Strength training counteracts motor performance losses during bed rest

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Shinohara, Minoru, Yasuhide Yoshitake, Motoki Kouzaki, Hideoki Fukuoka, and Tetsuo Fukunaga. Strength training counteracts motor performance losses during bed rest. J Appl Physiol 95: 1485–1492, 2003. First published June 27, 2003; 10.1152/japplphysiol.01173.2002.—The purpose of the study was to determine the effect of bed rest with or without strength training on torque fluctuations and activation strategy of the muscles. Twelve young men participated in a 20-day bed rest study. Subjects were divided into a non-training group (BRCon) and a strength-training group (BRTr). The training comprised dynamic calf-raise and leg-press exercises. Before and after bed rest, subjects performed maximal contractions and steady submaximal isometric contractions of the ankle extensor muscles and of the knee extensor muscles (2.5–10% of maximal torque). Maximal torque decreased for both the ankle extensors (9%, P < 0.05) and knee extensors (16%, P < 0.05) in BRCon but not in BRTr. For the ankle extensors, the coefficient of variation (CV) for torque increased in both groups (P < 0.05), with a greater amount (P < 0.05) in BRCon (88%) compared with BRTr (41%). For the knee extensors, an increase in the CV for torque was observed only in BRCon (22%). The increase in the CV for torque in BRCon accompanied the greater changes in electromyogram amplitude of medial gastrocnemius (122%) and vastus lateralis (59%) compared with BRTr (P < 0.05). The results indicate that fluctuations in torque during submaximal contractions of the extensor muscles in the leg increase after bed rest and that strength training counteracted the decline in performance. The response varied across muscle groups. Alterations in muscle activation may lead to an increase in fluctuations in motor output after bed rest.

sturdiness; knee extension; plantarflexion; electromyogram

of the fluctuations has been shown to vary with the level of force exerted, the muscle used for the task, the type of contraction, as well as the age of the subject (see Ref. 13 for review). For example, when contractions are performed with a single agonist muscle (first dorsal interosseus), fluctuations are larger in old adults compared with young adults during low-force isometric (15) as well as slow shortening and lengthening contractions (23). The decline in motor performance exhibited by old adults seems to be associated with changes in the strategies for activating motor units, in particular, synchronized discharge and discharge rate variability of motor units (23). Fluctuations in motor output during contractions that involve multiple muscles are apparently different from those for a single muscle (16, 33). Not much is known about the underlying mechanisms of those fluctuations during contractions of multiple muscles, but alteration in the strategies for distributing muscle activity is suggested as one of the possible mechanisms (16).

Reductions in habitual physical activity may also increase the magnitude of force fluctuations. Prolonged immobilization or unloading (spaceflight or bed rest) reduces habitual activity in some muscles, leading to reductions in the cross-sectional area and strength of the muscles (2, 3, 5, 18–20, 25, 27). Furthermore, prolonged reductions in activity due to these interventions alter a variety of features in the neuromuscular system such as discharge properties of motor units and level of neural activation (10, 11, 19, 26). In particular, activation strategy of agonist muscles is modified after prolonged reduced activity in rhesus monkeys (28, 29) and in humans (31). For example, rhesus monkeys experienced preferential recruitment of medial gastrocnemius compared with soleus during a foot pedal motor task and locomotion after a 2-wk spaceflight (28, 29). In humans, intermittent activity of all elbow flexor muscles appeared throughout the fatiguing contraction after 4 wk of elbow joint immobilization (31). It is not

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clear, however, whether reduced habitual use of muscles impairs the ability to exert a steady force.

Strength training has been shown to be effective in reducing the fluctuations in force (17, 21, 24). In the first dorsal interosseous muscle of old adults, for example, there was a decrease in the CV for force by >20%, after 4 (24) or 12 wk (21) of a dynamic strength training program, which diminished the differences in the CV for force between young and old adults. Thus it is hypothesized that unloading of muscles leads to increased force fluctuations during isometric contractions and is counteracted by strength training during the period of unloading. Examination of extensor muscles in the leg in response to bed rest was chosen because these muscles lose muscle mass and strength after bed rest and strength training can counteract some of the neuromuscular changes that occur during bed rest (1, 2, 5, 19, 20). The purpose of the study was to compare torque fluctuations and activation strategy of extensor muscles of the leg during submaximal contractions before and after bed rest in young subjects, who did or did not perform strength training during the bed rest period.

METHODS

Subjects. Twelve healthy young men voluntarily participated in the study. The subjects had no medical history or physical signs of neuromuscular disorder and did not regularly participate in strength-training exercises. Six subjects were randomly assigned to the group who performed strength training (BRTr), and the remaining subjects were assigned to the group who did not perform strength training (BRCon) during the bed rest period. There were no significant differences in physical characteristics between the groups. The age, height, and body mass of the subjects (means ± SD) were 22.7 ± 2.9 yr, 169.6 ± 7.8 cm, and 67.3 ± 13.7 kg for the BRCon group and 23.3 ± 4.9 yr, 169.8 ± 6.4 cm, and 65.5 ± 17.1 kg for the BRTr group, respectively. The right leg was the dominant leg in all the subjects as determined by the preferred leg to kick a ball. The subjects did not regularly participate in strength-training exercises. They gave informed consent to the procedures, which were approved by the Ethics Committee of the Faculty of Medicine, The University of Tokyo, Japan. General aspects of this bed rest study and its influence on maximal force for ankle extension have been reported elsewhere (4).

Bed rest. All the subjects completed a program of bed rest for 20 days. Subjects remained in a reclined position with the bed tilted at 0.1 rad (6°) to the horizontal, except during the strength-training exercise. The subject’s head was placed at the low end of the bed to simulate a microgravity environment (9). Subjects were instructed not to produce any unnecessary movements with their limbs. They were supervised by nursing staff throughout the period, and nutritional care was undertaken to avoid significant changes in body mass. Balanced diet for protein, lipid, carbohydrate, minerals, and vitamins were provided to the subjects. All the leftovers were weighed, and the calorie intake and nutritional content were calculated after each meal. Low-calorie bread or rice was served when subjects were hungry between the meals. Total caloric intake was 2,538 ± 24 kcal per day for each subject. The body mass was checked every day. As a result, no significant change in body mass was observed during the bed rest period.

Strength training. Subjects in the BRTr group performed the strength training in 16 of 20 days of the bed rest period. The four nontraining days were evenly distributed throughout the period. The training consisted of a dynamic bilateral calf-raise exercise and a dynamic bilateral leg-press exercise using modified leg-press training equipment (Leg Press VR-4100, Cybex). This equipment was used only for the strength training and was not used for the tests that examined the effects of bed rest on the maximal torque and torque fluctuations by the ankle extensors and the knee extensors (see Strength and torque fluctuation measurement). The maximal force was measured on the 1st, 6th, 13th, and 20th days of the bed rest period with the force transducer that was attached in series with the training load. The measured maximal force for the calf-raise and leg-press was used to determine the training load. The maximum value of the three trials was determined, and the training load corresponded to 70% of this value. Use of this load was based on a pilot study in which we found that perceived exertion reached maximum in the final repetitions of the exercise. If the subjects had difficulty in lifting the load through the range of motion (e.g., 8th to 10th repetitions of the 4th and 5th sets), they continued lifting with their maximal effort even though the range of motion became smaller. Leg-press exercises were performed in the morning and calf-raise exercises were performed in the afternoon. The calf-raise exercise was designed to train the ankle extensor muscles (Fig. 1A). The hip and knee joints were kept fully extended throughout the exercise. The ankle joint angle was fixed at 1.57 rad (90°) during the determination of the training load. The training exercise involved the subjects lifting a load with an ankle extension movement from the maximally flexed position up to the maximally extended position. The leg-press exercise was designed to train the knee extensor muscles (Fig. 1B). The angle of the

Fig. 1. Schematic illustration of the setup for strength training. Initial position of the subjects during strength training for the ankle extensor muscles (A) and knee extensor muscles (B). Maximal isometric force was measured with the force transducer that was attached in series with the training load.
hip, knee, and ankle joints at the initial position was 1.92, 1.57, and 1.40 rad (110, 90, and 80°), respectively. The training load was determined at the initial position. The training exercises required the subjects to lift the load in 3-8 cycles with 1 s for the shortening phase and 2 s for the lengthening phase. Each exercise was performed for 5 sets of 10 repetitions with a rest period of 60 s between the sets. An investigator supervised all the sessions, and subjects completed all the required sets of exercise. There were no systematic changes in the training load.

**Strength and torque fluctuation measurement.** Before and after the bed rest period, subjects performed isometric contractions with the ankle extensor and knee extensor muscles of the right leg (dominant leg) by using a specially designed dynamometer, which has been utilized previously in our laboratory (2, 19, 26). The testing session after the bed rest period was performed 1–2 days after the last training session. The sensitivity of the dynamometer was 76 N·m/V. For contractions of the ankle extensors, the subject was seated in a chair with the hip joint angle fully extended and the foot and the foot plate was adjusted so that the center of rotation of the knee joint was aligned with the center of rotation of the dynamometer. For the knee extensor muscles, the subject was seated in a chair with the hip joint angle flexed at 1.40 rad (80°) and the knee joint angle flexed at 1.57 rad (90°). The lever arm of the dynamometer was securely fastened to the subject’s right leg proximal to the lateral malleolus. The position and the height of the chair were adjusted so that the center of rotation of the knee joint was aligned with the center of rotation of the dynamometer. In both tests, the trunk and thigh were secured to the chair by straps. The order of testing for the two muscle groups varied across subjects. Care was taken to fix the subject’s trunk and lower limb to the same joint angles before and after the bed rest period.

A maximal voluntary contraction (MVC) test was conducted after a familiarization session, which included practice trials at submaximal intensities. Subjects were instructed to slowly increase the torque to a maximal level and maintain it for ~3 s. Subjects were given strong verbal encouragement during this task. Three trials were performed, and the maximal torque measured during any trial was taken as the MVC torque. Subjects were then instructed to exert a submaximal steady torque to match the target torque displayed on an oscilloscope for 30 s. The target torques were 2.5, 5.0, 7.5, and 10% of the MVC torque that was measured before the bed rest period. The order of the target was pseudo-randomized across subjects.

The surface electromyogram (EMG) was recorded during the maximal and submaximal contractions. The technique for recording EMG is the same as that repeatedly used in our laboratory (22, 32). EMG was detected with bipolar silver-silver chloride electrodes (interelectrode distance 2 cm) from the medial gastrocnemius and soleus muscles for the ankle extension task and from the vastus lateralis and rectus femoris muscles for the knee extension task. The bipolar electrodes were attached over the muscle belly along the direction of the fascicles of each muscle by utilizing the ultrasound B-mode images. After careful abrasion of the skin, the electrodes were placed at the same locations before and after the bed rest period with the use of permanent spot mark. The reference electrode was placed over the lateral portion of the knee. The electrodes were connected to a preamplifier and then a differential amplifier with a band-pass filter set to 5–500 Hz (model 1253A, MEC Medical Systems, Tokyo, Japan). The amplified EMG and torque signals were stored on a personal computer after analog-to-digital conversion with sampling frequency of 1 kHz (16 bit, PowerLab/16sp, ML795, ADInstruments, Japan). The resolution for measuring torque was 0.0114 N·m/bit in this system. In the MVC trials, the peak torque was determined and the root mean square value of EMG was calculated during the 300 ms period before the peak torque. In the submaximal contractions, torque and EMG signals over the middle 16 s of the contraction were used to calculate the CV for torque and root mean square value of EMG. The root mean square value of EMG for the submaximal contractions was normalized to that of MVC. Possible cross talk between muscles was not controlled. Correlation coefficients of the root mean square value of EMG before and after a 20-day interval, measured in other subjects, were 0.960, 0.945, 0.983, and 0.965 for medial gastrocnemius, soleus, vastus lateralis, and rectus femoris, respectively.

**Statistical analysis.** Physical characteristics of the subjects were compared with Student’s t-tests. The dependent variable was the root mean square value of EMG for the submaximal contractions. The dependent variables for the submaximal test were fluctuations in torque quantified by the CV for torque and the amplitude of EMG quantified by the root mean square value of EMG. In addition, relative changes of these variables in response to bed rest were calculated for each individual, as the difference between the pre- and post-bed rest values divided by the pre-bed rest value, and they were averaged across subjects in each group. MVC torque was compared with a three-factor ANOVA (2 subject groups × 2 muscle groups × 2 times) with repeated measures on muscle group and time. The CV for torque and amplitude of EMG for the submaximal contraction were compared with a three-factor ANOVA (2 subject groups × 4 intensities × 2 times) with repeated measures on intensity and time for each muscle group. An alpha level of 0.05 was chosen for all statistical comparisons, with post hoc comparisons (Newman-Keuls test) when appropriate. Relative changes in MVC, CV, and amplitude of EMG were compared between subject groups with Student’s t-tests. Unless stated otherwise, the data are presented as means ± SD in the text and tables and as means ± SE in the figures.

**RESULTS**

**Peak torque during MVC.** In the BRCon group, MVC torque after bed rest was significantly less ($P < 0.05$) compared with the pre-bed rest value when the data were collapsed across muscle groups. The decrease for the ankle extensors due to bed rest was 9% (see Fig. 4A), from 127.1 ± 23.3 N·m before bed rest to 115.3 ± 25.8 N·m after bed rest. The decrease for the knee extensors was 16% (see Fig. 4B), from 258.2 ± 85.2 N·m before bed rest to 212.7 ± 49.4 N·m after bed rest. In the BRTr group, the MVC torque did not differ before and after bed rest (see Fig. 4).

**Torque fluctuations and muscle activation.** When subjects performed isometric contractions to the target torque, the torque fluctuated about an average value (Fig. 2). Before bed rest, fluctuations in torque were not different between the subject groups (Fig. 3). The CV for torque of the ankle extensors (2.38 ± 0.79%) was significantly greater ($P < 0.01$) than the knee extensors (1.16 ± 0.46%) when data were collapsed across
target torques. For the ankle extensors, the relative increase in the CV for torque for each individual averaged 88% in the BRCon group, which was significantly greater ($P < 0.05$) than in the BRTr group (41%) (Fig. 4A). For the knee extensors (lower row of Fig. 3), the relative increase in the CV for torque for each individual averaged 22% in the BRCon group, which was significantly greater ($P < 0.05$) than that in the BRTr group (4%) (Fig. 4B).

Before bed rest, EMG amplitude was not significantly different between the subject groups in any muscle. When the data were averaged across subject groups and torques, EMG amplitude of medial gastrocnemius after bed rest (11.4 ± 5.5%) was significantly greater ($P < 0.01$) than the pre-bed rest value (6.8 ± 4.9%). In contrast, there was no significant difference in EMG amplitude of soleus between pre- (9.4 ± 3.7%) and post-bed rest (11.7 ± 5.2%) when collapsed across subject groups and torques. The relative change in EMG of the medial gastrocnemius for each individual averaged across torques was 122% in the BRCon group, which was significantly greater ($P < 0.05$) than in the BRTr group (26%) (Fig. 4A). In the knee extensors, the EMG amplitude of vastus lateralis in the BRCon group was significantly greater ($P < 0.05$) after bed rest (10.9 ± 8.4%) compared with the pre-bed rest value (6.8 ± 3.8%) when the data were averaged across torques. In contrast, EMG amplitude of rectus femoris was not different between pre- and post-bed rest in either subject group. The relative change in EMG of vastus lateralis for each individual across torques (Fig. 4B) was 59% in the BRCon group, which was significantly greater than the BRTr group ($P < 0.01$).

**DISCUSSION**

The aim of the study was to compare torque fluctuations of the extensor muscles of the leg in response to bed rest in two groups of young subjects, one that performed strength training during bed rest and the other that did not. The main novel findings were that the torque fluctuations increased after bed rest but that strength training counteracted this effect.

**Effects of bed rest and training on strength.** Prolonged bed rest induced declines in MVC torque for ankle extensors and knee extensors. The decline for ankle extensors was 9% in the BRCon group, which was less than the results from another study (13% decrease) after 14 days of bed rest (5). The decline for the knee extensors was 16%, which was greater than the 11% decline after 20 days of bed rest (19). The differences in the declines between these studies and between muscle groups may be due to the differences in the number and characteristics of the subjects, as well as muscle activity that occurred during bed rest. However, there have been no measurements of long-term muscle activity during bed rest, which limits the interpretation of the present findings. Reductions in cross-sectional area of the extensor muscles of the leg have been repeatedly observed after bed rest (1–3, 19, 25), which may partly explain the reduction in MVC torque. Another major factor that may reduce the strength is a decrease in the central neural activation. For example, Duchateau (10) concluded that the reduction in MVC force by the ankle extensors after 5-wk bed rest was explained by a 33% deficit in central activation and a 19% reduction in muscle force-generating capacity. Similarly, the loss of MVC force after 20 days of bed rest was accompanied by 8% decrease in cross-sectional area of the knee extensor muscles and 7% decline in muscle activation (19). Thus, in addition to the loss of cross-sectional area, it is likely that some neural adaptations were induced by bed rest.

The strength training during the bed rest period counteracted the decline in MVC torque. The present
The training protocol for the ankle extensor muscles was comparable to the one utilized by Bamman et al. (5), in which MVC force was preserved by the strength training. The training protocol for the knee extensor muscles was similar to the one used previously (1), which succeeded in maintaining the MVC force, cross-sectional area, and muscle activation (1, 19). Taken together, it appears that strength training can counteract changes in central neural activation during maximal contraction as well as cross-sectional area of the muscles.

**Effects of bed rest and training on torque fluctuations.** The torque fluctuations during isometric contractions increased after bed rest, in both ankle extensors and knee extensors. Strength training counteracted the increase in the torque fluctuations for the knee extensors but only partially for the ankle extensors.

For the knee extensors, the effects of bed rest on MVC torque and CV for torque can be compared with the changes that occur due to aging. For example, MVC force of the knee extensor muscles was found to be 39% less for old men (71 ± 4 yr) compared with young men.
(22 ± 2 yr), and there was a 40–64% increase in CV for force for the old men (33). Although there are other studies that did not find differences between young and old adults for the knee extensors (8, 17, 30), Tracy and Enoka (33) pointed out critical methodological differences that may have led to the contrary results. In the present study, the methods were similar to the ones used by Tracy and Enoka, and MVC torque decreased by 16% and the relative increase in the CV for torque for the old men (33). Although there are other studies that have some effect on the changes in the torque fluctuations after bed rest.

Effects of bed rest and training on muscle activation.

The potential neural mechanisms that may explain the changes in fluctuations include alterations in the characteristics or discharge behavior of motor units and alterations in muscle activation strategy among agonist and antagonist muscles. A substantial increase in the amplitude of EMG of the medial gastrocnemius and vastus lateralis for the same subjects was observed by Duchateau and Hainaut (11) in a change in the activation strategy of motor units to grade muscle force after 6–8 wk of limb immobilization. After bed rest, there was a 40% increase in CV for torque. Hence, it appears that alterations in the involvement of the agonist muscles have some effect on the changes in the torque fluctuations after bed rest.

Akima et al. (4) compared spin-spin relaxation time (T2) of the ankle extensor muscles immediately after unilateral calf-raising exercise for the same subjects and found a greater increase in the T2 of the gastrocnemius (2.3 ms) over the soleus (1.6 ms) in response to bed rest, which was lessened with the strength training. These alterations in the muscle activation strategy were associated with changes in the fluctuations of torque.

Table 1. Amplitude of EMG during submaximal steady contraction

<table>
<thead>
<tr>
<th>Target (% MVC)</th>
<th>Bed Rest</th>
<th>Bed Rest + Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media gastrocnemius</td>
<td>Soleus</td>
<td>Vastus lateralis</td>
</tr>
<tr>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>2.5</td>
<td>±4.0</td>
<td>±7.8</td>
</tr>
<tr>
<td>5.0</td>
<td>±5.5</td>
<td>±1.1</td>
</tr>
<tr>
<td>7.5</td>
<td>±7.2</td>
<td>±17.3</td>
</tr>
<tr>
<td>10</td>
<td>±9.3</td>
<td>±18.8</td>
</tr>
</tbody>
</table>

Values are group means ± SD of root mean square value of electromyogram (EMG) normalized to that of maximal voluntary contraction MVC (%). Pre, before bedrest; Post, after bedrest.
nemius or between the vastus lateralis and rectus femoris in response to 20-day bed rest (1–3, 20). This has also been confirmed in the present subjects (H. Akima, unpublished observation). Thus it is unlikely that changes in muscle activation strategy are related to differences in the rate of atrophy among the agonist muscles in humans.

As stated, muscle activity during bed rest has not been examined in any study, which is one of the limitations of the bed rest study: we cannot tell how much the activity was reduced in which muscles during bed rest. Muscle activation was measured with surface EMG in two agonist muscles in each muscle group. It is possible that muscle activation strategy may be altered in other unmeasured muscles. Nonetheless, it is clear that ability to exert a steady torque by the extensor muscles in the leg declined after bed rest and that strength training counteracted the decline in performance. Each target torque was the same absolute value for pre- and post-bed rest trials, resulting in the greater relative intensity in BRCon after bed rest. If the CV for torque were plotted against the relative intensity to corresponding MVC in Fig. 3, the curve for the post-bed rest data in BRCon would have been slightly shifted to the right. In that case, the difference in CV between the pre- and post-bed rest would have been exaggerated. In addition, the greater increase in the activation of gastrocnemius and vastus lateralis muscle could not have resulted from the increased relative intensity in the BRCon group because there was no systematic increase in the relative contribution of medial gastrocnemius over soleus or that of vastus lateralis over rectus femoris for pre-bed rest values in either group. Hence, the ability to exert a steady sub-maximal torque is mutable by habitual muscle activity in young subjects.

In conclusion, based on the present data and evidence in the literature, it appears that alterations in muscle activation strategy may be a factor that leads to an increase in fluctuations in motor output after bed rest.

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