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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)

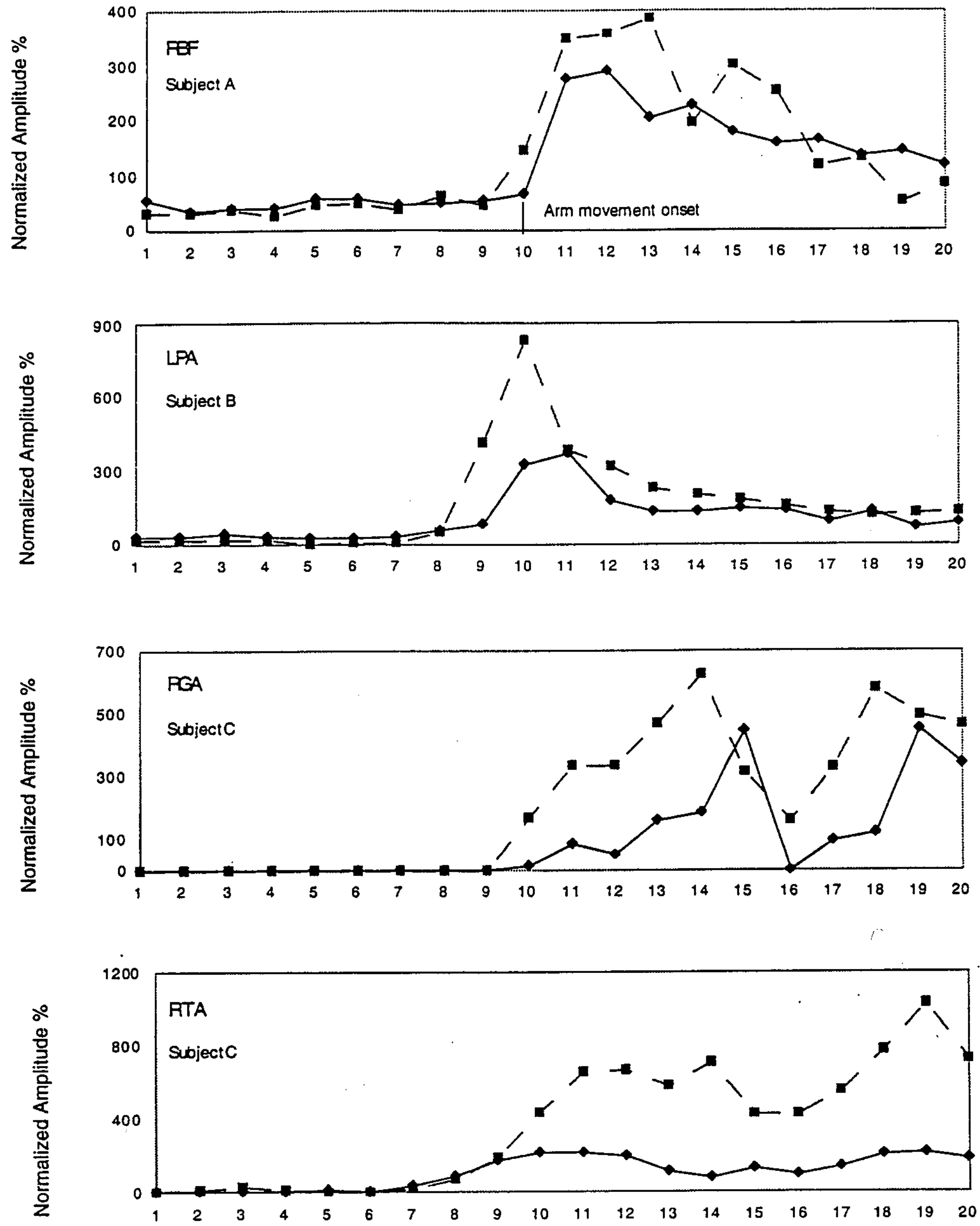

Figure 2. Differences in activation amplitudes between the NP and WP conditions for each muscle and subject.

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

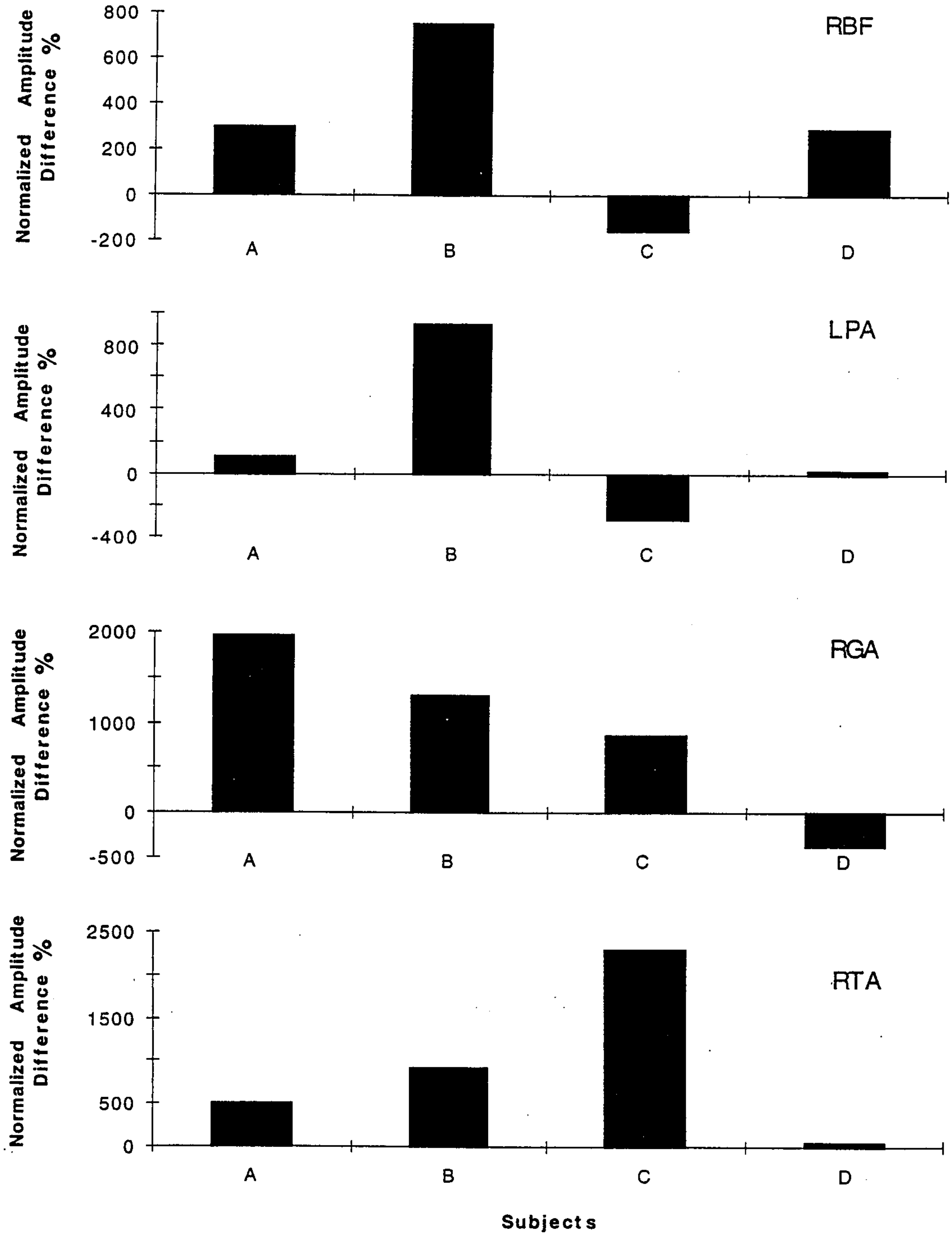

Figure 3. Sample EMG waveforms from individual subjects, displaying increases in neuromuscular activation amplitude associated with the addition of foot pressure. The solid lines represent EMG activation in the NP condition and the broken lines represent activation in the WP condition.

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.

REFERENCES

1. A.D. LeBlanc, C. Lin, R. Rowe, O. Belinchenko, V. Sinitsyn, B. Shenkman, V. Oganov, L. Shackelford, D.L. Feeback. Muscle loss after long duration spaceflight on Mir-18/STS-71. Life Sciences and Space Medicine Conference, Book of Abstracts, pp. 53–54, Institute of Aeronautics and Astronautics, Washington, DC (1996).

2. A.D. LeBlanc, R. Rowe, V. Schneider, H. Evans, T. Hedrick. Regional muscle loss after short duration spaceflight. *Aviat Space Environ Med* **66**, 1151–1154 (1995).

3. R.T. Whalen. Musculoskeletal adaptations to mechanical forces on Earth and in space. *The Physiologist* **36**(Supplement 1), S127–S130 (1993).

4. C. S. Layne, P.V. McDonald, A.P. Mulavara, I.B. Kozlovskaya, J.J. Bloomberg. Adapting neuromuscular synergies in microgravity. "Bernstein's Traditions in Motor Control" conference, Penn State University, University Park, PA (1996a).

5. C.S. Layne, P.V. McDonald, J.J. Bloomberg. Neuromuscular activation patterns during treadmill walking after space flight. *Exp Brain Res* **113**: 104-116 (1997).

6. C.S. Layne, B.S. Spooner. EMG analysis of human postural responses during parabolic flight microgravity episodes. *Aviat Space Environ Med* **64**, 994–998 (1990).

7. C.S. Layne, B.S. Spooner. Microgravity effects on "postural" muscle activity patterns. *Adv Space Res* **14**, 381–384 (1994a).

8. K.E. Hagbarth. Excitatory and inhibitory skin areas for flexor and extensor motoneuron. *Acta Physiol Scand* **86** (Suppl), 94 (1952).

9. E. Kugelberg, K. Eklund, L. Grimby. An electromyographic study of nociceptive reflexes of the lower limb. Mechanism of the plantar responses. *Brain* **83**, 394–410 (1960).

10. J.J. Sequin, J.D. Cooke. The effects of cutaneous mechanoreceptor stimulation on the stretch reflex. *Exp Brain Res* **52**, 152–154 (1983).

11. J.D. Brooke, W.E. McIlroy, D.F. Collins, J.E. Misiaszek. Mechanisms within the human spinal cord suppress fast reflexes to control the movement of the legs. *Brain Res* **679**, 255–260 (1995).

12. C. Capaday, R.B. Stein. Difference in the amplitude of the human soleus H reflex during walking and running. *J Physiol* **392**, 513–522 (1987).

13. J. Duysens, G.E. Loeb, B.J. Weston. Crossed flexor reflex responses and their reversal in freely walking cats. *Brain Res* **197**, 538–542 (1980).

14. C.S. Layne, A. P. Mulavara, P.V. McDonald, C.J. Pruett, J.J. Bloomberg. Somatosensory input enhances neuromuscular activation during movements performed while free-floating in microgravity. *Soc Neurosci Abstr* **22**, 425 (1996b).

15. S. Bouisset, M. Zattara. A sequence of postural movements precedes voluntary movement. *Neurosci Lett* **22**, 263–270 (1981).

16. W.A. Lee, T.S. Buchanan, M.W. Rogers. Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. *Exp Brain Res* **66**, 257–270 (1987).

17. C. S. Layne, J.J. Bloomberg, P.V. McDonald, G. Jones, C.J. Pruett. The application of Kistler instrumentation for human performance evaluation in the Shuttle-Mir program. *Kistler Biomechanics News* **2(3)**, 1–2 (1994b).

18. G. Clement, V.S. Gurfinkel, F. Lestienne, M.I. Lipshits, K.E. Popov. Adaptation of postural control to weightlessness. *Exp Brain Res* **57**, 61–72 (1984).

19. A. Prochazka. Sensorimotor gain control: a basic strategy of motor systems? *Prog Neurobiol* **33**, 281–307 (1989).

20. A. Nardone, M. Schieppati. Postural adjustments associated with voluntary contraction of leg muscles in standing. *Exp Brain Res* **69**, 469–480 (1988).

21. F.B. Horak, L.M. Nashner, H.C. Diener. Postural strategies associated with somatosensory and vestibular loss. *Exp Brain Res* **82**, 167–177 (1990).

22. F.B. Horak, P. Esselman, M.E. Anderson, M.K. Lynch. The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. *J Neurol Neurosurg Psychiatr* **47**, 1020–1028 (1984).