Effects of stimulation frequencies and patterns on performance of repetitive, nonisometric tasks

MAIKUTLO B. KEBAETSE,1 AMANDA E. TURNER,2 AND STUART A. BINDER-MACLEOD1,2

1Interdisciplinary Programs in Biomechanics and Movement Science, McKinly Laboratory, and
2Department of Physical Therapy, University of Delaware, Newark, Delaware 19107

Received 20 March 2001; accepted in final form 31 August 2001

Kebaetse, Maikutlo B., Amanda E. Turner, and Stuart A. Binder-Macleod. Effects of stimulation frequencies and patterns on performance of repetitive, nonisometric tasks. J Appl Physiol 92: 109–116, 2002.—The purpose of this paper was to determine the effects of stimulation pattern and frequency on repetitive human knee movements. Quadriceps femoris muscles were stimulated against a load equal to 10% of each subject’s maximum voluntary isometric force. The main variable of interest was the number of repetitions in which the leg reached a target angle of 40° of knee extension. Sixteen different trains were tested, including 1) six constant-frequency trains with frequencies ranging from 9 to 100 Hz, 2) five variable-frequency trains with an initial 5-ms triplet and mean frequencies ranging from 11 to 35 Hz, and 3) five doublet-frequency trains, which used doublets (2 pulses with a 5-ms interpulse interval) to replace single pulses, with mean frequencies of 17–57 Hz. Testing was stopped when the subject failed to reach the target angle for three consecutive activations. Results showed that no single pattern was best for all subjects. The 33- and 100-Hz constant-frequency trains, 35-Hz variable-frequency trains, and 27- and 36-Hz doublet frequency trains each met the target the most times for some subjects. The results showed that, under our testing conditions, higher frequency trains were better suited for producing repetitive knee movements than lower frequency trains.

Functional electrical stimulation; doublets; variable-frequency trains

FUNCTIONAL ELECTRICAL STIMULATION (FES) artificially activates paralyzed or weak muscles to produce functional movements in individuals with central nervous system disorders (24, 29). Traditionally, trains of equally spaced electrical pulses, known as constant-frequency trains (CFTs), are used during FES. Although CFTs can produce effective muscle contractions, rapid fatigue limits the utility of FES (15, 19). For FES to attain widespread clinical use, methods to minimize fatigue while still generating adequate forces must be identified. Recently, efforts to maximize force production during FES have focused on altering the stimulation frequency and pattern (varying the interpulse interval (IPI) within the train) of the stimulation being delivered to the muscle (8, 12, 13, 19, 30).

Burke and colleagues (11) were the first to show that, by including two pulses separated by a 5- to 10-ms IPI at the beginning of a low-frequency CFT, the force-time integrals (the area under a force-time curve) produced by cat gastrocnemius motor units could be markedly enhanced compared with the forces produced by stimulation with CFTs of similar frequencies. Train patterns that used a high-frequency burst (e.g., two or three pulses with a 10-ms IPI) followed by a series of lower frequency pulses have been termed variable-frequency trains (VFTs) (8, 17, 27, 33). Henceforth, for the present paper, this train pattern will be referred to as a VFT. Since the pioneering work by Burke and colleagues, other authors have demonstrated that VFTs produced faster rates of rise of force and higher average forces, peak forces, and force-time integrals during isometric contractions (1, 3, 7, 8, 32) and produced greater average power, peak power, peak forces, and excursions during nonisometric contractions (6, 23, 30) than CFTs of similar frequencies. The augmentations in force with VFTs were greater when the muscles were fatigued than nonfatigued (1, 6).

Recent studies have also investigated the amount of fatigue produced by repetitive activation of a muscle with CFTs vs. VFTs during isometric contractions (8, 9). Interestingly, although these studies showed that at the end of a fatiguing protocol VFTs produced greater forces than CFTs, there was also a greater force decline when the muscles were fatigued with VFTs than with CFTs. That is, although VFTs were able to produce more force from fatigued muscle than CFTs of similar frequencies, repetitive isometric activation of a muscle with VFTs produced more fatigue than repetitive isometric activation with CFTs (8, 9).

Because shortening dynamic contractions are an integral part of functional movements, our laboratory has previously investigated the effects of CFT and VFT stimulation on nonisometric performance (power, work, and excursion) of human femoris quadriceps muscles (6, 21–23). All of these studies used six-pulse trains to compare responses of CFTs and VFTs before and after the muscles were fatigued with a standardized fatiguing protocol (150 trains, 40-Hz CFTs). Re-
stimulation patterns before we conduct such tests on patients with paralyzed muscles.

**METHODS**

Data were collected from 12 healthy subjects (6 women) ranging in age from 20 to 32 yr (mean 24.25, SD 4.37). None had a history of cardiovascular problems or any neurological or orthopedic problems in the leg being tested. The dominant leg was tested (10 subjects on the right and 2 on the left). The study was approved by the University of Delaware Human Subjects Review Board, and each subject gave informed consent.

**Equipment and experimental setup.** Subjects were seated on a computer-controlled dynamometer (KinCom III 500–11, Chattanooga, Chattanooga, TN) with hips flexed to ~85°. 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” × 5” self-adhesive electrodes were used to stimulate the muscle. With the knee positioned at 90°, the anode was placed proximally over the motor point of the rectus femoris (quadriceps femoris muscle). The cathode was placed distally over the vastus medialis motor point with the knee at 15° of flexion to compensate for skin movement during knee extension (21). The trunk, pelvis, and thigh of the leg being tested were each stabilized with inelastic straps. A Grass S8800 stimulator with a SIU8T stimulus isolation unit, which delivers a constant current, was used for stimulation (Grass Instruments, West Warwick, RI). The stimulator was driven by a personal computer that controlled the timing parameters of each stimulation protocol. Custom-made hardware was used to terminate the stimulation train each time the knee reached the target angle during knee extension. Force, angle, and velocity data were digitized at 200 Hz and stored for subsequent analysis.

**Stimulation trains.** Sixteen different stimulation trains were tested (see Fig. 1 for examples). A wide range of mean frequencies (operationally defined as the total number of pulses in a train divided by the train duration in seconds) was tested because, although high-frequency stimulation is known to produce high forces, high-frequency stimulation has also been shown to produce greater fatigue than low-frequency stimulation (2, 5). Each train was ≤1 s in duration (see below for specific details), and each pulse was 600 μs. CFTs with IPIs of 10 ms (frequency = 100 Hz), 30 ms (33 Hz), 50 ms (20 Hz), 70 ms (14 Hz), 90 ms (11 Hz), and 110 ms (9 Hz) were tested. Five VFTs and five DFTs were also tested.

**Results** showed that VFTs augmented nonisometric performance, especially when the muscles were fatigued. More recently, another type of a nontraditional stimulation pattern, composed of closely spaced (~5-ms IPIs) pairs of pulses (doublets) separated by longer intervals (interdoublet intervals), was described (13, 16, 23). We have termed these patterns doublet-frequency trains (DFTs) (13). Recent modeling and experimental work in our laboratory showed that DFTs produced greater forces during isometric contractions in fatigued human muscles than CFTs of similar frequencies (4, 13). Except for one recent preliminary study (20), all previously published studies of DFTs used isometric contractions (4, 13, 19, 25, 26). There is, therefore, little information available on the effects of DFTs during nonisometric contractions. Trains with multiple doublets may be beneficial during repetitive nonisometric activity, especially as fatigue develops. This notion is supported by recent findings that multiple doublets may be beneficial during repetitive dynamic contractions. Unlike previous nonisometric studies from our laboratory that tested the effects of CFTs and VFTs in either the nonfatigued or fatigued state (6, 21–23), this study repetitively activated the muscles with either CFTs, VFTs, or DFTs to evaluate each train pattern’s ability to produce a 50° excursion (i.e., from 90 to 40° of knee flexion). Because the six-pulse trains used in our group’s previous nonisometric studies (6, 21–23) are too short for producing the range of joint excursions needed during some functional movements, the train duration was allowed to vary up to 1,200 ms. In addition, unlike our previous work, the primary outcome measure was the number of times the target was reached. The trains used were CFTs with an IPI of 50 ms (frequency = 20 Hz), VFTs with an initial 5-ms doublet and the remaining pulses with 50-ms IPIs (mean frequency = 21 Hz), and DFTs with 5-ms doublets and 50 ms between each doublet (mean frequency = 39.4 Hz). The DFT was the most successful pattern for producing repetitive movements. However, for several subjects the differences between patterns were small, and a few subjects performed best with VFTs. This preliminary study showed that DFTs had the potential to improve performance during repetitive nonisometric contractions, but only one frequency within each stimulation pattern was tested.

The effects of long trains of different stimulation patterns with varying frequencies on dynamic contractions have not been investigated. The purpose of the present study, therefore, was to explore the effects of a wide range of frequencies for each stimulation pattern on performance during repetitive nonisometric contractions of the quadriceps femoris muscles of healthy subjects. This work will help us understand how normal muscles respond to traditional vs. nontraditional...
The five VFTs had the same IPIs as the CFTs, except that each VFT had an initial triplet of pulses (three pulses with a 5-ms IPI between each pulse). A triplet of pulses was used for all VFTs because triplets were previously found to produce the greatest excursions and work when activating fatigued muscles with short trains during dynamic contractions (21). The VFTs tested in the present study had mean frequencies of ~35, 21, 16, 13, and 11 Hz. The DFTs each had an intradoublet interval of 5 ms and interdoublet intervals of 30, 50, 70, 90, and 110 ms, resulting in trains with approximate mean frequencies of 57, 36, 27, 21, and 17 Hz, respectively. DFTs with 10-ms interdoublet intervals and VFTs with 10-ms IPIs were not tested because we did not anticipate much difference in performance between these trains, which would have consisted of 5- and 10-ms IPIs, and the 100-Hz CFT, which contained 10-ms IPIs (6, 21).

The 16 train frequencies were tested during a total of six sessions, with each session testing two or three frequencies. At least 10 min of rest were required between the testing of each frequency to allow the muscles sufficient time to recover between tests. Pilot work showed that 10 min of rest between successive tests was sufficient to produce similar data between trials. At least 48 h separated each session, and only one pattern (i.e., either DFTs, CFTs, or VFTs) was tested in any given session. Within each session, the order of frequencies to be tested was randomized to help to distribute the practice effects (e.g., fatigue) equally to all trains. The order of the six sessions (i.e., 2 CFT sessions, 2 VFT sessions, and 2 DFT sessions) was also randomized. Subjects were asked to refrain from strenuous exercise for 24 h before each testing session.

Experimental sessions. A detailed description of the current methodology was previously reported (20). A summary of the current experimental protocol is provided in a flow chart (Fig. 2). Briefly, at the beginning of each session, subjects performed a maximum voluntary isometric contraction (MVIC) of the quadriceps femoris muscle with the knee positioned at 90° of flexion. A burst-superimposition technique was used to ensure that a maximal contraction was being performed (31). Testing during sessions 2–6 was conducted only when the subject’s maximal electrically elicited force was ≥95% of the first session’s maximal electrically elicited force. Sessions that did not meet this criterion were rescheduled for another day. Next, with the knee held at 90° of flexion, the stimulation intensity was set to produce an isometric force equal to ~20% of the subject’s MVIC using a 1-s-long 20-Hz CFT to activate the muscle; stimulation intensities ranged from 29 to 69 V for the 12 subjects studied. Subjects usually reported a sensation of a strong but not painful muscular contraction during the stimulation. Once the intensity was set, it was not changed for the remainder of the session.

After setting the intensity, the subject rested for 5 min before the testing trains were administered. The muscle was isometrically potentiated with 10 seven-pulse, 100-Hz trains (1 train every 5 s); within 5 s of the last potentiation train, the KinCom was switched to the isotonic mode and the first testing train was administered against an isotonic resistance (“load”) of 10% of the subject’s MVIC (i.e., 50% of the electrically elicited tetanic force). Stimulation was automatically terminated each time the knee reached a 40°-flexion target angle (i.e., a 50° excursion from 90° of flexion), and the dynamometer was set so that the weight of the leg returned the extremity to the starting position. Stimulation trains were delivered every 2 s, and testing was stopped after the knee failed to reach the target three consecutive times. The stimulation program was set to allow a maximum of 150 contractions for each frequency. The subject rested for 10 min before a different frequency was tested.

A group of nine subjects (2 of the 9 subjects were part of the main study) was tested with the 20-Hz and 100-Hz CFTs during two additional sessions to determine the reliability of the methodology used for measuring the number of times the target was reached. Each subject received both frequencies within each session, with a 10-min rest between each frequency. The order of the two trains was the same for both sessions for each subject; however, four of the subjects received the 100-Hz train first and five subjects received the 20-Hz train first. At least 48 h separated the two sessions. Pearson’s correlation coefficients (CCs) were calculated to determine the reliability of repeated testing for each frequency and to compare the differences in the performance between the two trains during each session. Complete data sets were collected on all nine subjects. On average, the 20-Hz CFT produced 19.8 ± 13.4 (SD) and 22.9 ± 16.8 successful contractions during the first and second sessions, respectively. The 100-Hz CFT produced 41.0 ± 27.0 and 46.9 ± 39.9 successful contractions during the first and second sessions, respectively. The CCs for the performances...
for the 20- and 100-Hz CFTs across the two sessions were 0.96 and 0.99, respectively. When the differences in the performances between the 20- and 100-Hz CFTs during each of the two sessions were compared, the intersession CC was 0.99. Thus, although there was considerable variability between subjects (see standard deviations for trains), there was a high degree of reliability within each subject between the two sessions for each train.

Data management. Force, angle, and velocity data were collected directly from the dynamometer for each shortening contraction. The variables studied were the number of times the leg reached (or exceeded) the 40° target angle (this was the primary outcome measurement) and the time (ms) required for the leg to move from the 90° starting position to the target angle. Custom-written software (LabView 4.0.1, National Instruments, Austin, TX) was used to calculate the dependent variables. Time (ms) was not recorded for any contraction that failed to reach the target.

The rest time (i.e., the time between stimulation trains) for each contraction was calculated by subtracting the duration of each stimulation train from 2 s, which is the time between the onsets of each successive contraction. Excursion was calculated as the maximum lower leg displacement in degrees. Although stimulation was stopped at the 40° target angle, excursions of >50° could be attained because of the momentum of the leg. Average time to target and rest times were examined for the first and last target meeting contractions.

Data analysis. One-way repeated-measures (within subjects) analyses of variance (ANO瓦s) were performed to analyze both the effect of frequency on the number of successful contractions and the time needed to reach the target angle during the first successful contraction. Separate ANO瓦s were performed for each stimulation pattern (CFT, VFT, or DFT). Normal quantile and residual plots were used to estimate normal distribution of the data for each frequency. Because time was not recorded for contractions that failed to reach the target, the ANO瓦s for time included only frequencies that produced at least one successful contraction in more than half of the subjects. Within each pattern (CFT, VFT, or DFT), if a significant effect was observed, paired t-tests were used to compare the frequency that produced on average the most successful contractions with each of the other frequencies. Only frequencies that produced at least one successful contraction in more than half of the subjects were included within the post hoc analyses. Finally, a one-way, repeated-measures ANO瓦 was used to compare the CFT, VFT, and DFT with the highest average number of successful contractions. Statistical significance was set at \( P \leq 0.05 \) for all tests.

RESULTS

Complete data sets were collected for all 12 subjects studied during experimental testing. The excursion and time to reach the target for each contraction for the CFTs, VFTs, and DFTs responses for a typical subject are presented in Figs. 3, 4, and 5, respectively. In Fig. 3, only the 20-, 33-, and 100-Hz CFTs produced target-meeting contractions, with the 100-Hz CFT producing the greatest excursions. The failure of the lower frequency CFTs (i.e., the 9-, 11-, and 14-Hz trains) to produce any contractions that reached the target was typical of 9 of the 12 subjects (see Table 1). Additionally, the 100-Hz CFT reached the target within the shortest time, followed by the 33-Hz CFT and the 20-Hz CFT. An increase in time was required to meet the target as the contractions proceeded. Figure 4 shows that the 35-Hz VFT was the VFT that produced the greatest excursion and number of successful contractions and required the least time to reach the target. For this subject (typical of 6 of the 12 subjects for VFTs), the 11-, 13-, and 16-Hz VFTs did not produce any successful contractions. Figure 5 shows that for this subject all DFTs produced successful contractions (typical of 7 of the 12 subjects). The 27-Hz DFT met the target more times than any other DFT, and the 57-Hz DFT produced the greatest excursions throughout most of the test. The 27-, 36-, and 57-Hz DFTs required less time than any other DFT to meet the target. Interestingly, there were minor differences in time to target among the 27-, 36-, and 57-Hz DFTs, and between the 17- and 21-Hz DFTs.

Group data. As demonstrated by the typical subjects, higher frequency trains were able to reach the target a greater number of times than lower frequency trains within each pattern (Fig. 6). Within each stimulation pattern, there was a significant effect for frequency for the number of successful contractions (\( F = 16.92 \) and \( P \leq 0.001 \), \( F = 21.09 \) and \( P \leq 0.001 \), and \( F = 7.47 \) and \( P \leq 0.001 \) for CFTs, VFTs, and DFTs, respectively).
Follow-up comparisons included the 20-, 33-, and 100-Hz CFTs; the 21- and 35-Hz VFTs; and all DFTs (i.e., only these frequencies produced successful contractions in more than half of the subjects). The frequencies that on average produced the best performance for each stimulation pattern were the 100-Hz CFT, 35-Hz VFT, and 36-Hz DFT. For the CFTs, the 100-Hz CFT produced a greater average number of successful contractions for each subject. IPI/IDI, interpulse interval/interdoublet interval; CFT, constant-frequency train; VFT, variable-frequency train; DFT, doublet-frequency train. *This subject had 2 trains with the most contractions because both trains reached the target the same number of times.

The bold print represents the frequency that produced the greatest number of successful contractions for each subject. IPI/IDI, interpulse interval/interdoublet interval; CFT, constant-frequency train; VFT, variable-frequency train; DFT, doublet-frequency train. *This subject had 2 trains with the most contractions because both trains reached the target the same number of times.

Table 1. Individual subject data for the number of times the target was reached with each pattern and frequency

<table>
<thead>
<tr>
<th>Pattern</th>
<th>CFTs</th>
<th>VFTs</th>
<th>DFTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPI/IDI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>35</td>
<td>110</td>
<td>35</td>
</tr>
<tr>
<td>70</td>
<td>21</td>
<td>90</td>
<td>21</td>
</tr>
<tr>
<td>90</td>
<td>16</td>
<td>110</td>
<td>16</td>
</tr>
<tr>
<td>110</td>
<td>36</td>
<td>70</td>
<td>36</td>
</tr>
<tr>
<td>Subject</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>43</td>
<td>38</td>
<td>13</td>
</tr>
<tr>
<td>2*</td>
<td>28</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>38</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>68</td>
<td>53</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>34</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>39</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>150</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>51</td>
<td>69</td>
<td>41</td>
</tr>
<tr>
<td>11</td>
<td>37</td>
<td>31</td>
<td>26</td>
</tr>
<tr>
<td>12</td>
<td>34</td>
<td>52</td>
<td>33</td>
</tr>
</tbody>
</table>

The bold print represents the frequency that produced the greatest number of successful contractions for each subject. IPI/IDI, interpulse interval/interdoublet interval; CFT, constant-frequency train; VFT, variable-frequency train; DFT, doublet-frequency train. *This subject had 2 trains with the most contractions because both trains reached the target the same number of times.

Fig. 4. Excursion (A) and time-to-target (B) data for variable-frequency trains (VFTs; numbers represent mean frequency in Hz) for the same subject as in Fig. 3. Horizontal line at 50° represents targeted excursion (see text for details). Any contraction that did not meet the target shows a 0-ms time-to-target value. VFT35 and VFT21 met the target 34 and 29 times, respectively. VFT16, VFT13, and VFT11 did not reach the target. The order of testing was VFT16, VFT13 and VFT35 during the first session and VFT21 and VFT11 during the second session.

Fig. 5. Excursion (A) and time-to-target (B) data for doublet-frequency trains (DFTs; numbers represent mean frequency in Hz) for the same subject as in Fig. 3. Horizontal line at 50° represents targeted excursion (see text for details). Any contraction that did not meet the target shows a 0-ms time-to-target value. DFT57, DFT36, DFT27, DFT21, and DFT17 met the target 33, 36, 44, 31, and 25 times, respectively. The order of testing was DFT57, DFT21 and DFT27 during the first session and DFT17 and DFT36 during the second session.
successful contractions than the 20-Hz CFT \((t = 2.39, P \leq 0.05)\) but not the 33-Hz CFT (see Fig. 6). For the VFTs, the 21- and 35-Hz frequencies were not different, although a trend toward significance was seen \((t = 2.01, P = 0.07)\). The 36-Hz DFT produced more contractions than the 17-Hz \((t = 5.49, P \leq 0.001)\) and 21-Hz \((t = 4.44, P \leq 0.001)\) DFTs but not the 27- or 57-Hz DFTs. Interestingly, when we compared the trains that produced the best performance for each stimulation pattern (i.e., the 100-Hz CFT, the 35-Hz VFT, and the 36-Hz DFT; see Fig. 6), there were no differences among the three patterns.

Table 1 shows the number of times each subject met the target when using each of the 16 different stimulation trains. The bold numbers show the train that reached the target the most times for each subject. A great deal of variation was seen among subjects in the number of times the target was met when each stimulation pattern and frequency was used. Four subjects reached the target the most times with the 100-Hz CFT (two of these subjects reached the 150-contraction ceiling), one with the 33-Hz CFT, four with the 35-Hz VFT, two with the 36-Hz DFT, and two with the 27-Hz DFT. Please note that subject 2 performed the most contractions with both the 35-Hz VFT and the 36-Hz DFT. That is, both trains met the target the same number of times for this subject.

By the last successful contraction, almost all trains had used all pulses allowed (i.e., the train duration was \(\sim 1,000\) ms), indicating that more time was required to reach the target as the muscle fatigued. During the first successful contraction, the time to target increased as frequency decreased for the CFTs and DFTs \((F = 42.19\) and \(P \leq 0.001, F = 5.97\) and \(P \leq 0.01,\) for the CFTs and DFTs, respectively) (see Fig. 7). Post hoc analyses showed that the 100-Hz CFT reached the target within a shorter time than the 20-Hz CFT \((t = 7.55, P \leq 0.001)\) and 33-Hz CFT \((t = 3.78, P \leq 0.01)\); the times to reach the target for the 21- and 35-Hz VFTs were not different, but they showed a tendency toward significance \((t = 2.19, P = 0.06)\); finally, the times for the 36- and 57-Hz DFTs were not different, but the 36-Hz DFT required less time to reach the target than the remaining DFTs \((t = 3.61, P \leq 0.01)\) versus the 27-Hz DFT; \(t = 3.54, P \leq 0.01)\) versus the 21-Hz DFT; and \(t = 3.83, P \leq 0.01)\) versus the 17-Hz DFT).

**DISCUSSION**

The purpose of the present study was to determine the effect of varying stimulation frequency and pattern (CFTs, VFTs, and DFTs) on the ability of the quadriceps femoris muscle to move the lower leg repetitively through 50° of knee extension. The primary dependent measure was the number of times the leg completed the targeted excursion. The present results showed that although the higher frequency trains generally reached the target the most times within each stimulation pattern, no single pattern was best for all subjects.

Two of the subjects met the target 150 times when using the 100-Hz CFT, indicating that they might have far exceeded this limit if more trains were allowed. Although the 100-Hz CFT performed the most contractions overall, it was outperformed by or produced similar performance to the 33-Hz CFT, 35-Hz VFT, and 36-Hz DFT for 6, 6, and 7 of the 12 subjects, respectively.

In a recent investigation of the effects of frequency of six-pulse trains on dynamic performance of the nonfatigued quadriceps muscles, \(\sim 20-\) to 25-Hz CFTs and \(\sim 16-\) to 20-Hz VFTs produced the greatest excursions, work, peak power, and average power (23). On the basis of these results (23), we predicted that the 20-Hz CFT and the 21-Hz VFT would reach the target the most times within their respective patterns. As predicted, the 20-Hz CFT reached the target more times than the 9- to 14-Hz CFTs, and the 21-Hz VFT reached the target more times than the 11- to 16-Hz VFTs.
Contrary to our predictions, however, the 33- and 100-Hz CFTs (both of which had comparable performances) each met the target more times than the 20-Hz CFT, and the 35-Hz VFT’s performance was comparable to that of the 21-Hz VFT (Fig. 6). These results suggest that ~1-s CFTs and VFTs may need higher frequencies to produce repetitive dynamic contractions than the six-pulse trains previously studied.

Within DFTs, the 57-Hz DFT and the 36-Hz DFT reached the target the most times (Fig. 6). Recently, Karu and colleagues (19) found that during isometric contractions of the human quadriceps muscle doublets with interdoublet intervals of 50–80 ms produced maximum average torque per pulse. We would therefore predict that interdoublet intervals of 50–80 ms (~25–36-Hz) would be optimal for DFTs during shortening contractions. This prediction was not consistent with the relative success of the 57-Hz DFT in the present study. Because the 36- and 57-Hz DFTs produced similar number of contractions, future studies should determine whether higher DFT frequencies (i.e., ~57-Hz) could produce greater performance than presently observed.

We did not anticipate that the higher frequency trains (33-Hz CFT, 100-Hz CFT, 35-Hz VFT, and 57-Hz DFT) would produce more contractions than the lower frequency trains because higher frequency trains have been shown to be more fatiguing than lower frequency trains (2, 5). A possible reason why these relatively higher frequency trains were more successful than the lower frequency trains may be that the time to target (ms) tended to decrease with increasing frequency. The higher frequency trains, therefore, allowed a longer rest time between successive contractions than the lower frequency trains, thus possibly minimizing fatigue (Fig. 7). For example, the 100-Hz and 20-Hz CFTs required 437.0 ± 13.7 and 648.9 ± 27.8 ms, respectively, to reach the target. Similarly, the failure of the 35-Hz VFT to produce more repetitions than the 21-Hz VFT may be explained by the similar times required to reach the target. The relationship between frequency, time, and the number of contractions described in the above examples, however, did not hold for the 33- vs. 100-Hz CFTs and the 27- vs. 36-Hz DFTs. Therefore, because the time required to reach the target does not consistently explain performance, other mechanisms must be operating. Unfortunately, identification of such mechanisms is beyond the scope of the present study.

There was a wide range of frequencies and patterns for trains that reached the target the most times, indicating that there was great variability across subjects. The frequencies for the trains that produced the most contractions ranged from 27 to 100 Hz (2 subjects with the 27-Hz DFT, 2 with the 36-Hz DFT, 4 with the 35-Hz VFT, 1 with the 33-Hz CFT, and 4 with the 100-Hz CFT), although for some subjects the within-subject differences between trains were very small. Interestingly, lower frequency VFTs worked extremely well for subject 1 (she met the target 76 times with the 16-Hz VFT and 84 times with the 13-Hz VFT) but hardly worked at all for the other subjects. Also, the 21-Hz DFT produced many target-meeting contractions for subjects 1-4 and 9–12 but not for the rest of the subjects (see Table 1). The present results are consistent with the work of Ding and colleagues (13) who predicted that there would be individual differences in the patterns producing maximum forces during isometric contractions due to individual differences in muscle contractile properties.

In conclusion, higher frequency trains were generally more successful at producing movements that met the 50° targeted excursion than lower frequency trains, and no pattern or frequency was uniformly optimal across the healthy subjects we tested for reaching the target the most times. Although our design was appropriate for evaluating long trains during large joint excursions, we do not know whether similar results would be observed if we studied different ranges of motion or required the muscle to contract against different loads.

This research was supported by the National Institute of Child Health and Human Development Grant HD-36797 (to S. A. Binder-Macleod).

REFERENCES

14. Duchateau J and Hainaut K. Nonlinear summation of contractions in striated muscle. II. Potentiation of intracellular


