Using Foot Pressure to Maintain Neuromuscular Function during Long-Duration Spaceflight

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Abstract. It is proposed that the application of foot pressure can result in enhanced lower limb neuromuscular activation over the course of a long-duration spaceflight. If confirmed, a device that generates increased foot sensory input can be developed for use on the International Space Station as a countermeasure to neuromuscular degradation. In the present experiment, surface EMG was collected from six subjects during freefloating arm raises performed with or without foot pressure. Two subjects performed the experiment multiple times during their flight. The results indicate that foot pressure results in significantly increased magnitudes of lower limb neuromuscular activation when compared to movements performed without foot pressure. Furthermore, repeated application of pressure throughout a flight continues to produce enhanced neuromuscular activation without significant modification of the phasic activation features. These findings suggest that the development of a countermeasure utilizing foot pressure merits continued exploration.

INTRODUCTION

With the development of the International Space Station (ISS) more crewmembers will be spending longer periods in space than ever before. Results from the Space Shuttle and Russian Mir space station scientific programs indicate that increasing mission length exacerbates the loss of muscle strength and the associated reduction in muscle function. The decrement in muscle function can negatively impact certain mission activities (e.g. EVAs) and prolong a crewmember's recovery upon return to Earth. Providing efficient measures to counter the deleterious effect of weightlessness upon the neuromuscular system is important to insure optimal utilization of the ISS. Currently, the primary means of maintaining muscle function are inflight exercise regimes using ergometers and treadmills. Although innovative technologies are being developed that will enable crewmembers to perform inflight resistive exercise, there may be additional techniques that when practiced in combination with resistive exercise, may result in the most efficient program of muscle maintenance. One potentially useful technique is the application of pressure to the feet which has been shown to increase inflight lower limb muscle activation above that normally observed without foot pressure (Layne, et al., 1998). It is hypothesized that the increased somatosensory input from the foot receptors can modify motoneuronal thresholds resulting in increased spatial and temporal summation within the motoneuronal pool during a given contraction. A foot pressure application system that provides controlled patterns of foot pressure could be used to 'drive' orderly neuromuscular activation throughout the course of an ISS mission, thus serving to maintain muscle function. A foot pressure 'shoe' could be worn during many inflight activities without interference and serve as a supplement to aerobic and resistive exercises. Moreover, bedridden patients could benefit from the use of foot pressure. The bipedal unloading associated with continuous stays in bed result in decrements of muscle function similar to those experienced by long-duration crewmembers. Using foot pressure to maintain patient muscle function would be a positive addition to the rehabilitation field.

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This investigation had two explicit goals: 1) to quantify the degree to which neuromuscular activation is enhanced with the application of foot pressure during arm movements performed while freefloating and 2) to determine if the neuromuscular response to foot pressure is maintained throughout a long-duration mission during multiple test sessions. The arm raise task was selected because of the stereotypical pattern of muscle activation that accompanies the movement in 1-g. Furthermore, it has been demonstrated that this stereotypical activation pattern is greatly attenuated during shoulder flexions performed while freefloating aboard the KC-135 (Layne and Spooner, 1990) and during short-duration flights on the Space Shuttle but is enhanced in the presence of foot pressure (Layne, et al., unpublished data). Evaluating modifications of a stereotypical activation pattern simplifies the process of determining how foot pressure affects neuromuscular control during long-duration spaceflight. Although previous reports have confirmed the application of foot pressure results in enhanced lower limb muscle activation during weightlessness, there have been no reports concerning the possible habituation of the enhanced activity in response to repeated exposure to foot pressure. For a countermeasure designed around the application of foot pressure to be effective, the enhanced neuromuscular response must be maintained throughout the flight. Two subjects conducted the 'foot pressure' experiment repeatedly throughout their Mir mission. The results from these two subjects will provide valuable information about whether the neuromuscular response to foot pressure is maintained during a long-duration flight.

METHODS

Six male volunteers who flew aboard the Russian Mir space station served as subjects for this investigation. All subjects provided informed consent that met the requirements of the NASA Institutional Review Board for Human Research. Two subjects participated in an 81-day mission, two subjects flew a 115-day mission, and the remaining two flew for 196 days. Subjects ranged in age from 34 to 53 years (mean = 43.2, SD = 8.1) and three had flown in space previously. Table 1 indicates that data were collected during only one session for four of the crewmembers while two crewmembers were tested four times throughout the mission. Multiple testing enabled us to explore the question of whether neuromuscular activation was modified as a result of repeated exposure to foot pressure.

TABLE 1. Flight Days of Data Collection.

Subject	Flight Day	Flight Day	Flight Day	Flight Day
A	13	56	141	188
B	13	56	141	188
C	61	x*	x	x
D	62	x	x	x
E	105	x	x	x
F	106	x	x	x

*The x indicates data were not collected due to flight constraints.

Subjects performed 15 rapid, right-arm 90° shoulder flexions while freefloating in two conditions: with or without foot pressure. Prior to each trial, subjects adopted a body configuration that mimicked that of upright 1-*g* stance by aligning their body segments in the sagittal plane. Once aligned, the subjects closed their eyes and performed the movement at a self-selected time. After a movement trial, subjects opened their eyes, realigned their body, and repeated the movement until the block of movement trials was complete.

During the 'with pressure' (WP) condition, foot pressure was applied using a pair of 'boots' that contained air bladders inflated with a hand-held sphygmomanometer pump. The thin aluminum boots, packed with comfortable, high-density foam, approximated a men's size 13 shoe, and weighed 2.2 kg in 1-*g*. Within the boots, individualized inserts were seated on top of the bladders. The inserts had slightly elevated areas under the heels and balls of the feet that when used in combination with the inflated bladders, generated a level and distribution of pressure that imitated that experienced during 1-*g* stance. The only difference between the WP and 'no pressure' (NP) condition was the elimination of foot pressure in the NP condition. Counterbalancing the order in which the subjects performed the conditions guarded against order effects.

Surface electromyography was collected from the right gastrocnemius (RGA), tibialis anterior (RTA), rectus femoris (RRF), biceps femoris (RBF) and anterior deltoid (RAD) and from the left biceps femoris (LBF) and paraspinals (LPA). Right arm tangential acceleration in the sagittal plane was measured with a uniaxial accelerometer. The accelerometer was attached to a wrist splint that limited the wrist's biomechanical degrees of freedom, thus simplifying the analysis of the accelerometer signal. A Belt Pack Amplifier System (BPAS, Kistler Instruments Inc, Layne, et al., 1994) was used to amplify the signals before they were stored on cassette data tapes (TEAC Inc.) The BPAS battery, amplifier and recorder were secured within a specially designed canvas vest. The BPAS vest insured that the subjects were completely untethered while performing the arm movements. This feature was important because it has been demonstrated that somatosensory input resulting from contact with the external environment can modify neuromuscular responses even if the magnitude of the contact is not enough to provide postural support (Cordo and Nashner, 1982). Thus, requiring that the subject be completely freefloating, enabled us to attribute any modifications in neuromuscular activation exclusively to the addition of foot pressure, under the assumption that the kinematics remained similar across conditions. Arm accelerometer data and surveillance video collected during several test sessions indicated that the addition of foot pressure did not modify the segmental motions in any obvious manner.

In the laboratory, the data were converted from analog to digital at 500 Hz, high-pass filtered at 30 Hz, full-wave rectified and smoothed using a 10 ms time constant. Average waveforms for each muscle and each subject were obtained by using arm acceleration initiation as a synchronization point around which a "data window" was developed. The first change in the steady-state arm accelerometer trace was used to represent arm movement initiation. Each "window" consisted of 300 ms prior to arm movement initiation and 50 ms of data after arm motion was complete (i.e. accelerometer trace returned to steady-state). Since we were only interested in whether foot pressure increased the stereotypical neuromuscular activation associated with the arm movement, we did not analyze the data beyond the conclusion of the arm motion. To simplify quantitative analyses between experimental conditions and subjects, the average EMG and accelerometer waveforms for each muscle and each subject were then reduced to 50 epochs. Each epoch represented between six and eight milliseconds of data, depending upon the duration of the arm movement. The data were amplitude normalized to facilitate comparisons between the NP and WP conditions. The average voltage value of the reduced waveform for each muscle in the NP condition was used as the normalizing voltage (Winter and Yack, 1987). That is, each of the 50 voltage values comprising the reduced waveform for each muscle were divided by the normalization value and then multiplied by 100. The procedure served to set the average voltage value in the NP condition to 100 percent. Peak arm acceleration was amplitude normalized in a similar manner with the exception that the voltage value associated with peak acceleration in the NP condition was used as the normalization value. To determine if foot pressure resulted in enhanced activation during the first exposure of the mission, the reduced waveforms for each muscle and subject were averaged. Student t tests were then used to assess potential amplitude differences between the two conditions for each muscle. Two subjects performed the experiment four times during the mission. The data from these subjects enabled us to explore whether repeated exposure to foot pressure continued to result in increased neuromuscular activation througout the flight. Student t tests were again used to determine if there were differences in neuromuscular amplitude between the NP and WP conditions for each muscle within each testing session. To determine if spaceflight altered the phasic features of each muscle's activation waveform, Pearson r correlation coefficients were developed between the inflight waveforms and waveforms obtained during arm movements made in 1-g. The NP and WP waveforms for each muscle, were also correlated to determine if foot pressure modified the phasic features of neuromuscular activation both during the initial exposure to pressure and in the case of two subjects, across multiple exposures during the mission.

RESULTS

This study monitored the neuromuscular activation of selected leg, trunk and shoulder muscles during freefloating arm movements to determine if foot pressure increased neuromuscular activation. A second goal was to determine if multiple exposures to foot pressure throughout a long-duration mission led to habituation of the enhanced response to pressure. The data indicate that applying foot pressure leads to increased neuromuscular activity that is consistently maintained during the mission.

The application of foot pressure during spaceflight consistently results in the enhancement of neuromuscular activation during a rapid arm raise task performed while freefloating. Figure 1 represents the group average normalized neuromuscular activation value for each muscle obtained during the first exposure to foot pressure (WP condition). All lower limb muscles showed significant increases in neuromuscular activation in response to foot pressure. These results are consistent with previous reports that the addition of foot pressure leads to increased levels of muscle activation during arm movements while freefloating, relative to movements performed without foot pressure (Layne and Spooner, 1990; Layne, et al., 1998). As hypothesized, the AD activation was not affected by the addition of foot pressure, nor was there a difference in the peak arm acceleration between the NP and WP conditions. Figure 2 displays exemplar reduced EMG waveforms showing increased amplitude and the consistency of the phasic features of neruomuscular activation across collection days with the addition of foot pressure.

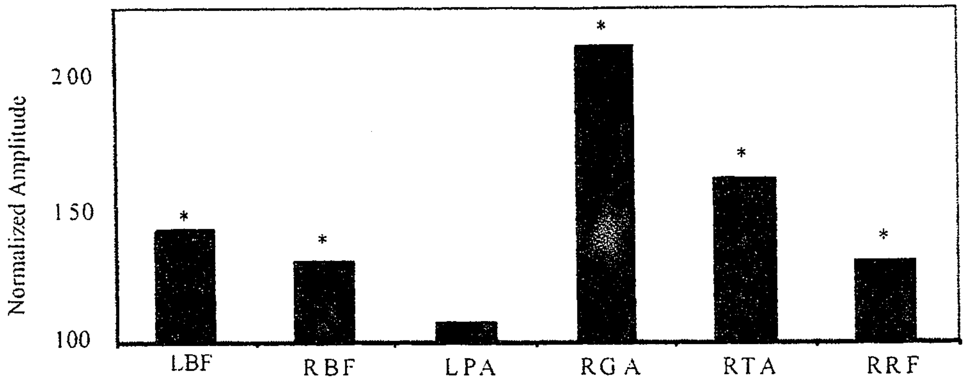

FIGURE 1. Group mean muscle activation magnitudes for each muscle obtained during the initial WP condition. The data are normalized with respect to the mean value of the NP condition (i.e. 100%). The asterisk indicates statistical significance at $p < 0.05$.

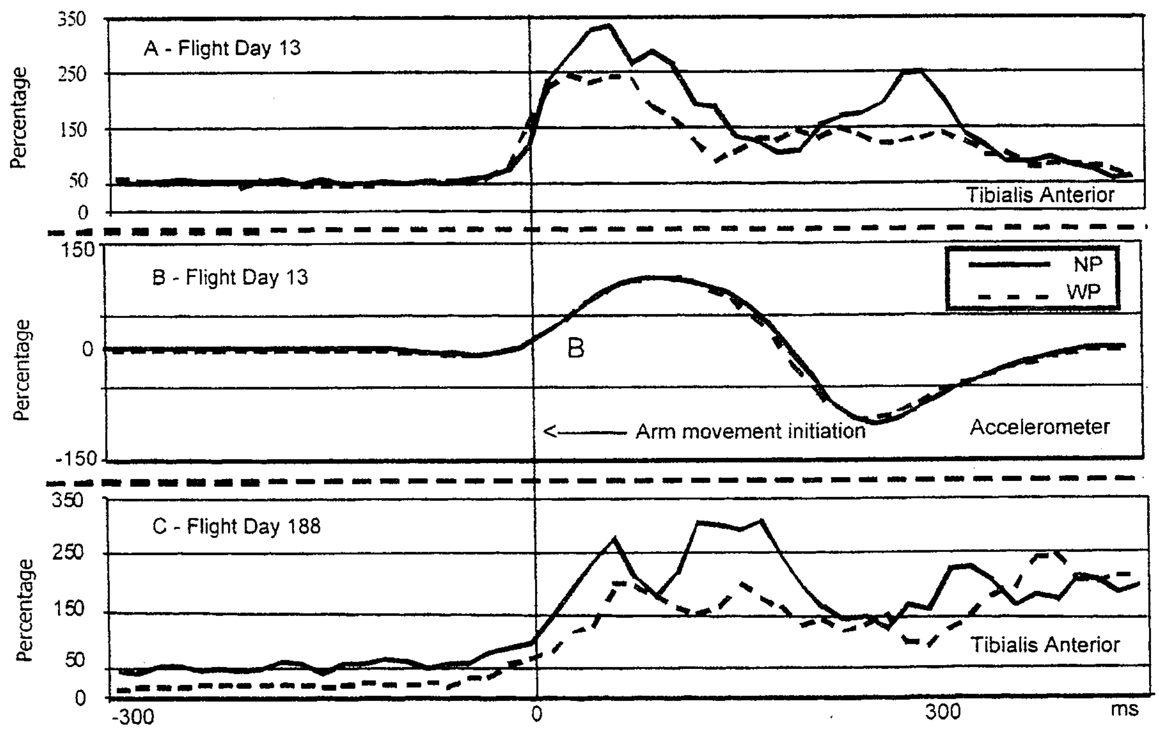

FIGURE 2. Temporally and amplitude normalized EMG waveforms for Subject B displaying the continued enhancement of lower limb neuromuscular activity despite repeated applications of foot pressure throughout the long-duration spaceflight (Panels A and C). Panel B displays the accelerometer waveform obtained in the NP and WP conditions during the initial testing condition and indicates that arm acceleration is not affected by the addition of foot pressure (see text for details).

Table 2 indicates that for two subjects, lower limb neuromuscular activation continued to be enhanced in the presence of foot pressure across multiple testing sessions.

TABLE 2. Results of Student t Tests Assessing Potential Differences in Neuromuscular Activation Amplitudes Between the NP and WP Conditions Across Repeated Exposures to Foot Pressure.

NP-WP	Subject A Test 1	Subject A Test 2	Subject A Test 3	Subject A Test 4	Subject B Test 1	Subject B Test 2	Subject B Test 3	Subject B Test 4
LBF	X*	#	#	X	O	O	O	O
RBF	O	O	O	X	X	X	O	O
LES	X	O	O	O	O	O	O	X
RGA	X	X	X	X	O	X	O	X
RTA	X	X	X	X	X	X	X	X
RRF	X	X	X	X	X	X	O	X

*The X represent that there were significant differences between the NP and WP conditions at $p < 0.05$. The # represents the data were unavailable due to technical considerations.

Table 3 shows the correlation coefficients between the average neuromuscular activation waveforms obtained during preflight testing and the two inflight experimental conditions. The high coefficients indicate that the waveforms obtained during spaceflight, regardless of condition, are similar to those observed during arm movements performed prior to spaceflight. Moreover, the high correlations between the NP and WP conditions support the contention that the addition of inflight foot pressure does not modify the phasic features of muscle activation while the subjects are performing freefloating arm movements.

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TABLE 3. Correlation Coefficients between EMG waveforms obtained in 1-*g*, and the NP and WP Conditions

Muscles	Pre-NP	Pre-WP	NP-WP
LBF	.93	.90	.81
RBF	.69	.58	.83
LES	.94	.88	.97
RGA	.73	.41	.74
RTA	.78	.69	.95
RRF	.88	.71	.89

Table 4 indicates that the application of foot pressure does not modify the phasic activation characteristics between the NP and WP conditions despite repeated application of foot pressure throughout the flight. (i.e. high correlations between muscle activation waveforms).

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TABLE 4. Correlation Coefficients between the No Pressure (NP) and With Pressure (WP) Conditions.

NP-WP	Subject A Test 1	Subject A Test 2	Subject A Test 3	Subject A Test 4	Subject B Test 1	Subject B Test 2	Subject B Test 3	Subject B Test 4
RAD	.95	.97	.95	.94	.95	.92	.96	.93
LBF	.89	*	*	.84	.86	.51	.88	.75
RBF	.76	.49	.83	-.24	.87	-.20	.81	.84
LES	.99	.98	.97	.74	.96	.95	.96	.77
RGA	.58	.20	.94	.76	.89	.46	.70	.74
RTA	.93	.94	.96	.87	.92	.32	.88	.84
RRF	.72	.74	.97	.57	.96	.70	.92	.88

***Data unavailable**

DISCUSSION

This investigation confirms previous findings that foot pressure can be used to increase lower limb neuromuscular activation levels of freefloating astronauts during rapid arm movements. Additionally, these increases are sustained throughout long-duration flight despite repeated application of foot pressure. This last finding is important because for a countermeasure that utilizes foot pressure to be effective, it is imperative that the neuromuscular response to the pressure is maintained throughout a mission.

Although the present investigation was not designed to identify the neurophysiological mechanisms associated with enhanced neuromuscular activation, there are several previously identified mechanisms that are likely to contribute to the response. For instance, heel cutaneous afferents have been shown to increase both static and dynamic fusimotor drive by increasing the discharge rate of the gamma motoneurons (Ellaway, 1995). This modulatory action on the stretch reflex arc can be expected to increase the contribution of the muscle spindles to neuromuscular activation. Additionally, muscle spindle afferent fibers synapse directly on to alpha motor neurons thereby providing a pathway by which afferent information generated by foot pressure can modulate neuromuscular activation. However, there have been reports that neuromuscular responses to sensory stimulation may be modified throughout the course of a spaceflight (Roll, et al., 1998). This suggests that sensorimotor adaptation can take place during a mission which may alter the neuromuscular response to foot pressure. In the present study, two findings suggest that long-duration exposure to microgravity does not result in the elimination of enhanced neuromuscular activation.

Table 1 indicates the initial testing session occurred as early as Flight Day 13 and as late as Flight Day 106. It would be expected that any sensorimotor adaptations would have occurred by the later test day. However, the initial application of foot pressure produced enhanced neuromuscular activation regardless of the flight day when it was first applied. Secondly, the repeated application of foot pressure with two subjects throughout the flight indicates that the enhanced neuromuscular response continues to remain intact over multiple exposures to the pressure. Thus, our results strongly suggest that the neuromuscular response to foot pressure is not "adapted out" during the course of a flight.

CONCLUSIONS

The present results indicate that foot pressure results in enhanced neuromuscular activation of the lower limb muscles and that the enhanced response remains intact throughout a long-duration spaceflight despite repeated applications of pressure. This suggests that in the future, a device that generates sensory input from the feet could be utilized as a component of neuromuscular degradation countermeasures program aboard the ISS.

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