Effect of long-duration spaceflight on postural control during self-generated perturbations

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[1]*Department of Health and Human Performance, University of Houston, Houston 77204;* [2]*Wyle Life Science Laboratories, and* [5]*Life Sciences Research Laboratories, National Aeronautics and Space Administration/Johnson Space Center, Houston, Texas 77058;* [3]*Tecmath, Troy, Michigan 48098; and* [4]*Institute of Biomedical Problems, Moscow 123007, Russia*

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Layne, Charles S., Ajitkumar P. Mulavara, P. Vernon McDonald, Casey J. Pruett, Innessa B. Kozlovskaya, and Jacob J. Bloomberg. Effect of long-duration spaceflight on postural control during self-generated perturbations. *J Appl Physiol* 90: 997–1006, 2001.—This report is the first systematic evaluation of the effects of prolonged weightlessness on the bipedal postural control processes during self-generated perturbations produced by voluntary upper limb movements. Spaceflight impacts humans in a variety of ways, one of which is compromised postflight postural control. We examined the neuromuscular activation characteristics and center of pressure (COP) motion associated with arm movement of eight subjects who experienced long-duration spaceflight (3–6 mo) aboard the Mir space station. Surface electromyography, arm acceleration, and COP motion were collected while astronauts performed rapid unilateral shoulder flexions before and after spaceflight. Subjects generally displayed compromised postural control after flight, as evidenced by modified COP peak-to-peak anterior-posterior and mediolateral excursion, and pathlength relative to preflight values. These changes were associated with disrupted neuromuscular activation characteristics, particularly after the completion of arm acceleration (i.e., when subjects were attempting to maintain upright posture in response to self-generated perturbations). These findings suggest that, although the subjects were able to assemble coordination modes that enabled them to generate rapid arm movements, the subtle control necessary to maintain bipedal equilibrium evident in their preflight performance is compromised after long-duration spaceflight.

neuromuscular activation; electromyogram; proprioception

ASTRONAUTS RETURNING FROM spaceflight exhibit a variety of postural control problems. These include deficits while balancing on rails of varying widths (13), increased sway of the body's center of gravity (33, 34), modifications in body segment motion (1), and increased response latencies to external perturbations (17). Preliminary reports indicate that returning astronauts have difficulty assembling the coordination strategies necessary to perform rapid voluntary arm raises efficiently during bipedal stance (20, 21). These deficits are accompanied by decreases in lower limb strength (12), in part stemming from muscular atrophy (22) and hyperactive proprioceptive and neuromuscular reflexes (16, 18, 35). Moreover, returning astronauts experience alterations in vestibular system functioning (36), head movement control (4), and abnormal proprioceptive functioning (38), which also can contribute to postural control deficits.

Previous research examining postural control has primarily centered on various manipulations of sensory input or responses to external perturbations. Few investigations have assessed returning astronauts' ability to perform voluntary limb movements with the constraint that bipedal equilibrium must be maintained (7, 8, 30). The present study quantifies the degree to which human bipedal postural control is modified during voluntary arm movements after extended periods of microgravity (3–6 mo). The arm movement utilized, a rapid unilateral arm raise, has been used extensively as a method to investigate the ability of normal and patient populations to control self-generated postural perturbations. Belen'kii and colleagues (2) were the first investigators to report that trunk and lower limb muscles are activated before the initiation of arm motion. This "anticipatory" postural activity is specific to the particular arm-raise task (e.g., unilateral vs. bilateral, weighted vs. nonweighted) and counters the potentially destabilizing reactive forces arising from upper limb motion (6). A variety of patient populations exhibit postural control problems while performing voluntary arm movements. These difficulties are manifested as inappropriate anticipatory neuromuscular activation strategies, increased motion of the center of pressure (COP), and decreased arm-movement velocity relative to normal subjects (14, 37). Therefore, the rapid arm raise is an ideal task with which to evaluate the ability of returning astronauts to maintain upright bipedal posture while performing a voluntary limb movement. We hypothesized that, dur-

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ing the arm-raise task after extended periods of microgravity, subjects would display diminished postural control quantified by using COP measures (see METHODS). Measures of COP motion as indexes of postural control have often been used to assess differences between normal subjects and patients (9, 23, 25) and between healthy young adults and the elderly (11, 26, 29).

In addition, we were interested in how neuromuscular activation characteristics associated with the arm raise were affected by spaceflight. Therefore, we assessed potential modifications in muscle activation strategies in response to long-duration spaceflight. We were particularly interested in two questions regarding neuromuscular activation: whether, after spaceflight, subjects could produce neuromuscular phasic patterns that were similar to preflight patterns *1)* during the movement-initiation phase and *2)* after the self-generated perturbation (i.e., after arm acceleration was completed). Previous investigators have detailed changes in proprioceptive functioning and loss of muscle strength, both of which may impact the ability to produce task-appropriate neuromuscular control (22, 38). Thus we hypothesized that the neuromuscular patterns associated with maintaining preflight postural control in response to the reactive forces produced during the arm movement would be more disrupted after flight than those associated with the initiation of the arm movement.

METHODS

Subjects. Eight subjects (2 US astronauts, 6 Russian cosmonauts, mean age 43 ± 8 yr) who experienced 3–6 mo of microgravity aboard the Mir space station participated in this study. All were volunteers and had completed the NASA Institutional Review Board for Human Research Informed Consent form.

Protocol. The task comprised 15 right-shoulder flexions performed from a bipedal standing position. Subjects assumed a comfortable stance on a force plate (Kistler Instruments, Amherst, NY) with their arms resting at their sides with the right elbow extended. The self-initiated movements consisted of first closing their eyes and then raising the arm by flexing the shoulder as rapidly as possible until the arm was parallel to the force plate. Throughout the task, subjects were required to maintain their upright bipedal stance (i.e., no stepping or falling). Preflight measures were obtained ~10 days before spaceflight, and postflight measures were obtained, with one exception, 1 day after landing. One crewmember was tested on landing day. All subjects were well-practiced before the preflight data collection. To ensure that subjects adopted the same foot placement before and after spaceflight, during preflight testing the borders of the feet were marked relative to the axes of the force plate. These markings were then used to position the subjects properly during postflight testing.

Data collection and processing. Tangential arm acceleration was measured by using a uniaxial accelerometer (Kistler Instruments) mounted on a wrist splint. Additionally, ground reaction forces from the force plate and surface electromyography (EMG) from the right anterior deltoid, left and right biceps femoris, left paraspinals, right lateral gastrocnemius, and right tibialis anterior were obtained during data collection. These muscles were monitored because they are activated in most subjects in preparation for and/or during the arm-raise task (2, 7, 14, 24). After the skin was cleaned, preamplifier electrodes (Therapeutics Unlimited, Iowa City, IA) were attached to the skin over the muscles using adhesive collars. To prevent motion artifacts, the electrodes were further secured with neoprene wraps or hypoallergenic tape. All data were digitally sampled at 500 Hz. Because of temporal and programmatic constraints, we were unable to obtain kinematic data.

Arm angular acceleration. For each trial, the gravity component of the tangential arm acceleration was removed, and the remaining linear acceleration component was divided by the radius of the arm to provide arm angular acceleration (28). Arm-movement initiation was determined by using the resulting angular acceleration waveform. For each trial, the time of arm-movement initiation was used to synchronize the force plate and EMG data records that were collected on separate computers. The arm-acceleration signal was recorded on both computers, which enabled data synchronization. Arm-movement initiation time was also used to obtain a data window for each trial that consisted of 1 s before and 1.25 s after arm-movement initiation. The 1-s interval before arm-movement initiation was chosen to obtain a quiet EMG and COP baseline before the initiation of anticipatory neuromuscular activity and associated COP motion. The 1.25-s interval after arm-movement initiation encompassed the arm movement itself and the time required for the subjects' COP maximal excursion to be reached and begin to return to its initiation point. This data window was of appropriate length to investigate the features of postural control and the underlying neuromuscular activation during the arm-raise task. With the use of the appropriate zero crossing of the accelerometer waveform, two movement phases were identified: *1)* the initiation phase, which is from the beginning of the data record through the end of arm acceleration, and *2)* the recovery phase, which is from the beginning of arm deceleration until the end of the data record (Fig. 1). The division of the trial into the initiation and recovery phases enabled us to assess the similarity of the initial phasic activation features used to prepare for and initiate arm movement separately from the activity primarily used to arrest the arm motion and maintain and/or regain bipedal postural control. Peak acceleration values were obtained from the arm-acceleration records of each trial.

COP. For each trial, the COP signals were obtained from commercially available software (Bioware 2.0, Kistler Instruments) and then low-pass filtered with a 10-Hz cutoff (Butterworth, 4th order, 0-phase response). Our operational measures of postural control were anterior-posterior (A-P) and mediolateral (M-L) peak-to-peak motion and COP pathlength. Peak-to-peak COP motion within each trial in the A-P and M-L plane and the COP pathlength within the two identified phases were obtained, and within-subject averages were calculated. As our subjects were healthy and well practiced in the task, we considered our preflight COP measures (A-P and M-L peak-to-peak motion, COP pathlength) as representative of stable postural control. Therefore, we considered subjects experiencing significantly different COP motion during the postflight arm-raise task relative to their preflight measures as demonstrating deficits in bipedal postural control.

Muscle activation. For each muscle of each subject, the EMG signals were first band-pass filtered (20–300 Hz), full-wave rectified, smoothed (10-ms time constant), and averaged. Arm-movement initiations for each of the 15 trials obtained from the accelerometer waveform were used as the

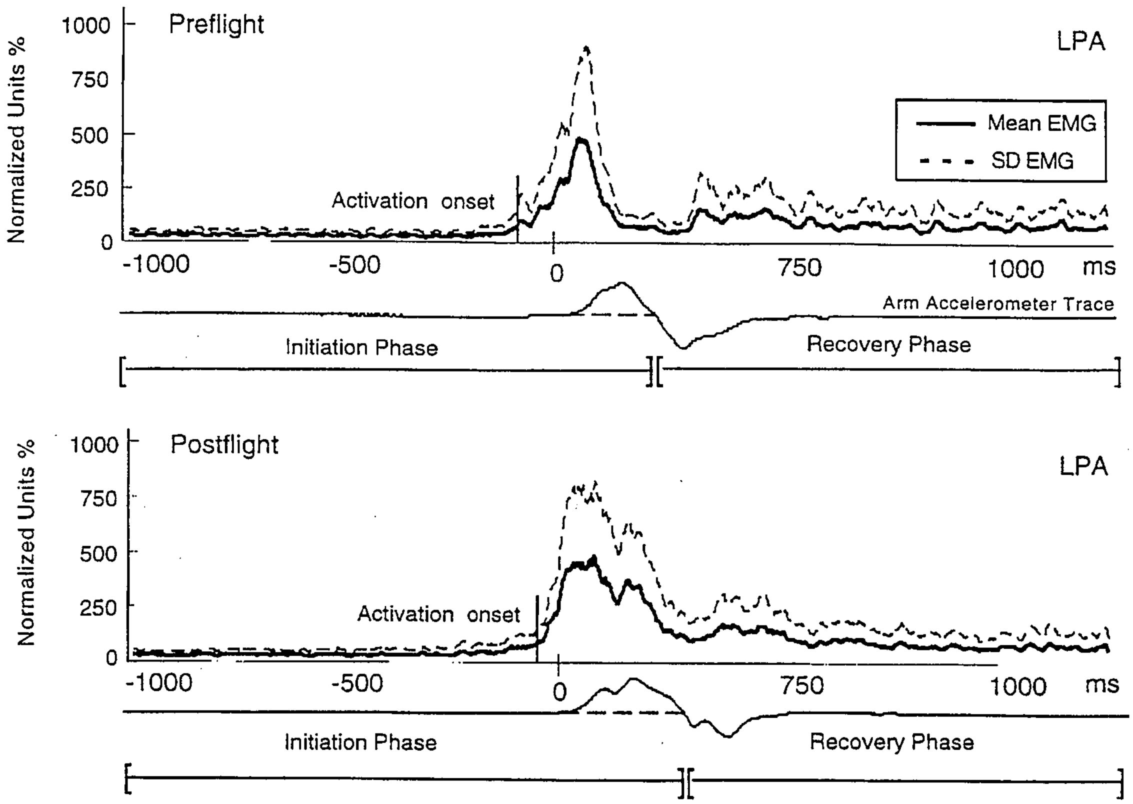

Fig. 1. Preflight (*top*) and postflight (*bottom*) exemplar mean left paraspinals (LPA) activation waveforms (mean: thick solid trace; +1 SD: dashed trace) and accelerometer records (thin solid trace). The initiation phase consists of data 1 s before the initiation of arm motion through arm acceleration. The recovery phase consists of data from the completion of acceleration until the end of the data record. EMG, electromyography.

synchronization point for signal averaging. Muscle activation latencies (relative to arm-movement initiation) were determined by using an interactive graphics program (EGAA, RC Electronics, Santa Barbara, CA) and visual inspection (Fig. 1). To be considered active, a muscle's voltage had to exceed the baseline voltage by 2 SDs and remain active for at least 30 ms (5). Because the nature of the task dictated that the subjects adopt quiet stance before arm-movement initiation, in all cases muscle activation levels were very low. This made muscle activation onset identification straightforward. To assess the degree of similarity between pre- and postflight muscle activation features, cross-correlation coefficients were calculated for the two phases of the individual subject mean waveforms.

RESULTS

One purpose of this report is to provide quantitative information that illustrates how spaceflight differentially impacts individuals in terms of postural control during self-initiated perturbations. Consistent with our laboratory's and others' previous work (4, 16, 19, 31), we have observed that, in holistic tasks requiring sensory-motor integration, spaceflight is associated with a wide range of adaptive postflight behavioral responses. Therefore, we believe it is important that individual subject data be presented whenever appropriate. Thus throughout this report each subjects' pre- and postflight responses are presented. However, to provide a statistical indication of the magnitude of the potential pre- vs. postflight differences of the measures, paired *t*-tests were applied to the data of each subject.

Arm angular acceleration. Figure 2 displays the pre- and postflight peak arm-acceleration data for each subject. Four subjects significantly decreased (*A*, *C*, *D*, and *F*), two subjects increased (*G* and *H*), and two subjects (*B* and *E*) displayed no change in their peak acceleration after spaceflight.

COP. Figure 3 displays pre- and postflight peak-to-peak, A-P, COP motion. Peak-to-peak, A-P, COP motion increased significantly in six subjects (*B*, *C*, *D*, *F*, *G*, and *H*), decreased in one subject (*A*), and was unchanged in the remaining subject (*E*) after spaceflight. Figure 4 displays pre- and postflight peak-to-peak, M-L, COP motion. Four subjects showed significant increases (*B*, *C*, *E*, and *G*) after spaceflight, whereas *subject A* displayed significantly decreased motion. Three subjects' M-L peak-to-peak motion was unchanged by spaceflight (*D*, *F*, and *H*).

Figure 5 displays exemplar single-trial COP data from one subject during pre- and postflight arm move-

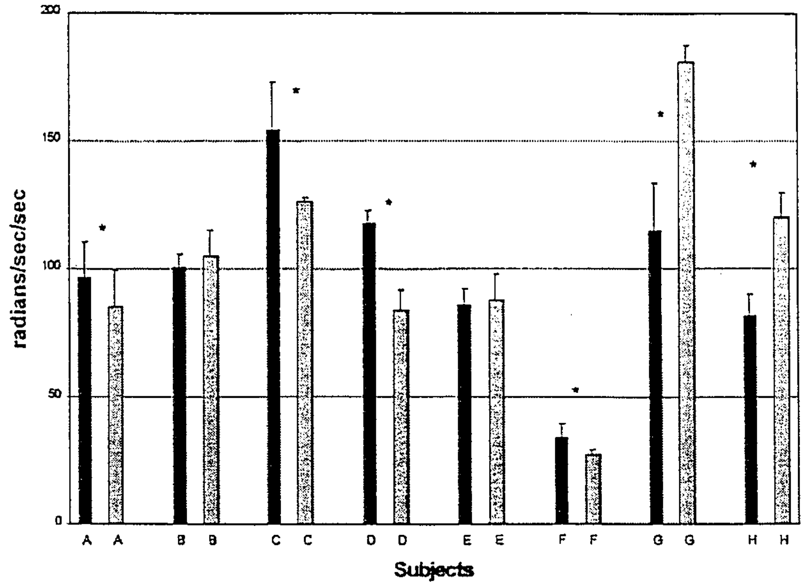

Fig. 2. Individual subject mean (+1 SD) pre- and postflight peak arm angular acceleration. Black bars, preflight performance; gray bars, postflight performance. *A–H*: *subjects A–H*. *Statistical significance, pre- vs. postflight, $P < 0.05$.

ments. It can be observed that postflight COP motion increased in both the initiation and recovery phases of the task after spaceflight. Figure 6 shows that the COP pathlength in the initiation phase of the movement significantly increased in six subjects (*B*, *C*, *D*, *F*, *G*, and *H*) and was unchanged in two subjects (*A* and *E*) after spaceflight. Figure 7 shows that COP pathlength during the recovery phase significantly increased in six subjects (*B*, *C*, *E*, *F*, *G*, and *H*), one subject had no change (*D*), whereas *subject A* displayed a decrease after spaceflight. Although COP motion significantly increased after spaceflight, none of the subjects fell during the testing.

Muscle activation. Pre- and postflight muscle activation latencies are tabulated in Table 1. Although there were large individual differences, there was no consistent trend to suggest that spaceflight modifies the time of initial activation of muscles during the task. Spaceflight had minimal effect on the sequence of muscle activation. In general, and consistent with previous reports (2, 14, 24), the postural muscles right biceps femoris and left paraspinals were activated in an anticipatory fashion well in advance of arm-movement onset during both pre- and postflight testing.

Table 2 lists the cross-correlation coefficients for each muscle of each subject, representing the maxi-

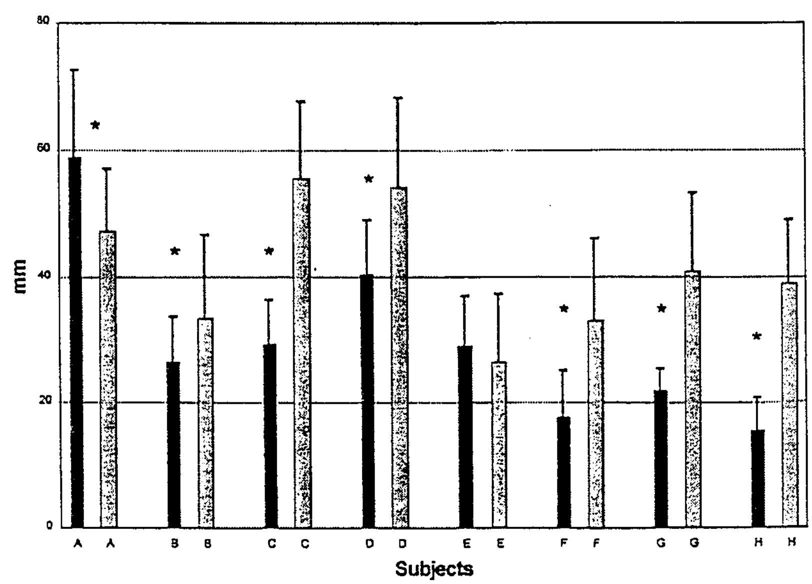

Fig. 3. Individual subject mean (+1 SD) pre- and postflight anterior-posterior peak-to-peak center of pressure (COP) motion. Bars are as defined in Fig. 2 legend. *Statistical significance, pre- vs. postflight, $P < 0.05$.

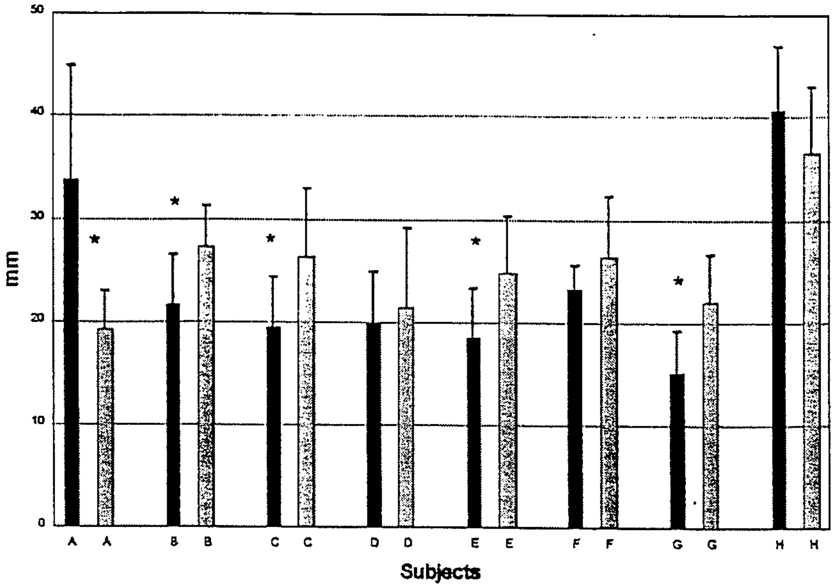

Fig. 4. Individual subject mean (+1 SD) pre- and postflight mediolateral peak-to-peak COP motion. Bars are as defined in Fig. 2 legend. * Statistical significance, pre- vs. postflight, $P < 0.05$.

mum degree of similarity between the neuromuscular activation patterns within the initiation and recovery phases between the pre- and postflight waveforms. Consistent with the recommendations of Dickey and Winter (10), we used a coefficient value of 0.71 (r^2 = 0.50) as the criterion to indicate that the pre- and postflight activation patterns were significantly different. On the basis of this criterion, 9 of the 48 (19.0%) waveforms during the initiation phase were modified by spaceflight. Seven of the nine modified initiation

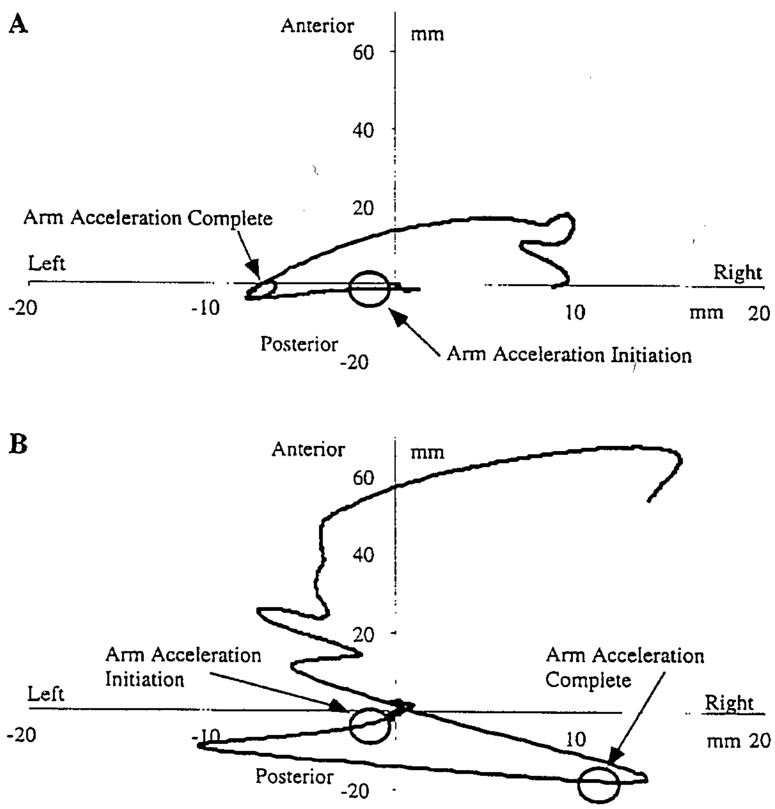

Fig. 5. One example trial showing pre- (*A*) and postflight (*B*) COP trace. Increased postflight motion is shown during both the initiation and recovery phases of the arm movement.

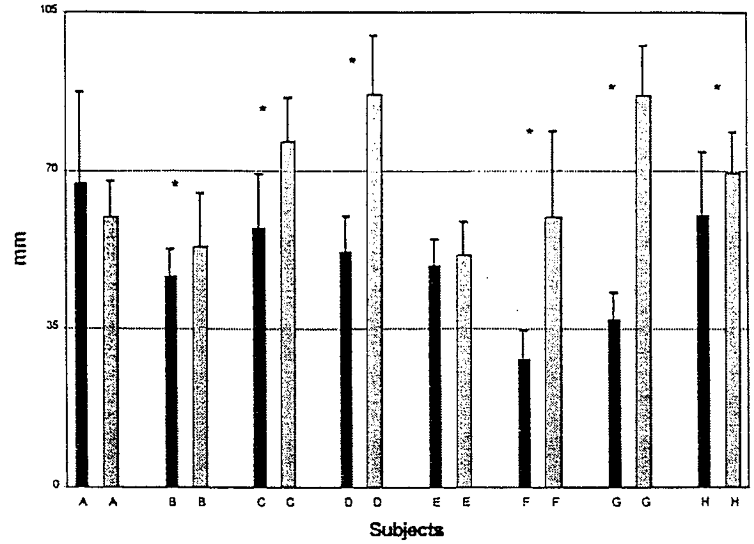

Fig. 6. Individual subject mean (+1 SD) pre- and postflight COP pathlength during the initiation phase. Bars are as defined in Fig. 2 legend.

waveforms were obtained from the two shank muscles (right lateral gastrocnemius and right tibialis anterior). Thirty-four of the forty-eight (71%) activation patterns during the recovery phase were altered after flight. If the right anterior deltoid comparisons are not considered, 83% (33 of 40) of the postflight lower limb and trunk neuromuscular activation patterns during the recovery phase were significantly different. Further analyses of the phase-lag data indicated that 95.8% (92 of 96) of all waveform comparisons displayed either a lag or lead between the pre- and postflight waveforms. However, there was no consistent direction or magnitude associated with the lags, either across subjects or within subjects. Despite accounting for the phase lag between the pre- and postflight waveforms, the results of the cross-correlation analyses indicate that the phasic features of the waveforms were modified by spaceflight. Both the COP and neuromuscular activation measures indicate that, for exposure to microgravity within the 3- to 6-mo range, there is no association between the time spent in space and the degree to which postflight postural control is modified relative to preflight.

DISCUSSION

The present findings are the first describing the degree to which long-duration spaceflight affects returning astronauts' ability to initiate and control self-generated postural perturbations in the form of voluntary arm movements. The results generally indicate that, although subjects can initiate the necessary neu-

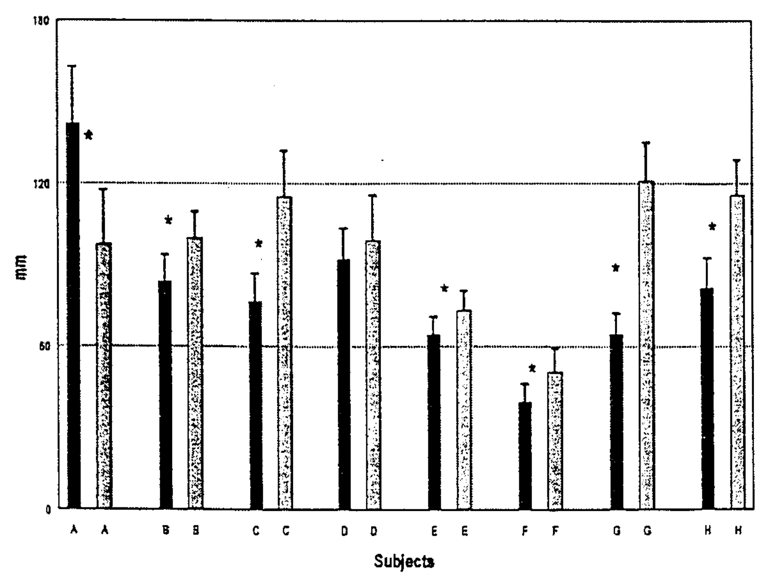

Fig. 7. Individual subject mean (+1 SD) pre- and postflight COP pathlength during the recovery phase. Bars are as defined in Fig. 2 legend. *Statistical significance, pre- vs. postflight, $P < 0.05$.

Table 1. *Pre- and postflight mean EMG activation onsets*

Subject	RAD		LBF		RBF		LPA		RGA		RTA	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
A	−46	−44	−68	−6	−118	−114	−58	−96	−16	−32	−96	−60
B	−26	−32	−8	−12	−156	−162	−92	−90	−6	2	−8	−2
C	−34	−26	6	26	−110	−102	−56	−46	−70	18	−82	6
D	−54	−38	30	−6	−106	−72	−94	−56	−24	−44	−62	−54
E	−24	−22	−6	−10	−126	−142	−64	−74	−30	−42	*	*
F	−48	−52	*	*	*	*	−78	−70	*	*	*	*
G	−54	−86	−12	−18	−124	−122	−78	−90	−34	−28	*	*
H	−32	−48	−14	−10	−142	−134	−32	−48	−16	−28	−34	−40
Mean	−39.8	−43.5	−18.9	−5.1	−126	−121.1	−69	−71.6	−28	−22	−56.4	−30
±SD	12.2	20.1	24.2	14.3	17.7	29.2	20.7	19.8	20.8	23.2	35.7	30.2

Values are reported in ms and are relative to arm-movement initiation. RAD, right anterior deltoid; LBF, left biceps femoris; RBF, right biceps femoris; LPA, left paraspinals; RGA, right lateral gastrocnemius; RTA, right tibialis anterior; Pre, preflight; Post, postflight; EMG, electromyography. *Burst was not present in the averaged record.

romuscular activation sequences to perform rapid arm movements, upright postural control during the task is compromised after long-duration flight. The results of this study are consistent with those of other investigators who have reported that astronauts returning from spaceflight display a variety of postural control problems (1, 3, 19, 31, 34). Previous spaceflight-related research has primarily focused on postural control in the context of bipedal stance in response to externally generated perturbations and manipulations of the sensory input (for exceptions, see Refs. 7, 8, 30).

The arm-raise task contains at least two explicit behavioral goals: *1*) move the arm as rapidly as possible until it is parallel to the floor, and *2*) maintain an upright bipedal posture with the feet remaining in contact with the support surface. These two goals may not be mutually compatible and, therefore, suggest a possible trade off, such that the potential postural perturbation resulting from the arm movement can be reduced or increased by reducing or increasing arm acceleration. This potential trade-off in postural stability for arm acceleration makes the subjects' perception of, and confidence in, their ability to control bipedal stance an important consideration. Astronauts who perceive themselves as having postural control decrements after spaceflight can reduce their arm acceleration relative to preflight levels to ensure that they remain upright. Conversely, returning astronauts with full confidence in their ability may choose to increase arm acceleration at the risk of challenging upright stance. Most interesting, perhaps, is the possibility that astronauts may misperceive the degree of diminished postural control after spaceflight because of modified proprioceptive processing (18). Thus they may still threaten their bipedal stability, despite decreased arm acceleration.

Our measures of A-P and M-L peak-to-peak COP motion and COP pathlength generally reflect deficits in postflight postural control relative to preflight. With the exception of *subject A*, our subjects generally displayed increases in COP motion. These increases in COP motion were observed despite the fact that the majority of our subjects decreased their peak arm acceleration. The increases in COP motion may be related to the subjects' misperception of their postflight postural control capabilities. We suggest that these subjects correctly perceived that they were experiencing compromised postural control but were unable to perceive the degree to which their control was compromised after spaceflight. This possibility may be reflected in the increased COP motion, despite decreases in arm acceleration.

Two subjects significantly increased their peak arm angular acceleration and displayed significant in-

Table 2. *Cross-correlations between the pre- and postflight EMG records during each phase of the movement*

Subject	RAD		LBF		RBF		LPA		RGA		RTA	
	Init	Rec	Init	Rec	Init	Rec	Init	Rec	Init	Rec	Init	Rec
A	0.97	0.75	0.96	0.58	0.95	0.46	0.92	0.42	0.87	0.43	0.96	0.57
B	0.95	0.92	0.99	0.24	0.98	0.59	0.93	0.72	0.60	0.51	0.90	0.78
C	0.98	0.96	0.96	0.69	0.88	0.48	0.96	0.46	0.80	0.59	0.94	0.88
D	0.99	0.93	0.96	0.58	0.98	0.49	0.89	0.66	0.94	0.75	0.96	0.82
E	0.99	0.89	0.92	0.38	0.96	0.88	0.98	0.64	0.50	0.33	0.26	0.31
F	0.97	0.58	0.22	0.29	0.53	0.18	0.88	0.69	0.18	0.34	0.43	0.36
G	0.98	0.82	0.93	0.58	0.91	0.73	0.94	0.71	0.52	0.33	0.47	0.29
H	0.98	0.95	0.97	0.63	0.97	0.59	0.98	0.61	0.90	0.65	0.95	0.71
Mean	0.98	0.85	0.86	0.50	0.89	0.55	0.94	0.61	0.66	0.49	0.73	0.59
±SD	0.01	0.13	0.26	0.17	0.15	0.21	0.04	0.12	0.26	0.16	0.29	0.24

Init, initiation phase; Rec, recovery phase.

creases in postflight peak-to-peak A-P COP motion (87% for *subject G*, 41% for *subject H*). On the assumption that these subjects had full confidence in their ability and wished to retain their preflight performance levels, these increases may suggest the inability of these subjects to perceive their postflight postural control capabilities correctly.

It is noteworthy that, after spaceflight, only *subject A* displayed decreases in peak arm acceleration, peak-to-peak COP motion, and pathlength in both movement phases compared with his preflight values. In other words, this subject accompanied his decreased postflight arm acceleration by a generalized depression of the associated COP motion. This pattern of decreased motion may suggest that this subject was able to accurately perceive that his postural control was compromised after spaceflight. Therefore, he utilized a strategy that enabled him to complete the task while maintaining postural stability. This is in contrast to the remaining subjects who, for most measures, showed a significant increase in COP motion.

The suggestion that subjects may experience adaptive postflight proprioceptive problems leading to misperception of postural control capabilities is reasonable. Both Watt et al. (38) and Kozlovskaya et al. (18) reported that returning astronauts display disordered proprioception that results in inaccurate perceptions of the interaction between themselves and the environment. Additionally, anecdotal evidence indicates that many astronauts experience sensations of "heaviness" and/or illusions of "sinking" into the floor while standing (C. S. Layne, personal observation). Such sensations would be expected to influence our subjects' perceptions of their postural control capabilities. This disruption in perceptual abilities and associated neuromuscular control may be related to a combination of several physiological changes associated with spaceflight. Changes in postflight ankle proprioceptive functioning could result in greater ankle sway before adequate detection and/or interpretation by the proprioceptive system. Altered functioning of the vestibular system could also result in deficits in sway detection after spaceflight (3, 33, 34). It is also possible that spaceflight affects muscle spindle sensitivity in such a way that the interaction between central motor commands and peripheral feedback is altered. Thus, although the command for movement is initiated properly after spaceflight, as evidenced by the generally high correlations between the pre- and postflight waveforms in the initiation phase, the ability to sustain or generate additional bursts of muscle activity is impaired. Loss of muscle strength, particularly in the ankle and trunk musculature, may also play a role in our subjects' inability to prevent increases in postflight COP motion. The antigravity musculature, including the trunk muscles, tends to show a preferential loss of strength after spaceflight (12, 22), which may also have influenced the ability to generate the subtle neuromuscular features necessary for optimal control.

The loss of optimal neuromuscular control after spaceflight would negatively impact the kinematic strategies used to produce the arm movement and associated postural control. Although cross-correlation analysis generally revealed that the neural activation patterns needed for the preparation and initiation of the arm movement remained similar during testing 1 day after spaceflight, we observed increases in COP motion during the initiation phase. These seemingly paradoxical findings can be explained as follows. Despite the fact that the shape of pre- and postflight EMG waveforms was quite similar during the initiation phase of the movement, the timing of the activation pattern relative to arm-movement initiation was generally altered by spaceflight. Ninety-seven percent of the lower limb and trunk muscle comparisons during the initiation phase indicated that the postflight waveforms either lagged or led the preflight waveforms at the point of maximum correlation. Thus the postflight temporal relationships associated with muscle force generation relative to arm-movement initiation were different than those observed preflight. Moreover, the magnitudes of the muscle force associated with the altered postflight neuromuscular activation features were unlikely to be the same as those of preflight, particularly because loss of muscle strength typically accompanies extended stays in weightlessness. Additionally, we only obtained EMG from a limited number of muscles. Other musculature undoubtedly contributed to the control of the bipedal arm-raise task. The force-generating capabilities of these muscles could also be expected to be impacted by exposure to long-duration spaceflight. Thus precise force magnitudes and the optimal timing of when forces are being produced with respect to arm-movement initiation may have been significantly altered as a result of spaceflight. These disruptions could lead to the diminishment of postural control reflected in the observed increases in COP motion during the initiation phase.

The cross-correlation analyses of the lower limb and trunk EMG waveforms during the recovery phase revealed that 87.5% of the comparisons indicated either a lag or lead in the postflight waveform at the point of maximum correlation relative to preflight. Additionally, 80% of the lower limb and trunk muscle cross-correlation coefficients during the recovery phase were significantly different ($r \leq 0.71$), indicating that the phasic features of postflight neuromuscular activation generally did not conform with those observed preflight. These findings further suggest a consequential loss of neuromotor control after spaceflight that is reflected in the increases in postflight COP motion observed during the recovery phase.

The finding that the vast majority of initial muscle activation patterns during the initiation phase of the movement was not different pre- vs. postflight is somewhat inconsistent with the report of Massion and colleagues (30). These authors reported that, during backward trunk bending, the early activation of the soleus observed preflight was replaced by early tibialis anterior activation during their first postflight session. They attributed this change in neuromuscular patterning to a vestige of the neuromuscular activation sequence used during in-flight trunk bending. The normal sequence of activation was restored by the second postflight data collection session (8 days after landing). However, in general, our subjects did display the same initial phasic muscle activation characteristics pre- and postflight. These patterns were quite similar to the patterns our subjects used during rapid in-flight arm movements performed when they were restrained to the support surface of the Mir space station (Layne, unpublished observations). Thus the neuromuscular synergies observed preflight were also appropriate to accomplish the in-flight arm movement; thus it is not particularly surprising that we found the "shapes" of the pre- and postflight activation waveforms during the initial phase of movement to be similar. However, the fact that 97% of the postflight EMG waveforms obtained during the initiation phase either led or lagged the preflight waveforms is consistent with the findings of Massion et al. of disrupted postflight neuromuscular activation.

Because of programmatic constraints, data were collected for seven of the subjects 1 day after landing. Undoubtedly the diminished postural control and modified neuromuscular activation characteristics exhibited by our subjects would have been exacerbated had we had the opportunity to test them on landing day. One of the subjects, who was scheduled for testing on landing day, was unable to perform the task despite a strong desire to do so. This finding is consistent with previous reports indicating that bipedal postural control recovers rapidly toward preflight performance after spaceflight, especially in the first hours after landing, but recovery is not complete for several days after landing. In particular, Paloski and colleagues (34) calculated that subjects recover 50% of the postflight equilibrium deficits experienced at the time of landing within 2.7 h after short-duration spaceflight.

To summarize, the present results indicate that astronauts returning from long-duration spaceflight are able to initiate rapid voluntary arm movements without difficulty. However, these movements are accompanied by decreases in bipedal postural control as assessed by measures of COP motion. This is consistent with previous reports that postflight postural control is compromised in response to external perturbations and/or during tests of static postural control in altered sensory environments (3, 18, 34). Additionally, there were often significant modifications in neuromuscular activation that may have contributed to the compromised postural control exhibited by our subjects. These modifications in neuromuscular activation may have resulted from central and peripheral physiological changes associated with spaceflight. Our subjects' behavior may also suggest that returning crewmembers' ability to perceive the full functional capabilities of their postural control systems may also be compromised, particularly after long-duration spaceflight. Our findings contribute to a growing body of evidence defining the precise nature of task-specific sensory-motor integration deficits experienced by crewmembers returning from spaceflight (4, 7, 18, 19, 30, 31, 34). Although we chose to investigate a task that included a well-documented anticipatory postural component associated with vigorous arm motion, all movements necessarily involve a postural component. Therefore, the finding that the postural control associated with voluntary limb motion is compromised after flight is important. Understanding the underlying adaptive processes is an important step toward mitigating the postflight postural control problems experienced by returning astronauts.

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THE USE OF IN-FLIGHT FOOT PRESSURE AS A COUNTERMEASURE TO NEUROMUSCULAR DEGRADATION

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ABSTRACT

The purpose of this study was to determine whether applying foot pressure to unrestrained subjects during space flight could enhance the neuromuscular activation associated with rapid arm movements. Four men performed unilateral arm raises while wearing —or not wearing— specially designed boots during a 81- or 115-day space flight. Arm acceleration and surface EMG were obtained from selected lower limb and trunk muscles. Pearson *r* coefficients were used to evaluate similarity in phasic patterns between the two in-flight conditions. In-flight data also were magnitude normalized to the mean voltage value of the muscle activation waveforms obtained during the no-foot-pressure condition to facilitate comparison of activation amplitude between the two in-flight conditions. Foot pressure enhanced neuromuscular activation and somewhat modified the phasic features of the neuromuscular activation during the arm raises.

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INTRODUCTION

The lower limb musculature, particularly the antigravity muscles, undergoes significant atrophy during short or long space flight [1,2]. The combination of sensorimotor adaptation and muscle atrophy is expected to compromise the ability to perform certain tasks on return to a gravitational environment, as well as increasing the risk of injury during orbital extravehicular activities (EVA). As mission durations continue to increase in anticipation of assembling the International Space Station, understanding the mechanisms underlying muscle degradation and developing means of countering this degradation have become increasingly important.

In space, the absence of the constant muscle loading experienced on Earth leads to declines in neuromuscular activation and eccentric muscle contractions [3], the long-term consequence of which is atrophy of the lower limb musculature. On Earth, the weight-bearing and locomotor responsibilities of the lower limbs ensure that activation of the lower limb musculature is nearly constant, thereby maintaining muscle mass and function. In weightlessness, the lower limbs play a less important role in postural and locomotor activities. Except for exercise and other activities that involve restraining crewmembers at the feet, the lower limbs are rarely used in space. The current requirement for 2 hours of daily exercise on long space flights is insufficient to maintain preflight levels of muscle strength and coordination [1].

Exposure to weightlessness produces changes in neuromuscular-activation patterns; these changes can persist during the immediate postflight period and may contribute to movement deficits [4/5]. Deficits in motor control can affect crew safety if they contribute to muscle injuries or falls during locomotion or other postflight activities.

If in-flight muscle atrophy and neuromuscular activation are related, then enhancement of muscle activation during space flight could serve as a countermeasure by attenuating muscle atrophy and by maintaining the integrity of the spinal circuitry involved in neuromuscular activation. Although complete prevention of muscle atrophy requires muscle activation in resistance to external loads, regular maintenance of low-amplitude muscle activation should retard lower-limb atrophy during space flight.

We have pursued a method of enhancing neuromuscular activation through the use of controlled manipulation of sensory input from the feet. Preliminary evidence indicates that patterns of neuromuscular activation observed in 1*g*, but absent in weightlessness, could be restored in space through the addition of foot pressure. For instance, Layne and Spooner [6,7] reported that preparatory patterns of muscle activation normally associated with rapid arm movement were either absent or greatly attenuated when those arm movements were performed in the free-fall periods of parabolic flight. However, the stereotypical pattern of muscle activation normally observed in standing subjects was enhanced when pressure was applied to the feet of the free-floating subjects.

A possible explanation of this phenomenon is based on the presence of sensory receptors (e.g., cutaneous, type Ia, type Ib, and type II) in the feet. Hagbarth [8] and Kugelberg et al. [9] demonstrated that alpha and gamma motoneuron activity was modulated in response to cutaneous stimulation. Seguin and Cooke [10] reported that mild plantar stimulation resulted in modified EMG responses in decerebrate cats. Numerous other examples exist of phase-dependent responses, in which a cutaneous stimulus delivered during one phase of a movement produces a different muscle response from applying the same stimulus during a different movement phase [11,12,13]. Thus, manipulation of somatosensory input can directly affect the magnitude of muscle activation associated with a particular movement.

This report describes an investigation of whether foot pressure could enhance the neuromuscular activation associated with voluntary arm movements in space. (We did not address the functional roles of the monitored musculature during arm raises.) We hypothesized that since the neuromuscular activation of the leg and trunk muscles during arm movements made in 1-*g* is associated with the control of bipedal stance, eliminating these requirements during an arm movement made while free-floating would result in minimal neuromuscular activation. We further hypothesized that restoring somatosensory input from the feet, through applying foot pressure to free-floating subjects, would enhance the neuromuscular activity associated with the arm movement. Positive results would suggest that manipulating sensory input to the feet could be useful in maintaining and enhancing neuromuscular activation during space flight, which in turn could attenuate the degree of muscle atrophy. Preliminary results of this investigation have been reported in abstract form [14].

METHODS

Subjects

The subjects for this investigation were four men who flew aboard the Russian Mir space station. All volunteered to participate in this investigation, and all gave informed consent according to the requirements of the National Aeronautics and Space Administration (NASA) Institutional Review Board for Human Research. Two subjects participated in a 115-day mission, and the others in an 81-day mission. Subjects ranged in age from 34 to 53 years (mean = 44.5, SD = 8.1) and three had flown in space previously.

Movement Task

Subjects were required to perform rapid, unilateral shoulder flexions while free floating. This arm-movement task was chosen on the basis of its well documented, stereotypical neuromuscular activation pattern of the shoulder, trunk and leg musculature when performed in 1-*g* [15,16]. This 1-*g* activation pattern has been shown to remain intact during arm raises performed while free floating with the addition of foot pressure during parabolic flight [7] and during short-duration space flight (Layne et al., unpublished data). Our aim in this investigation was to determine whether foot pressure could enhance neuromuscular activation during arm movements performed during long space flights.

The two experimental conditions differed in terms of whether foot pressure was applied or not during rapid arm raises. Each experimental condition consisted of 15 arm raises, during which subjects flexed their right shoulders to 90° from the side of the body as rapidly as possible while maintaining their elbows in an extended position. Before each arm movement, the subjects aligned their body segments in the sagittal plane to approximate the position assumed during upright stance in 1-*g* and then closed their eyes. After each self-initiated arm raise, the subjects assumed the aligned position and performed the next trial. In the 'with pressure' (WP) condition, constant pressure was applied to the feet through the use of foot pressure 'boots.' The boots, made of thin aluminum lined with high-density foam, were about the size of a man's U.S. size 13 high-top athletic shoe; each weighed 2.2 kg (Figure 1). Each boot contained an air bladder and customized sole inserts. When the bladders were inflated, the elevated surface of the inserts exerted pressure on the balls and heels of each foot. The boots were inflated with a hand-held sphygmomanometer pump attached to hoses leading to the boot's bladders. Crewmembers were trained to inflate the bladders to a level such that the distribution and amount of pressure resembled those obtained during preflight testing in 1-*g*.

Figure 1. The foot pressure boots.

The 'no pressure' condition (NP) was identical to the WP condition except that it was performed without the pressure boots. Pilot testing during parabolic flight revealed that wearing the uninflated boots provided enough somatosensory input to affect the neuromuscular response. To eliminate this stimulus, subjects did not wear the boots during the NP condition.

The pressure boots were designed so that inflating the boots produced pressure on both the soles and the top of the feet. (This study was not designed to identify the exact receptors that may have contributed to enhanced neuromuscular activation. Thus, the fact that pressure was increased on the soles and the top of the feet was incidental to this experiment.) The boots added so little mass to the body that any possible changes in inertia during the free-floating arm movements were unlikely to affect the neuromuscular-activation characteristics, particularly since the monitored muscles were all active during initiation of the arm movement.

We predicted that any changes observed in the neuromuscular activation associated with the arm raise would be the direct result of increased somatosensory input from wearing the inflated pressure boots. The order in which the conditions were performed was counterbalanced across subjects.

Data Collection

Preamplifier electrodes were used to obtain surface EMG from the right biceps femoris (RBF), the left paraspinals (LPA), the right tibialis anterior (RTA) and the lateral head of the gastrocnemius (RGA) during the arm-raise task. These muscles were monitored because they are all electrically active before the onset of arm movement in 1-*g*, and thus are directly associated with performance of this task. A Belt Pack Amplifier System (BPAS, Kistler Instruments Inc.) [17], specifically designed and manufactured for this experiment, was used to amplify the signals before they were stored on cassette data tapes (TEAC Inc.). The tape speed was set to allow recordings up to 1330 Hz. The BPAS system, its battery, and the cassette recorder were secured in a specially designed flight vest that allowed the subjects to float freely within the space station.

In addition to EMG, tangential arm acceleration in the sagittal plane were measured with a uniaxial accelerometer secured to a wrist splint worn on the right hand. Voice records were obtained to substantiate the experimental condition and trial number. During some trials, surveillance video was obtained, inspection of which confirmed that subjects had no difficulty in assuming the appropriate body configuration before each arm movement. The two subjects on the 115-day mission collected data on flight day 105; the other two subjects collected data on flight day 62.

Data Analysis

After the data tapes were returned to Earth, the analog signals were downloaded with a TEAC playback unit (TEAC Inc.) before being digitized at 500 Hz. The EMG data were then highpass-filtered at 30 Hz, offset, full-wave rectified, and smoothed with a 10 ms time constant. Average waveforms for each muscle and each subject were obtained by using arm acceleration initiation as a synchronization signal. The data were then amplitude normalized, with the mean activity for each muscle and subject obtained during the NP condition set to a value of 100. This value was used to normalize each muscle's average waveform obtained for each experimental condition, and served to convert the voltage values into percentages of activation relative to the mean value for the NP condition. Normalizing the data in this manner facilitated both intra- and intersubject comparisons.

Each average waveform contained 300 ms of data before arm acceleration, and ended at the completion of arm movement, as determined from the accelerometer traces. To facilitate quantitative analyses, the averaged waveforms were then reduced to 20 epochs, with each epoch containing 30–38 ms of data, depending upon the duration of the motion, for an individual subject in a particular condition. Since we were interested only in the neuromuscular activity associated with preparation for and the generation of the arm movement itself, and since intersegmental torques could lead to variable efforts to stabilize the body after each arm movement, neuromuscular activity after completion of the arm movement was not analyzed. Average arm acceleration waveforms were developed in the same manner as that of the EMG waveforms, except that the waveforms were not amplitude normalized. Before waveform reduction, peak arm acceleration values, for each subject and condition, were obtained from the averaged records.

To ascertain whether foot pressure modified the phasic characteristics of neuromuscular activation, Pearson *r* correlation coefficients were used to compare the NP and WP pressure waveforms for each muscle. To determine whether EMG amplitude was enhanced by the addition of foot pressure, for each waveform, the four consecutive epochs with the greatest total magnitude were summed. Four consecutive epochs (approximately 120–150 ms in duration) generally corresponded to the burst duration for a muscle. The difference in the summed values between the NP and WP condition was calculated for each muscle and each subject. Because individuals displayed wide ranges of physiological and behavioral responses to space flight, descriptive statistics from individual subjects were used to describe the neuromuscular responses to foot pressure.

RESULTS

Results from the peak arm acceleration for the NP and WP conditions are shown in Table 1. Little difference was apparent between the two conditions, except for Subject B. Differences in activation amplitudes between the two conditions for each muscle and subject are shown in Figure 2. Although some variation was present, neuromuscular activation generally was enhanced by the addition of foot pressure. Some degree of increased activation was present in 12 of 16 the monitored muscles (4 subjects x 4 muscles). Subjects A and B, in particular, displayed large increases in response to the increased pressure.

Table 1: Mean (with one standard deviation) peak arm acceleration during free floating unilateral arm movements (m/s^2)

Subject	NP	WP
A	34.0 (7.8)	38.4 (7.3)
B	53.5 (11.2)	62.5 (11.3)
C	50.3 (3.6)	46.0 (4.4)
D	65.8 (7.2)	64.3 (7.8)

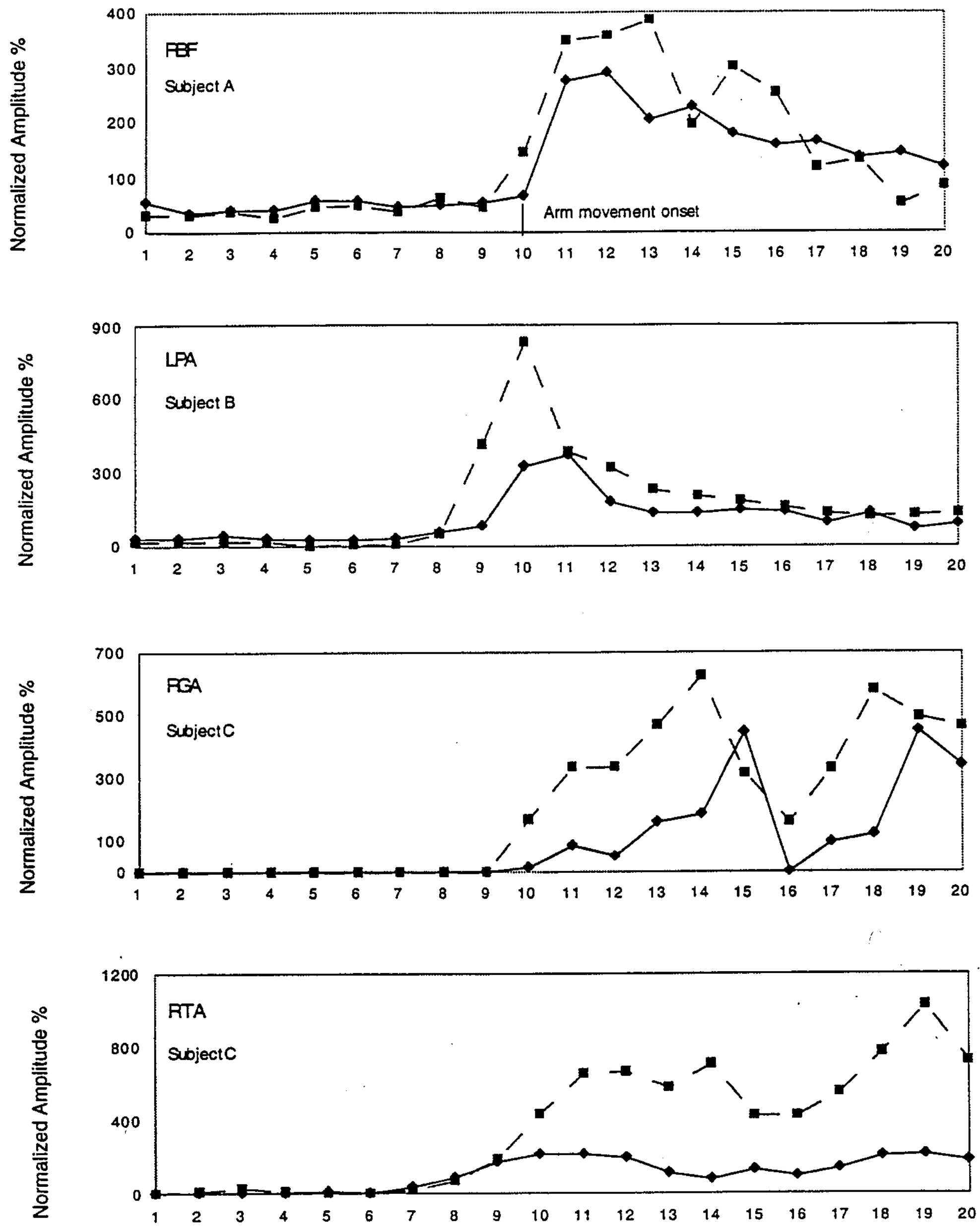

Figure 2. Differences in activation amplitudes between the NP and WP conditions for each muscle and subject.

Typical activation increases associated with the addition of foot pressure are shown in Figure 3. Pearson *r* values indicating the degree of similarity between the phasic properties of the NP and WP activation waveforms are given in Table 2. Correlations between the NP and WP waveforms

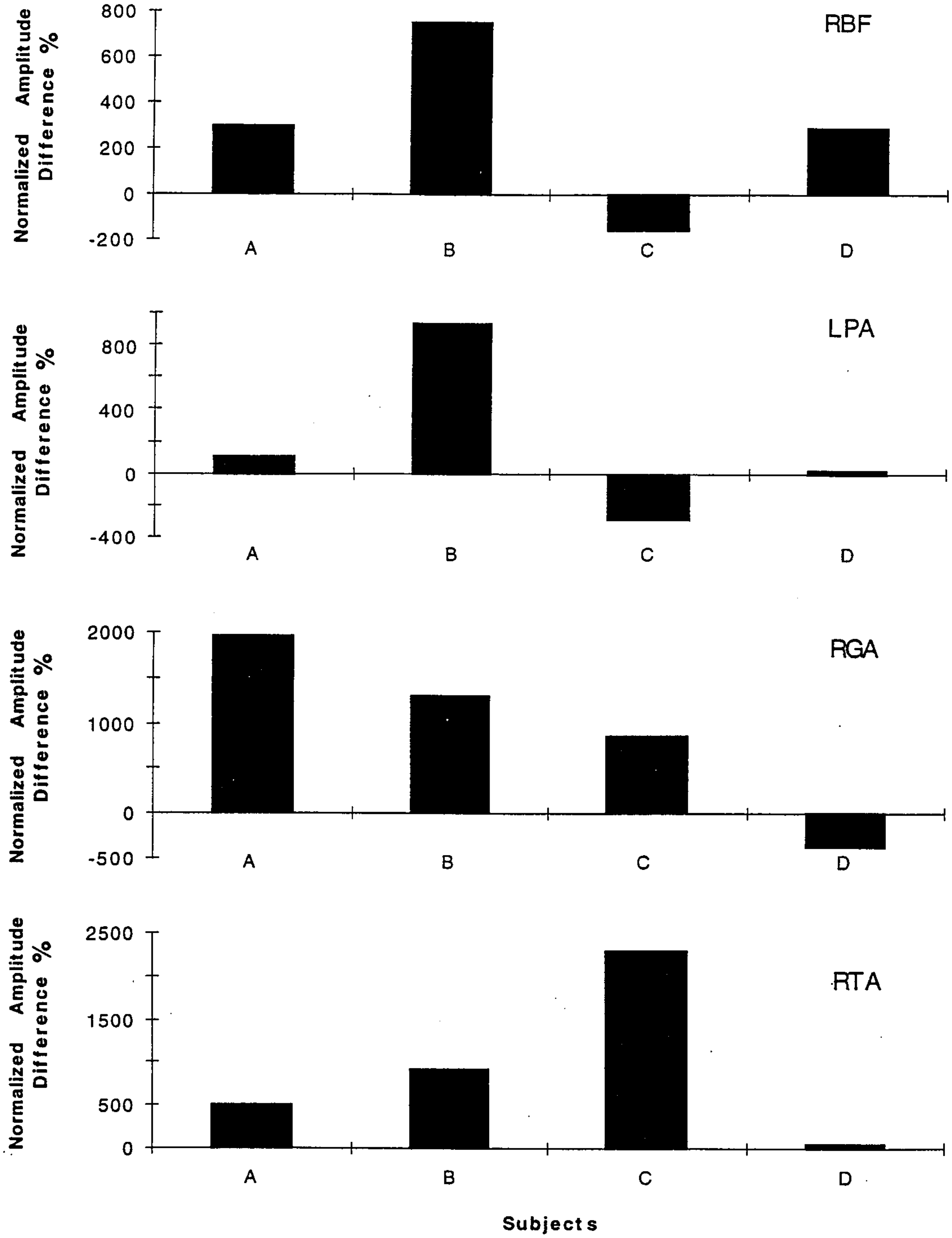

Figure 3. Sample EMG waveforms from individual subjects, displaying increases in neuromuscular activation amplitude associated with the addition of foot pressure. The solid lines represent EMG activation in the NP condition and the broken lines represent activation in the WP condition.

Table 2: Within-subject Pearson r correlation coefficients for each muscle activation waveform across conditions. An r value of 0.40 represents a significant correlation at $p < .05$.

Subject	RBF NP–WP	LPA NP–WP	RGA NP–WP	RTA NP–WP
A	.88	.92	.47	.70
B	.54	.83	.84	.87
C	.57	.97	.70	.74
D	.74	.90	.69	.84

generally were moderate to high. However, the RBF and RGA had somewhat lower correlations than the other two muscles. These results indicate that foot pressure modifies not only the amplitude characteristics but the phasic properties of the neuromuscular activation as well.

DISCUSSION

The present study was conducted to determine whether foot sensory input modifies the phasic characteristics, or enhances the magnitude, of stereotypical 1-*g* patterns of neuromuscular responses associated with unilateral arm raises, performed while free floating during space flight. In general, the application of foot pressure enhanced lower limb and trunk activation, and modified the phasic patterns of activation to some extent during the arm movement. The finding of enhanced activation is consistent with reports that foot pressure increased the 'preparatory' activation of the lower limb and trunk musculature during arm raises in free fall during parabolic flight [7].

In contrast to other reports of habituation of preparatory neuromuscular activation during arm raises performed while anchored at the feet during space flight [18], all of our (free-floating) subjects displayed enhanced responses to the application of foot pressure well into the mission. No differences in response were apparent between those obtained on flight day 62 vs. those on flight day 105. Our results indicate that foot pressure can enhance neuromuscular activation during rapid arm movements performed while free floating, despite extended exposure to weightlessness.

Subjects in this study were tested only once during the mission, which limited their exposure to the foot pressure provided by the boots. Thus, the question remains as to whether extended or repeated exposure to foot pressure during space flight would result in habituation of the neuromuscular responses. The protocol described in this report has now been performed several times by other subjects; these data are being analyzed to assess potential habituation of response.

The observed increase in neuromuscular activation may have resulted from an overall facilitation of the segmental motoneuronal pools in response to increased peripheral sensory input. The fact that not all muscles in all subjects showed increased activation from the addition of foot pressure suggests that the enhancement of activation may depend on a convergence of primary afferent, interneuronal, and descending input upon the motoneurons [19]. Different individuals may activate their muscles in a task-specific manner such that intersegmental processes prevent the enhancement of neuromuscular activation. In addition, the vast changes in the sensory environment, and in individual exercise, diet, and sleep habits, in space make it unlikely that all subjects will respond uniformly to a common stimulus.

Nevertheless, 75% of the muscles evaluated during our task showed at least some degree of enhanced activation with the addition of foot pressure. Moreover, the lack of perfect correlation between the NP and WP waveforms indicates that foot pressure modified the phasic activation characteristics. This finding also suggests that the observed increase in neuromuscular activity is not the result of simple global facilitation of the motoneuron pools interacting with a descending neural command. Rather, it is a more complex neuromuscular activation pattern designed to promote the completion of the task. These data support previous findings that manipulation of foot sensory input affects neuromuscular activation characteristics during goal-directed movement tasks [7,20,21].

Evidence obtained during rapid arm movements made in 1-*g* indicates that the amplitude of neuromuscular activation is positively correlated with arm movement velocity [16,22]. Although only two of the four subjects in this study showed increased peak accelerations with the addition of foot pressure, all showed increases in neuromuscular activation across several muscles. Thus the enhancement in neuromuscular activity is not necessarily related to increases in arm acceleration, as is true for movements on Earth.

These results support the concept that in-flight foot pressure can be used to enhance the level of neuromuscular activation in muscles that are active during a movement. If additional research continues to support these findings, then carefully controlled temporal patterns and magnitudes of foot pressure may be useful for facilitating neuromuscular activation throughout the course of a space flight, thereby perhaps attenuating muscle atrophy and the associated postflight motor control deficits experienced by crewmembers.

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