Pergamon

Acta Astronautica Vol. 43, Nos. 3 6, pp. 107 119, 1998

Printed in Great Britain
0094-5765/98/$—see front matter

PII: S0094-5765(98)00148-9

ADAPTATION OF NEUROMUSCULAR ACTIVATION PATTERNS DURING TREADMILL WALKING AFTER LONG-DURATION SPACE FLIGHT

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ABSTRACT

The precise neuromuscular control needed for optimal locomotion, particularly around heel strike and toe off, is known to be compromised after short duration (8- to 15-day) space flight. We hypothesized here that longer exposure to weightlessness would result in maladaptive neuromuscular activation during postflight treadmill walking. We also hypothesized that space flight would affect the ability of the sensory-motor control system to generate adaptive neuromuscular activation patterns in response to changes in visual target distance during postflight treadmill walking. Seven crewmembers, who completed 3- to 6-month missions, walked on a motorized treadmill while visually fixating on a target placed 30 cm (NEAR) or 2 m (FAR) from the subject's eyes. Electronic foot switch data and surface electromyography were collected from selected muscles of the right lower limb. Results indicate that the phasic features of neuromuscular activation were moderately affected and the relative amplitude of activity in the tibialis anterior and rectus femoris around toe off changed after space flight. Changes also were evident after space flight in how these muscles adapted to the shift in visual target distance.

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INTRODUCTION

During the 36 years of humans space exploration, very few investigations have focused on quantifying the effects of weightlessness on human locomotion after return to Earth. Early reports from both the U.S. and Russian space programs documented a variety of locomotor problems that generally were related to loss of bipedal stability [1,2]. Returning crewmembers compensate for the potential loss of stability by adopting a wide base of support, taking shorter strides and using their arms more than they did before flight. Although these adaptations serve to maintain stability, walking speed is reduced and more steps are needed to locomote a specified distance. Recently, our laboratory conducted a comprehensive investigation designed to assess the effects of space flight on segmental kinematics and the underlying neuromuscular-control features during treadmill walking.

Previously we reported alterations in head-trunk coordination and variations in lower limb kinematics during treadmill walking, particularly around the behavioral events of toe off and heel strike, after short-duration space flights [3,4]. We also have identified changes in neuromuscular activation characteristics of the lower limb during postflight treadmill walking [5]. The current investigation extends the scope of the previous study by assessing the impact of long-duration space flight (flights of 3-6 months) on kinematic and neuromuscular-activation characteristics during treadmill walking. This report describes postflight modifications in neuromuscular-activation features of the lower limb musculature while subjects walked on a treadmill and fixated gaze at a visual target. We were also interested in the degree of lower limb neuromuscular activation response adaptability and how space flight would affect this adaptability. By manipulating visual target distance while maintaining a constant treadmill belt speed, we subtly modified the task constraints to determine if subjects modified their lower limb neuromuscular activation features in response to varying target distances. An index of adaptability was calculated to quantify the degree of adaptation in neuromuscular activation when visual target distance was changed and preflight-to-postflight differences were examined to determine if space flight impacted the ability to adapt neuromuscular control features.

METHODS

Subjects

Seven male astronauts/cosmonauts, mean age = 44.7 (SD = 6.9) years, who flew aboard the Russian space station Mir for 3 to 6 months, served as subjects for this investigation. Each subject provided informed consent, as required by the NASA Johnson Space Center Institutional Review Board. Subjects had no history of neurological or musculoskeletal disorders and all had previous space flight experience, either aboard the U.S. Space Shuttle or aboard Mir.

Procedures

The two test conditions involved subjects walking on a treadmill while fixating visually on an Earth-fixed target (a light emitting diode) that was positioned in the center of view at the subject's eye level. In the FAR target condition, the visual target was 2 m from the outer canthus of the eyes; in the NEAR target condition, the target was 30 cm away. Each trial consisted of several seconds to permit the subject to become familiar with the treadmill speed, followed by two trials of 20 s of data collection, separated by a one minute rest. All subjects were familiarized with the test procedures during two practice sessions before preflight data collection. Preflight data were collected about 10 days before launch. Postflight data were collected from 5 subjects within 24 hours after landing, and from the remaining 2 subjects within 72 hours after landing.

Subjects walked at a fast pace (6.4 km/h) on a motorized treadmill (Quinton™ Series 90 Q55, surface area 51 cm x 140 cm). While walking, the subjects wore a safety harness that was suspended from an overhead frame adjusted to accommodate each subject's height. The harness did not interfere with limb motion and provided no support unless the subject's trunk was displaced at least 15 cm downward; this displacement also activated a treadmill "stop" switch. A spotter was positioned next to the treadmill during testing. No subjects fell or needed assistance from the harness or the spotter during testing.

Subjects wore shorts, sleeveless shirts, athletic socks, and running shoes during testing. Piezoresistive force transducers were taped to the heel and toe of the right and left shoes. The signals from the force transducers were used to identify the heel strike and toe off points during each trial. Pre-amplifier electrodes were used to record surface electromyography from the right rectus femoris (RF), biceps femoris (BF), medial gastrocnemius (MG), and tibialis anterior (TA). After the skin was cleansed with alcohol, the electrodes were placed on the skin over the belly of the muscles. The electrodes were secured to the leg with hypoallergenic tape and covered with elastic leg wraps to prevent motion artifacts. Foot switch and EMG data were digitally sampled at 500 Hz and stored for future analysis.

Data Reduction

The raw EMG output was high-pass filtered (30 Hz), full-wave rectified, and smoothed with a 15 ms time constant. For each subject and condition, approximately 40 individual strides, from right heel strike to right heel strike, were extracted from the processed EMG on the basis of voltage records obtained from the foot switches. The EMG for all strides were temporally normalized by using cubic spline interpolation. For each subject, files with 20 data points (epochs) were created from the splined data by averaging the amplitude of each 5% interval. The EMG activity of each stride was then represented by 20 epochs. Since the average stride time for the group, across conditions was 950 ms, each epoch represented approximately 48 ms of data. An individual subject average stride EMG record for each muscle (plus 1 SD) was created from the average data of each epoch. Each muscle's average waveform was amplitude-normalized by scaling the measured voltage at each sample to the mean voltage value for that muscle obtained during the NEAR target condition. This mean voltage value for each muscle defined unity; consequently, scaled values less than 1 indicate activation amplitude less than the mean, and scaled values greater than 1 indicate amplitude greater than the mean. These reduction techniques produced EMG waveforms that accurately represented the phasic features of each muscle across the stride cycle [5] and allowed relative amplitude activation to be compared between preflight and postflight activation waveforms.

Data Analysis

The following techniques were applied to each muscle activation waveform for each subject. To determine whether space flight modified the phasic features of neuromuscular activation within a visual condition, Pearson product-moment correlations were calculated for the preflight vs. postflight waveforms. Potential changes in relative amplitude between preflight and postflight activation waveforms, within visual target condition, were determined by subtracting the preflight waveform values from the postflight waveform values at each epoch. Student *t* -tests assessed potential preflight-to-postflight changes in relative amplitude at each of the 20 epochs. Coefficients of variation (CV) were calculated across the waveforms to quantify the amount of variability in activation before vs. after flight.

We developed an index of adaptability to evaluate the magnitude of change in the activation amplitude between the NEAR and FAR target condition, and to determine how space flight may have affected that change. The index is calculated using the following equation for each epoch:

$$\text{Adaptability Index} = \left(\frac{\text{Far} - \text{Near}}{\text{Near}}\right) * 100$$

Student t-tests were used to evaluate potential preflight vs. postflight differences in the adaptability index for each epoch

Preflight versus postflight stride times were evaluated with a repeated measures analysis of variance (ANOVA) to determine whether space flight affected the temporal characteristics of gait. An alpha value of 0.05 was adopted for all statistical tests.

RESULTS

Figure 1 illustrates the preflight and postflight group mean stride times within each visual target distance condition. There were significant postflight decreases in both the FAR and NEAR conditions compared to preflight values. However these decreases were quite small; 3.7% and 2.6% for the FAR and NEAR conditions respectively. The present findings should be interpreted in light of the fact that representatives of the treadmill manufacturer indicated that treadmill belt speed could vary up to 5% across data collection sessions.

Pearson *r* values that reflect the degree of correlation between the preflight and postflight activation waveforms within a visual target condition, are shown in Table 1. Eighty percent of the comparisons in the FAR target condition, and 92% of the comparisons in the NEAR target condition, had a coefficient value of 0.81 or greater. These high correlations indicate that space flight had little effect on the *phasic* features of neuromuscular activation within a particular visual target condition during treadmill walking. Thus, when the muscle is active or inactive as a

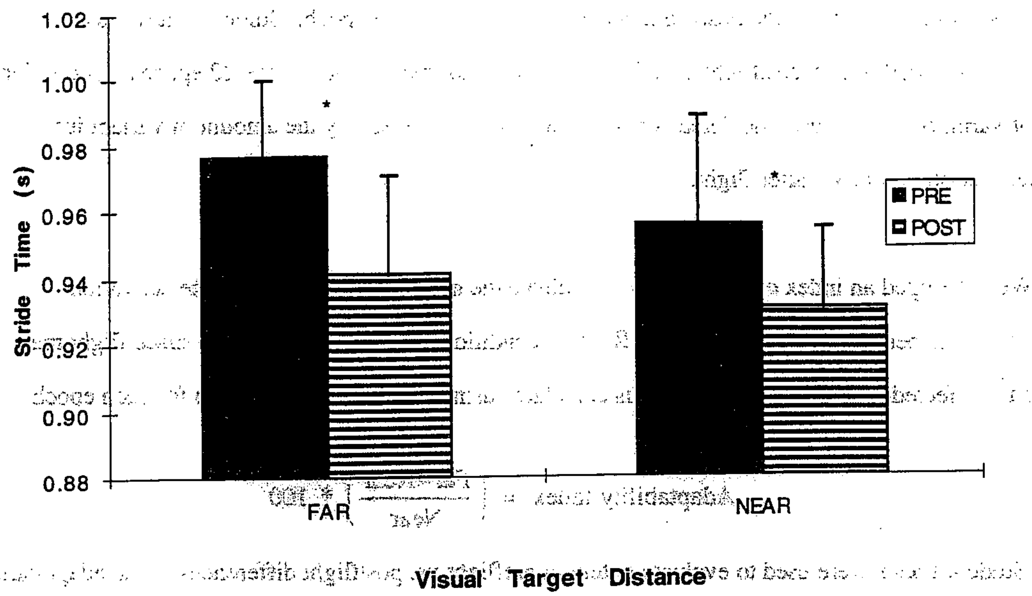

Figure 1. Group mean (plus one SD) preflight and postflight stride times for FAR and NEAR visual target distance conditions. *Significantly different after flight from before, $p < 0.05$.

percentage of the gait cycle did not change as a result of space flight. However, there were significant pre- vs. postflight changes in other measures of neuromuscular activation.

Figures 2 and 3 illustrate the mean normalized amplitude-difference values between the preflight and postflight activation waveforms for each muscle, at each epoch, for the FAR and NEAR target

Table 1: Preflight-to-postflight correlations in EMG waveforms

	Rectus Femoris	Biceps Femoris	Medial Gastrocnemius	Tibialis Anterior	Total	Percent
Far Target Condition:						
1.00–0.91	2	4	5	6	17	65
0.90–0.81	1	1	2	0	4	15
0.80–0.71	3	0	0	0	3	12
0.70–0.61	0	1	0	1	2	8
0.60–0.00	0	0	0	0	0	0
Near-Target Condition:						
1.00–0.91	2	5	7	6	20	77
0.90–0.81	3	0	0	1	4	15
0.80–0.71	1	1	0	0	2	8
0.70–0.61	0	0	0	0	0	0
0.60–0.00	0	0	0	0	0	0

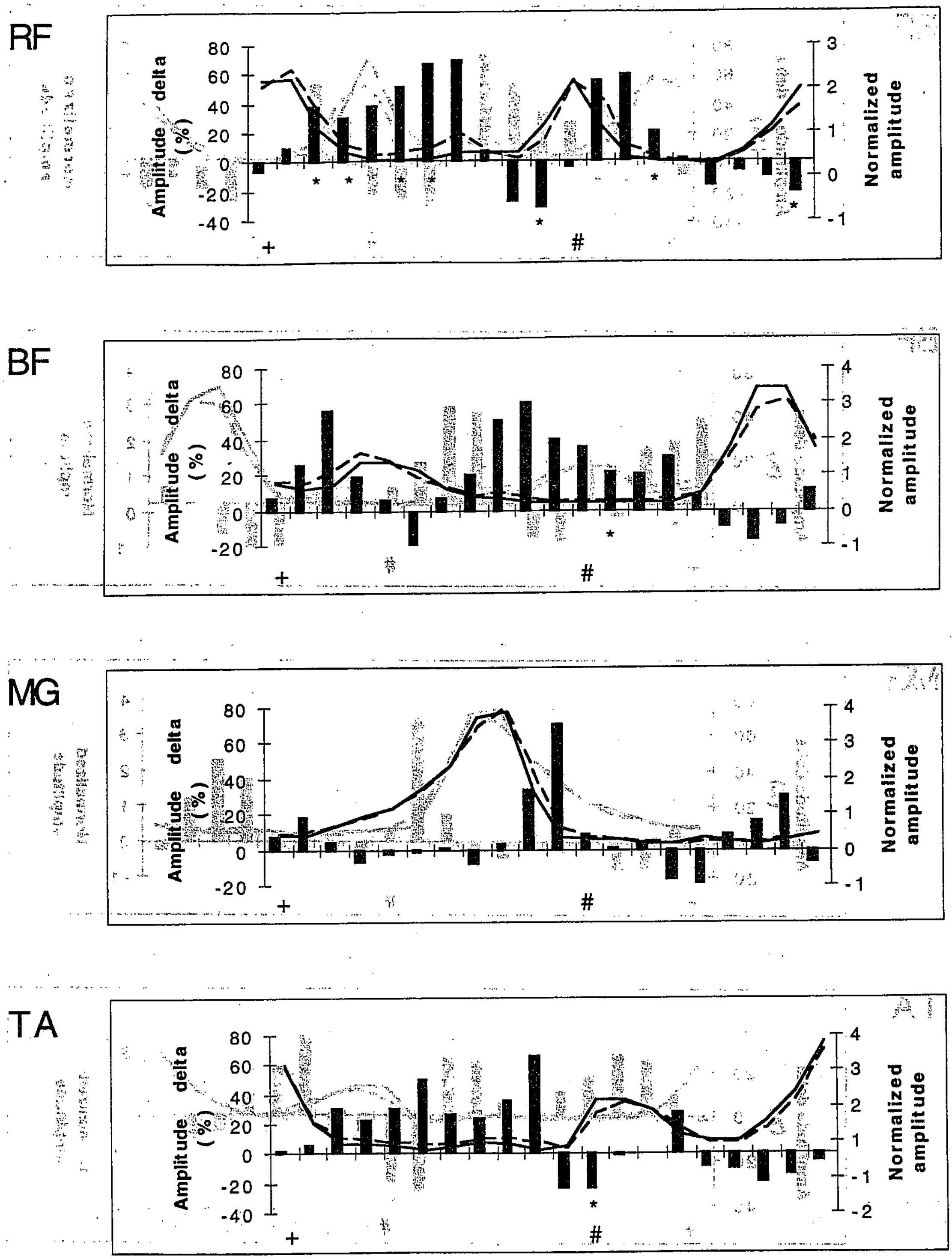

Figure 2. Preflight-to-postflight changes in activation amplitude (group means) at each epoch of the gait cycle for the FAR target condition (bars). Values greater than zero indicate that amplitude was greater after flight than before; *significantly different from preflight, $p \leq 0.05$. Heel strike and toe off are signified by + and #, respectively. Mean activation waveforms also are shown for before flight (solid line) and after flight (dashed line).

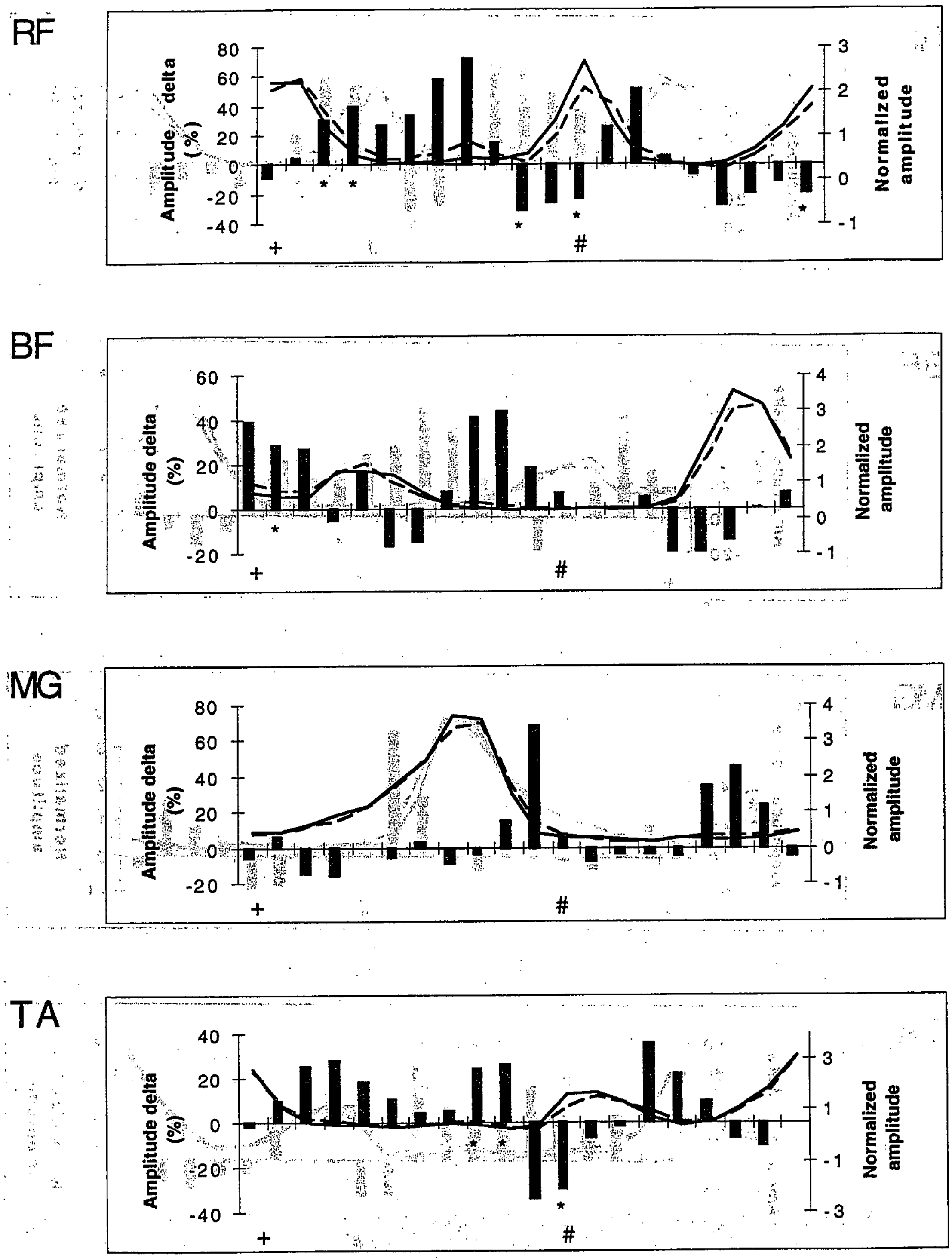

Figure 3. Preflight-to-postflight changes in activation amplitude (group means) at each epoch of the gait cycle for the NEAR target condition (bars). Values greater than zero indicate that amplitude was greater after flight than before; *significantly different from preflight, $p < 0.05$. Heel strike and toe off are signified by + and #, respectively. Mean activation waveforms also are shown for before flight (solid line) and after flight (dashed line).

conditions, respectively. The mean preflight and postflight activation waveforms have been included in the figures to facilitate evaluation of the pre- vs. postflight amplitude differences. For example, notice the large percentage differences in the BF around toe-off. However, since the muscle is essentially inactive during this period, it is likely these differences are of little importance, either from a motor control or functional perspective. For both visual target conditions, significant differences in activation amplitude were seen in the RF and TA around toe off. The RF also showed significant differences around heel strike in both target conditions. No consistent differences in amplitude were seen across target conditions for the MG or BF.

Preflight and postflight mean coefficients of variation for each muscle and target condition are shown in Table 2. In the FAR target condition, variability across all muscles increased but the changes in the coefficients of variation in the NEAR target condition were more mixed (i.e. some values increased while others decreased). The variability of activation in the RF for the FAR condition was 21.5% greater after flight than before, and 31.3% greater in the NEAR condition. Potential differences between pre- and postflight variability were not tested for statistically because the nature of the measure violates assumptions necessary for the application of traditional inferential statistical tests. However, the large percentage increases suggest the sensory-motor system was more variable in it's generation of RF neuromuscular activation after space flight.

Group mean preflight and postflight adaptability index values for each muscle, for each epoch, are shown in Figure 4. The neuromuscular response of the BF and MG to the change in target distance was not affected by space flight. However, the RF, around the toe off point, responded

Table 2: Preflight and postflight coefficients of variability (Cvs) for all muscles and both visual target distance conditions

	Preflight	Postflight
Far-Target Condition:		
Rectus Femoris	30.7	37.3
Biceps Femoris	37.3	39.1
Medial Gastrocnemius	29.5	34.4
Tibialis Anterior	32.2	36.5
Near-Target Condition:		
Rectus Femoris	31.0	40.7
Biceps Femoris	38.6	36.5
Medial Gastrocnemius	30.7	33.5
Tibialis Anterior	38.0	37.7

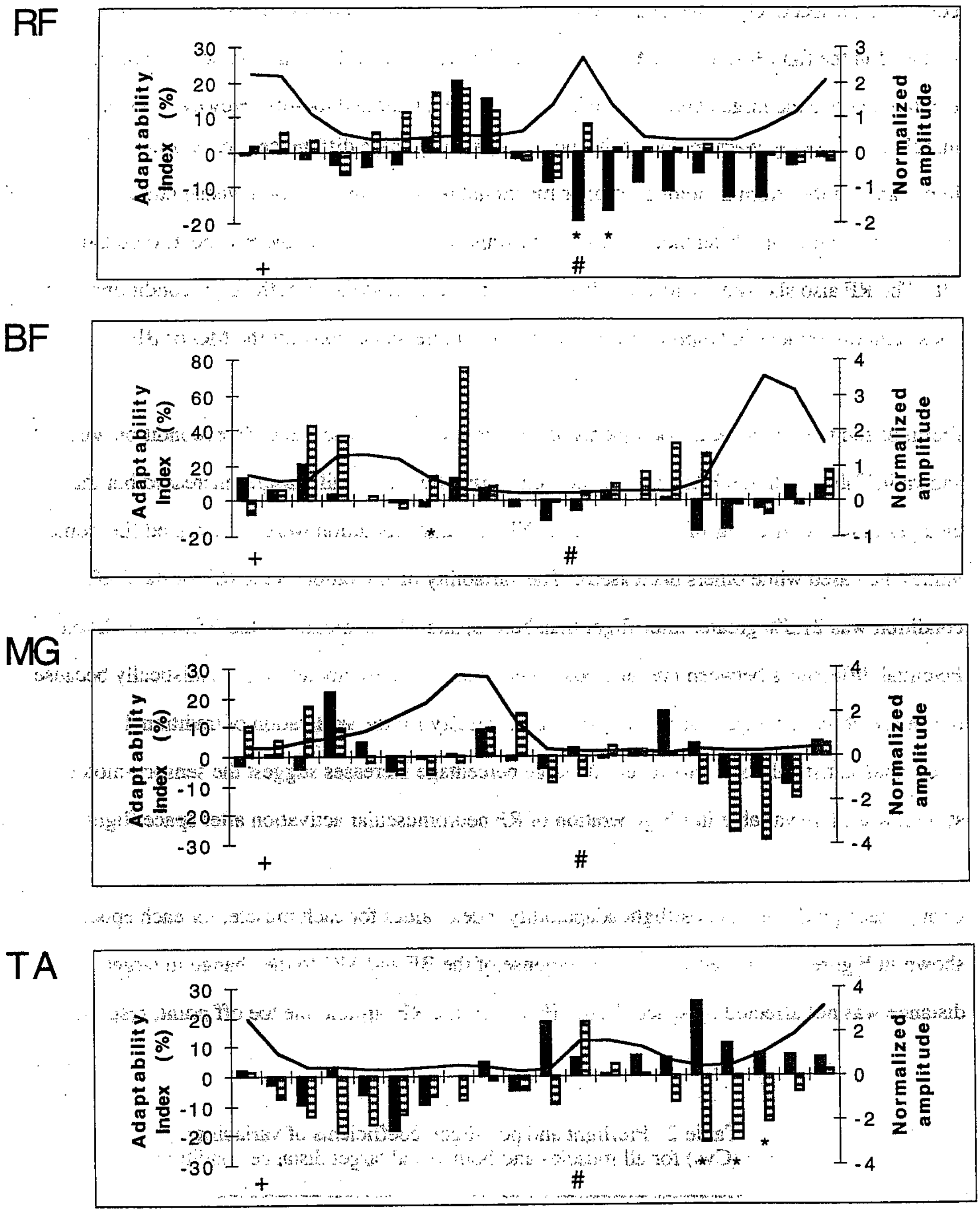

Figure 4. The adaptability index before (solid bars) and after (hatched bars) flight. Values greater than zero indicate that amplitude was greater in the FAR target condition than in the NEAR condition at a particular epoch of the gait cycle; values less than zero indicate that amplitude was greater in the NEAR condition than in the FAR condition. *Significantly different after flight from before, $p < 0.05$. Heel strike and toe off are signified by + and #, respectively. A representative activation waveform for each muscle has been included to facilitate the evaluation of the pre- vs. postflight differences.

to the change in target distance differently after flight: before flight, activation amplitude was greater in the NEAR target condition than in the FAR; after flight, this pattern was reversed. The response of the TA to a change in target distance also was affected by space flight. During the mid to late swing phase of the gait cycle, the adaptability index for the TA changed: before flight, activation amplitude was less in the NEAR condition than in the FAR; after flight, this pattern was reversed.

DISCUSSION

This investigation was designed to determine whether long-duration space flight influenced the neuromuscular-activation characteristics of the lower limbs during treadmill walking. The question of how space flight affected subjects' ability to modify their neuromuscular activation in response to changing visual target distance also was addressed. The generally high correlations between the preflight vs. postflight activation waveforms indicates that subjects were able to generate the phasic neuromuscular-activation features that supported effective treadmill walking. However, two muscles (RF and TA) displayed significant postflight changes in relative activation amplitude, particularly around toe-off. Additionally, activation variability was not substantially affected by space flight, except in the rectus femoris. Our findings are consistent with previous reports [5] of high correlations between preflight and postflight neuromuscular features during treadmill walking after shorter (i.e., 8- to 15-day) space flights. Our findings also support kinematic evidence that crewmembers returning to Earth can assemble neuromuscular and segmental coordination patterns that are adequate for locomoting on a motorized treadmill [4,5].

Although preflight-to-postflight changes in relative amplitude were evident in several epochs, these changes were present often when the muscle was "quiescent" (e.g., the tibialis anterior during mid to late stance [Figures 2 and 3]). Changes in relative activation amplitude probably would be functionally significant only during those phases of the gait cycle in which the muscle is active (e.g., around toe off for the rectus femoris and tibialis anterior [Figures 2 and 3]). These changes in relative amplitude, particularly around toe off in the RF and TA, suggest that exposure to weightlessness may produce subtle changes in neuromuscular activation. The postflight changes in neuromuscular activation around toe off are consistent with previous reports that brief space flight affects the activation features of the RF and TA around toe off [5]. The large segmental energy transfer that occurs during toe off requires effective neuromuscular control if hip and trunk stability are to be maintained while the toe adequately clears the support surface. Although none of our subjects tripped while performing this task, some toe-scraping was present during postflight treadmill locomotion, which may have been related to the changes in activation characteristics around toe off. During overground locomotion, failure to achieve proper toe clearance would result in tripping, which would increase the risk of postflight injury to the crewmembers.

The adaptability index reflects modifications in neuromuscular-activation features in response to a shift in visual-target distance during treadmill walking. Significant preflight-to-postflight changes in this index suggest that space flight affects how subjects adaptively respond to changes in task constraints. Interestingly, activation amplitude was different for the two visual-target conditions in many epochs for the various muscles measured, independent of space flight. This finding signifies the presence of subtle adaptations in neuromuscular control when all task parameters except visual-target distance remain constant: if no adaptation occurred when the target distance was shifted, then the index would equal zero across the 20 epochs.

In general, space flight had little effect on the direction of amplitude change associated with the change in target distance. Only the index of adaptability for the RF around toe off, and for the TA during the mid to late swing phase, were influenced by space flight; specifically, the postflight indices for these two muscles showed a reversal in the direction of adaptation (relative to the preflight measurement). This finding suggests that neural control adaptability may be modified, at least for some muscles during certain phases of the gait cycle. The failure of postflight neuromuscular responses to adapt in a manner similar to that observed for preflight responses may reflect a more generalized deficit in the ability to respond to changing environmental conditions after long-duration space flight.

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