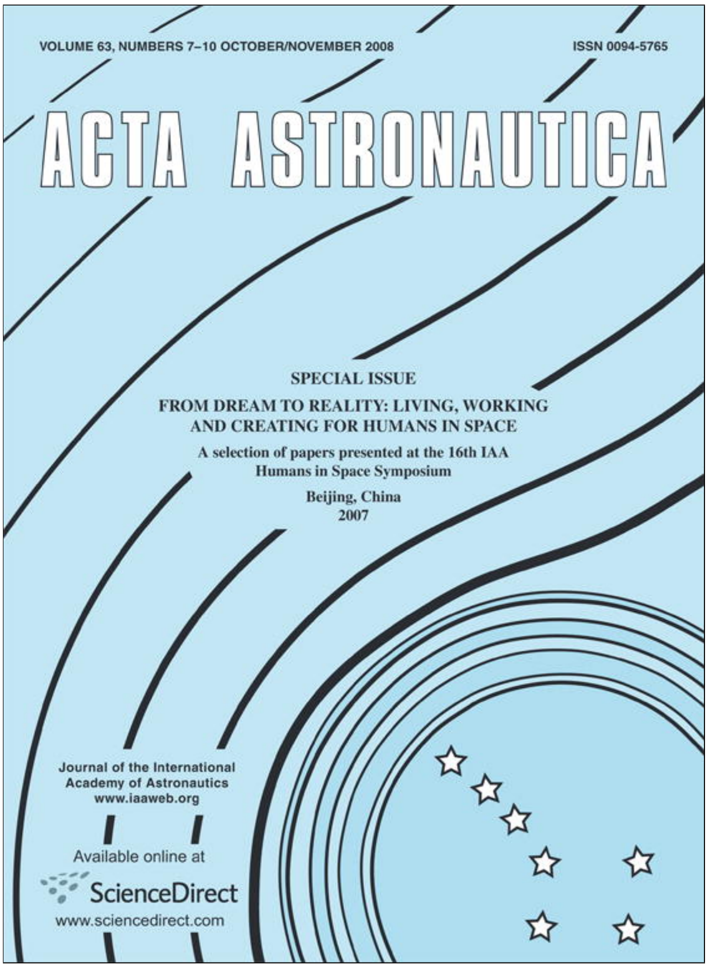
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Muscle contractions in response to foot stimulation as an inflight countermeasure

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Abstract

We propose that a passive countermeasure employing mechanical stimulation of the feet can be used during spaceflight to attenuate neuromotor degradation. The purpose of this investigation was to determine whether the time between consecutive stimuli to the human sole influences the subsequent muscle contraction response. Participants were exposed to mechanical stimulation of the right sole in a protocol of six conditions of stimulation couplets. Stimulation couplets consisted of two closely timed stimuli separated by an interstimulus interval (ISI) of either 100, 140, 180, 220, 260, or 300 ms. Electromyography of the leg musculature was collected. The focus of the analyses was the amplitude of the response to the second stimulus of each couplet relative to the isolated baseline response. The results indicate that the second response in a couplet was inhibited up to 220 ms ISI, but returned to baseline with greater ISIs. When developing an inflight dynamic foot stimulator it will be important to ensure that the timing between the stimulations is separated by ISIs that prevents the inhibition of neuromuscular activation.

Keywords: Countermeasures; Spaceflight; Neuromuscular; EMG; Stimulation; Inhibition

1. Introduction

Astronauts returning from extended duration spaceflight missions often experience a variety of motor control problems including those of bipedal posture and locomotor control [1–3]. These problems stem from a variety of neurophysiological responses to the microgravity environment that are appropriate inflight adaptations but are maladaptive when they persist upon return to Earth's 1*g* environment [4–6]. Crewmembers can reduce the negative consequences of these maladaptive responses by performing a variety of countermeasure activities during their flight. Currently, the vast majority of inflight countermeasures consist of 'active' exercises adapted from traditional gymnasium equipment designed to maintain cardiovascular, aerobic, and musculature strength capacity. Typical activities include treadmill running, ergometer cycling, and resistive exercises that require a good deal of the crew's time. Due to a variety of reasons, including time commitment and malfunctioning exercise equipment, it is not surprising that very few crewmembers display full compliance with the currently prescribed countermeasure program [7]. These difficulties point to the need to develop countermeasures that are less intrusive

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upon a crew's time and level of effort but are effective in attenuating the negative physiological consequences of microgravity exposure. New generations of countermeasures that do not require a crewmember to abandon their prescribed daily operational activities are needed to ensure the well being of crewmembers, particularly during future exploratory missions. These devices are referred to as 'passive' countermeasures [8].

A unique feature of passive countermeasures is that they interact with the body's inherent physiological functions to generate positive responses, but do not require additional time be devoted to 'exercising'. Although not designed to replace traditional inflight exercises, passive countermeasures can serve as important supplements. Passive countermeasures have long been employed within the Russian crew health program in the form of pressure cuffs and the 'penguin suit' that provides resistance to body segmental motions [8]. One possible passive countermeasure that has recently received increasing attention is a dynamic foot stimulator (DFS) [8–12].

A DFS provides mechanical stimulation to the soles of the feet and thereby provides support afferentation that is removed upon entry into microgravity. Kozlovskaya and her colleagues have long suggested that a host of negative physiological effects stemming from exposure to microgravity result from loss of support afferentation (i.e. somatosensory input from the soles associated with 1g bipedal stance) leading to muscle atrophy and loss of optimal neuromotor control. The removal of support afferentation initiates a cascade of negative consequences beginning with the suppression of tonic muscle activity of the lower limb extensor muscles. Several studies employing dry immersion as an analog to microgravity have demonstrated the negative consequences of the removal of support afferentation in that the responses to dry immersion closely mimic those observed during actual exposure to microgravity [10,13]. These effects include development of a flexed posture, decreases in lower limb muscle stiffness, decreases in soleus EMG activity accompanied by increases in tibialis anterior activity, modification in motor unit recruitment, and ultimately, muscle atrophy. These modifications in the underlying neurophysiological mechanisms lead to altered patterns of muscle activation during both bipedal postural and locomotor control. However, these same experiments have shown that the intermittent application of a dynamic stimulus to the soles of the feet during dry immersion suppress nearly all of the negative neurophysiological and subsequent behavior consequences associated with the removal of support afferentation [10,13]. Additionally, there have been several reports that demonstrate providing somatosensory input during hindlimb suspension prevents atrophy in rat soleus and gastrocnemius [11,14,15].

Although there are multiple reports suggesting that dynamic foot stimulation may provide effective protection against the neuromotor degradation associated with micogravity, it remains to be determined if a particular pattern (i.e. a combination of spatial and temporal sole stimulation) provides an optimal substitution of support afferentation. Several investigations by our research group have been aimed at determining how both the behavioral context and dynamic foot stimulation parameters impact the resulting neuromuscular responses. We have investigated the effects of background level of activity, body configuration, anatomical stimulation site, muscle spindle input, and Achilles tendon vibration on the responses to mechanical foot stimulation in laboratory settings [9,16,17]. Particularly important for the continued development of an inflight DFS are the findings that the location of stimulation on the sole influences the magnitude of the resulting neuromuscular response and that close temporal pairing of two stimuli from different anatomical sites on the sole can inhibit the response to the second stimulus. These results suggest that close attention should be paid to the pattern of stimulation. One stimulus parameter that has not been investigated is the influence of timing between two consecutive mechanical stimuli to the sole. The previous finding of an inhibition of the response to the second stimulus of two closely temporally paired stimuli occurred in a protocol with an interstimulus interval (ISI) of less than 5 ms [17]. The purpose of the present experiment was to expand the range of ISIs to determine if there were general limits upon the inhibitory response 'window' identified in our previous work [17]. Identifying the limits of any such inhibitory window would provide valuable information regarding the temporal components of a stimulation pattern designed to elicit facilitatory neuromuscular responses to dynamic foot stimulation. It was hypothesized that the second neuromuscular response to two closely timed foot stimulations would result in inhibition of that response but as the time between the two stimuli increased; the amplitude of the second response would also increase.

2. Materials and methods

2.1. Participants

Twelve, healthy, right-handed male ($n = 4$) and female ($n = 8$) volunteers between the ages of 19 and

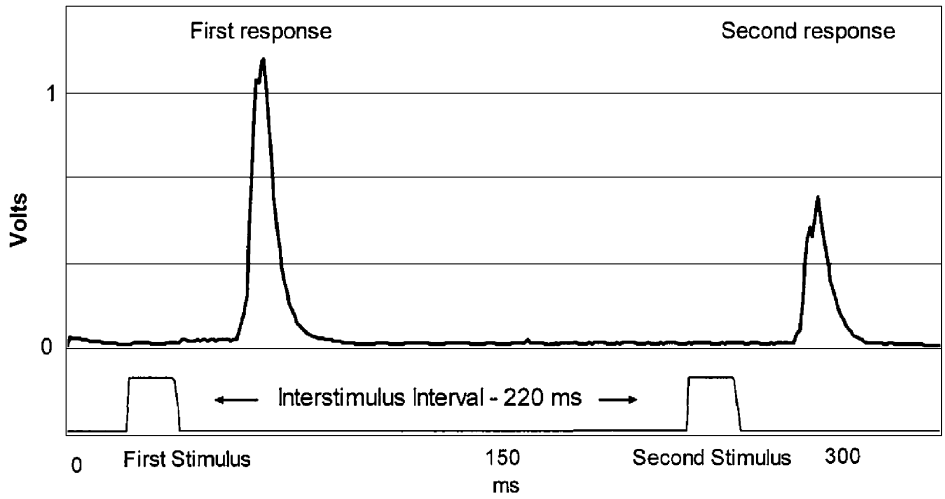

Fig. 1.

35 served as participants in this investigation. All participants provided informed consent as required by the University of Houston's Institutional Review Board.

2.2. Experimental protocol

The basic protocol involved the presentation of a series of stimulation *couplets* consisting of different ISIs. Specifically, each couplet was composed of two mechanical stimuli of 20 ms in duration applied under the fifth metatarsal head at $13.8\,N/cm^2$ over a $1.77\,cm^2$ surface area. Each stimulation couplet was separated in time by either 100, 140, 180, 220, 260, or 300 ms (Fig. 1).

To eliminate possible interaction effects between couplets each couplet was randomly separated by 1, 2, or 3 s. Twenty couplets for each of the six ISI conditions were presented to the participants, totaling 120 experimental stimulation couplets plus an additional 20 'baseline' trials. Each baseline trial consisted of a single stimulus randomly separated by 1, 2, or 3 s. Each ISI condition was separated by a 2-min rest period to prevent the possibility of fatigue. The order of the ISI condition was randomly presented to each subject and the completion of each condition was less than 2 min. Prior to the start of data collection, each participant experienced 10 stimulations to familiarize them with the sensation they would experience during the experiment. This procedure also served to eliminate the possibility of any 'startle' responses from being included in the data analyses.

Various mental activities and mental states have been shown to alter performance [18,19]. Consistent mental

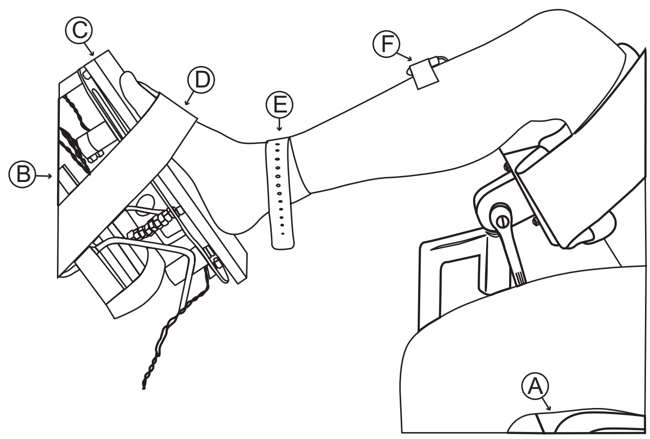

Fig. 2.

activity was maintained with the use of a simple mental task consisting of subjects verbally reciting a series of random numbers positioned in front of the participants at a visually comfortable reading distance. The participants were encouraged to relax with hands on his or her lap and to focus on reciting the numbers rather than the foot stimulation.

2.3. Instrumentation

A Biodex System 3 machine was used to position the participants in a seated position (Biodex Medical Systems, Shirley, NY, USA). Biodex is commonly used in a rehabilitative setting for strength assessment. However, in this study the Biodex was used to standardize and stabilize participant position during mechanical stimulation from the DFS (Fig. 2).

The DFS was attached to the foot plate of the Biodex with the foot being secured over the DFS. This ensured that both the location of the stimulus and the hip, knee and ankle joint remained identical for each stimulation trial.

A custom DFS provided mechanical stimulation to the plantar surface under the fifth metatarsal head with the use of an electrically driven solenoid. Previous work using the DFS indicated that stimulation at this location consistently resulted in the greatest response magnitude in the soleus and lateral gastrocnemius [17]. The DFS was controlled by a LabView program that regulated the solenoid, stimulus duration, and ISI. An electrical signal from the DFS interfaced with an Enhanced Graphics Acquisition and Analysis (EGAA) system (R.C. Electronics Inc., Santa Barbara, CA, USA) system to provide temporal synchronization between stimulation information and EMG data.

Surface EMG was collected from the right lateral gastrocnemius (LG), soleus (SO), and tibialis anterior (TA) with the use of silver–silver chloride preamplifier electrodes attached with double-sided adhesive pads and hypoallergenic medical tape (Therapeutics Unlimited, Iowa City, IA, USA). A reference electrode was secured on the lateral malleolus. The electrode amplifier gain was set to 5 K and root mean square (RMS) values were collected using a moving window with a time constant on the amplifier set to 5.5 ms. Sample rate was set to 1000 Hz. All signals were routed through the EGAA A/D board prior to storage on a desktop computer.

2.4. Data analysis

A data analysis ‘window’ was identified and the data extracted from the window using a custom designed Excel macro routine (Microsoft Corporation, Redmond, Washington, USA). The analysis window was defined as 40–100 ms after the initiation of a stimulus. Onset of neuromuscular activity above quiet baseline typically occurs at approximately 40 ms and ends within 100 ms after initiation of a stimulus. Neuromuscular activity within this window was referred to as a waveform. Peak amplitude and positive integrated area (PIA) were obtained for each individual waveform. The baseline condition (i.e. one stimulus was delivered by the DFS) yielded a waveform labeled the Baseline Response. Each couplet yielded two neuromuscular waveforms in response to the first stimulus and second stimuli. These were labeled as the First Response and Second Response, respectively. For each muscle, condition, and participant, the mean response of the 20 trials was calculated.

Mean scores for each ISI condition, muscle and participant were pooled for group analysis. Repeated measures analysis (SPSS Inc., Chicago, IL, USA) was used to test for significance. A priori planned contrasts (simple and polynomial) were used to compare the First Response of all ISI conditions with Baseline Responses, the Second Response of all ISI conditions with Baseline Responses, and the recovery of the second response with increasing ISI. Second order polynomial trend lines were fit to the data.

3. Results

To identify the temporal parameters associated with neuromuscular inhibition in response to mechanical stimulation of the human sole; this investigation utilized the ISI paradigm, where two stimuli were presented with varying time intervals between the two stimuli. The results indicate that two closely spaced stimuli results in a near complete inhibition of the response to the second stimulus with the response gradually returning to baseline levels as the time between the two stimuli increases.

Preliminary analyses revealed no differences between the responses of male and female participants so the data were collapsed over gender for additional analyses. There was a high positive correlation between peak responses and PIA ($r > 0.95$), therefore only the results for the peak measures will be reported. For each muscle, there were no significant difference between first peak of all ISI conditions and the baseline peak response. For the TA and SO, the amplitude of the second response was significantly less than that of the baseline response, with the

Table 1
Statistical comparisons between baseline and second peak responses of the ISIs ($p < 0.05$)

Muscle	100 ms	140 ms	180 ms	220 ms	260 ms	300 ms
TA	Decrease	Decrease	Decrease	Decrease	Decrease	No change
SO	Decrease	Decrease	Decrease	Decrease	Decrease	No change
LG	Decrease	Decrease	Decrease	Decrease	No change	No change

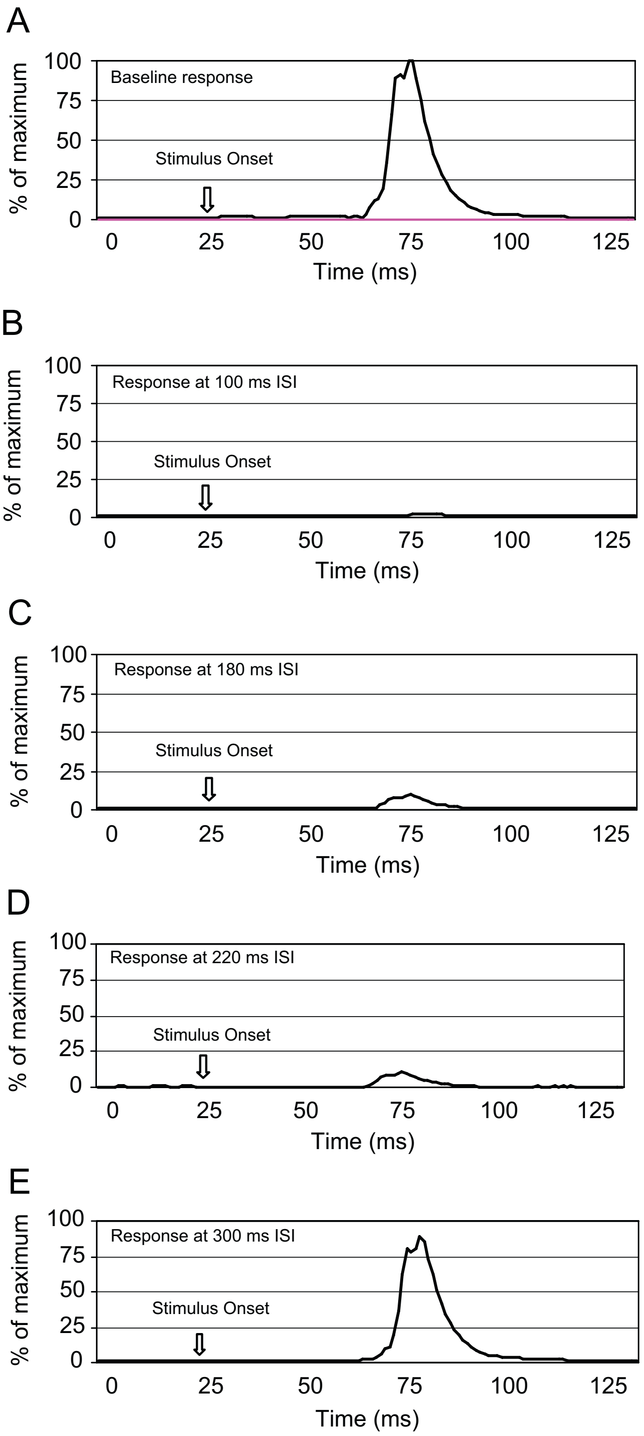

Fig. 3.

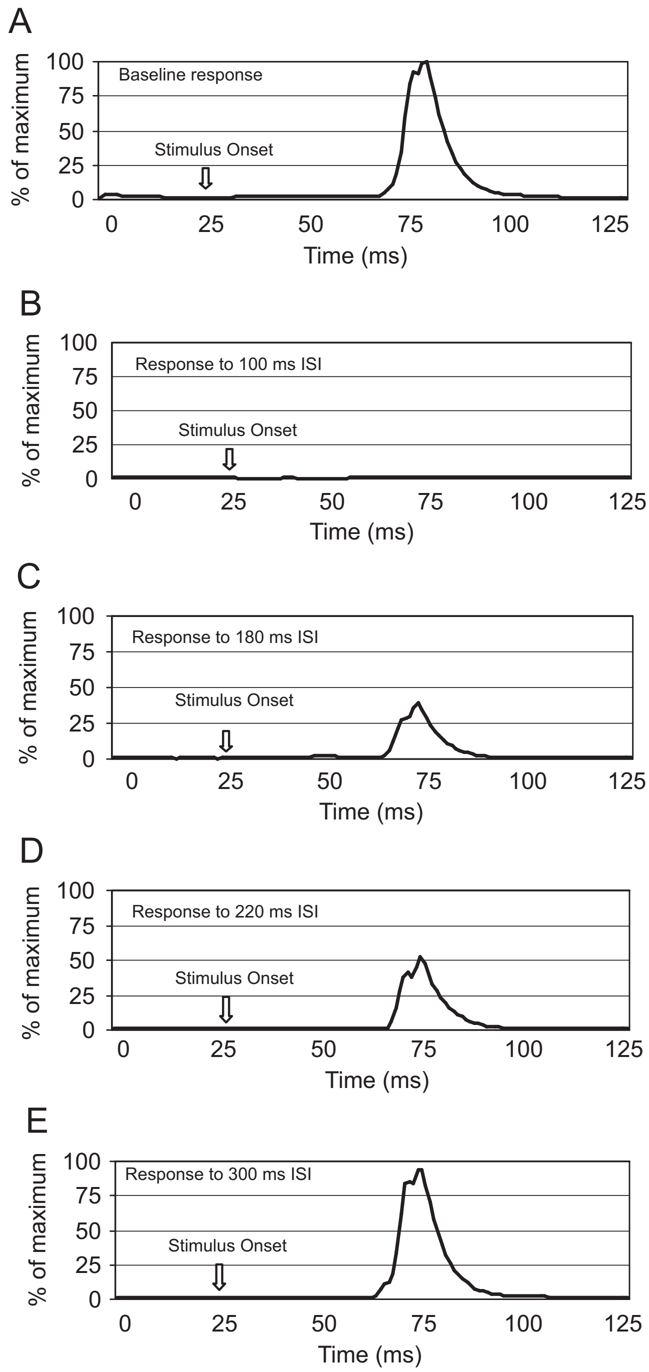

Fig. 4.

exception of the 300 ms ISI condition. For the LG, the second response in the 100, 140, 180, and 220 ISI conditions were less than those of baseline (Table 1).

Figs. 3–5A–E reflect exemplar data for each muscle within each ISI condition. Fig. 6 A–C displays the group average of the normalized peak amplitudes for each ISI condition as well as the resulting trend lines of linear regression equations. As can be observed in Fig. 6, the regression equation for each muscle's response pattern quite accurately models the observed data ($R^2 > 0.91$).

4. Discussion

This investigation was designed to examine if the interval of time between two closely spaced stimuli

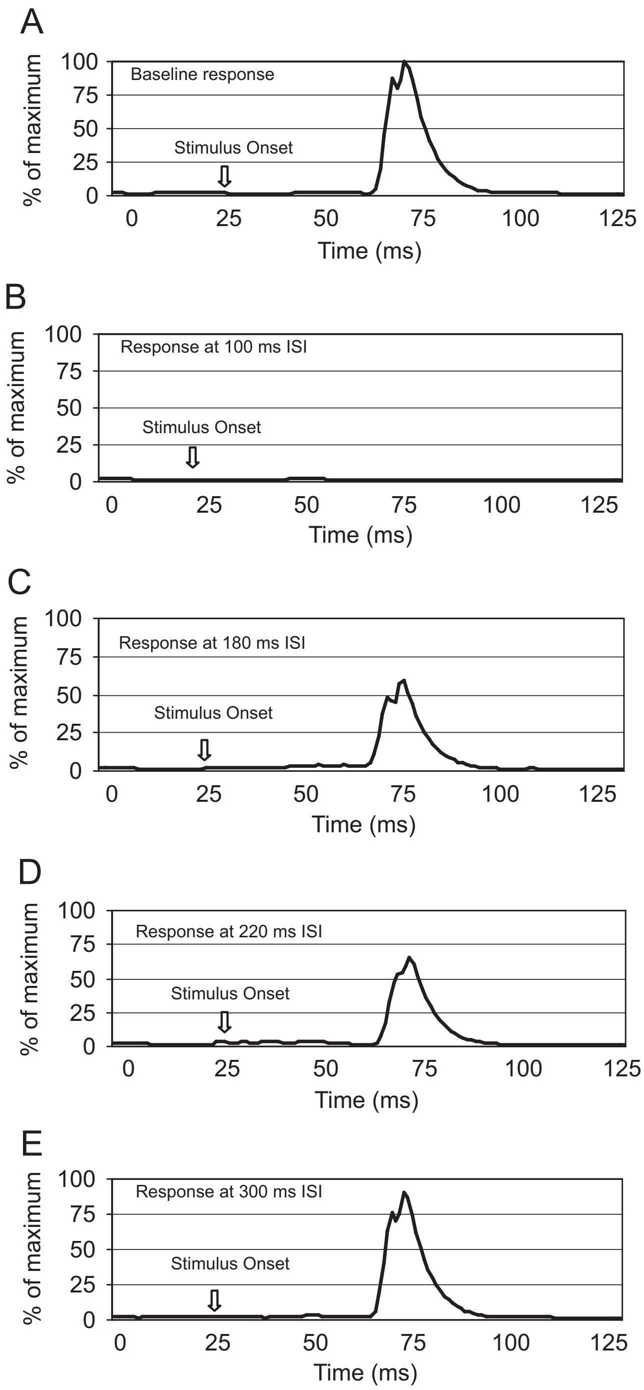

Fig. 5.

attenuated the neuromuscular response to the second stimulus. Identifying such an 'inhibitory window' has important implications for the development of a DFS that would be designed to promote neuromuscular activation in crewmembers during extended duration spaceflight.

This investigation revealed that when two mechanical stimuli are closely temporally paired, the response to the second stimulus is significantly attenuated, but as the time between stimuli increased, the second response returned to amplitude levels equivalent to the baseline response. For the muscles tested, all second responses returned to baseline levels when the ISI was 300 ms. The second order trend analyses displayed in Fig. 6 A–C indicate that generally there is a 'threshold' effect in that responses remain suppressed through the 220 ISI but return to 75% or more of baseline values by 260 ISI. This pattern is particular true for the responses in the LG and SO. These results strongly suggest that the neural pathway involved in the response has a 'refractory' period which needs to be accounted for in the development of any inflight DFS countermeasure designed to promote increased neuromuscular activation. The data make clear that it is important to temporally separate consecutive stimuli when providing patterned stimuli to the soles of a crewmember.

Although it is beyond the scope of this investigation to determine the precise neurophysiological mechanisms responsible for either the increase in neuromuscular activation in response to DFS or the attenuation of the second response of two closely paired stimuli, the latency of the response suggests it is of spinal origin. All active responses were initiated within 50 ms of the application of the stimulus consistent with spinal reflexe latencies. However, we do not believe the observed responses can be classified as stretch reflexes since the magnitude of stimulus was not great enough to modify ankle angle (i.e. no stretch of the SO and LG) and a foot strap was employed to ensure the foot remained in contact with the DFS device. Additionally, similar neuromuscular responses to those observed in the plantar flexors were recorded from the TA which was not subject to the possibility of stretch in our experimental protocol. We suggest that the observed responses are likely to be polysynaptic resulting from a combination of cutaneous and muscle spindle input from the foot musculature. Previous work has demonstrated these responses are inhibited by Achilles tendon vibration, suggesting a role for Ia afferents in the generation of the response [17]. Tendon vibration is known to preferentially influence the firing rates of Ia afferents [20,21]. Future investigations will attempt to determine the various contributions of cutaneous versus muscle spindle input in the generation of the neuromuscular responses to DFS.

It is also important to note that consistent with our previous investigations, the current protocol resulted in neuromuscular responses to mechanical stimulation of the sole despite the fact that the muscles were in a quiescent state prior to the delivery of the stimulus.

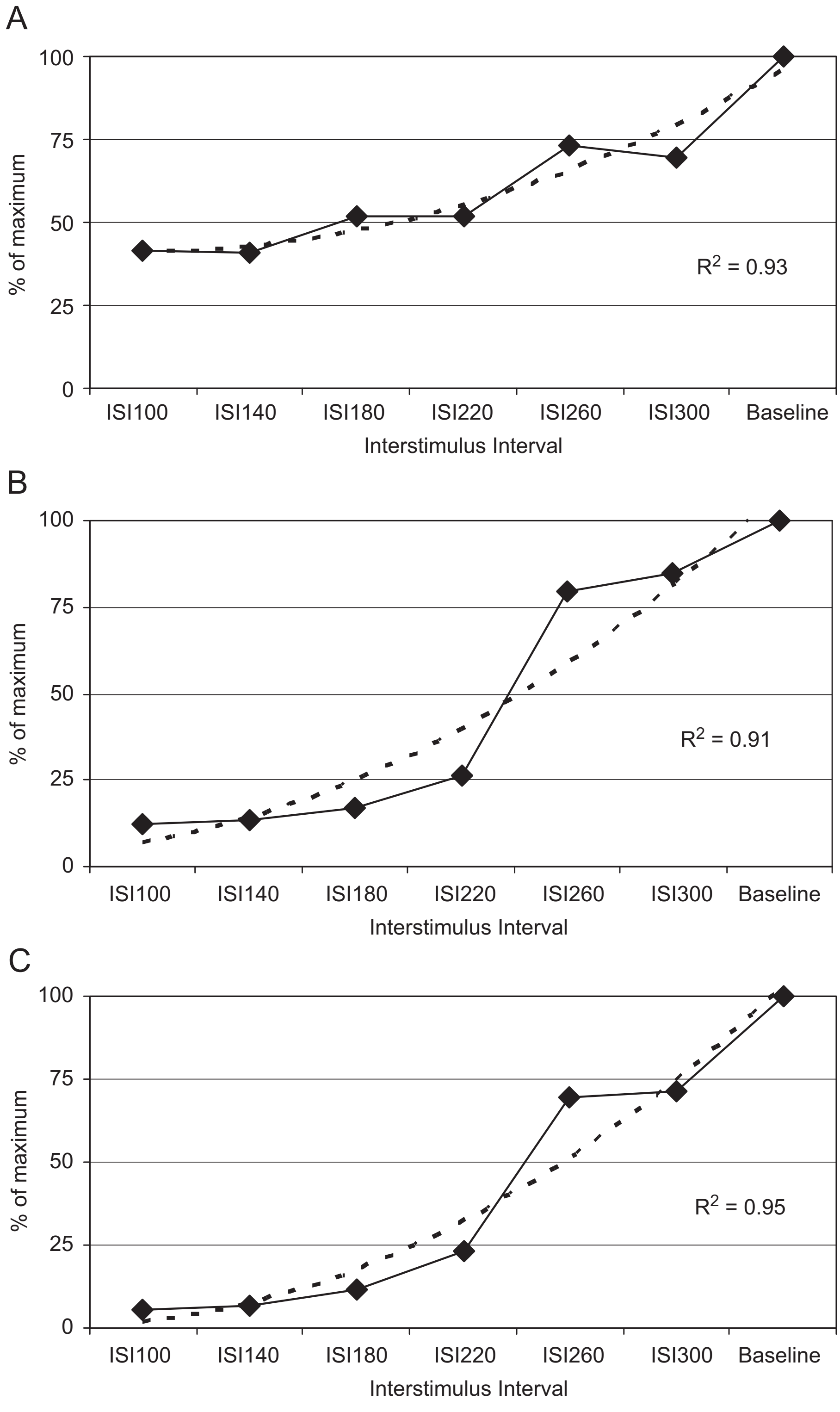

Fig. 6.

This is in contrast to sub-pain threshold level electrical stimulation of the sole which requires that the muscle be voluntarily activated before responses are observed [22,23]. Thus, the current results provide additional evidence that mechanical stimulation to the soles can be used to promote neuromuscular activation even in quiescent muscles, thereby suggesting that a passive in-flight DFS countermeasure can be developed to attenuate the neuromotor degradation typically experienced by crewmembers.

References

[1] J.J. Bloomberg, M.F. Reschke, W.P. Huebner, B.T. Peters, S.L. Smith, Locomotor head–trunk coordination strategies following space flight, Journal of Vestibular Research 7 (1997) 161–177.

[2] C.S. Layne, A.P. Mulavara, P.V. McDonald, C.J. Pruett, I.B. Kozlovskaya, J.J. Bloomberg, The effect of long duration spaceflight on postural control during self-generated perturbations, Journal of Applied Physiology 90 (3) (2001) 997–1006.

[3] P.V. McDonald, C. Basdogan, J.J. Bloomberg, C.S. Layne, Lower limb kinematics during treadmill walking after space flight: implications for gaze stabilization, Experimental Brain Research 112 (2) (1996) 325–334.

[4] R.H. Fitts, D.R. Riley, J.J. Widrick, Physiology of a microgravity environment: invited review: microgravity and skeletal muscle, Journal of Applied Physiology 89 (2000) 823–839.

[5] I.B. Kozlovskaya, Y.V. Kreidich, V.S. Oganov, O.P. Koserenko, Pathophysiology of motor functions in prolonged manned space flights, Acta Astronautica 8 (1981) 1059–1072.

[6] C.S. Layne, A.P. Mulavara, P.V. McDonald, C.J. Pruett, I.B. Kozlovskaya, J.J. Bloomberg, Alterations in human neuromuscular activation during over ground locomotion after long-duration spaceflight, Journal of Gravitational Physiology 11 (2004) 1–16.

[7] I.B. Kozlovskaya, I.V. Sayenko, O.L. Vinogradova, T.F. Miller, D.R. Khusnutdinova, K.A. Melnik, E.N. Yarmanova, New approaches to countermeasures of the negative effects of microgravity in long-term space flights, Acta Astronautica 59 (2006) 13–19.

[8] I.B. Kozlovskaya, A.D. Egorov, Some approaches to medical support for Martian expedition, Acta Astronautica 53 (2003) 269–275.

[9] K.E. Forth, C.S. Layne, Background muscle activity enhances the neuromuscular response to mechanical foot stimulation, American Journal of Physical Medicine & Rehabilitation 86 (2006) 50–56.

[10] I.B. Kozlovskaya, I.V. Sayenko, D.G. Sayenko, T.F. Miller, D.R. Khusnutdinova, K.A. Melnik, Role of support afferentation in control of tonic muscle activity, Acta Astronautica 60 (2007) 285–294.

[11] A. Kyparos, D.L. Feeback, C.S. Layne, D.A. Martinez, M.S.F. Clarke, Mechanical stimulation of the plantar foot surface attenuates soleus muscle atrophy induced by hindlimb unloading in rats, Journal of Applied Physiology 99 (2) (2005) 739–746.

[12] C.S. Layne, A.P. Mulavara, P.V. McDonald, C.J. Pruett, I.B. Kozlovskaya, J.J. Bloomberg, The use of inflight foot pressure as a countermeasure to neuromuscular degradation, Acta Astronautica 42 (1998) 231–246.

[13] A.I. Netreba, D.R. Khusnutdinova, O.L. Vinogradova, I.B. Kozlovskaya, Effect of dry immersion in combination with stimulation of foot support zones upon muscle force–velocity characteristics, Journal of Gravitational Physiology 11 (2) (2004) 129–130.

[14] M. Falempin, S.F. In-Albon, Influence of brief daily tendon vibration on rat soleus muscle in non-weight-bearing situation, Journal of Applied Physiology 87 (1) (1999) 3–9.

[15] L. De-Donckeer, F. Picquet, M. Falempin, Effects of cutaneous receptor stimulation on muscular atrophy developed in hindlimb unloading condition, Journal of Applied Physiology 89 (6) (2000) 2344–2351.

[16] C.S. Layne, K.E. Forth, M.F. Baxter, J.J. Houser, Voluntary neuromuscular activation is enhanced when paired with a mechanical stimulus to human plantar soles, Neuroscience Letters 334 (2002) 75–78.

[17] C.S. Layne, K.E. Forth, A.F. Abercromby, Spatial factors and muscle spindle input influence the generation of neuromuscular responses to stimulation of the human foot, Acta Astronautica 5 (2005) 809–819.

[18] G. Ebersbach, M.R. Dimitrijevic, Influence of concurrent tasks on gait: a dual-task approach, Perceptual and Motor Skills 81 (1995) 107–113.

[19] A.L. Adkin, J.S. Frank, M.G. Carpenter, G.W. Peysar, Postural control is scaled to level of postural threat, Gait and Posture 12 (2000) 87–93.

[20] D. Burke, K.-E. Hagbarth, L. Lofstedt, B.G. Wallin, The responses of human muscle spindle endings to vibration of non-contracting muscles, Journal of Physiology 261 (1976) 673–693.

[21] G. Courtin, T. Pozzo, B. Lucas, M. Schieppati, Continuous, bilateral Achilles' tendon vibration is not detrimental to human walk, Brain Research Bulletin 550 (2001) 107–115.

[22] R.B. Stein, P. Bawa, Reflex responses of human soleus muscle to small perturbations, Journal of Neurophysiology 39 (1976) 1105–1116.

[23] D. Burke, H.G. Dickson, N.F. Skuse, Task-dependent changes in the response to low-threshold cutaneous afferent volleys in the human lower limb, Journal of Physiology 432 (1991) 445–458.