Short-Term Immobilization after Eccentric Exercise. Part I: Contractile Properties

STEPHEN P. SAYERS, BRIAN T. PETERS, CHRISTOPHER A. KNIGHT, MARIA L. URSO, JASCHA PARKINGTON, and PRISCILLA M. CLARKSON

Department of Exercise Science, University of Massachusetts, Amherst, MA

ABSTRACT

SAYERS, S. P., B. T. PETERS, C. A. KNIGHT, M. L. URSO, J. PARKINGTON, and P. M. CLARKSON. Short-Term Immobilization after Eccentric Exercise. Part I: Contractile Properties. *Med. Sci. Sports Exerc.*, Vol. 35, No. 5, pp. 753–761, 2003. **Purpose:** The purpose of this study was to examine the compound muscle action potential (M-wave) and evoked contractile properties of immobilized muscle after high-force eccentric exercise. We believed that changes in these variables would contribute to the enhanced recovery of maximal voluntary force observed after short-term immobilization of damaged muscle. We hypothesized that immobilization after eccentric exercise would result in an enhanced M-wave and a change in contractile properties toward characteristics of faster muscle fibers. **Methods:** Twenty-five college-age males were matched according to force loss after 50 maximal eccentric contractions of the elbow flexors and placed into an immobilization (IMM, $N = 12$) or control (CON, $N = 13$) group. IMM had their arm immobilized at 90° and secured in a sling during a 4-d treatment. Maximal isometric torque (MVC) was assessed at baseline and for 8 d after treatment. M-wave and evoked contractile properties of the muscle (twitch torque [TT], maximal rate of torque development [MRTD], time to peak torque [TPT], and one-half relaxation time [HRT]) were assessed at baseline and for the first 5 d after treatment. **Results:** Immediately postexercise, MVC was reduced 43% and 42% in IMM and CON, respectively. Recovery of MVC was significantly greater in IMM during recovery ($P < 0.05$), 95% of baseline MVC compared with 83% in CON. M-wave was reduced 32%, and all contractile properties were altered immediately postexercise. M-wave, MRTD, TPT, and HRT were not significantly different between groups during recovery ($P > 0.05$). TT demonstrated enhanced recovery in IMM ($P < 0.05$). **Conclusions:** Short-term immobilization after eccentric exercise resulted in enhanced recovery of maximal voluntary force. However, enhanced force recovery cannot be explained by muscle activation and evoked contractile properties of the muscle. **Key Words:** MUSCLE DAMAGE, PERIPHERAL ACTIVATION, M-WAVE, TWITCH TORQUE, ONE-HALF RELAXATION TIME

Short-term immobilization has been found to improve muscle fiber regeneration in animal models of muscle injury (12) and enhance force recovery after eccentric contraction-induced injury in humans (3,19). We previously reported an enhanced pattern of voluntary force recovery in subjects whose arms were immobilized for 4 d after eccentric exercise compared to a free-living cohort (19). In the present study, we sought to address the mechanisms that contributed to this enhanced recovery of force by examining the compound muscle action potential (M-wave) and evoked contractile properties of immobilized muscle after eccentric exercise.

The M-wave is the sum of the recorded action potentials in a muscle resulting from a brief but maximal stimulus to the motor nerve innervating the muscle. This measure is often used to examine excitability of the muscle or the ability to activate the muscle peripherally (9). Studies using animal models have found increased excitatory postsynaptic potentials (EPSP) in the spinal cord after short-term disuse (13), which suggests increased excitation to the motor nerve innervating the disused muscle. Remodeling of the neuromuscular junction (NMJ) has also been reported in animal models after short-term immobilization that could favor impulse transmission to the muscle (6). Taken together, changes in nerve excitation and the neuromuscular junction with immobilization point to an enhanced ability to activate the muscle. Thus, the enhanced force recovery with immobilization after eccentric exercise may be explained by increased M-wave amplitude, which would point to an enhanced ability to activate the muscle in human subjects.

The evoked twitch contractile properties of the muscle are the recorded amplitude and temporal characteristics of the muscle twitch in response to maximal stimulation of the nerve innervating the muscle. These indirect measures can reveal the inherent contractile force generation and speed of the twitch characteristics of the muscle, with Type II muscle fibers having larger twitch amplitudes and faster temporal characteristics compared to Type I fibers (17). Short-term disuse studies (6–7 d) have not only shown increased temporal aspects of the twitch in humans (11) but also increases in soleus Type IIx myosin heavy chain (MHC) isoforms in animals (2). Thus, contractile properties appear to take on

Address for correspondence: Stephen P. Sayers, Human Physiology Laboratory, Department of Health Sciences, Boston University, Sargent College of Health and Rehabilitation Sciences, 635 Commonwealth Avenue, Boston, MA 02215; E-mail: ssayers@bu.edu.
Submitted for publication March 2002.
Accepted for publication December 2002.

0195-9131/03/3505-0753
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.MSS.0000064932.55998.CC

the characteristics of "faster" Type II muscles after brief periods of disuse. Because Type II muscle fibers generate greater force than Type I muscle fibers, a shifting of muscle phenotype with disuse could impact the recovery of force with immobilization after eccentric exercise.

The purpose of the present study was to determine whether changes in either activation of the muscle or the muscle's contractile characteristics with immobilization would enhance the recovery of maximal voluntary force after eccentric exercise. The rationale for this study was based on the premise that if disuse results in either an increased excitability of the muscle fiber or an alteration of the contractile properties of the muscle in a manner favoring Type II characteristics, force production during voluntary contractions could potentially be enhanced. Thus, the hypothesis to be tested was that short-term immobilization after eccentric exercise would result in enhanced M-wave amplitude and alter the contractile properties of the muscle toward those with "faster" contractile characteristics.

METHODS

Approach to the Problem and Experimental Design

Dependent variables in the study included muscle function measurements of relaxed arm angle (RANG), flexed arm angle (FANG), and maximal voluntary isometric torque (MVC). Dependent variables also included peripheral activation of the muscle (M-wave) and evoked contractile properties of the muscle (maximal rate of torque development [MRTD, the derivative of the peak torque measure], twitch torque [TT], time to peak torque [TPT], and half-relaxation time [HRT] from peak torque until torque fell to half of maximum). We measured these variables in two distinct groups of subjects, both of which performed a maximal eccentric exercise of the elbow flexors. One group was a treatment group that underwent immobilization of the elbow for a period of 4 d immediately after the exercise, a time period chosen for the improved recovery of maximal voluntary force demonstrated in a previous study (19). The second group was not restricted in their arm activity after exercise. We measured peripheral activation and evoked contractile properties of the muscle to determine whether changes in these variables that have been observed in healthy muscle with short-term immobilization (2,6,11,13) would also occur in damaged muscle with short-term immobilization. If activation of the damaged muscle increased, then the increase in impulse transmission to the muscle could contribute to enhanced recovery of force. Moreover, if damaged muscle's contractile properties shifted toward those with greater Type II characteristics, then an improved force generating capacity of the muscle could contribute to the enhanced recovery of voluntary force after eccentric exercise reported previously (19). In order not to compromise the immobilization treatment, no voluntary or stimulated contractions were performed during the four-day treatment period. Instead, stimulated contractions were only performed in the first few days after the treatment period to examine changes in these variables resulting from the immobilization. Voluntary contractions were performed on each day after treatment to examine the extended recovery of force, similar to methods from a previous study (19).

Subjects

Twenty-five college age males were recruited to participate in the study. After a detailed explanation of the study, subjects signed an approved informed consent document consistent with the guidelines of the University of Massachusetts Human Subjects Review Committee. All subjects participating in the study were nonweight-trained individuals who had not participated in any structured resistance-training program for at least 6 months before participation in the present study.

Study Design

The 15-d study consisted of 3 d of baseline measurements and a 12-d recovery period from exercise in which the first 4 d constituted a treatment period where subjects either had their arms immobilized or underwent no immobilization. Baseline muscle function measurements (RANG, FANG, and MVC), M-wave and evoked contractile properties of the muscle (MRTD, TT, TPT, and HRT) were assessed on each of the three baseline days.

Immediately after the MVC measurements on the third baseline day, a high-force eccentric exercise regimen consisting of 50 maximal eccentric contractions of the nondominant elbow flexors was performed. Immediately after the exercise, RANG, FANG, M-wave, evoked contractile properties of the muscle, and MVC were assessed to establish a postexercise decrement in muscle function. Subjects were matched according to their loss of torque after the eccentric exercise, as this is the best indirect indicator that damage has occurred to the muscle (24). Subjects were then placed into one of two groups, immobilization (IMM: $N = 12$) or control (CON: $N = 13$). The subjects assigned to the IMM group had their exercised arm placed in an orthotic device (model no. 20-220, Omniflex Orthotic Rehab, Tampa FL) with their elbow joint immobilized at 90° and their arm secured in a sling for the duration of the 4-d treatment period. Immobilization at 90° was chosen to minimize the hypertrophy or atrophy associated with immobilizing at longer or shorter muscle lengths, respectively. Volunteers were not allowed to remove the device for any reason during the immobilization period, and compliance was monitored using accelerometers attached to the wrist that monitored arm activity.

Days 5–9 postexercise consisted of recovery measures of RANG, FANG, MVC, M-wave, and evoked contractile properties of the muscle. Measurements of RANG and FANG were also assessed on day 4 upon removal of the orthotic device to assess responses immediately postimmobilization as well as in the CON group. Days 10–12 postexercise consisted of recovery measures of MVC only (see Fig. 1)

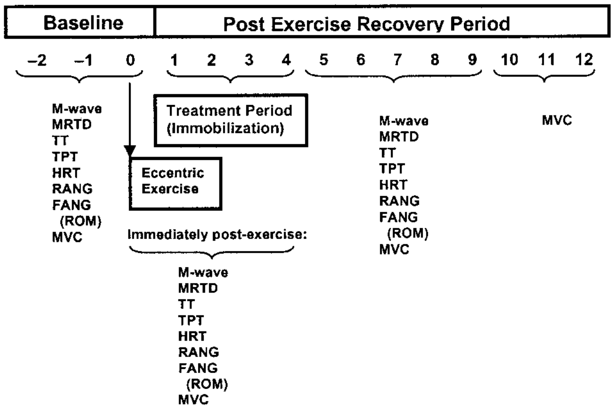

FIGURE 1—Schematic representation of the study timeline.

Eccentric Exercise Protocol

The exercise regimen was designed to induce muscle damage through eccentric contractions using a modified preacher curl apparatus. The regimen consisted of 50 maximal eccentric contractions of the elbow flexors of the nondominant arm. While the subject applied maximal resistance against a firm pad located at the distal forearm, the investigator pulled down on a lever causing forced elbow extension. Because of the mechanical advantage offered by the lever system, the investigator was able to exceed the maximal resistance exerted by the subject throughout the entire range of motion. The subject was instructed to maximally resist against the action of the investigator with special emphasis on the end-range of motion, at which subjects typically yield to the external resistance. Each subject performed two sets of 25 maximal contractions, separated by a 5-min rest period. Each action lasted approximately 3 s, with 12 s of rest between actions. The regimen has been previously established to induce a prolonged impairment of muscle function (21).

Criterion Measures

Muscle function measures. *Range of motion.* Elbow joint angles were assessed using a standard 12-inch clinical goniometer (Jamar, Inc., Clifton, NJ). The two angles being measured were RANG and FANG. On the first day of baseline measurements, an indelible marker was used to specify anatomical landmarks to ensure reliability in day-to-day measures. These markings were made directly below the acromion process on the upper arm, on the lateral epicondyle of the humerus, and on the styloid processes of the radius and ulna. Pen markings were highlighted each day before measurements. RANG was measured with the arm hanging passively at the side, with the subjects facing straight ahead, with eyes on a fixed point on the wall. FANG was measured with the subjects staring straight ahead, with the elbow fixed at the side as the subject attempted to flex the elbow and touch the shoulder with the palm of the hand. The mean of the three measurements for each elbow joint angle was used as the criterion measure. Range of motion (ROM) of the arm was derived by subtracting FANG from RANG, resulting in a measure of the full range through which the exercised arm could be voluntarily moved (excluding voluntary extension capabilities beyond RANG).

Voluntary torque measurements. For MVC assessment of the elbow flexors, subjects were seated on a custom built apparatus with the upper arm resting in the horizontal position and the forearm vertical (arm flexed at 90°). Seat height was adjusted and recorded to ensure all subjects were seated consistently on subsequent days. A wide strap (Velcro U.S., Inc., Manchester, NH) was secured around the chest to maintain the seated position during maximal efforts as well as to minimize extraneous movement or the recruitment of muscles other than the elbow flexors to assist the MVC. The forearm was held immobile between a padded spring-loaded plate and a force transducer (model no. MB-250, Interface, Inc., Scottsdale, AZ), which rested against the wrist. To avoid compression of the skin and discomfort during MVC an orthotic wrist-hand device (no. 1011, Orthomerica Products Inc., Newport Beach, CA) was worn. An adjustable height setting for installation of the force transducer ensured that during MVC measurements force was exerted by the subject's wrist against the force transducer at the level of the styloid processes of the radius and ulna. This transducer height setting was recorded before baseline measures and used as the site for force transducer placement on each subsequent MVC measure. The torque applied at the elbow was calculated by multiplying the measured force by the perpendicular distance between the point of application of the force and the center of rotation of the elbow. Subjects were asked to perform three, 5-s isometric contractions at 100% of their MVC and were instructed to produce maximum torque as rapidly as possible. Each contraction was followed by a rest period of 60 s. The force data were recorded to a computer at 1000 Hz using a 12-bit A/D board (model no. CIO-DAS08/Jr-AO 12-bit, Computerboards, Inc., Mansfield, MA). The force data were recorded to a computer at 1000 Hz using a 12-bit A/D board (model no. CIO-DAS08/Jr-AO 12-bit, Computerboards, Inc., Mansfield, MA). The mean value obtained from these three contractions was used as the measure of maximal voluntary contraction torque. Calibration of the MB-250 force transducer was performed before the study began and at the conclusion of the study and excellent linearity was observed ($R^2 = 0.9999$).

Peripheral activation and evoked contractile properties. *M-wave and contractile properties.* To assess M-wave and evoked contractile properties of the biceps brachii muscle, subjects were seated on the same apparatus used to obtain MVC measures. Again, subjects were seated with the upper arm resting in the horizontal position and the forearm vertical (arm flexed at 90°). The design of the apparatus ensured that the forearm was not required to overcome gravity during maximally evoked contractions, potentially affecting the magnitude of twitch force measurements. Seat height was positioned in the same manner as during MVC measurements. Maximum twitches were evoked with a single maximal stimulus (0.2-ms duration) to the musculocutaneous nerve (innervating the biceps brachii

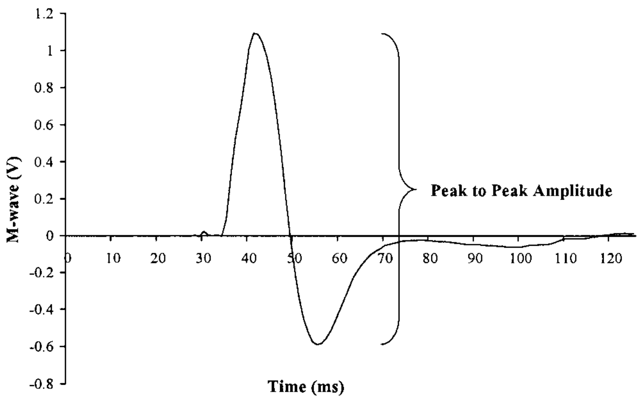

FIGURE 2—Typical M-wave response to maximal peripheral nerve stimulation. Measurement of peak-to-peak amplitude is often used as an indication of muscle excitability (10).

muscle) at Erb's point and the resulting M-wave was recorded. Sixty seconds of rest was given between trials. Custom written software (DasyLab, Dasytec U.S., Amherst, NH) was used to trigger a stimulus out to a stimulator (DISA [Medtronic, Inc.] Minneapolis, MN) and simultaneously provide a stimulus to the subject and an event marker back into the software acquisition routine through the A/D board. Data were acquired at 1000 Hz. Stimulation to the musculocutaneous nerve was applied with a Teca stimulator wand (model no. 9523-1, Pleasantville, NY), with an interelectrode spacing of 2.5 cm. Twitch torque measurements were calculated using measures from the same force transducer and interfaced with the same data collection and storage system used for MVC assessment (see above). Stimuli were delivered to the nerve with increasing voltage intensity until no increase in twitch force with increasing stimuli occurred (7). A voltage of approximately 10% above that which elicited the maximal twitch torque was used to ensure a supramaximal stimulation to the nerve (16); thus, it was assumed that full activation of the muscle was achieved. For surface recordings of M-wave, an AC preamplifier (model no. P55, Astro-Med, Inc., Grass Instrument Division, W. Warwick, RI) with a bandpass filter of 10 Hz−3 kHz and an amplification of 10, 100, and 1000 coupled to regulated power supply (model no. RPS 112, Astro-Med, Inc.) was used. The acquisition routine sampled 250 ms of baseline electromyography before the stimulus and lasted ~200 ms beyond the typical duration of the M-wave (~30–50 ms). Software (DasyLab, Dasytec U.S., Amherst, NH) enabled the contractile properties of the muscle (MRTD, TT, TPT, and HRT) to be recorded simultaneously. Three separate trials were acquired, and the average of the three maximal twitch torques was used for statistical analyses. Using the maximal TT trials, concomitant measures of M-wave, MRTD, TPT, and HRT were used for statistical analysis. Twitch contractions were performed before MVC measurements in order to avoid potentiation of the twitch by a previous maximal effort (23). Because excitability of the muscle membrane was of primary interest in the study, peak to peak amplitude of the M-wave was assessed (see Fig. 2). To quantify M-wave and the evoked contractile properties of the muscle, a custom written program using Matlab software version 5.3 (The Mathworks, Inc, Natick, MA) was used.

Electromyography. Each subject was prepared for bipolar surface EMG measurements before supramaximal stimulation of the musculocutaneous nerve. The skin directly overlying the biceps brachii muscle of the nondominant arm was abraded and thoroughly cleaned with alcohol prep pads (no. 326895, Becton Dickinson Co., Franklin Lakes, NJ) and allowed to dry. Two adhesive electrodes (no. F-E11D, Astro-Med, Inc.) were attached to the skin over the mid-line and parallel to the biceps brachii muscle. An indelible marker was used to delineate anatomical landmarks on each subject's arm and electrode placement location to ensure consistency in day-to-day measures. The interelectrode spacing was 20 mm. A 4 × 7.5-cm copper ground was taped to the skin overlying the anterior deltoid muscle of the same arm used for EMG measurements (between the active electrodes and the site of stimulation).

Accelerometry

Subjects in IMM were required to wear accelerometers on the wrist of their nondominant (exercised) arm during the 4-d immobilization period. The activity monitor (model no. 7164, Computer Science and Applications, Inc., Shalimar FL) is a single plane accelerometer (5.1 × 4.1 × 1.5 cm, 43 g), assessing motion in the vertical plane. The activity monitor assessed vertical accelerations ranging from 0.05 to 2.0 *g* and is band limited with a frequency response from 0.25 to 2.5 Hz. Normal body motion is detected by these parameters and high-frequency vibrations are filtered. An analog bandpass filter acts to filter the acceleration signal and this signal is digitized by an 8-bit A/D converter at 10 samples per second. Each digitized signal was summed over a user specified time interval and the activity counts were stored internally. Each day, activity monitors were removed from the arm and downloaded into a custom written software program on a Gateway 2000 personal computer (model no. GP6-350). A previous study (20) and pilot data using accelerometers enabled us to determine approximately how much activity an immobilized arm registered during an average day. Activity counts were inspected each day for any anomalies or inconsistencies.

Statistical Analyses

Sample size calculation was performed using data from a prior eccentric exercise and immobilization study (19). Using an effect size of 1 obtained from the means and standard deviation of the immobilization and control group, alpha of 0.05, and a power ($1-\beta$) of 0.80, 11 subjects per group were necessary to detect significant differences in MVC from our intervention. To assess reliability and stability of the baseline measures of RANG, FANG, ROM, MVC, M-wave, and evoked contractile properties of the muscle, an intraclass correlation coefficient and ANOVA with repeated measures over time was used. To assess the effects of eccentric

TABLE 1. Subject characteristics.

Group	Height (cm)	Weight (kg)	Age (yr)
Immobilization (N = 12)	178.5 ± 1.3	72.8 ± 3.3	20.3 ± 0.4
Control (N = 13)	178.2 ± 1.5	75.0 ± 3.2	21.4 ± 0.6

Data represent means ± SEM.

exercise, a two-factor (2 × 2; group × time) ANOVA with repeated measures over time was used to determine changes from baseline to immediately postexercise for RANG, FANG, ROM, MVC, M-wave, and evoked contractile properties of the muscle. To assess the effects of treatment for range of motion measurements (RANG, FANG, ROM) and MVC, a two factor (2 × 7; group × time) ANOVA and a two factor (2 × 9; group × time) ANOVA with repeated measures over time, respectively, was used to determine changes from the first day postexercise to the final day postexercise. To assess the effects of treatment for M-wave and evoked contractile properties of the muscle, a two factor (2 × 6; group × time) ANOVA with repeated measures over time was used to determine changes from the first day postexercise to the final day postexercise. Recovery of M-wave values and evoked contractile properties of the muscle were also compared to baseline using a two factor (2 × 7; group × time) ANOVA with repeated measures over time. Tukey's honestly significant difference (HSD) *post hoc* tests were used to determine the source of statistically significant differences. The level of significance for all tests was accepted at $P < 0.05$.

RESULTS

Subject characteristics and baseline measures. There were no significant differences in height ($F = 0.03$; $df = 1{,}23$; $P = 0.86$), weight ($F = 0.13$; $df = 1{,}23$; $P = 0.72$), or age ($F = 2.5$; $df = 1{,}23$; $P = 0.12$) between IMM and CON. Physical characteristics of the subjects in the study are shown in Table 1. The three baseline day measures for each group are presented in Table 2. Intraclass R values for RANG, FANG, ROM, MVC, M-wave, MRTD, TT, TPT, and HRT were, respectively, R = 0.95, R = 0.96, R = 0.97, R = 0.98, R = 0.97, R = 0.94, R = 0.95, R = 0.88, and R = 0.80. There were no significant differences over days or between groups for any measure ($P > 0.05$). Twitch torque represented 9% of isometric MVC during baseline measures, consistent with the 5–15% range reported in the literature (10).

Changes from baseline to immediately postexercise. It was important to analyze changes due to exercise to determine whether the groups were equally stressed before imposing the treatment. For RANG, FANG, ROM, and MVC, there was no significant group × time interaction, indicating that the groups responded similarly to the exercise (Figs. 2 and 3). However, there were significant main effects for time, with all measures changing significantly after exercise ($P < 0.001$). There was an overall 11.4° reduction in RANG (see Fig. 3A), an 18.9° increase in FANG (see Fig. 3B), a 29.7° reduction in ROM (see Fig. 3C), and a 43% reduction in MVC (see Fig. 4) immediately after eccentric exercise that were consistent with responses observed in similar exercise protocols (4,19). There was a 43% and 42% MVC reduction for the IMM and CON group, respectively, suggesting that the subjects underwent similar losses of force after eccentric exercise.

TABLE 2. Baseline values for each group.

	Baseline 1	Baseline 2	Baseline 3
Immobilization (N = 12)			
RANG (°)	157.5 ± 0.9	157.2 ± 1.0	157.0 ± 0.9
FANG (°)	32.8 ± 1.8	32.8 ± 1.9	33.2 ± 1.9
ROM (°)	124.8 ± 2.2	124.4 ± 2.2	123.8 ± 1.9
MVC (N·m)	81.4 ± 5.1	82.4 ± 4.8	82.1 ± 4.5
M-wave (V)	1.61 ± 0.15	1.53 ± 0.15	1.51 ± 0.15
MRTD (N·m·s^{-1})	212.4 ± 28.8	213.3 ± 27.0	194.8 ± 17.9
TT (N·m)	7.81 ± 0.9	7.52 ± 0.9	6.86 ± 0.8
TPT (ms)	74.2 ± 2.3	72.4 ± 2.3	72.9 ± 3.2
HRT (ms)	111.8 ± 13.7	114.6 ± 13.4	126.2 ± 12.4
Control (N = 13)			
RANG (°)	157.9 ± 1.8	156.0 ± 1.7	156.4 ± 1.8
FANG (°)	35.3 ± 1.6	36.0 ± 1.2	36.6 ± 0.9
ROM (°)	122.7 ± 2.8	120.0 ± 2.4	119.8 ± 2.2
MVC (N·m)	74.8 ± 5.8	78.3 ± 5.4	79.9 ± 5.1
M-wave (V)	1.45 ± 0.1	1.42 ± 0.11	1.40 ± 0.13
MRTD (N·m·s^{-1})	178.0 ± 20.9	184.7 ± 20.6	179.4 ± 24.9
TT (N·m)	7.17 ± 0.8	7.28 ± 0.9	6.80 ± 0.9
TPT (ms)	77.3 ± 2.3	73.4 ± 2.3	75.1 ± 3.0
HRT (ms)	115.7 ± 11.5	128.9 ± 11.3	131.2 ± 17.2

Data represent means ± SEM.

For M-wave, MRTD, TT, TPT, and HRT there was no significant group × time interaction, indicating that the groups responded similarly to the exercise (see Table 3). However, there were significant main effects for time, and all measures changed significantly after exercise ($P < 0.001$). There was a 32% reduction in M-wave amplitude, 52% reduction in MRTD, 77% reduction in TT, 45% decrease in TPT, and 57% decrease in HRT.

Changes due to treatment during postexercise period. For RANG, FANG, ROM, and MVC, there was a significant time main effect ($P < 0.001$) as each variable recovered toward baseline. There was no significant group × time interaction in RANG ($F = 1.5$; $df = 6{,}138$; $P = 0.19$), indicating that the pattern of response to treatment was not different between groups (see Fig. 3A). However, there were significant group × time interactions in FANG ($F = 2.3$; $df = 6{,}138$; $P = 0.04$), ROM ($F = 2.7$; $df = 6, 138$; $P = 0.02$), and MVC ($F = 2.4$; $df = 8, 184$; $P = 0.02$), indicating that the pattern of response to treatment was different between the groups. Therefore, immobilization improved FANG (Fig. 3B) and overall range of motion (Fig. 3C) during the postexercise period compared with the control condition. Immobilization also resulted in a greater improvement in MVC recovery compared with CON (see Fig. 4). By day 12 postexercise, IMM had recovered 95% of baseline MVC while CON had recovered 83%.

The M-wave and evoked contractile property responses to treatment for all subjects and each individual group are presented in Table 3. For all variables, there was a significant time main effect ($P < 0.001$) as each recovered toward baseline. There was no significant group × time interaction

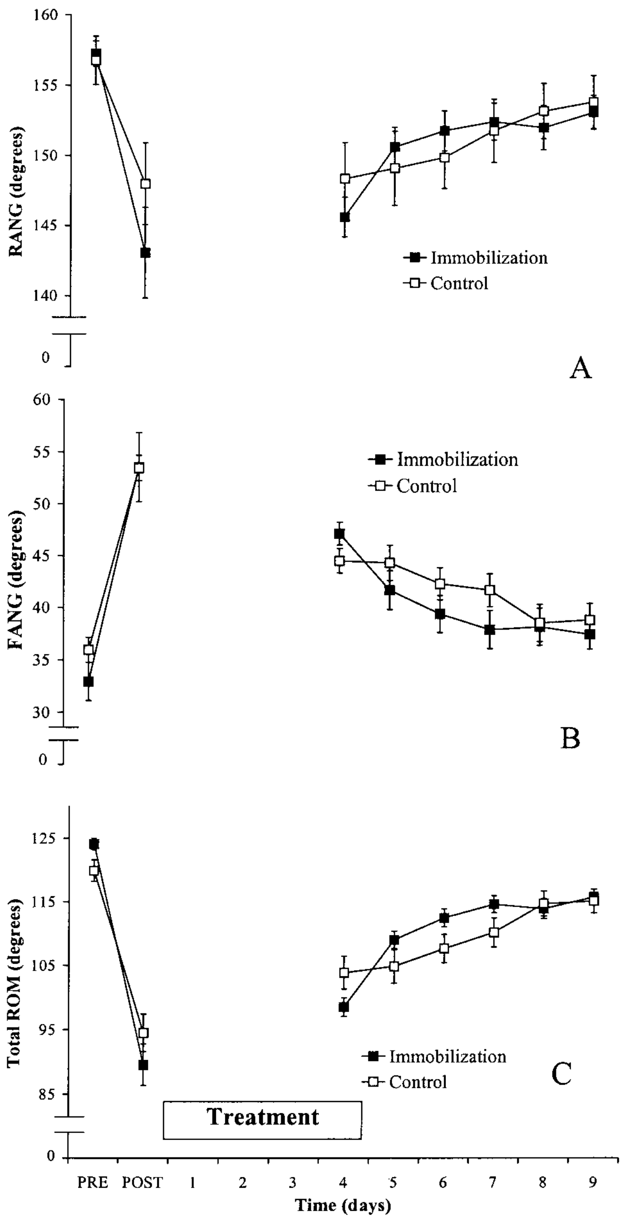

FIGURE 3—A. Relaxed arm angle (RANG), B. flexed arm angle (FANG), and C. total range of motion (ROM) response to eccentric exercise between immobilization and control group. PRE refers to the baseline period, POST refers to immediately posteccentric exercise. Days 1–4 represent the 4-d treatment period, and days 5–9 are the postexercise recovery period. RANG and FANG were assessed on the final day of treatment in addition to the recovery period. Data are expressed as means ± SEM.

in M-wave, MRTD, TPT, or HRT, indicating that the pattern of response to treatment was not different between groups. There was a significant group × time interaction in TT ($F = 2.3$; $df = 5, 115$; $P = 0.046$), indicating that the IMM group showed a greater recovery of twitch torque compared with CON.

Additional analyses. A repeated-measures ANOVA was run for M-wave and evoked contractile properties variables from baseline through recovery. This was done to establish the time course of recovery for these variables, as this has not been reported previously in the literature. For all

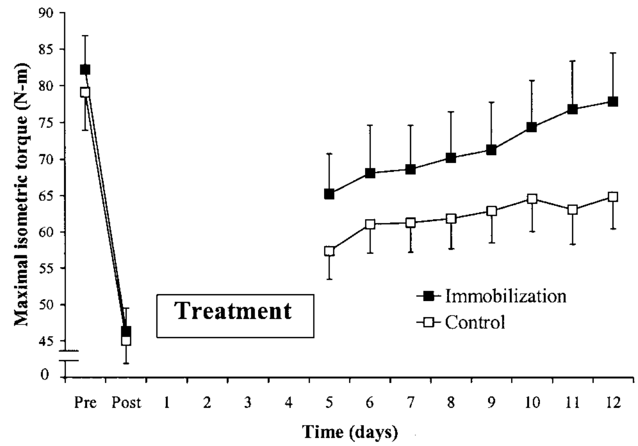

FIGURE 4—Maximal voluntary torque (MVC) response to eccentric exercise between immobilization and control group. PRE refers to the baseline period, and POST refers to immediately posteccentric exercise. Days 1–4 represent the 4-d treatment period, and days 5–12 are the postexercise recovery period. Data are expressed as means ± SEM.

variables, there was a significant main effect for time ($P < 0.05$) as each recovered toward baseline. M-wave, MRTD and TT were not significantly recovered by 9 d postexercise, whereas TPT and HRT were recovered by day 5 (see Overall Data, Table 3).

DISCUSSION

Muscle function measurements of MVC, RANG, FANG, and overall range of motion demonstrated their expected response to eccentric exercise (4,5,19). In addition, there were large changes in M-wave and evoked contractile properties of the muscle after exercise. Because there were no differences observed between groups in any measure immediately after eccentric exercise, we were confident that both groups were similarly stressed by the eccentric exercise protocol and were similar to each other before treatment. Thus, we could effectively test the effects of the immobilization treatment imposed after the eccentric exercise.

Similar to the findings of previous studies (3,19), the present study suggests that short-term immobilization resulted in an enhanced recovery of MVC and ROM compared with the control group. We hypothesized that one potential mechanism responsible for the improved recovery of MVC with immobilization involved enhanced M-wave amplitude and improved ability to activate the muscle. Two animal studies reported improved remodeling of the NMJ (6) and increased EPSP within the spinal cord (13), suggesting a potential enhancement of excitation to the motor nerve and muscle fiber with short-term disuse models. These adaptations could contribute to enhanced M-wave amplitude by improving excitation to the peripheral nerve and impulse transmission across the NMJ. However, we observed no difference in the M-wave response between groups, suggesting that activation of the muscle was not greater after short-term immobilization and did not contribute to MVC recovery.

TABLE 3. Evoked contractile properties of the muscle in IMM and CON groups.

	M-wave (V)	MRTD ($N \cdot m \cdot s^{-1}$)	TT (N·m)	TPT (ms)	HRT (ms)
Overall					
Pre	1.48 ± 0.09	193.3 ± 15.7	7.2 ± 0.6	74.3 ± 1.7	122.2 ± 8.2
Post	1.01 ± 0.08*	92.9 ± 10.2*	1.7 ± 0.2*	40.4 ± 3.3*	52.3 ± 8.8*
Day 5	1.32 ± 0.11	150.5 ± 15.4*	4.9 ± 0.5*	74.9 ± 4.6	98.8 ± 10.8
Day 6	1.33 ± 0.11	151.7 ± 15.9*	4.9 ± 0.6*	77.9 ± 4.3	110.8 ± 9.4
Day 7	1.25 ± 0.10*	151.9 ± 18.3*	4.7 ± 0.7*	72.8 ± 4.7	104.5 ± 11.3
Day 8	1.28 ± 0.10*	155.9 ± 18.7*	5.3 ± 0.7*	82.8 ± 3.0	106.4 ± 10.1
Day 9	1.25 ± 0.09*	152.9 ± 17.9*	5.4 ± 0.7*	78.8 ± 4.9	105.3 ± 10.2
	(N = 23)	(N = 25)	(N = 25)	(N = 25)	(N = 24)
Immobilization					
Pre	1.55 ± 0.15	206.8 ± 23.3	7.4 ± 0.9	73.2 ± 2.3	118.6 ± 12.6
Post	1.11 ± 0.14	100.1 ± 16.7	1.4 ± 0.3	38.7 ± 5.0	47.5 ± 9.2
Day 5	1.48 ± 0.17	180.9 ± 25.5	5.3 ± 0.9	72.0 ± 7.6	100.9 ± 17.9
Day 6	1.52 ± 0.17	173.9 ± 25.9	5.3 ± 1.0	66.5 ± 5.8	122.9 ± 13.0
Day 7	1.40 ± 0.15	181.4 ± 32.7	5.7 ± 1.2	73.9 ± 6.9	121.3 ± 17.9
Day 8	1.42 ± 0.14	184.2 ± 33.2	6.0 ± 1.2	80.3 ± 4.5	114.2 ± 19.1
Day 9	1.33 ± 0.15	180.8 ± 14.5	6.1 ± 1.3	76.1 ± 7.6	94.4 ± 15.5
	(N = 11)	(N = 12)	(N = 12)	(N = 12)	(N = 11)
Control					
Pre	1.42 ± 0.11	180.7 ± 21.4	7.1 ± 0.8	75.3 ± 2.5	125.3 ± 11.2
Post	0.91 ± 0.09	86.3 ± 12.6	1.9 ± 0.4	41.9 ± 4.6	56.3 ± 14.4
Day 5	1.18 ± 0.13	122.4 ± 14.8	4.5 ± 0.6	77.6 ± 5.7	96.9 ± 13.7
Day 6	1.15 ± 0.13	131.2 ± 18.3	4.4 ± 0.6	88.4 ± 4.6	100.5 ± 13.0
Day 7	1.11 ± 0.13	124.6 ± 15.8	3.8 ± 0.5†	71.6 ± 6.8	90.3 ± 13.6
Day 8	1.14 ± 0.13	129.7 ± 17.2	4.6 ± 0.7	85.0 ± 4.2	99.9 ± 9.7
Day 9	1.18 ± 0.12	127.1 ± 14.5	4.7 ± 0.6	81.3 ± 6.5	114.7 ± 13.6
	(N = 12)	(N = 13)	(N = 13)	(N = 13)	(N = 13)

Data represent means ± SEM. MRTD represents maximal rate of torque development; TT represents twitch torque; TPT represents time to peak twitch torque; HRT represents half-relaxation time.

* Significant difference from baseline in overall data only.

† Significant difference from IMM using an independent samples *t*-test.

M-wave data were unavailable for one subject in IMM and one subject in CON. HRT data were unavailable for one subject in IMM.

We also hypothesized that the improved recovery of MVC with immobilization could be due to changes in the evoked contractile properties of the muscle. Significant increases in soleus Type IIx MHC isoforms (and decreases in Type I and IIa MHC isoforms) have been reported in the animal model after 6 d of spaceflight (2,18). Koryak (11) reported a decreased HRT in electrically evoked contractions in humans after a 7-d dry water immersion protocol (simulating weightless conditions), suggesting an increase in contractile speed more characteristic of Type II muscle. Because Type II muscle fibers are known to generate greater force than Type I muscle fibers, a shifting of muscle phenotype that may be occurring rather quickly with disuse could impact the recovery of force with immobilization after eccentric exercise. In the present study, the only difference observed between groups in the evoked contractile properties was a significantly greater recovery of TT in IMM compared with CON (see Table 3). MRTD, TPT, and HRT were not different between groups over time. Despite an increase in TT over the recovery period in the IMM group (similar to the observed recovery of MVC), the significant interaction term ($P = 0.046$) was likely due to the reduction in TT on day 7 in CON compared to IMM. Thus, it is unlikely that enhanced MVC recovery in the days after eccentric exercise in the IMM group can be attributed to changes in TT, which were presumably not immobilization-induced.

Enhanced recovery of MVC with immobilization is likely due to factors other than activation of the muscle or changes in the muscle's contractile properties. Enhanced MVC recovery with immobilization may be due to an improved healing process within the contractile and noncontractile elements of the muscle fiber. In the animal model, Lehto et al. (12) reported that muscle fiber regeneration was enhanced and evidence of fiber disruption was less after 5 d of immobilization compared with immediate mobilization of the muscle after injury. Increased Type I collagen synthesis was also observed after short-term immobilization, suggesting an increase in strength of the muscle during the early stages of repair. Thus, a short period of immobilization may be necessary for the muscle to develop sufficient tensile strength to withstand mechanical forces associated with remobilization and avoid muscle fiber rerupture. Future studies replicating the techniques employed in the animal model may be necessary in humans to determine why MVC recovery after immobilization is enhanced after eccentric exercise.

Why we observed changes in voluntary contractions with immobilization and no changes in stimulated contractions in the present study is not known. Comparing stimulated and voluntary contractions may be limited by an additional neural component contributing to maximal voluntary contractions. Thus, if a significant neural adaptation to voluntary contractions occurred with immobilization then this would not be manifested in changes in M-wave and evoked contractile properties of the muscle. Moreover, the effect of immobilization on synergistic muscles in the elbow flexor muscle group, such as the brachialis and brachioradialis, could not be determined in this study by stimulating the musculocutaneous nerve (which innervates the biceps brachii muscle only). Therefore, it is not known whether any immobilization-induced changes in synergistic muscles contributed to enhanced MVC.

Although we did not prove the hypothesis that changes in the ability to activate the muscle or in the evoked contractile properties of the muscle contributed to enhanced force recovery after eccentric exercise, we can now eliminate these variables as potential mechanisms. However, in doing this experiment we did find some interesting changes in M-wave and evoked contractile properties due to eccentric exercise alone. No previous study had recorded M-wave and evoked contractile properties of the muscle for more than 4 d postexercise. In the present study, large and prolonged reductions in M-wave amplitude were observed immediately after eccentric exercise and remained significantly reduced compared to baseline until at least 9 d postexercise (see Table 3). Decreased M-wave amplitude has not been observed in previous eccentric exercise studies in humans possibly due to low statistical power because of small sample sizes (1) or somewhat "nonstrenuous" exercise protocols (1,15). MRTD and TT were not recovered by 9 d after eccentric exercise, while temporal aspects of the twitch demonstrated recovery to baseline values by day 5 postexercise for both TPT and HRT. The prolonged decrements in MRTD and TT implicate damage predominantly to the contractile machinery of the muscle after eccentric exercise. Because changes in sodium-potassium balance after eccentric exercise can reduce resting membrane potential and action potential propagation (14), the changes in M-wave amplitude for up to 9 d postexercise also suggests prolonged damage to the muscle fiber membrane.

We also found some interesting changes in muscle function measurements due to the immobilization treatment. For example, unlike MVC and FANG, RANG did not demonstrate an enhanced recovery with the imposed treatment. This could be due to the hypothesized role that RANG may play in muscle function recovery as a self-splinting phenomenon (22). Eccentric exercise results in a spontaneous shortening of the muscle (Fig. 3A) that is thought to be due to shortening connective tissue elements (8). This serves to place the damaged muscle fibers in a position optimal to the healing process, similar to an immobilization condition. If this were the case, an extended period of decreased RANG (maintaining the muscle in a shortened position), as occurred during immobilization, may be beneficial, thereby contributing to an overall improvement in function due to less stress being imposed on damaged fibers. Furthermore, MVC and FANG had a remarkably similar recovery pattern after eccentric exercise, which suggests that the enhanced recovery of both FANG and MVC in the IMM group may be due to a similar mechanism (4).

SUMMARY

As expected, immobilization improved the recovery of muscle function, specifically MVC, FANG, and ROM. This result suggests that reducing muscle activity when the muscle is damaged from contraction-induced injury can result in improved functional recovery. We hypothesized that the improved recovery of MVC after immobilization was due to changes in ability of motor nerve action potentials to activate the muscle and altered contractile characteristics to enhance force production. However, changes in M-wave and most of the evoked contractile properties of the muscle were not different between groups, thus the contribution of these factors to the effect of immobilization on MVC recovery appears to be minimal.

This study was supported by a grant from the American College of Sports Medicine Foundation. We would like to thank James T. Haas of Orthotics & Prosthetics Laboratories, Inc. (Northampton, MA) for the generous use of the orthotic devices used in the immobilization procedure. Finally, we express our gratitude to Diane Parslow for her assistance in data collection.

REFERENCES

1. Bulbulian, R., and D. K. Bowles. Effect of downhill running on motoneuron pool excitability. *J. Appl. Physiol.* 73:968–973, 1992.
2. Caiozzo, V. J., M. J. Baker, R. E. Herrick, M. Tao, and K. M. Baldwin. Effect of spaceflight on skeletal muscle: mechanical properties and myosin isoform content of a slow muscle. *J. Appl. Physiol.* 76:1764–1773, 1994.
3. Clancy, S. P., and P. M. Clarkson. Immobilization during recovery from eccentric exercise-induced muscle damage (Abstract). *Med. Sci. Sports Exerc.* 22:S37, 1990.
4. Clarkson, P. M., K. Nosaka, and B. Braun. Muscle function after exercise-induced muscle damage and rapid adaptation. *Med. Sci. Sports Exerc.* 24:512–520, 1992.
5. Clarkson, P. M., and S. P. Sayers. Exercise-induced muscle damage in humans. In: *The1997 Nagano Symposium on Sports Science,* H. Nose, E. R. Nadel, and R. Morimoto (Eds.). Carmel, IN: Cooper Publishing Group, 1998, pp. 545–563.
6. Fahim, M. Rapid neuromuscular remodeling following limb immobilization. *Anat. Rec.* 224:102–109, 1989.
7. Gibala, M. J., J. D. MacDougall, M. A. Tarnopolsky, W. T. Stauber, and A. Elorriaga. Changes in human skeletal muscle ultrastructure and force production after acute resistance exercise. *J. Appl. Physiol.* 78:702–708, 1995.
8. Jones, D. A., D. J. Newham, and P. M. Clarkson. Skeletal muscle stiffness and pain following eccentric exercise of the elbow flexors. *Pain* 30:233–242, 1987.
9. Kent-Braun, J. A. Noninvasive measures of central and peripheral activation in human muscle fatigue. *Muscle Nerve* 20:S98–S101, 1997.
10. Kent-Braun, J. A., and R. Le Blanc. Quantitation of central activation failure during maximal voluntary contractions in humans. *Muscle Nerve* 19:861–869, 1996.
11. Koryak, Y. Electromyographic study of contractile and electrical properties of the human triceps surae muscle in a simulated microgravity environment. *J. Physiol.* 510:287–295, 1998.
12. Lehto, M., V. C. Duance, and D. Restall. Collagen and fibronectin in a healing skeletal muscle injury: an immunohistological study of the effects of physical activity on the repair of injured gastrocnemius muscle in the rat. *J. Bone Joint Surg.* 67-B:820–828, 1985.
13. Manabe, T., S. Kaneko, and M. Kuno. Disuse-induced enhancement of Ia synaptic transmission in spinal motoneurons of the rat. *J. Neurosci.* 9:2455–2461, 1989.
14. McBride, T. A., B. W. Stockert, F. A. Gorin, and R. C. Carlsen. Stretch-activated ion channels contribute to membrane depolar-

ization after eccentric contractions. *J. Appl. Physiol.* 79:1260–1270, 2000.
15. Michaut, A., M. Pousson, Y. Ballay, and J. Van Hoecke. Effects d'une séance d'exercises excentriques sur la recuperation a court term de la contractile musculaire. *J. Soc. Biol.* 194:171–176, 2000.
16. Ng, A. V., and J. A. Kent-Braun. Slowed muscle contractile properties are not associated with a decreased EMG/force relationship in older humans. *J. Gerontol.* 54:B452–B458, 1999.
17. Rothwell, J. *Control of Human Voluntary Movement*, 2nd Ed. Chapman & Hall, London, 1995, pp. 41.
18. Roy, R. R., K. M. Baldwin, and V. R. Egerton. Response of the neuromuscular unit to spaceflight: what has been learned from the rat model. *Exerc. Sports Sci. Rev.* 24:399–425, 1996.
19. Sayers, S. P., P. M. Clarkson, and J. Lee. Activity and immobilization after eccentric exercise: I. Recovery of muscle function. *Med. Sci. Sports Exerc.* 32:1587–1592, 2000.
20. Sayers, S. P., P. M. Clarkson, and J. Lee. Activity and immobilization after eccentric exercise: II. Serum CK. *Med. Sci. Sports Exerc.* 32:1593–1597, 2000.
21. Sayers, S. P., C. A. Knight, P. M. Clarkson, E. H. van Wegen, and G. Kamen. Effect of ketoprofen on muscle function and sEMG after eccentric exercise. *Med. Sci. Sports Exerc.* 33:702–710, 2001.
22. Smith, L. L. Acute inflammation: the underlying mechanism in delayed onset muscle soreness? *Med. Sci. Sports Exerc.* 23:542–551, 1991.
23. Vandervoort, A. A., J. Quinlan, and A. J. Mccomas. Twitch potentiation after voluntary contraction. *Exp. Neurol.* 81:141–152, 1983.
24. Warren, G. L., D. A. Lowe, and R. B. Armstrong. Measurement tools used in the study of eccentric contraction induced injury. *Sports Med.* 27:43–59, 1999.