform better when tested first, and performed particularly poorly when preceded by DFTs. By contrast, DFTs did not seem to be affected by the order of testing. Table 2 presents the means for the number of times each pattern reached the target when the CFT, VFT, or DFT were tested first. The mean values presented in Table 2 show that the order of testing markedly affected performance for the CFTs and VFTs only. In particular, the CFTs and VFTs performed most poorly when the DFTs were the first train tested.

DISCUSSION

The purpose of this study was to determine the feasibility of using VFTs or DFTs to improve perfor-

Table 2. Testing sequence and the number of times the target was reached.*

Testing sequence	CFT	VFT	DFT
CFT first	26.0 ± 7.2	31.0 ± 15.1	36.0 ± 6.7
VFT first	18.2 ± 13.5	34.8 ± 19.4	41.2 ± 19.9
DFT first	7.0 ± 6.7	8.8 ± 9.3	32.2 ± 14.5

*Data are mean ± SD for each group of 6 subjects who received the CFT, VFT, or DFT as the first train in the testing sequence.

mance during dynamic (shortening) contractions designed to produce 50° of knee extension (starting at 90° of knee flexion). Of the three train types tested, the DFT reached the target the most times, followed by the VFT and CFT. During the initial contraction, the DFT produced the greatest work and average power within the shortest time and, during the final contraction, it produced the greatest average power within the shortest time. This study supports our recent claims that DFTs may be better than VFTs at augmenting nonisometric performance over CFTs.^{5,14}

We previously showed that VFTs, similar to those presently studied, are more fatiguing than CFTs during isometric contractions.⁸ Nevertheless, during isometric contractions, augmentation in force with VFTs is sufficiently robust that repetitive activation with VFTs still produces more force than repetitive activation with CFTs at the end of an 180-contraction fatigue test.⁸ Recent studies during dynamic contractions of human quadriceps femoris muscle also showed that VFTs produced better performance than CFTs when the numbers of trains and pulses were held constant.^{6,24,25} The present work is consistent with previous studies in that VFTs performed better than CFTs in the number of times the target angle was reached or exceeded. The present work also showed that DFTs attained the target more times than either the CFTs or VFTs.

One possible explanation for the DFTs' ability to perform more movement repetitions and work and to generate more power than CFTs and VFTs is that DFTs reached the target sooner than the other train types. The shorter time to target allowed DFTs to have the most rest before the next train. Because trains were delivered every 2000 ms, the initial rest times (2000 ms minus time to target) between stimulation trains were 1129 ms for CFTs, 1253 ms for VFTs, and 1478 ms for DFTs. At failure, when all trains used the maximum number of pulses, these times decreased to 800, 795, and 1335 ms for CFTs, VFTs, and DFTs, respectively. Thus, the rest time for DFTs remained relatively long throughout the course of the test, but decreased considerably for the other two train types.

The present study shows that there were marginal differences in rest time, work, and average power between CFTs and VFTs at the beginning of the test. These differences consistently remained small or disappeared by the end of the test. VFTs, therefore, had a limited advantage over CFTs in terms of forces (as implied by similar work and average power) produced during movement and rest

times between repetitions. This may help explain the smaller performance augmentation for VFTs than DFTs (over CFTs).

Another possible reason that VFTs had smaller improvement over CFTs may be related to the frequencies tested. The CFTs and VFTs tested in the present study had nearly the same train durations (1200 ms for the CFT versus 1205 ms for the VFT) and were different by only one pulse. The mean frequencies for the two patterns were, therefore, very similar (~20 Hz). Moreover, the two trains each had a constant-frequency IPI duration of 50 ms. In previous studies where VFTs performed better than CFTs during shortening contractions of both the fresh and fatigued human quadriceps muscles, CFTs and VFTs (constant-frequency portion) had IPIs of 70 ms.^{6,24} Recently, the relationship between stimulation frequency and shortening muscle performance (knee joint excursion, work, peak power, and average power) was investigated.²⁴ This study demonstrated a frequency dependence of trains used to produce dynamic contractions. In general, when muscles were fresh, CFTs showed better performance than VFTs at IPIs of 20–60 ms, and VFTs performed better than CFTs at IPIs of 70–100 ms. When muscles were fatigued, VFTs generally performed better than CFTs at IPIs of 30–100 ms. These results show that performance may depend on the fatigue state of the muscle and stimulation frequency. Because all of these studies^{6,24,25} measured performance before and after the muscle was fatigued, they may not provide an adequate explanation for the present work where performance was being evaluated from the beginning (fresh muscle) through the end (fatigued muscle) of the test. Research using methodology similar to that in the present study is being conducted in our laboratory to understand better the effects of frequency and stimulation pattern on performance.

Increased muscle stiffness and enhanced calcium release from the sarcoplasmic reticulum (SR) are two mechanisms that have previously been proposed to account for the enhanced performance of trains containing doublets.^{6,15,31} With VFTs, the initial burst of pulses is thought to take up the slack in the series elastic component, and thus increase muscle stiffness so that subsequent pulses in the train are used to increase force.³¹ A stiff muscle will, therefore, more effectively transmit force and generate movement.^{24,25,39} The use of multiple doublets by the DFTs in the present study may have resulted in repeated increases in muscle stiffness and thus better movement generation than with VFTs or CFTs.

The relationship between force and intracellular

ionized calcium concentration ($[Ca^{2+}]_i$) is sigmoidal, so that muscle force increases with increasing $[Ca^{2+}]_i$.^{12,16,38} Doublets have been shown to enhance calcium release from the SR.¹⁵ VFTs and DFTs may have performed better than CFTs because of this enhanced calcium release. Furthermore, DFTs may have performed better than VFTs because they contained multiple doublets, which may have enhanced calcium release multiple times throughout the contraction, as opposed to a single doublet.

Based on the experimental design used, it should not be surprising that there was an ordering effect for the testing sequence of the stimulation patterns (Table 2). Inspection of the data presented in Tables 1 and 2 shows that, in general, when DFTs were first, CFTs and VFTs seemed to perform poorly. However, DFTs performed best in most subjects, irrespective of sequence. Because DFTs performed the most contractions, they may have had a greater effect on subsequent testing within each session than the VFTs or CFTs. This may explain the poor performance seen in some subjects when DFTs preceded CFTs and VFTs. Even though the study design assumes the likelihood of an ordering effect, and the data seem to suggest the same, we cannot conclusively say there was an ordering effect, because we did not have a large enough sample size to perform a two-way ANOVA with order as a second factor. Such an analysis would result in 3 subjects per testing sequence, which would not have sufficient power. We will therefore consider a future study with testing on separate days, or with an increased sample size.

Finally, there may be a need to identify the optimal stimulation pattern for each subject. Across subjects, performance ranged from 0–34 contractions for CFTs, 0–66 contractions for VFTs, and 9–62 contractions for DFTs (see Table 1). Although most subjects performed best with DFTs, a few subjects performed best with VFTs. Alternatively, in a few cases, there were small differences in performance between CFTs and VFTs or VFTs and DFTs. These data, available evidence,^{14,19} and current work in our laboratory (unpublished observations) suggest that the optimal pattern may be different for each subject.

In conclusion, the present study shows that DFTs and VFTs may have beneficial effects in FES applications by augmenting performance in dynamic contractions. DFTs may have improved performance by completing tasks more quickly than other train patterns, thus giving the muscle more time to relax between contractions. Further research is needed to determine the optimal frequency and pattern for each subject and to determine their effectiveness during FES in paralyzed muscles.

This research was supported by the National Institutes of Health Grant HD 36797 to Dr. S. A. Binder-Macleod.

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