Effects of activation frequency on dynamic performance of human fresh and fatigued muscles

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human fresh and fatigued muscles. *J Appl Physiol* 88:
2166-2175, 2000.—The force-frequency relationship for an
individual muscle depends on the fatigue state, the length at
which it is activated, and the muscle's activation history. The
relationship among stimulation frequency and dynamic (non-
isometric) muscle performance measurements (e.g., excur-
sion, work, peak power, and average power) has not been
reported. The purpose of this study was to identify the
relationship between stimulation frequency and dynamic
performance measurements for fresh and fatigued muscles.
Constant-frequency and catchlike-inducing trains (CFT and
CIT, respectively) were tested. When fresh, interpulse inter-
vals of 40–50 ms [20–25 pulses/s (pps)] produced maximum
performance for CFTs. For CITs, maximum performance
occurred at interpulse intervals of 50–60 ms ($\sim$16–20 pps).
Generally, CFTs produced slightly greater performance than
did CITs. When fatigued, however, CITs produced greater
performance than did CFTs. Maximum performance for CFTs
occurred at interpulse intervals of 20–40 ms (25–50 pps) and
at 30–50 ms (20–33 pps) for CITs. Enhancement of perfor-
mance by CITs when fatigued may be due to less susceptibil-
ity to impairments in excitation-contraction coupling and
greater ability to maintain rates of rise of force than CFTs.

human quadriceps femoris muscle; catchlike property; iso-
tonic; functional electrical stimulation

THE FORCE-FREQUENCY RELATIONSHIP is traditionally char-
acterized by using long stimulus trains (1–2 s) during
isometric contractions when the muscle is fresh and
held at optimal or near optimal length (11, 22). The
peak forces generated at each frequency of stimulation
are then plotted as a function of frequency. For human
quadriceps femoris muscle, stimulation frequencies
ranging from $\sim$70 to 100 pulses/s (pps) produce maxi-
mum peak forces (6, 7). The force-frequency relation-
ship is not unique for an individual muscle, however.
Rather, it depends on various physiological conditions
of the muscle, such as the fatigue state (6) and the
length (27, 31, 33) at which the muscle is activated.

Recently, our laboratory used brief stimulus trains (6
pulses) to characterize the force-frequency relationship
of the human quadriceps femoris muscle and reported
both peak forces and force-time integrals produced by
the muscles in response to each stimulation frequency
(6). The relationship between the peak force and fre-
quency for these brief stimulus trains had the typical
sigmoidal shape (11), with maximum peak forces occur-
ring at frequencies $\geq$25 pps (see Fig. 5). With fatigue,
higher frequencies (100 pps) were needed to generate
maximum peak forces. In contrast, if the force-
frequency relationship was expressed in terms of the
force-time integral, the relationship was parabolic,
with maximum force-time integrals produced at fre-
quencies of 10–13 pps and lower force-time integrals
produced at lower and higher frequencies. With fatigue,
a flattening of the parabolic relationship was observed
with maximum force-time integrals produced at fre-
quencies 20–30 pps. Because peak forces and force-
time integrals were optimized at very different frequen-
cies when the muscles were either fresh or fatigued, the
selection of the optimal strategy for activating the
muscle depends on the force parameter (peak force vs.
force-time integral) under consideration.

Because it is known that the force-frequency relation-
ship depends highly on the muscle's activation history
(3), our laboratory has also studied the ability of brief,
variable-frequency trains that exploit the catchlike-
property of skeletal muscle (catchlike-inducing trains)
to augment isometric forces vs. constant-frequency
trains (6). Catchlike-inducing trains were not advanta-
geous when muscles were fresh. When fatigued, how-
ever, catchlike-inducing trains were highly effective in
augmenting both peak force and force-time integral
compared with constant-frequency trains. Thus stimu-
lus train patterns should be considered when attempt-
ing to optimize force from a muscle.

Dynamic (nonisometric) contractions are integral
components of normal movements and often occur
when electrical stimulation is used to aid function in
patients with paralysis (e.g., functional electrical stimu-
lation to produce standing or walking) (1, 23, 28, 29).
The relationship between stimulation frequency and
dynamic performance measurements (e.g., excursion,
work, peak power, and average power) has not been
reported. Furthermore, it is not known whether the
force-frequency relationship plotted by using either the
isometric peak force or force-time integral reflects the
dynamic performance-frequency relationship. Addition-
ally, it is not known what changes in the dynamic
performance-frequency relationship occur with fatigue.
The purpose of this study, therefore, is to identify the

relationship between stimulation frequency on dynamic performance measurements and to examine the changes in these relationships after repetitive fatiguing contractions. Additionally, because of our laboratory's long-standing interest in using the catchlike property of skeletal muscle to augment muscle forces, catchlike-inducing trains were also used to identify their effect on the dynamic performance-frequency relationships.

METHODS

Subjects

Data were obtained from 13 healthy volunteer subjects (7 men, 6 women) ranging in age from 18 to 31 yr old [mean 22.84 $\pm$ 3.78 (SD) yr], with no history of lower extremity orthopedic problems. This study was approved by the University of Delaware Human Subjects Review Board, and all subjects signed informed consent forms.

Experimental Setup

Details of the experimental setup have been previously described (24). Briefly, subjects were seated on a computer-controlled dynamometer (KinCom III, Chattecx, Chattanooga, TN) with hips flexed to ~90° (Fig. 1). The dynamometer axis was aligned with the knee joint axis, and force was measured with the force transducer pad positioned ~3 cm proximal to the lateral malleolus. The left quadriceps femoris

muscle was stimulated by using a Grass S8800 stimulator with a SIU8T stimulus isolation unit. All stimulation pulses were 600 μs in duration. Two self-adhesive, 3- × 5-in. electrodes were used to stimulate the muscle. The stimulator was driven by a personal computer that controlled all timing parameters of each stimulation protocol. Force, angle, and velocity data were digitized on-line at a rate of 200 samples/s and stored for subsequent analysis.

Training Sessions

Before the commencement of the experimental sessions, all subjects participated in one training session. Subjects were familiarized with the experimental protocol and trained to relax during stimulation of their quadriceps muscle during both isometric and dynamic contractions. For each subject, the maximum voluntary isometric contraction (MVIC) was determined by using a burst superimposition technique that has been previously described (36). Subjects were instructed to refrain from strenuous activity for at least 24 h before their scheduled experimental session. The training and experimental sessions were separated by at least 48 h.

Experimental Sessions

Each of the 13 subjects participated in one experimental session that included a prefatigue-testing sequence, a fatigue-producing sequence, and a fatigue-testing sequence (Fig. 2). The experimental session tested one load condition (see below). At the beginning of the experimental session, MVIC
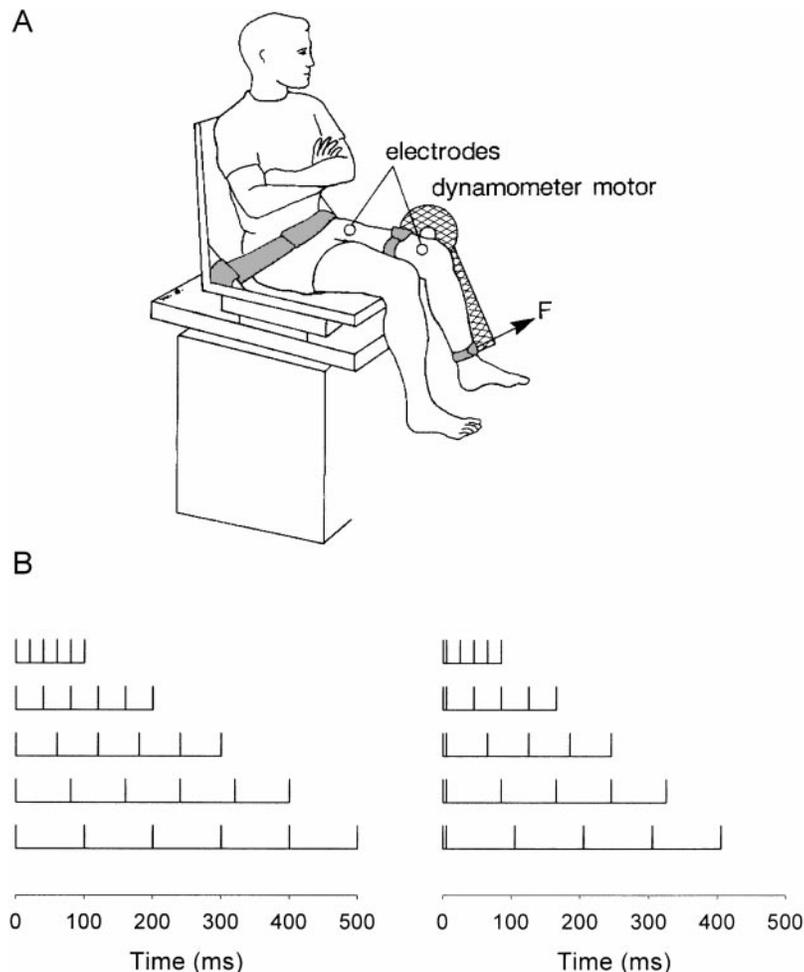

Fig. 1. A: experimental setup showing a subject seated on computer-controlled dynamometer. Self-adhesive electrodes were placed over rectus femoris (anode) and vastus medialis (cathode) portions of left quadriceps femoris muscle. Testing of maximum voluntary isometric contractions was performed at a knee joint angle of 90° of flexion (see text for details). B: schematic representation of 5 of the 10 constant-frequency trains (left) and 5 comparable catchlike-inducing trains (right) used during the study. Each vertical line represents each stimulus pulse within a train. Each train contained 6 pulses. Traces shown are examples of 6-pulse constant-frequency trains (left) with interpulse intervals equal to 20, 40, 60, 80, and 100 ms, respectively, and comparable catchlike-inducing trains (right). All catchlike-inducing trains have an initial 5-ms interpulse interval. F, force.

Pre-Fatigue Testing Sequence--one train every 5 s

Isometric Response Testing Portion

Twitch	Tetanus	Tetanus	Twitch	Tetanus	Tetanus

5 second pause

Isotonic Response Testing Portion

C-80	C-30	D-50	C-50	D-100	D-90	D-60	C-20	C-90	D-80	C-10	C-70	C-40	C-100	D-30	D-40	C-60	D-10	D-70	D-20
D-20	D-70	D-10	C-60	D-40	D-30	C-100	C-40	C-70	C-10	D-80	C-90	C-20	D-60	D-90	D-100	C-50	D-50	C-30	C-80

↓

5 min. rest

↓

Fatigue Producing Sequence--one train every 1.5 s

6-pulse, 40-pps train repeated 150 times

↓

1.5 second pause

↓

Fatigue Testing Sequence--one train every 1.5 s

Isotonic Response Testing Portion

Two fatigue producing trains (6-pulse, 40-pps trains) inserted between each of the following test trains

C-80	C-30	D-50	C-50	D-100	D-90	D-60	C-20	C-90	D-80	C-10	C-70	C-40	C-100	D-30	D-40	C-60	D-10	D-70	D-20
D-20	D-70	D-10	C-60	D-40	D-30	C-100	C-40	C-70	C-10	D-80	C-90	C-20	D-60	D-90	D-100	C-50	D-50	C-30	C-80

1.5 second pause

Isometric Response Testing Portion

Two fatigue producing trains (6-pulse, 40-pps trains) inserted between each of the following test trains

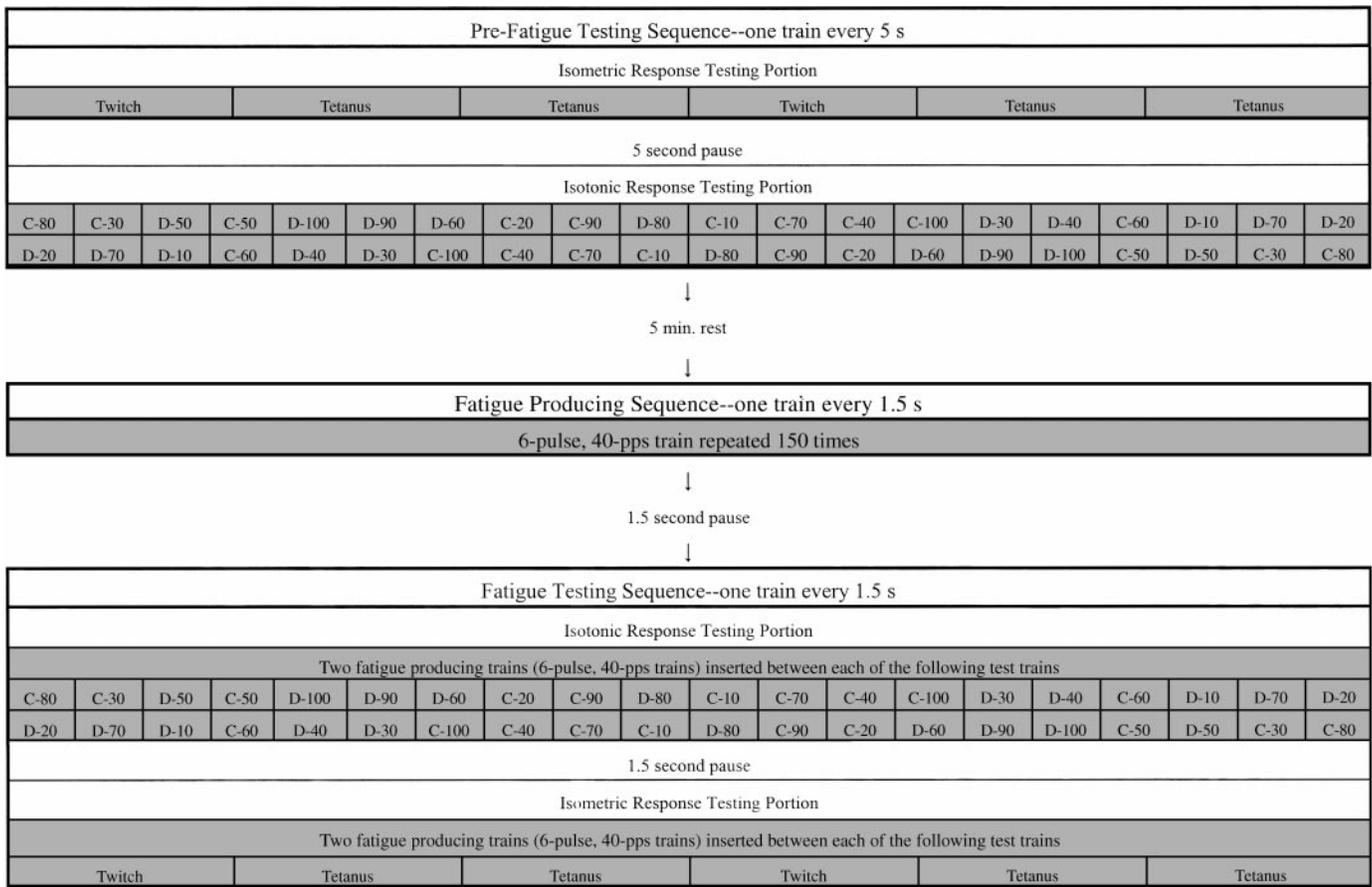| Twitch	Tetanus	Tetanus	Twitch	Tetanus	Tetanus

Fig. 2. Flow sheet illustrating prefatigue-testing, fatigue-producing, and fatigue-testing sequences that comprised the experimental protocol. Prefatigue-testing sequence included both isometric and isotonic testing portions. Shown is order of testing trains for an individual subject. C, constant-frequency trains; D, catchlike-inducing trains. Interpulse intervals ranged from 10 to 100 ms and are designated numerically. Each subject received his or her own random sequence of trains (see first shaded row of Isotonic Response Testing Portion), and the same sequence was repeated in reverse order (see second shaded row). For each subject, the same sequence was used for both prefatigued and fatigued testing, except that 2 fatigue-producing trains were inserted between each testing train during fatigue testing (see text for additional details). pps, Pulses/s.

testing was conducted. The session was continued only if the subject was able to perform an MVIC that was ≥95% of the MVIC produced during the training session. If a subject was unable to meet this MVIC standard within four attempts, the experimental session was rescheduled for another day.

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

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

After the stimulation intensity was set, the dynamometer was set in the isotonic mode by using the maximum velocity setting (250°/s). This setting allowed the velocity of movement to vary up to a maximum of 250°/s. The dynamometer settings were adjusted to begin all movements at 90° of knee flexion and to provide the appropriate resistance to knee extension. Resistance was set at 50% of the stimulated tetanic force (i.e., 10% of the subject's MVIC). The dynamometer's has three available accelerations: "low," "medium," and "high." The medium setting was used as a trade-off to reduce the damping effects while system stability is maintained.

Prefatigue-testing sequence. Before the prefatigue-testing sequence, the muscle was repotentiated isometrically by using ten 6-pulse, 100 pps trains delivered once every 5 s. Within 5 s of potentiation, the prefatigue-testing sequence commenced. The initial part of the prefatigue testing sequence was designed to obtain isometric twitch and tetanic responses and to maintain the potentiated, but fresh, state. The protocol started with a sequence of a twitch followed by two 6-pulse, 100 pps trains, which was repeated for a total of 2 twitches and 4 trains (see Fig. 2). The remainder of the prefatigue-testing sequence tested dynamic responses to constant-frequency and catchlike-inducing trains. All constant-frequency and catchlike-inducing trains had 6 pulses (5 interpulse intervals). To determine muscle performance as a

function of stimulation frequency, constant-frequency trains had equal interpulse intervals from 10 ms and increased by 10-ms intervals up to 100 ms (10 constant-frequency trains; see Fig. 1*B, left*). Comparable catchlike-inducing trains had an initial interpulse interval of 5 ms (a doublet) and remaining interpulse intervals the same as those for the different constant-frequency trains (10 catchlike-inducing trains; see Fig. 1*B, right*). The order of the 20 different trains was randomized for each subject and repeated in reverse random order for a total of 40 trains (Fig. 2). All trains were delivered once every 5 s to prevent muscle fatigue.

Fatigue-producing sequence. The fatigue-producing protocol followed the prefatigue-testing protocol after a 5-min rest. Before commencement of the fatigue-producing protocol, the muscle was repotentiated isometrically, and then the isotonic mode of the dynamometer was enabled. Six-pulse, 40 pps trains were delivered to the muscle once every 1.5 s for a total of 150 isotonic contractions to fatigue the muscle. The 1.5-s period allowed sufficient time for the leg to return to the start position. Short trains (125 ms, 6 pulse) were used to allow the stimulation to end before the knee reached full extension. Additionally, brief trains were used because short bursts of activity typify activation patterns used to produce functional movements (18). Hennig and Lømo (18) demonstrated that motor units typically fire in short bursts (up to 6 pulses) during normal activity in rats. Stimulators used in cardiomyoplasty, a procedure in which a skeletal muscle is wrapped around the heart and stimulated to assist systole, all use 6-pulse trains (9) because this functional electrical stimulation application is constrained by the cadence of the heartbeat.

Fatigue-testing sequence. Fatigue testing began immediately (1.5 s) after the last fatigue-producing train was delivered. All trains continued to be delivered in 1.5-s intervals. The subject's same dynamic prefatigue sequence (40 testing trains) was delivered, with the exception that two fatigue-producing stimulation trains (6 pulse, 40 pps) were delivered

before the presentation of each testing train (see Fig. 2). This was done to control for prior activation history and to ensure a stable level of fatigue during the fatigue testing sequence. Thus the fatigue testing sequence consisted of the 40 trains of the prefatigue sequence plus 78 intervening fatigue-producing trains for a total of 118 trains. After the last fatigue-testing train, two twitches were delivered in 1.5-s intervals. The two twitches signaled the experimenter to switch the dynamometer from isotonic to isometric modes. Then, continuing in 1.5-s intervals, fatigue-producing trains (6 pulse, 40 pps), twitches, and tetanic trains (6 pulse, 100 pps) were delivered to the muscle. Two fatigue-producing trains were delivered before each twitch or tetanic train to ensure a stable level of fatigue and to control for previous activation history. Four twitches and two tetanic trains were used.

Data Management

All force responses were gravity corrected, and the four dependent variables were calculated by using custom-written software (Labview 4.0). The dependent measurements of muscle performance were joint excursion, work, peak power, and average power produced during the shortening portion of each contraction. All performance measures were calculated by using the force, angle, and velocity data from the dynamometer during the period between force onset and maximum shortening (Fig. 3). Excursion was calculated as the maximum knee joint displacement in degrees, work was calculated as the numerical integration (trapezoidal method) of force times the arc of movement (knee joint displacement in radians times the transducer lever arm) over the time interval from force onset to the time of maximum knee extension (muscle shortening), and average power was calculated by dividing the work by the time interval from force onset to maximum knee extension.

Prefatigue-testing sequence. The prefatigue data analysis used the responses of the constant-frequency and catchlike-
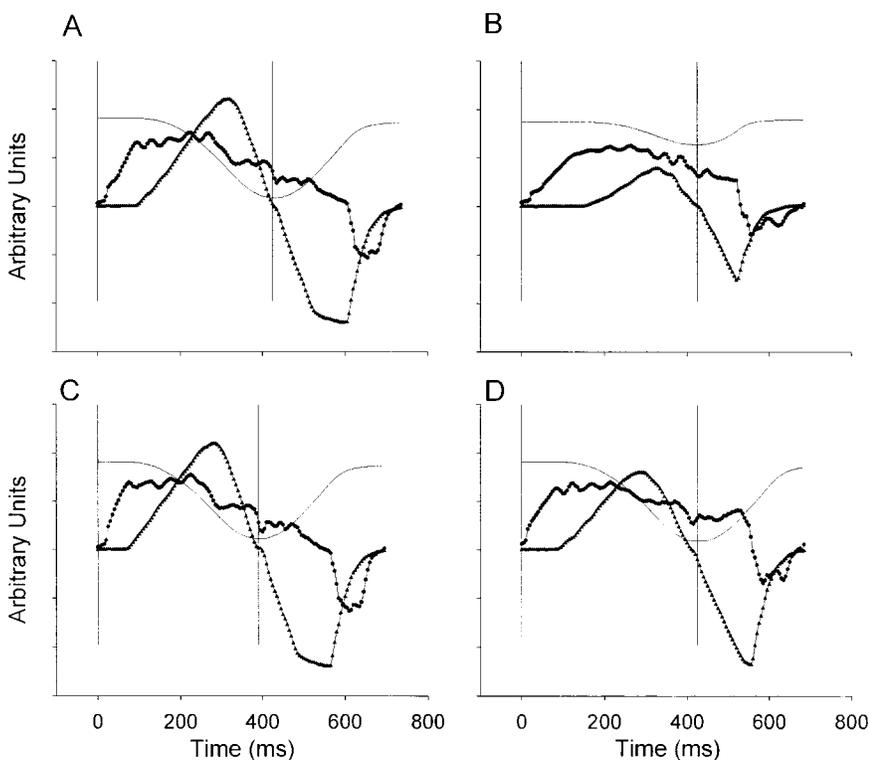

Fig. 3. Prefatigue (*A* and *C*) and fatigued (*B* and *D*) raw data traces from a representative subject. Gravity-corrected force (●), angle (line), and velocity (▲) data in response to a 50-ms interpulse interval (*A* and *B*) and a comparable catchlike-inducing train (*C* and *D*). Excursion, work, peak power, and average power were calculated over period of force onset to maximum shortening of the muscle (interval between vertical lines). Relative scales for force, excursion, and velocity are the same across all panels.

inducing trains collected during the prefatigue-testing proto-col. The two occurrences of each train were averaged to help to control for previous muscle activation history. Peak forces produced during the isometric twitch and tetanic responses were also calculated. The two twitch responses and the second and forth tetanic responses were each averaged (see Fig. 2). The twitch-to-tetanus ratio was then calculated from the resulting isometric data.

Fatiguing sequence. The responses to each train in the fatigue-producing sequence were recorded. The percent de-cline for each dependent measure of muscle performance was calculated from the maximum response and the average response of the last three fatiguing trains (see Fig. 4).

Fatigue-testing sequence. Analogous to prefatigue data, fatigue data analysis used the average of the two constant-frequency and two catchlike-inducing train responses during the fatigue testing sequence. Similarly, isometric twitch and tetanic responses were each averaged as described for the prefatigue data.

Data Analysis

Prefatigue and fatigue-testing sequences. For testing trains, separate analyses were performed for each dependent mea-sure and for fresh and fatigued responses. Two-way, within-subjects, factorial ANOVAs were performed to test the effects of train type (constant-frequency vs. catchlike-inducing) and interpulse interval on the dynamic performance data. If significant effects were observed, two-tailed, paired t-tests were used to compare the greatest constant-frequency train response with the comparable catchlike-inducing train re-sponse. Similarly, if the interpulse interval of the catchlike-inducing train that produced the greatest response was different from the greatest constant-frequency train, two-tailed, paired t-tests were used to compare the greatest catchlike-inducing train response with the comparable con-stant-frequency train response. Lastly, if not already com-pared, two-tailed, paired t-tests were used to compare the constant-frequency train that produced the greatest response with the catchlike-inducing train that produced the greatest response for each of the dynamic performance measurements.

Two-tailed, paired t-tests were used to compare prefatigue with fatigued isometric twitch, tetanic train responses, and twitch-to-tetanus ratio data. For all group data, means ± SE

are presented. For all analyses, an observation was signifi-cant if $P \leq 0.05$.

RESULTS

Fatigue-Producing Sequence

Complete data sets were collected for all 13 subjects. All four muscle performance measurements showed slight potentiation from the onset of the fatiguing protocol until approximately the 15th contraction, after which a rapid decline was observed until approxi-mately the 75th contraction (Fig. 4). After the 75th contraction, the decline for each measure moderated. By the end of the fatigue-producing sequence ~50, ~58, ~57, and ~51% declines in excursion, work, peak power, and average power from their maximum potenti-ated responses, respectively, were observed.

Response to Prefatigue Testing Trains

Across performance measurements (i.e., excursion, work, peak power, and average power), constant-frequency trains produced slightly greater performance than did catchlike-inducing trains for interpulse inter-vals ≤40–50 ms (Fig. 5). At longer interpulse intervals, catchlike-inducing trains produced greater perfor-mance than did constant-frequency trains. For the prefatigue condition, most performance measurements had significant main effects for both train type (con-stant frequency vs. catchlike inducing) and interpulse interval (see Table 1). For both work and peak power, the main effect for train type was not significant. Significant interactions were observed for all perfor-mance measurements.

For constant-frequency trains, an interpulse interval of 50 ms produced the greatest excursion, work, and peak power, which was significantly greater than the comparable catchlike-inducing train for each measure (8.2, 10.7, and 6.9%, respectively). The 40-ms inter-pulse interval constant-frequency train produced the

Fig. 4. Averaged group (n = 13) excursion (*A*), work (*B*), peak power (*C*), and average (Avg) power (*D*) in response to fatigue-producing sequence. To produce fatigue, quadriceps femo-ris muscle was repetitively activated 150 times at a rate of 1 train per 1.5 s by using 6-pulse, 40 pps trains. Note that the 268 trains in the isotonic portion of fatigue-producing (150 trains) and fatigue-testing (118 trains) se-quences lasted 6.7 min. Dynamometer's soft-ware limits continuous exercise protocols to a maximum of 5 min. Thus, to continue for longer than 5 min, the isotonic exercise rou-tine had to be stopped and restarted. We chose to stop and restart isotonic mode at *contrac-tion 130,* at which a relatively stable level of fatigue was attained. This procedure resulted in 2–3 isometric contractions (*130–132*) dur-ing the fatigue-producing sequence that were omitted from Fig. 4 with no appreciable effect on the subsequent data. Deg, degrees.
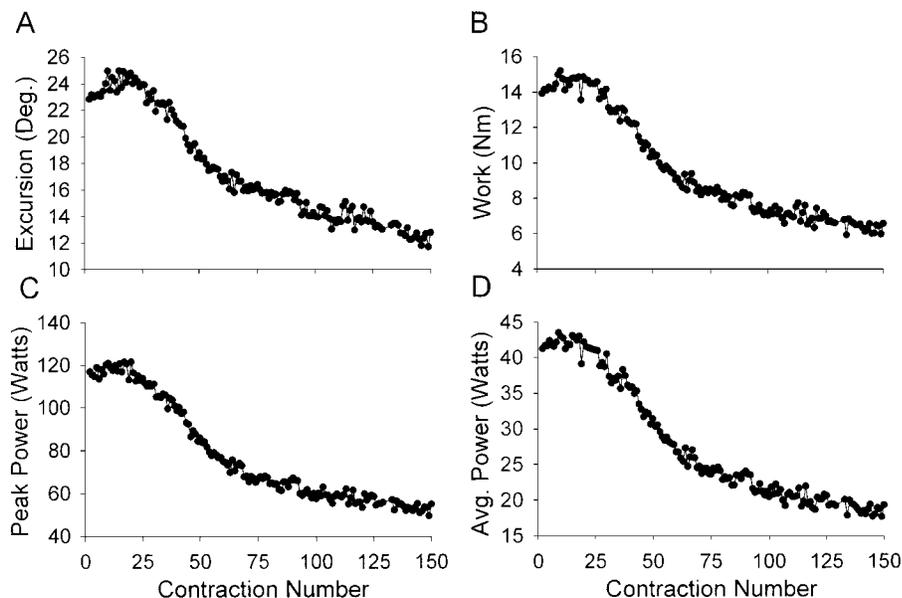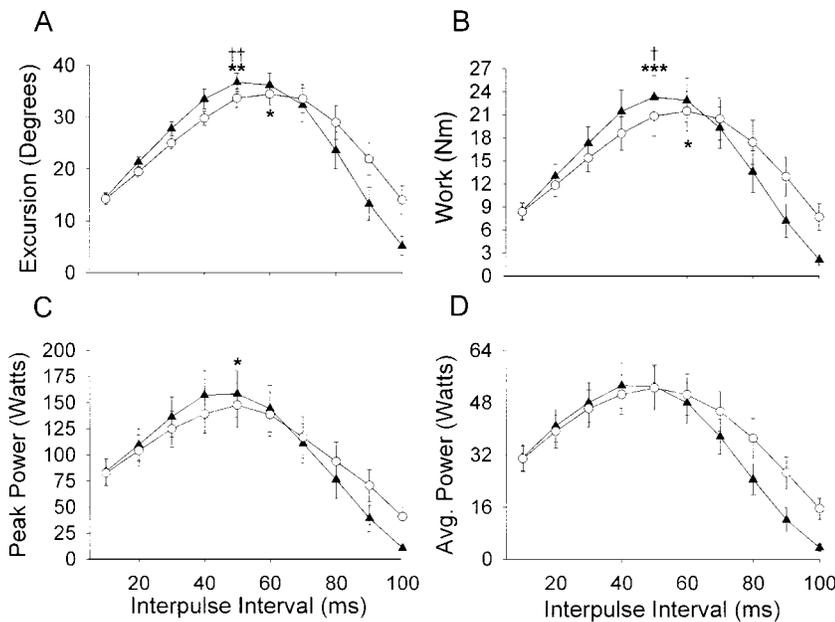
Fig. 5. Averaged group ($n = 13$) excursion (*A*), work (*B*), peak power (*C*), and average power (*D*) in response to constant-frequency train (▲) and catch-like-inducing train (○) plotted as a function of interpulse interval for fresh muscles. Two-tailed, paired *t*-tests were used to compare constant-frequency train that produced greatest response with comparable catchlike-inducing train (see *), catchlike-inducing train that produced greatest response with comparable constant-frequency train (see *), and greatest catchlike-inducing train with greatest constant-frequency trains (see †). * $P \leq 0.05$. ** $P \leq 0.01$. *** $P \leq 0.001$. † $P \leq 0.05$. †† $P \leq 0.01$. See text for additional details.

greatest average power for constant-frequency trains but did not produce significantly greater average power than did the comparable catchlike-inducing train.

An interpulse interval of 60 ms produced the greatest excursion and work for catchlike-inducing trains; however, their comparable constant-frequency trains produced significantly greater responses (4.8 and 6.2%, respectively). For peak power and average power, catchlike-inducing trains with 50-ms interpulse intervals produced the greatest responses for all catchlike-inducing trains. For peak power, the comparable constant-frequency train (50-ms interpulse interval) produced significantly greater responses (6.9%) than did the catchlike-inducing train, whereas no significant difference was observed in the average power produced by the 50-ms catchlike-inducing and constant-frequency trains. Overall, the constant-frequency trains that produced maximum responses produced significantly greater excursion (4.8%), work (6.2%), and peak power (6.9%) than did the catchlike-inducing trains that produced maximum responses. For average power, no significant differences were noted between the constant-frequency and catchlike-inducing trains that produced the maximum responses (40- and 50-ms interpulse intervals, respectively).

Response to Fatigue-Testing Trains

In contrast to fresh muscle responses, catchlike-inducing trains produced greater performance than did constant-frequency trains for all measurements for interpulse intervals >20 ms (Fig. 6).

For fatigued muscle, significant main effects of train type and interpulse interval were observed for all performance measurements (see Table 1). All performance measurements except excursion showed significant interactions.

The 40-ms interpulse interval produced the greatest excursion and work for constant-frequency trains, whereas the 20-ms interpulse interval constant-frequency train produced the greatest peak power and average power. The 40-ms constant-frequency train produced significantly less work (26%) than its comparable catchlike-inducing train, but otherwise no significant differences in excursion, peak power, and average power were observed between the optimal constant-frequency trains and their comparable catchlike-inducing trains.

For catchlike-inducing trains, the 50-ms train produced the greatest excursion, the 40-ms train produced the greatest work, and the 30-ms train produced the

Table 1. *ANOVA summary table*

Isotonic Performance Parameter	Fatigue State	Main Effect: IPI	Main Effect: Train Type	Interaction
Excursion	Prefatigue	$F = 55.837, P < 0.001$	$F = 6.463, P = 0.026$	$F = 23.045, P < 0.001$
Excursion	Fatigued	$F = 7.559, P < 0.001$	$F = 8.038, P = 0.015$	$F = 1.723$, NS
Work	Prefatigue	$F = 31.094, P < 0.001$	$F = 3.294$, NS	$F = 14.35, P < 0.001$
Work	Fatigued	$F = 8.974, P < 0.001$	$F = 9.297, P = 0.01$	$F = 2.077, P = 0.038$
Peak power	Prefatigue	$F = 26.741, P < 0.001$	$F = 3.283$, NS	$F = 13.559, P < 0.001$
Peak power	Fatigued	$F = 16.261, P < 0.001$	$F = 8.942, P = 0.011$	$F = 2.444, P = 0.014$
Average power	Prefatigue	$F = 34.053, P < 0.001$	$F = 21.78, P = 0.001$	$F = 15.257, P < 0.001$
Average power	Fatigued	$F = 18.421, P < 0.001$	$F = 17.426, P = 0.001$	$F = 3.205, P = 0.002$

IPI, interpulse interval; NS, not significant.

A

B

C

D

Fig. 6. Averaged group (*n* = 13) excursion (*A*), work (*B*), peak power (*C*), and average power (*D*) in response to constant-frequency train (▲) and catchlike-inducing train (○) plotted as a function of interpulse interval for fatigued muscle. Two-tailed, paired *t*-tests were used to compare constant-frequency train that produced greatest response with comparable catchlike-inducing train (see *), catchlike-inducing train that produced greatest response with comparable constant-frequency train (see *), and the greatest catchlike-inducing train with the greatest constant-frequency trains (see †). *$P \leq 0.05$. **$P \leq 0.01$. ***$P \leq 0.001$. †$P \leq 0.05$.
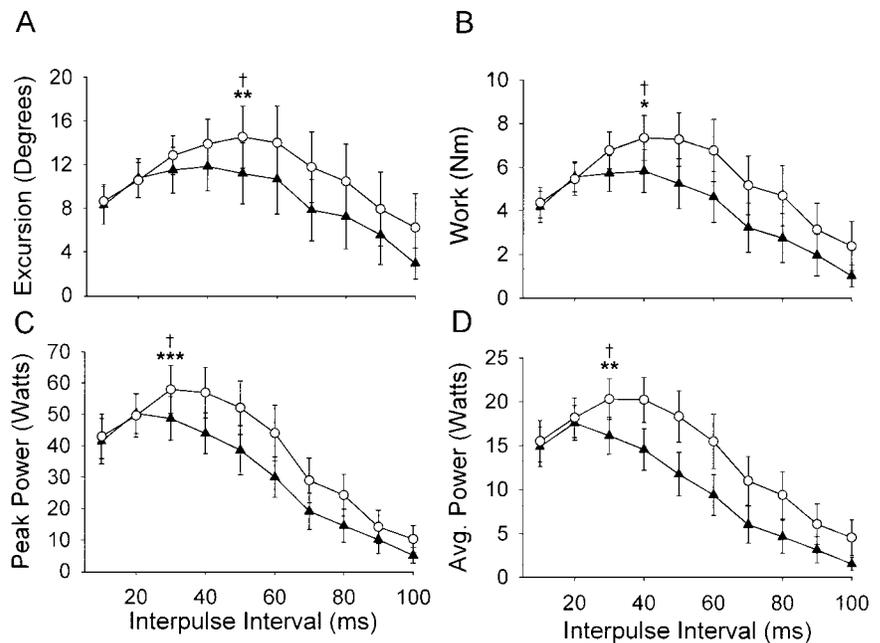
greatest peak and average power. The optimal catchlike-inducing trains produced significantly greater excursion (29.8%), work (26.0%), peak power (19.0%), and average power (25.8%) than did their respective comparable constant-frequency trains. Additionally, the catchlike-inducing trains that produced the greatest responses produced significantly greater excursion (18.4%), work (26.0%), peak power (15.3%), and average power (15.4%) than did the maximum responses to the constant-frequency trains.

Isometric Twitch and Tetanic Responses

Isometric twitch and tetanic force declined from 61 to 34 N (44% decline) and from 229 to 172 N (25% decline), respectively, with fatigue (Fig. 7*A*). The twitch-to-tetanus ratio declined with fatigue from 0.26 to 0.20 (24% decline; Fig. 7*B*).

DISCUSSION

Dynamic Performance vs. Interpulse Interval

This is the first study to investigate the effects of frequency and train pattern in producing dynamic contractions of the human quadriceps femoris muscle during fresh or fatigued conditions. All dynamic performance-frequency relationships (excursion, work, peak power, and average power) were parabolic when expressed as a function of interpulse interval (see Figs. 5 and 6). With fatigue, frequencies producing maximum performance shifted to shorter interpulse intervals (higher frequencies), but catchlike-inducing trains were optimal at longer interpulse intervals (lower frequencies) than were constant-frequency trains regardless of fatigue state. Similar shifts in force-frequency relationships with fatigue have been reported for isometric contractions (6, 7, 11, 16, 20, 37).

The observations that catchlike-inducing trains were able to maximize dynamic performance at lower fre-

quencies than were constant-frequency trains are of interest because fatigue may be related to stimulation frequency (2, 17, 21). In general, the higher the frequency of stimulation, the greater the rate of fatigue. Thus because maximum performance was attained at lower frequencies for catchlike-inducing trains vs. constant-frequency trains, they may provide a strategy for minimizing fatigue. For example, when the muscle was fatigued, catchlike-inducing trains with 80-ms interpulse intervals produced greater excursion than constant-frequency trains with 40-ms interpulse intervals.

Comparison Between Isotonic Performance- and Isometric Force-Frequency Relationships

In a recent study, our laboratory reexamined the isometric force-frequency relationship of the human quadriceps femoris muscle by using brief constant-frequency and catchlike-inducing trains (6). When peak forces were plotted as a function of interpulse-interval, the relationships showed a sigmoidal decline when the muscle was fresh and a relatively linear decline when the muscle was fatigued. If, however, the force-time integrals were plotted as a function of interpulse interval, for fresh and fatigued muscles, the relationships were parabolic. The present dynamic performance relationships are qualitatively similar to isometric force-time integral-interpulse interval relationships and not to the nonparabolic isometric peak force-interpulse interval relationships. A reason for diminished performance with the shorter interpulse interval trains (higher frequencies) may be due to the short train duration resulting from the constraints we imposed on the number of pulses within the trains (6 pulses). Longer high-frequency trains may not show the same diminished performance. The ranges of frequencies producing maximum dynamic responses, however, are higher than those producing maximum isometric force-time integrals. Thus, although the relationship be-
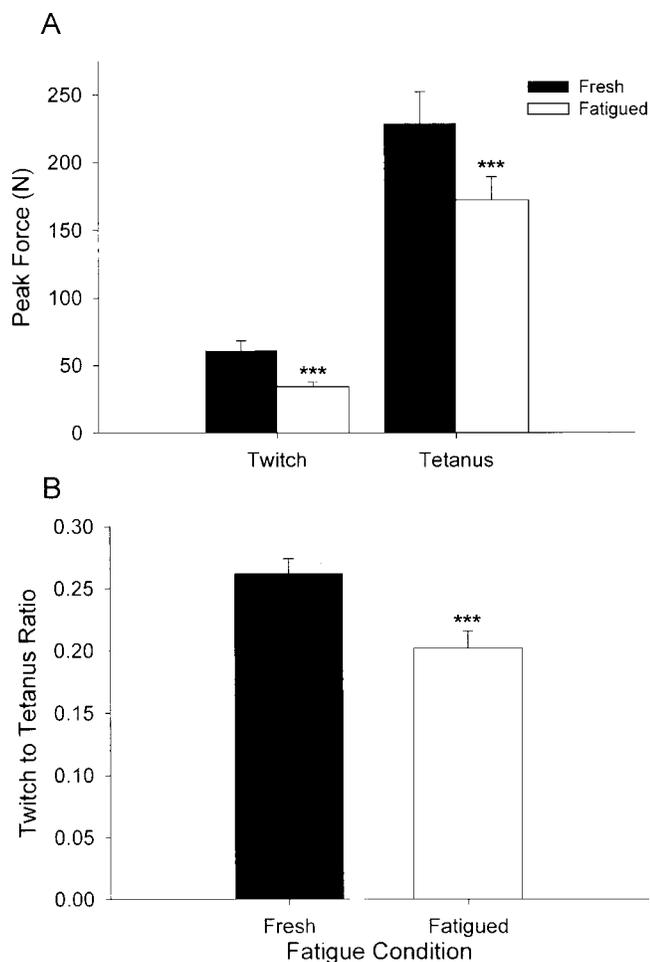
A

B

Fig. 7. Averaged group ($n = 13$) fresh and fatigued isometric twitch and tetanic peak force data (*A*) and prefatigue and fatigued isometric twitch-to-tetanus ratio data (*B*). Two-tailed, paired *t*-tests were used to compare prefatigue with fatigued responses. *** $P \leq 0.001$.

tween the interpulse interval and dynamic performance and the relationship between interpulse interval and isometric force-time integrals look similar, very different frequencies may be needed to optimize dynamic vs. isometric performance of a muscle. It is, therefore, prudent to examine the relationships during conditions that are most applicable to the condition in which the muscle is operating.

Isometric Twitch and Tetanic Train Responses

Both twitch and tetanic responses were attenuated as a result of fatigue, but the relative attenuation of twitch responses was greater than that of tetanic train responses. The disproportionate decline in the twitch responses was evident in the twitch-to-tetanus ratio, which showed a significant decline with fatigue. The declines in the isometric tetanic response (25%), however, were smaller than the declines in isotonic performance. Declines in isotonic performance for the 100 pps testing train (10-ms interpulse interval) ranged from 48 to 57% across isotonic performance variables. Previous investigations have also shown that fatigue develops more rapidly in isotonic contractions than in isomet-

ric contractions (32, 35). Additionally, greater loss in power of shortening contractions than loss in isometric force has been observed (13, 14, 19, 35). Thus assessment of fatigue on the basis of loss of isometric force can seriously underestimate functional impairment of isotonic contractions (14, 19).

The decline in the twitch-to-tetanus ratio with fatigue suggests a problem in excitation-contraction coupling. This observation is consistent with characteristics of low-frequency fatigue that our laboratory has observed in other similar isotonic (24) and isometric studies (5, 6, 8, 26, 27, 34).

Potential Mechanisms for Performance Augmentations By Using Catchlike-Inducing Trains During Fatigue

The relative performance of catchlike-inducing trains vs. constant-frequency trains during isotonic contractions is similar to the results from previous studies of isometric contractions that showed catchlike-inducing trains became beneficial only when muscles were fatigued (4–6). The relative efficacy of catchlike-inducing trains to augment force during fatigue may be related to the proposed mechanisms by which catchlike-inducing trains augment force. Enhanced muscle stiffness is one of the proposed mechanisms by which trains that evoke the catchlike response augment force production over constant-frequency trains (30). During fatigue, Curtin and Edman (12) noted a decrease in stiffness of frog muscle fibers and attributed the decrease in muscle stiffness to fewer attached crossbridges. Thus, if stiffness decreases with fatigue, then improving muscle stiffness with catchlike-inducing trains may produce enhanced dynamic performance because muscle force would be transmitted more effectively to the skeletal system and allow better take-up of the series elastic components than would constant-frequency trains (4). Consistent with a decline in muscle stiffness during fatigue is the observation that the rates of rise of force slowed for constant-frequency trains when the muscle was fatigued (e.g., see Fig. 3, *A* and *B*). Catchlike-inducing trains, however, were less susceptible to slowing in the rate of rise of force. The observation that catchlike-inducing trains were better able to maintain their rates of rise of force are consistent with previous isotonic (24), isovelocity (4), and isometric studies (5, 6). Enhanced muscle stiffness could account for the ability of catchlike inducing trains to maintain their rate of rise of force, which allows a greater number of pulses in the train able to contribute to muscle shortening than constant-frequency trains (24).

Enhanced calcium release by the sarcoplasmic reticulum (15, 30) is another proposed mechanism by which trains that evoke the catchlike response augment force production over constant-frequency trains during fatigue. Duchateau and Hainaut (15) demonstrated that catchlike-inducing trains augmented force by increasing calcium release from the sarcoplasmic reticulum, and Parmiggiani and Stein (30) showed that the increase in calcium release was greater per pulse for catchlike-inducing trains than for constant-frequency

trains. Westerblad et al. (38) have shown that although the action potential is normal during low-frequency fatigue, the calcium transient is lower for a given level of stimulation. Low-frequency stimulation (i.e., frequencies producing subtetanic responses) produces calcium transients that fall on the steep portion of the sigmoidal force-calcium concentration curve (10). Thus, during low-frequency stimulation, small changes in calcium release result in large changes in force. In contrast, during high-frequency stimulation, the intracellular calcium concentrations fall on the flat, asymptotic portion of the force-calcium concentration curve. Greater calcium release with the catchlike-inducing trains could partially compensate for decreased calcium release that occurs with muscle fatigue. This could explain the augmentation with catchlike-inducing trains for all frequencies ≤ 50 pps (>20-ms interpulse intervals) when the muscles were fatigued.

Conclusions

Because we used activation patterns and shortening contractions that were designed to mimic physiological conditions, the relationships we presented are more appropriate than previous work during isometric contractions in helping researchers and clinicians to identify the relationship between the activation pattern of the muscle and the potential for producing functional movements. Generally, for all performance measurements (excursion, work, peak power, and average power), a parabolic relationship, qualitatively similar to the isometric relationship between force-time integral and interpulse interval, was observed. When the muscles were fresh, the constant-frequency trains generally produced greater performance than did the catchlike-inducing trains. When fatigued, however, the catchlike-inducing trains produced greater performance than did all constant-frequency trains. Because catchlike-inducing trains with longer interpulse intervals (lower frequencies) than constant-frequency trains can be used to produce equivalent or greater performance, catchlike-inducing trains may offer a strategy for minimizing fatigue during functional electrical stimulation applications. Lastly, enhancement in performance by catchlike-inducing trains when the muscles were fatigued may be due to less susceptibility to impairments in excitation-contraction coupling and greater ability to maintain their rates of rise of force than constant-frequency trains.

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