Effect of aging on fatigue characteristics of elbow flexor muscles during sustained submaximal contraction

MARTIN BILODEAU, TARA K. HENDERSON, BRIAN E. NOLTA, PAUL J. PURSLEY, AND GRETCHEN L. SANDFORT

Physical Therapy Graduate Program, University of Iowa, Iowa City, Iowa 52242

Received 10 May 2001; accepted in final form 15 August 2001

Bilodeau, Martin, Tara K. Henderson, Brian E. Nolta, Paul J. Pursley, and Gretchen L. Sandfort. Effect of aging on fatigue characteristics of elbow flexor muscles during sustained submaximal contraction. J Appl Physiol 91: 2654-2664, 2001.—The purpose of this study was to compare fatigue-related measures of central and peripheral mechanisms between young and elderly subjects for a task performed with elbow flexor muscles. Ten young and nine elderly subjects performed a sustained submaximal fatigue task at 35% of their maximum voluntary contraction torque. Measures of neuromuscular function, reflecting changes in neuromuscular propagation, voluntary activation, excitation-contraction-relaxation processes, and metabolite buildup, were taken before, during, and after the fatigue task. The main results were the absence of neuromuscular propagation failure in either young or elderly subjects, the presence of central fatigue at the end of the fatigue task in 7 of 9 elderly but only 3 of 10 young subjects, and lesser changes in twitch torque contraction-relaxation variables and electromyographic median frequency in elderly compared with young subjects. The lesser fatigue-related changes in twitch contraction speed and median frequency in elderly compared with young subjects could reflect the increase in type I-to-type II fiber area reported with old age. The presence of significant central fatigue can apparently minimize some of the potential differences present in peripheral fatigue sites.

neuromuscular propagation; voluntary activation; excitation-contraction-relaxation coupling; electromyography

MUSCLE FATIGUE CAN BE DEFINED as “any reduction in the force-generating capacity of the total neuromuscular system, regardless of the force required in any given situation” (16). The specific mechanism(s) responsible for this reduction in force production capacity will vary according to the specific demands of a given task. This has been referred to as the task-dependency nature of fatigue (13). For example, with young, healthy adults performing a sustained isometric maximum voluntary contraction (MVC), fatigue would mostly involve changes associated with the accumulation of metabolites and the depletion of metabolic substrate within the muscle group performing the task (28). In contrast, sustained submaximal contractions have been shown to involve failure in excitation-contraction coupling processes and impairment in neuromuscular propagation (14). A decrease in muscle activation by the central nervous system (central fatigue) can also develop with sustained activity (2). Fuglevand et al. (14) have shown that the extent of failure in neuromuscular propagation, the series of events encompassing the transmission of nerve impulse across the neuromuscular junction, and the generation and propagation of action potentials at the sarcolemma are dependent on the target force sustained until exhaustion. In their study, an isometric submaximal target force of 35% of the MVC caused a greater failure in neuromuscular propagation compared with target forces of 20 and 50% MVC. A target force of 35% MVC was thus chosen in the present study in an attempt to maximize neuromuscular propagation failure.

Various changes take place in the neuromuscular system with normal aging. Of specific interest to this study, it has been suggested that age-related morphological changes at the neuromuscular junction (30) or changes related to the excitability of the sarcolemma (8) would tend to increase neuromuscular transmission failure with aging. Accordingly, Smith (35) concluded that, with repetitive activation, there is a more pronounced synaptic depression in aged animals, and the onset of conduction block occurs at lower frequencies. However, the functional consequences of the age-related changes at the neuromuscular junction remain largely unexplored in humans. Cupido et al. (7) induced fatigue in the tibialis anterior of young and elderly subjects with electrical stimulation. No differences were observed between the groups concerning relative changes in the M wave (reflecting neuromuscular propagation) with sustained activity, with both young and elderly subjects showing neuromuscular propagation failure mostly at high frequencies of stimulation. Hicks et al. (18) found no significant decrease in the M-wave amplitude of three muscles for both young and elderly subjects during a fatigue task consisting of intermittent MVCs. The M-wave amplitude remained constant for the elderly and even potentiated for the younger subjects. They attributed this difference to a decreased activity in the Na"+-K"+ pump with aging. However, these protocols may not have been

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Address for reprint requests and other correspondence: M. Bilodeau, Physical Therapy Graduate Program, Univ. of Iowa, Iowa City, IA 52242 (E-mail: martin-bilodeau@uiowa.edu).

2654
8750-7587/01 $5.00 Copyright © 2001 the American Physiological Society http://www.jap.org
optimal in terms of inducing failure in neuromuscular propagation. Our laboratory’s preliminary data (15) from young and elderly subjects performing a fatigue task that appears to put a greater demand on neuromuscular propagation (intermittent submaximal task) indicate that elderly subjects may experience a greater decrease in M-wave amplitude with sustained activity. However, this remains to be confirmed.

The purpose of this study was to compare fatigue-related changes in measures reflecting neuromuscular propagation, as well as voluntary activation, metabolic status, and excitation-contraction-relaxation (E-C-R) coupling mechanisms between young and elderly healthy adults. As mentioned above, the fatigue protocol used was a sustained submaximal voluntary contraction (35% MVC) performed with the elbow flexor muscle group. Some of the present results have been presented in abstract form (4).

METHODS

Subjects and Overall Design

Ten young (26.3 ± 3.1 yr; 5 women, 5 men) and nine elderly (70.8 ± 3.9 yr; 4 women, 5 men) healthy adults volunteered for the study. All subjects had to be free from present or past neuromuscular conditions that could affect motor function. Subjects gave their informed consent before participating in the study, which was approved by the Institutional Review Board at the University of Iowa. Each subject participated in a single experimental session in which various measures of neuromuscular function were taken before, during, and after a fatigue task, with the intent of comparing fatigue responses and recovery profiles between young and elderly subjects.

Material

Torque measurements. A multiaxial force and torque transducer (model 45E15A-U760, JR3, Woodland, CA) was used to measure elbow flexion torques generated voluntarily and with electrical stimulation. Subjects were seated in an experimental chair with their right arm at about shoulder height and at 45° of horizontal abduction. The elbow joint was aligned with the transducer and set at a 90° angle, with the forearm in a neutral position (midway between supination and pronation). The wrist was secured in a padded metal cuff attached to a metal arm extending from the transducer. Subjects produced isometric elbow flexion efforts by pulling against the wrist cuff.

Electromyographic recordings. Electromyographic (EMG) signals of the biceps brachii (BB), brachioradialis (BR), extensor carpi radialis (ECR), and triceps brachii muscles were recorded with bipolar surface electrodes (8-mm surface area, 20-mm center-to-center interelectrode distance) taped to the skin in a direction parallel to the muscle fibers of each muscle. A common reference electrode was positioned on the dorsum of the right hand. Signals were preamplified at the muscle. A common reference electrode was positioned on the skin in a direction parallel to the muscle fibers of each 20-mm center-to-center interelectrode distance) taped to the recorded with bipolar surface electrodes (8-mm surface area, signals of the biceps brachii (BB), brachioradialis (BR), excitation-contraction-relaxation (E-C-R) propagation, as well as voluntary activation, metabolic related changes in measures reflecting neuromuscular decrease in M-wave amplitude with sustained activity. However, this remains to be confirmed.

The purpose of this study was to compare fatigue-related changes in measures reflecting neuromuscular propagation, as well as voluntary activation, metabolic status, and excitation-contraction-relaxation (E-C-R) coupling mechanisms between young and elderly healthy adults. As mentioned above, the fatigue protocol used was a sustained submaximal voluntary contraction (35% MVC) performed with the elbow flexor muscle group. Some of the present results have been presented in abstract form (4).

METHODS

Subjects and Overall Design

Ten young (26.3 ± 3.1 yr; 5 women, 5 men) and nine elderly (70.8 ± 3.9 yr; 4 women, 5 men) healthy adults volunteered for the study. All subjects had to be free from present or past neuromuscular conditions that could affect motor function. Subjects gave their informed consent before participating in the study, which was approved by the Institutional Review Board at the University of Iowa. Each subject participated in a single experimental session in which various measures of neuromuscular function were taken before, during, and after a fatigue task, with the intent of comparing fatigue responses and recovery profiles between young and elderly subjects.

Material

Torque measurements. A multiaxial force and torque transducer (model 45E15A-U760, JR3, Woodland, CA) was used to measure elbow flexion torques generated voluntarily and with electrical stimulation. Subjects were seated in an experimental chair with their right arm at about shoulder height and at 45° of horizontal abduction. The elbow joint was aligned with the transducer and set at a 90° angle, with the forearm in a neutral position (midway between supination and pronation). The wrist was secured in a padded metal cuff attached to a metal arm extending from the transducer. Subjects produced isometric elbow flexion efforts by pulling against the wrist cuff.

Electromyographic recordings. Electromyographic (EMG) signals of the biceps brachii (BB), brachioradialis (BR), extensor carpi radialis (ECR), and triceps brachii muscles were recorded with bipolar surface electrodes (8-mm surface area, 20-mm center-to-center interelectrode distance) taped to the skin in a direction parallel to the muscle fibers of each muscle. A common reference electrode was positioned on the dorsum of the right hand. Signals were preamplified at the electrode site (×30) and fed through a differential amplifier with total gain range between 100 and 100,000 (frequency range between 15 and 4,000 Hz; Therapeutics Unlimited, Iowa City, IA). Elbow flexion torque and EMG signals were fed through an analog-to-digital converter (1401 Plus, Cambridge Electronic Design, Cambridge, UK) and saved onto a personal computer for analysis. Torque was sampled at 5,000 Hz, and EMG signals were sampled at 2,000 Hz for BB and triceps brachii and 10,000 Hz for BR and ECR. The higher sampling rate for BR and ECR allowed for a better resolution to characterize M waves.

Electrical stimulation. To assess neuromuscular propagation and voluntary activation, a constant-current electrical stimulator (model S-8800, Grass Instruments) and a high-voltage constant-current stimulator (model DSTAH, Digitimer) were used to stimulate the BB, BR, and ECR muscles. The BB muscle was stimulated with pad electrodes (4 × 4 cm). The cathode was placed proximally over the innervation zone, and the anode was placed distally over the tendon. BB stimulation consisted of trains of five 0.5-ms pulses given at 100 Hz and single 0.5-ms pulses. Only the force response to both types of BB stimulation (train torque and single-twitch torque) was measured (no M wave). BR and ECR stimulation was delivered through a bipolar electrode placed over the radial nerve on the distal aspect of the tested arm (lateral side). Stimulation for the BR and ECR muscle consisted of five to six single 1-ms pulses to elicit M waves and single twitches. Moving the electrode until a maximal response was observed ensured optimal electrode placement. Supramaximal responses were sought by increasing stimulus intensity until no further increase occurred in the muscle response [electrical (M waves) or mechanical (train or twitch torque)]. One of the main variables of interest in the study was the change in M-wave amplitude of the BR muscle, which reflects the status of neuromuscular propagation for this main contributor to elbow flexion. Changes in the ECR M-wave amplitude were monitored to ensure that the stimulation intensity remained constant during the experiment. The ECR crosses the elbow; however, its main function is wrist extension.

Activity level. The level of activity of each subject was assessed with the Habitual Physical Activity Scale (1) and the Yale Physical Activity Scale (10).

Procedures

Subjects were seated as described above and were allowed 10–12 warm-up submaximal contractions in elbow flexion. The appropriate supramaximal stimulus intensity was then set for both the BB and the BR and ECR. Subjects then performed two to three brief isometric elbow flexion MVCs, from which the highest was retained for later calculations. For each MVC trial, once the subject reached his or her maximum force (plateau in the force signal seen on an oscilloscope), two trains of supramaximal stimulation to the BB were superimposed on the ongoing maximal effort to assess the level of voluntary activation (see Data Analysis). The subject was then instructed to relax, and two more trains of stimulation were delivered to the BB, followed by two single pulses. Finally, five to six single pulses of stimulation were given to the BR and ECR to elicit M waves. Subjects were also asked to perform one maximum contraction in elbow extension to obtain the maximum EMG amplitude of the triceps brachii muscles for the purpose of normalization. These constituted the prefatigue measurements.

Subjects then had to perform a sustained submaximal fatigue task (Fig. 1). A target line set at 35% MVC was displayed on an oscilloscope facing the subjects. The torque generated by the subjects was also displayed as a line moving up or down based on the torque exerted. Subjects were instructed to match their torque line with the target line as closely as possible for as long as they could. The fatigue task was ended when torque fell below the target for a 5-s period, even though the subjects were provided with strong verbal encouragement to increase force to the target. The subjects

J Appl Physiol  •  VOL 91  •  DECEMBER 2001  •  www.jap.org
subject BS at the end of the task. Fatigue progresses to the point of being negligible in the force signal. The extra force produced by the train of stimulation was easily seen on both EMG traces, with a corresponding brief increase of electrical stimulation given to the biceps brachii every 30 s. The artifact from the train EMG signal amplitude can be seen for the young compared with the elderly subject. A relatively more pronounced increase in bottom trace) displayed for 1 young (subject AS) and 1 elderly subject (subject BS; B) during their respective fatigue task. The endurance time for the young subject was 284 s compared with 512 s for the elderly subject. A relatively more pronounced increase in EMG signal amplitude can be seen for the young compared with the elderly subject (brachioradialis muscle). The artifact from the train of electrical stimulation given to the biceps brachii every 30 s is easily seen on both EMG traces, with a corresponding brief increase in the force signal. The extra force produced by the train of stimulation decreases as fatigue progresses to the point of being negligible at the end of the task.

Data Analysis

The following variables were obtained: MVC flexion torque; BR and ECR M-wave peak-to-peak amplitude and duration; torque variables associated with trains [train peak torque (TrPT), train time to peak torque (TrTPT), train half relaxation time (TrHRT)] and single pulses [twitch peak torque (TwPT), twitch time to peak torque (TPT), twitch half relaxation time (HRT)] of stimulation for the BB and BR; level of voluntary activation for pre- and postfatigue MVCs; force fluctuations and extra force produced by superimposed trains of stimulation to the BB during the fatigue task; EMG root mean square (RMS) amplitude during the fatigue task; EMG median frequency during the fatigue task; and endurance time.

The level of voluntary activation during the brief pre- and postfatigue MVCs was estimated with the following activation index (AI)

\[
AI(\%) = \left[ 1 - \frac{\text{interpolated train torque}}{\text{control train torque}} \right] \times 100
\]

where interpolated train torque is the extra torque produced by the train of electrical stimulation above the voluntary maximal torque; and control train torque is the torque produced by the same train but with the subject at rest. A mean activation index (from the two superimposed trains) was calculated for each MVC and used as the estimate of voluntary activation. The trains of stimulation given to the BB every 30 s during the fatigue task were used to calculate a ratio of the extra torque produced by a given train expressed as a percentage of the ongoing torque (torque immediately before the train of stimulation). At exhaustion, one would expect the extra torque produced by a train of stimulation to be very small (close to 0) if the subject were driving the BB muscle maximally.

EMG RMS amplitude was calculated over consecutive 2-s windows throughout the fatigue task for the BB, BR, and triceps brachii muscles. Frequency analysis of BB and BR EMG signals [512 points (BB) or 2,048 points (BR), raised cosine window, fast Fourier transform] was also performed on consecutive 2-s windows throughout the fatigue task. The median frequency [which can reflect changes in muscle fiber conduction velocity due to accumulation of metabolites and change in pH (26)], the frequency that divides the EMG power spectrum in two parts of equal power, was obtained for each 2-s windows.

A ratio of the torque produced by single pulses compared with the trains of high-frequency (100 Hz) stimulation was calculated for the BB. Fatigue-induced changes in such a torque ratio reflect changes in excitation-contraction coupling processes (12).

Statistics

Mixed-design, two-way ANOVA were used to assess differences in the variables of interest between the young and elderly subjects (age factor) and changes due to the fatigue protocol and with recovery (time factor; repeated measures with four levels: prefatigue, postfatigue, and 5 and 20 min of recovery). Analyses of covariance (ANCOVA) were also used to assess the effects of the age and time factors on the variables of interest. For this model, a measure reflecting the extent of central fatigue at the end of the fatigue task (ratio of the extra force produced by a train of stimulation to the ongoing force) was entered as a covariate to see whether age-related differences could be explained by a different amount of central fatigue between young and elderly subjects. An ANCOVA with the prefatigue MVC torque as the covariate was also performed to assess whether age-related differences could be explained by a difference in strength. Pearson product-moment correlation coefficients were used to assess the relationship between selected variables. Student t-tests and Mann-Whitney U-tests were also used when
RESULTS

Level of Activity, Endurance Time, and MVC Torque

The level of activity, as measured by the two questionnaires, was found to be similar between young (data available from 6 subjects) and elderly (all 9 subjects) subjects (Mann-Whitney U-tests, \( P > 0.05 \)). Maximum torque was \( \sim 20\% \) greater in young (prefatigue MVC: \( 101.6 \pm 42.0 \) N·m) compared with elderly (\( 83.8 \pm 19.1 \) N·m) subjects. However, this difference was not significant (\( t \)-test, \( P > 0.05 \)). Also, the absolute torque sustained during the fatigue task was not different between the young (\( 37.9 \pm 14.5 \) N·m) and elderly (\( 29.0 \pm 7.4 \) N·m) group (\( P > 0.05 \)). MVC torque decreased after the fatigue task and was not fully recovered after 20 min (\( \sim 88\% \) of prefatigue value for both groups). The changes in MVC torque were similar between young and elderly subjects (age \( \times \) time interaction; \( P > 0.05 \)). Endurance time was significantly longer in elderly (\( 471.7 \pm 260.8 \) s) compared with young (\( 179.6 \pm 51.3 \) s) subjects (\( t \)-test, \( P < 0.05 \)). Overall, men and women presented with similar results with respect to the fatigue-related behavior of all variables of interest. Consequently, their data were pooled for each group.

\( M \) Waves

\( M \) waves were obtained from the 10 young and 8 elderly subjects (in 1 elderly subject, \( M \) waves were too difficult to elicit, even at high-stimulation intensity). Prefatigue BR \( M \)-wave amplitude was generally greater in young (6.14 \( \pm \) 2.07 mV) compared with elderly (2.60 \( \pm \) 2.08 mV) subjects (\( t \)-test, \( P < 0.05 \)). ECR \( M \)-wave amplitude was similar between the two groups (2.7 \( \pm \) 1.2 mV for young; 2.6 \( \pm \) 1.3 mV for elderly). \( M \)-wave amplitude did not change with fatigue or recovery for the ECR muscle, indicating a stable stimulus intensity throughout the experiment (Fig. 2). BR \( M \)-wave amplitude was not decreased immediately after the fatigue task in either group. However, the amplitude progressively decreased, mostly for young subjects in the later stages of recovery, which leads to a significant time effect (\( P < 0.05 \); Fig. 2). There was no significant interaction between age and time (\( P > 0.05 \)). The duration of the \( M \) wave, measured from the peak-negative phase to the peak-positive phase, was not affected by the fatigue task (time factor) or age.

Voluntary Activation

No age difference or age \( \times \) time interaction was noted for the level of voluntary activation calculated for the MVCs performed pre- and postfatigue (\( P > 0.05 \)). Young subjects had a mean level of voluntary activation of 97.1 \( \pm \) 3.9\% compared with 94.5 \( \pm \) 3.2\% for elderly subjects (\( t \)-test, \( P > 0.05 \)). The extra torque produced by the trains of electrical stimulation given to the BB every 30 s during the fatigue task decreased to almost zero in young subjects, indicating that they were maximally activating their BB at the end of the fatigue task. In contrast, the extra torque decreased only to \( \sim 25\% \) of its initial magnitude in elderly subjects (\( t \)-test on final value between young and elderly subjects, \( P < 0.05 \)). Three of the ten young subjects presented with an extra-to-ongoing torque ratio at the end of the fatigue task, \( >10\% \) of its initial value. In contrast, seven of the nine elderly subjects had a ratio \( >10\% \) of initial at the end of the fatigue task. However, when the extra torque produced by the trains of electrical stimulation was expressed in relation to the magnitude of fluctuations in the torque signal (standard deviation calculated for the first and last minute of the fatigue task), the extra torque-to-torque standard deviation ratio of both groups decreased to the same low level (<3\%, \( t \)-test; \( P > 0.05 \)). Whether expressed as the standard deviation or coefficient of variation, force fluctuations were slightly greater in young (standard deviation: 1.4 \( \pm \) 0.8 N·m; coefficient of variation: 3.5 \( \pm \) 1.0\%) compared with elderly (0.7 \( \pm \) 0.3 N·m; 2.2 \( \pm \) 0.9\%) subjects for the first minute of the fatigue task (\( t \)-test, \( P < 0.05 \)). The magnitude of fluc-
tuations in torque increased with fatigue in both groups, with this being significantly more pronounced in the elderly (mean increase of 210 ± 67 and 224 ± 76% for standard deviation and coefficient of variation, respectively) compared with young (80 ± 61 and 87 ± 68%, respectively) subjects (t-test, P < 0.05).

EMG RMS Amplitude

EMG RMS amplitude increased during the fatigue task to a greater extent in young compared with elderly subjects (age × time interaction; P < 0.05 for BB; Fig. 1). At the end of the fatigue task, the RMS EMG amplitude was 318 ± 95% of initial for BB, 277 ± 155% for BR, and 173 ± 54% for the triceps in young subjects and 251 ± 158% (BB), 224 ± 125% (BR), and 178 ± 60% (triceps) for elderly subjects. Even though RMS amplitude increased significantly in both groups, it did not reach levels observed during prefatigue maximum efforts. At the end of the fatigue task, BB RMS amplitude was 72 ± 14 and 60 ± 43% of the level obtained during prefatigue MVCs for young and elderly subjects, respectively. For the BR, those values were 93 ± 59 and 71 ± 33%, respectively. This higher relative EMG amplitude at the end of the fatigue task for young compared with elderly subjects also suggests that elderly subjects were not activating their muscles to the same extent as young subjects at the end of the task.

Elicited Torque and EMG Median Frequency

Figures 3 (BB) and 4 (BR) contrast the single-twitch data for both groups of subjects. Before fatigue, TwPT was significantly higher in young compared with elderly subjects for the BB (10.1 ± 5.7 N·m for young and 5.8 ± 1.4 N·m for elderly; P < 0.05) but not for the BR (8.5 ± 4.0 N·m for young and 7.2 ± 2.1 N·m for elderly; P > 0.05). In contrast, TPT and HRT were not different (P > 0.05) between the two groups of subjects for either BB (TPT: 64 ± 15 ms for young and 75 ± 18 ms for elderly; HRT: 60 ± 13 ms for young and 56 ± 9 ms for elderly) or BR (TPT: 62 ± 12 ms for young and 54 ± 6 ms for elderly; HRT: 43 ± 14 ms for young and 50 ± 11 ms for elderly). With fatigue, TwPT showed a more pronounced decrease in young compared with elderly subjects for the BB (significant age × time interaction; P < 0.05). Such an interaction was not significant for the BR. TPT remained at prefatigue levels immediately after fatigue and early in the recovery period. It decreased slightly later in the recovery period (significant time effect; P < 0.05), mostly in young subjects. However, there was no significant age × time interaction for either muscles. HRT was increased after fatigue in young (24% for BB, 61% for BR) but not in elderly (3% increase for BB, 19% decrease for BR) subjects (significant age × time interaction; P < 0.05). Figure 5 shows the BB train torque data for both groups. TrPT, TrTPT, and TrHRT were not different between young and elderly subjects before fatigue. TrPT decreased and recovered similarly in young and elderly subjects (no age × time interaction). TrTPT and TrHRT were increased after fatigue in young but not elderly subjects (age × time interaction; P < 0.05). TrHRT decreased below prefatigue values in both groups (time effect; P < 0.05). There was a similar decrease in the BB twitch-to-train torque ratio (mea-
sure of low-frequency fatigue) after fatigue in both groups (significant effect of time only; $P < 0.05$; Fig. 6A). The median frequency of both BB and BR decreased significantly with fatigue. This was more pro-

![Graph A](image1.png)

![Graph B](image2.png)

![Graph C](image3.png)

Fig. 4. Group mean ± SD of peak torque (A), time to peak torque (B), and half relaxation time (C) for the brachioradialis single twitches of young and elderly subjects. Values are shown for twitches elicited before (first data point to the left of time 0) and immediately after the end of the fatigue task (time 0), as well as at 1, 2, 5, 10, 15, and 20 min of recovery.

![Graph D](image4.png)

![Graph E](image5.png)

Fig. 5. Group mean ± SD of peak torque (A), time to peak torque (B), and half relaxation time (C) of the torque response of biceps brachii to the 100-Hz trains of stimulation in both young and elderly subjects. Values are shown for torque responses elicited before (first data point to the left of time 0) and immediately after the end of the fatigue task (time 0), as well as at 1, 2, 5, 10, 15, and 20 min of recovery.
nounced in young compared with elderly subjects (age \times time interactions for both BB and BR, \( P < 0.05 \); data shown for BB in Fig. 6B).

Correlations and ANCOVA

Because fatigue-related changes in measures reflecting central mechanisms (extra-to-ongoing torque ratio and EMG RMS amplitude at the end of the fatigue task) differed between young and elderly subjects, two additional analyses were performed. First, a Pearson product-moment correlation analysis was used to assess the potential association between central and peripheral measures of fatigue. Table 1 gives the \( r \) value associated with pairs of variables of interest. Significant associations were observed between measures reflecting central fatigue (extra-to-ongoing torque ratio at the end of the fatigue task) and measures of peripheral fatigue (extent of changes in median frequency, train and twitch torque variables), where the presence of central fatigue was related to a lesser degree of peripheral fatigue (Fig. 7A). The various measures of peripheral fatigue were also related among themselves (Fig. 7B). Second, a measure of the extent of central fatigue [extra-to-ongoing torque ratio at the end of fatigue (% initial)] was entered as a covariate in a multivariate analysis model (ANCOVA), looking at the effect of age on the fatigue-related behavior of the variables reflecting peripheral fatigue. There was no effect of central fatigue as a covariate on any of the BR variables. Also, central fatigue did not have any effect as a covariate on age-related differences in BB TrPT, TrTPT, TPT, and twitch-to-train torque ratio. However, there was an effect of central fatigue when it was entered as a covariate for BB TrHRT, TwPT, HRT, and BB median frequency. This lead to the absence of age \times time interactions, whereas the interactions were significant in the original analyses for these variables (see above). It should be noted that the age \times time interaction still approached significance for all four variables, with \( P \) values ranging from 0.07 to 0.20. Even though not significant, it could be argued that the difference in prefatigue MVC torque could explain some of the age-related differences observed. We also used the prefatigue MVC torque as a covariate in an ANCOVA and found that the age-related differences observed for all dependent variables of interest were not affected by the difference in strength between the two groups.

DISCUSSION

Neuromuscular Propagation

Neither group showed a failure in neuromuscular propagation for a task that had been shown to induce failure in the first dorsal interosseus muscle (14). The absence of a difference in neuromuscular propagation suggests that the age-related changes at the neuromuscular junction do not lead to a significant decrease in the capacity to sustain activity. This is consistent with previous studies in which no age-related differences were found in the behavior of the M-wave with fatigue (7, 18). However, a number of studies looking at M-wave changes with sustained activity have shown potentiation and not failure for elbow flexor muscles (6, 18). This potentiation could mask a potential age-related decline in neuromuscular propagation. A progressive decrease in M-wave amplitude was observed in young subjects during the recovery period. Such a delayed and prolonged decrease in M-wave size has also been observed by Cupido et al. (6) in the BB muscle. Processes with a relatively slow time course are most likely involved in this decrease. For example, the progressive recovery in the activity of the Na\(^{+}\)-K\(^{+}\) pump, from the enhanced state caused by sustained activity, is not complete by 15 min postfatigue (20). This could be paired with other factors that can influence the electrophysiological properties of muscle fibers, such as an increase in intracellular water content, which effectively decreases the concentration of intracellular K\(^{+}\) and may cause a decrease in membrane potential (34). The time course of such a shift in
would also be consistent with a greater type II fiber

and half relaxation time (BB HRT, BR HRT, BB

difference in the behavior of contraction speed with

nounced slowing has been observed in lower limb mus-

subjects does exist but was not found to be significant

because type II fibers are more prone to alterations

and/or failure of E-C-R coupling mechanisms with sus-

tained activity (33). It should be noted that age-related

differences in contraction speed (and their change with

fatigue) have been explained not only by a change in

fiber-type distribution (amount or type of myosin heavy

chain isoform present) but also by alterations in spe-

cific E-C-R coupling mechanisms (22, 38), such as

Ca²⁺-dependent sarcoplasmic reticulum function, or a

combination of both factors (31). Therefore, both fiber-
type content and E-C-R coupling can contribute to

changes in contraction speed independently, and their

respective contribution will most likely vary between
different muscles. This could explain the fact that not
all variables showed the same age-related differences
for BB and BR in the present study and the observation
of greater slowing of muscle relaxation in elderly com-
pared with young subjects for other muscle groups (22).

Central Fatigue

Data from the superimposed trains of electrical stimu-
lation and the changes in EMG signal amplitude dur-
ing the fatigue task suggest a significant contribu-
tion of central fatigue to the decreased force capacity
experienced with sustained activity in the present
group of elderly subjects. Whereas most young subjects
were activating BB maximally at the end of the fatigue

 task, the train of electrical stimulation still produced a

significant amount of extra force over the voluntary

force (25% of initial) in elderly subjects, suggesting

incomplete voluntary activation. In addition, the in-

Table 1. Summary of the correlation analysis performed on selected variables

<table>
<thead>
<tr>
<th>Extra torque</th>
<th>BB RMS</th>
<th>BR RMS</th>
<th>BB mf</th>
<th>BR mf</th>
<th>BB TrPT</th>
<th>BB TrHRT</th>
<th>BB TwPT</th>
<th>BB HRT</th>
<th>BB TWPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB RMS</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>0.30</td>
<td>−0.16</td>
<td>−0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td>(19)</td>
<td>(19)</td>
<td>(19)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>0.34</td>
<td>−0.44*</td>
<td>−0.01</td>
<td>0.54†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td>(19)</td>
<td>(19)</td>
<td>(19)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>0.71‡</td>
<td>−0.43*</td>
<td>−0.36</td>
<td>0.46†</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td>(19)</td>
<td>(19)</td>
<td>(19)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>−0.63‡</td>
<td>0.39</td>
<td>0.43†</td>
<td>−0.51†</td>
<td>−0.22</td>
<td>−0.76‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>0.74‡</td>
<td>−0.31</td>
<td>−0.27</td>
<td>0.43*</td>
<td>0.30</td>
<td>0.83‡</td>
<td>−0.70‡</td>
<td></td>
</tr>
<tr>
<td>BB BR</td>
<td>(19)</td>
<td>(19)</td>
<td>(19)</td>
<td>(19)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(18)</td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>−0.36</td>
<td>0.02</td>
<td>−0.17</td>
<td>−0.09</td>
<td>−0.00</td>
<td>−0.40*</td>
<td>0.51†</td>
<td>−0.34</td>
</tr>
<tr>
<td>BB BR</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
<td>(18)</td>
<td>(17)</td>
<td>(18)</td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>−0.14</td>
<td>−0.16</td>
<td>0.05</td>
<td>0.46*</td>
<td>0.19</td>
<td>0.01</td>
<td>−0.28</td>
<td>0.09</td>
</tr>
<tr>
<td>BB BR</td>
<td></td>
<td>−0.41</td>
<td>0.58†</td>
<td>0.62*</td>
<td>−0.27</td>
<td>−0.33</td>
<td>−0.51*</td>
<td>0.72‡</td>
<td>−0.58†</td>
</tr>
</tbody>
</table>

Nos. are r values; nos. in parentheses are no. of subjects with available data. BB, biceps brachii; BR, brachioradialis; RMS, root mean square; extra torque, extra-to-ongoing torque ratio at the end of the fatigue task (%initial); BB mf, median frequency of the BB at the end of the fatigue task (%initial); BR mf, median frequency of the BR at the end of the fatigue task (%initial); BB TrPT, train peak torque (BB) immediately postfatigue (%prefatigue); BB TrHRT, train half relaxation time (BB) immediately postfatigue (%prefatigue); BB TwPT, twitch peak torque (BB) immediately postfatigue (%prefatigue); BR TrPT, train peak torque (BR) immediately postfatigue (%prefatigue); BR TrHRT, train half relaxation time (BR) immediately postfatigue (%prefatigue); BR TwPT, twist peak torque (BR) immediately postfatigue (%prefatigue); BR HRT, twitch half relaxation time (BR) immediately postfatigue (%prefatigue); BR TwPT, twist peak torque (BR) immediately postfatigue (%prefatigue); BR HRT, twitch half relaxation time (BR) immediately postfatigue (%prefatigue). Significant correlation: *P < 0.10, †P < 0.05, ‡P < 0.01.
crease in EMG signal amplitude was more pronounced for the BB of young compared with that of elderly subjects. The greater proportion of subjects with evidence of central fatigue with a submaximal compared with a maximal fatigue task is consistent with the results of Behm and St. Pierre (2), who have reported a greater degree of central fatigue in lower force, longer duration compared with higher force, shorter duration fatigue tasks. The greater central fatigue observed in elderly compared with young subjects could thus be confounded by the greater endurance time observed in the former group. The significance of central fatigue in various tasks and in other muscle groups has yet to be thoroughly documented in elderly individuals. Authors report both greater (36) and no age-related difference (19) in activation failure with sustained activity in elderly compared with young subjects.

Even though significant associations between measures of central fatigue and peripheral fatigue were observed (subjects with greater central fatigue showing less peripheral fatigue), most of the age-related differences (or lack of) in measures of peripheral fatigue were still present even when central fatigue was taken into account (ANCOVA). In fact, central fatigue had no effect on any of the BR variables. Central fatigue had an effect on some of the BB variables (BB TrHRT, TwPT, HRT, and BB median frequency), for which the effect of age on fatigue-related changes became nonsignificant when central fatigue was taken into account (P values of age × time interaction increasing to between 0.07 and 0.20). In general, the effect of peripheral changes (e.g., fiber-type composition) seemed to precede the potential effect of the increased central fatigue observed in our sample of elderly vs. young subjects. However, the effect of specific peripheral changes with aging on fatigue mechanisms might be underestimated when central fatigue is present and not taken into account (21), and this seems to be muscle dependent. The differential effect of central fatigue on BB and BR could be explained by the fact that these two muscles have been shown to present different fatigue-related behaviors in measures reflecting the status of peripheral structures, with subjects presenting with more central fatigue (mostly elderly subjects) showing less changes in peripheral measures of fatigue (A); and 2) the significant association among certain measures reflecting peripheral fatigue changes (B).

Concerning the difference between young and elderly subjects, Graves et al. (17) have recently shown that the modulation of the various elbow flexor muscles (BB, BR, and brachialis) is different between young and elderly subjects for a constant-load (anisometric) task. They found that elderly subjects seem to rely more on the BB to lift various loads compared with young subjects. This differential mod-

---

**Fig. 7.** Scatter plots of the extra-to-ongoing torque ratio at the end of the fatigue task vs. the biceps brachii (BB) twitch peak torque immediately after fatigue (expressed as %prefatigue) (A), and the BB twitch peak torque immediately after fatigue (%prefatigue) vs. the BB twitch half relaxation time immediately after fatigue (%prefatigue) (B). These plots show 1) the significant association between measures of central fatigue and measures reflecting the status of peripheral structures, with subjects presenting with more central fatigue (mostly elderly subjects) showing less changes in peripheral measures of fatigue (A); and 2) the significant association among certain measures reflecting peripheral fatigue changes (B). n, No. of subjects with available data.
ulation was task dependent, as it was not observed for isometric tasks. Other factors that could explain the difference between BB and BR are their different cross-sectional area and the elbow angle used in this study. The BB has a greater cross-sectional area than the BR (39), and an elbow angle of ~90–100° (used here) is optimal for the BB but not for the BR (5). Therefore, these factors could lead to the preferential use of a specific muscle over other elbow flexors, and this could lead to a different extent of central fatigue.

The functional consequences of greater central fatigue in elderly adults is unclear (9), as other factors may also affect motor output during sustained activity. A lesser ability to maintain a steady force and torque level in elderly compared with young subjects has been reported for the first dorsal interosseous muscle in the unfatigued state (25). In contrast, elderly subjects presented with decreased steadiness of elbow flexor muscles for a constant-load task (shortening-lengthening contraction) but not for a constant-force task (isometric) (17). The present study showed that, with sustained activity, the magnitude of force fluctuations increased with fatigue in both groups, with older subjects showing a greater relative increase in fluctuations compared with young subjects. When the extra force produced by the train of electrical stimulation given to the BB was normalized to the amplitude of the force produced by the train of electrical stimulation given to the BR, the magnitude of force fluctuations at the end of the fatigue task, there was no difference between young and elderly subjects. The value of this ratio was relatively small, indicating that the extra force produced by the superimposed electrical stimulation was negligible relative to the amount of “noise” (fluctuations in the force) in both group of subjects.

This project was supported in part by an internal grant from the College of Medicine, University of Iowa.

REFERENCES