Voluntary Muscle Contractions in Advance of Mechanical Foot Stimulation To Enhance Neuromuscular Reflex Responses

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Abstract—Researchers seek to determine the modulating effect of background muscle activity on enhanced neuromuscular responses to mechanical foot stimulation. A small solenoid embedded within a platform provided non-noxious stimulation to the lateral portion of the sole for 100 ms at 3 mm protrusion. Stimulation was applied during different contraction levels of the homonymous muscle and of remote, Jendrassik-like contractions. Root mean square electromyography was measured from the soleus and lateral gastrocnemius. Homonymous muscle contraction linearly increased the neuromuscular response to foot stimulation, although no effect was exhibited from remote contractions. The levels of response to stimulation in all conditions were 80-100 percent of maximal contraction levels. Mechanical foot stimulation can be used to elicit and enhance neuromuscular activity of the *triceps surae* muscles, particularly when combined with preexisting "background" voluntary contractions. This activity could be used to attenuate neuromuscular degradation experienced during prolonged bedrest and during extended stays in microgravity.

Muscle atrophy is a concern for many populations, including the elderly, bedridden patients, patients with injured spinal cords, and astronauts. Often the environments or circumstances surrounding these individuals do not facilitate exercise volumes and/or magnitudes required to maintain muscle mass. Electrical stimulation, sensory stimulation and robotically driven movements are among the various stimulation techniques used in rehabilitation to counter muscle atrophy and unorganized neuromuscular activation patterns with the aim of facilitating normal neuromuscular activity and patterns.[1,2]

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Non-noxious cutaneous stimulation of the soles of the feet can also modify neuromuscular activity, alter lower limb activity,[3] postural responses[4,5] and even restore anticipatory postural responses that vanish in microgravity.[6,7] Exhibiting a sensitivity to ground reaction forces, cutaneous afferents from the soles of the feet are thought to be included in the general category of load afferents. Load-detecting afferents are important for the existence and maintenance of postural and locomotion patterns in normal[8,9] and spinal cord injured patients.[2,10] Moreover, attenuation of muscle atrophy has been achieved with the application of non-noxious, dynamic mechanical stimulation to the hindfeet of rats in a hindlimb suspension model.[11-13] For example, Kyparos et al.[12] demonstrated complete attenuation of soleus muscle atrophy relative to controls in a rat hindlimb suspension protocol by providing low levels of intermittent mechanical stimulation to the plantar surface.

For therapeutic use, a specialized "boot" that provides mechanical stimulation to the foot could be used to increase lower limb neuromuscular activation. The benefits would extend beyond muscle atrophy attenuation to include an elevated use of sensory and neural apparatus that otherwise degenerates with disuse.[14] Such foot stimulations could be tailored to the needs of the patient, including whether the "boot" is worn when passive or in combination with voluntary muscle activity.[15]

To date, the primary methods used to counter neuromotor degradation during flight consist of modified exercises traditionally performed in 1 g. These include treadmills, bicycle ergometers, bungy cords, and modified resistance exercise devices. These exercise devices assist astronauts in maintaining cardiovascular and skeletal-musculature fitness. However, even in combination, these exercises are not completely effective in preventing the negative consequences of unloading on the neuromotor system. Additionally, performing these exercises is time-consuming, thereby preventing the crewmembers from completing important operational tasks.

Before therapeutic cutaneous foot stimulation can be applied to humans, however, we need further understanding of the human response to mechanical cutaneous stimulation. The integration of cutaneous stimulation into the motor system is widely accepted in the literature as being task-dependent and context specific.[16,17] Two fundamental differences between separate tasks are the muscles involved and the level to which they are contracted.

Preexisting muscle contraction levels are a determining factor for the expression of cutaneous reflexes, for these reflexes are only present in actively contracting muscles.[16,18] As a result, research into cutaneous reflex responses often involves a maintained level of background voluntary contraction.[18,19] A variety of voluntary contraction levels have been previously used, ranging from 1-2% to 50% maximum voluntary contraction (MVC), although few investigators have varied the level of contraction within a study. Aniss et al.[18] compared single motor unit responses in ankle muscles elicited from cutaneous stimulation of the foot, during both weak and strong contractions, 5% and 30% MVC, respectively. At the level of the individual motor unit, a greater magnitude of response was measured for the higher contraction level.[18]

Cutaneous reflexes from the studies referenced above were elicited following electrical stimulation to nerves radiating from areas of the feet. Mechanical foot stimulation to the soles of the feet has also generated facilitating effects during maximal background voluntary contractions. Agonist neuromuscular activity during seated maximal ankle dorsiflexion and plantar flexion was enhanced significantly when coupled with mechanical foot stimulation.[3] A passive response to mechanical foot stimulation has since been elicited by applying a 100 ms stimulation to the lateral side of the forefoot.[20] The response has been shown to be sensitive to static ankle angles, and inhibited by soleus stretch.[20] However, the relationship between the level of background voluntary contractions and subsequent response to mechanical foot stimulation is still unknown.

Furthermore, most natural movements are not isolated to a single muscle contraction but often include multiple or even distant muscle groups, suggesting an integrated method of control. The Jendrassik maneuver is a widely researched set of remote isometric contractions of the upper body. The maneuver requires the hands to be interlocked and pulled against each other. The Jendrassik maneuver is often used as a clinical test because of its potentiating effect on the tendon tap reflex and H reflex,[21,22] both of which are considered "spinal reflexes." This potentiation has been attributed to the excitation of soleus motoneuron pools or reduction of presynaptic inhibition to enhance the reflex response.[23-25] Short latency neuromuscular responses observed with mechanical foot stimulation are also suggested to be of spinal origin.[20] Therefore, it is reasonable to suggest the Jendrassik maneuver might also facilitate neuromuscular responses to mechanical foot stimulation.

Consequently, before mechanical foot stimulation can be incorporated into a therapeutic device that provides controlled stimulation and response, we must determine the effect of background muscle activity because the same stimulation may result in different responses if patients are performing different activities. This study investigated the changes in response to mechanical foot stimulation with different levels of voluntary local, i.e., homonymous (*triceps surae*) and remote (upper body) contractions. We hypothesized that both local and remote background contractions would facilitate the neuromuscular response to mechanical foot stimulation. These findings will not only contribute to the development of a therapeutic device, but provide implications for use with individuals unable to reach contraction levels required to maintain muscle mass.

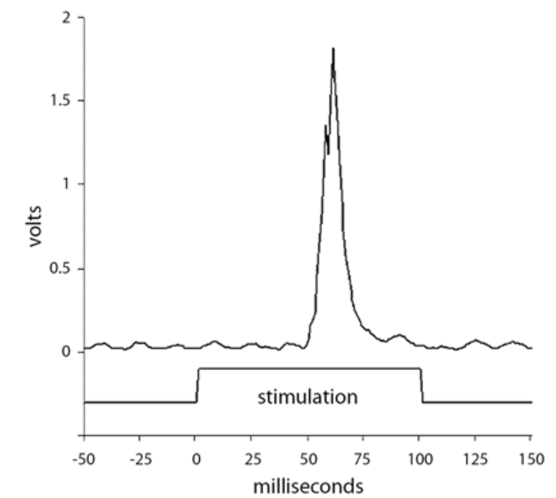

Figure 1. A Typical Response of the SOL to a Single Lateral Foot Stimulation

Methods

Dynamic Foot Stimulator (DFS) Protocol

This study applied a non-noxious mechanical stimulus to the lateral portion of the sole of the foot during different levels of voluntary local, i.e., homonymous (*triceps surae*) and remote (upper body) contractions. Neuromuscular responses were measured with surface electromyography of the soleus (SOL) and lateral gastrocnemius (GA). This study was conducted in the Laboratory of Integrated Physiology, University of Houston, and performed by 15 right-handed healthy subjects aged between 18 and 35 years. All were free of any known muscular or neurological medical conditions. Subjects were recruited from the university community. They provided their informed consent to participate in this study, which was approved by the University of Houston's Committee for the Protection of Human Subjects. Exclusion criteria included failure to respond to the stimulation while seated and passive. Only one potential subject failed to respond.

Electrode sites were located and prepared and electrodes positioned over the belly of the SOL and GA (see EMG collection procedure below). The experimental environment for all experiments minimized external stimulation such as noise, light, and distractions.

Lateral foot stimulation was applied after two seconds of maintained steady state of contraction at the appropriate level (see foot stimulation and background activity levels for more details). Table 1 provides summary information about each condition. The order of the conditions was randomized for each subject to eliminate any order affect.

Table 1. Experimental conditions

Condition	Position	Contraction	Contraction Level
Base	Seated	None	0%
TS40	Seated	*Triceps surae*	40%
TS80	Seated	*Triceps surae*	80%
Jend40	Seated	Jendrassik	40%
Jend80	Seated	Jendrassik	80%
Both40	Seated	Both	40%
Both80	Seated	Both	80%

Foot Stimulation

The DFS device contained one solenoid (surface area 2.5 cm), controlled through customized software (LabView, National Instrument Corp, Austin, Texas). The device was embedded within a custom-built wooden platform. Velcro straps, fed through narrow slits in the platform on either side of the foot, secured the foot in place. Each condition consisted of lateral sole stimulation applied for 100 ms at 20 psi, to 3 mm protrusion, 16 times within a 5-minute period. A variable inter-stimulus interval with a two-minute rest period between each condition were used to prevent event anticipation and sensory receptor habituation. To avoid muscle fatigue, stimulations were delivered in series of 5-7 stimulations with rest periods in between. During stimulations, subjects were required to read aloud a series of random numbers, to control mental attention.[26] The random numbers were displayed on paper, a meter in front of the subject at head height, which partially covered the computer screen.

Background Muscle Activity

The subjects performed isometric plantar flexion and Jendrassik-like contractions at maximal contraction from which 40 and 80 percent of maximal effort contraction levels were calculated. SOL maximal contraction levels were determined with a minimum of three isolated trials. A mean peak amplitude value was calculated from three peak amplitudes, each the peak amplitude of a separate 1 s sample of the maximal contractions. *Triceps surae* contraction levels were controlled by subjects through visual feedback of the EMG associated with their soleus contraction from an oscilloscope. In all conditions, EMG responses to foot stimuli were hidden from subjects as only a limited viewing portion was visible on the oscilloscope screen. Jendrassik-like contraction levels were determined with a modified use of a hand dynamometer (Lafayette Instrument, Lafayette, IN). The right hand grasped the handle, and a glove was used on the left hand for comfort. Subjects were instructed to have the thumbs pointing up and not to squeeze the hand dynamometer in the hand, but, instead, to pull against the fingers, as an extension of force generated from the arms. Maintenance of background muscle levels was practiced at 40% and 80% of maximal effort levels with visual feedback of the hand dynamometer. Conditions involved subjects performing separate *triceps surae* and Jendrassik-like contractions, as well as simultaneous TS and Jendrassik-like contractions, at 40% and 80%.

EMG Data Collection

The skin was cleansed, abraised, and a silver-silver chloride preamplifier electrode (Therapeutics Unlimited, Iowa City, Iowa, USA) attached to the site with electrode gel and double-sided adhesive tape. Surgical tape ensured that the electrode maintained its position on the skin over the belly of the respective muscle. The ground lead was placed just above the right ankle using an elastic strap. Sampling rates were preset to 1000 Hz. Both the EMG root mean squared data from the SOL and GA (5.5 ms time constant) and solenoid activation signal were simultaneously collected by the Enhanced Graphics Acquisition and Analysis (EGAA) Board (R.C. Electronics Inc., Santa Barbara, CA), in order to synchronize stimulus and EMG data waveforms for the analysis.

Data Analysis

A custom Excel program (Microsoft Corporation, Redmond, WA, USA) identified a 300 ms period surrounding the stimulation: 100 ms preceding stimulation, 100 ms during stimulation and 100 ms post-stimulation. Visual inspection of the 100 ms preceding stimulation identified a consistent baseline level prior to stimulation. A 200 ms window of analysis for each stimulation was defined by the initiation of the stimulus and the following 200 ms. For each condition, the first response waveform was disregarded to reduce a potential startle response, and the subsequent 15 response waveforms were averaged. The peak amplitude of the average waveform was next determined for each condition for each subject. This method ensured that the response peak amplitude was extracted rather than peaks associated with voluntary contraction, for a clear response peak to the stimulus was easily identified. The data were transformed with a square root function to adjust for a mild distribution skew and to facilitate a normal distribution. Repeated measures analysis was used to test for possible differences between peak amplitude respsonses of experimental conditions. Two factors were included: "contraction type" and "level of contraction." Greenhouse-Geissner adjustments were made when the covariance matrix circularity assumption was violated. *A priori* contrasts were used to test planned comparisons.

Results

Basic Neuromuscular Response

In both the SOL and GA, the basic neuromuscular reflex response to lateral foot stimulation was consistent in pattern, duration, and latency. The response latency was ~50 ms, and continued for ~20 ms. The peak latency typically occurred at 60 ms; however, the amplitude of the response was highly variable (Fig. 1).

Peak Amplitude of Response

Overall, greater local background contractions of the *triceps surae* elicited a greater neuromuscular reflex response to mechanical stimulation of the sole in both the SOL and GA. The GA demonstrated a significant linear increase in reflex response with increasing voluntary *triceps surae* contraction levels ($p = 0.028$). The SOL reflex response approached significance exhibiting the same trend ($p = 0.074$) (Fig. 2).

Conversely, the conditions involving a remote contraction from the upper body combined with no voluntary *triceps surae* activation (jend40 and jend80) yielded no difference from the baseline neuromuscular reflex response of the SOL or GA to foot stimulation ($p > 0.05$). Additionally, Jendrassik-like contractions did not alter the response profile or amplitude when paired with background *triceps surae* contractions. There was no difference between "TS" and "both" conditions.

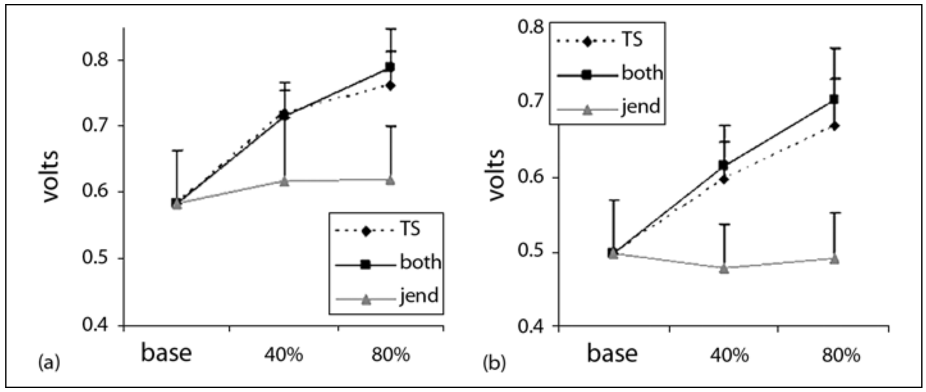

Figure 2. The linear increase in peak amplitude response with voluntary background contraction levels of the TS and BOTH (TS + Jendrassik): (a) SOL mean (+SE) amplitude response; (b) GA mean (+SE) amplitude response.

Response vs. Maximum Contraction

Peak reflex response amplitudes in the SOL reached similar levels as those measured during voluntary maximal contractions in a seated position. Figure 5 represents the SOL reflex peak as a percentage of voluntary SOL maximal contraction. Contraction levels reached by the reflex response to mechanical stimulation of the sole were sufficient to create visible contractions of the SOL and GA and accompanying leg movement (Fig. 3).

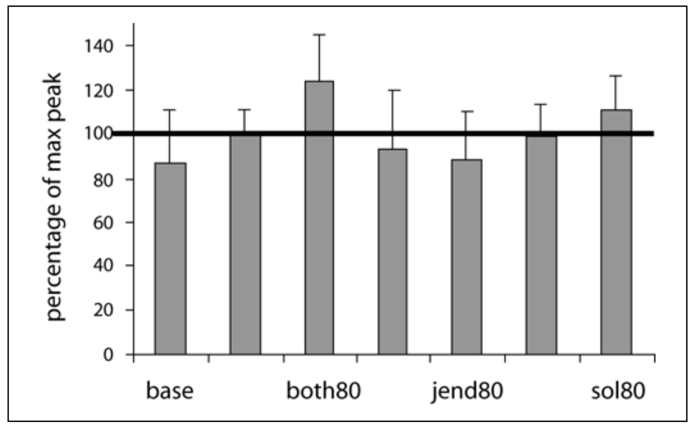

Figure 3. The level of SOL peak amplitude reflex response as a percentage of SOL voluntary maximum contraction peak amplitude (+SE). The bold line represents maximal peak amplitude values.

Inhibition

For all conditions, including a voluntary background *triceps surae* contraction, an additional response waveform feature was observed: an inhibition for ~50 ms post-response. This inhibition is also maintained when a background Jendrassik contraction is added to the background *triceps surae* contraction.

Discussion

The aim of this study was to determine the modulating effect of background muscle activity on the neuromuscular response of the plantar flexor musculature upon mechanical foot stimulation. Sensory stimulation generated by lateral foot stimulation elicited a similar sharp neuromuscular response in both passive and active *triceps surae* musculature. This suggests that a therapeutic device incorporating mechanical foot stimulation to facilitate plantar flexor neuromuscular activity can be applied to patients with low mobility as well as to individuals during some form of physical activity.

The temporal features of the responses remained constant across all conditions with variations only displayed in response peak amplitudes. A response with a latency as short as ~50 ms and duration of ~20 ms suggests an oligosynaptic pathway for this response to mechanical foot stimulation. The non-noxious lateral stimulus, which presented rapid contact with a 3 mm depression of the sole site, likely stimulated fast and slow adapting cutaneous mechanoreceptor units[27] and may also stimulate muscle spindles of intrinsic foot muscles. The mechanical stimulation generated a response with a latency 20 ms shorter than cutaneous reflexes elicited electrically,[19,28] 10-20 ms longer than short latency components, and 15-25 ms shorter than medium latency components of mechanically induced stretch reflexes.[29] Also, the response occurring when the *triceps surae* is electrically silent is inconsistent with cutaneous reflexes elicited with non-noxious electrical stimulation, which require an actively contracting muscle.[16,18]

Regardless of the exact neurophysiological mechanisms, the presence of background voluntary contractions of the *triceps surae* produced a positive linear relationship between the level of background *triceps surae* contractions and the amplitude of the peak responses. Present findings are generally consistent with an increase in electrically elicited cutaneous responses with background contractions of the homonymous muscle from both non-noxious[18] and noxious foot stimulation.[30] The response to noxious stimulation with increasing background contractions demonstrated a linear trend until 30-40% maximal contraction, after which the response was saturated.[30]

For all conditions, including a condition when no voluntary background contraction was present, the SOL peak amplitudes reached with foot stimulation were at least 80% of the maximum peak amplitude. Moreover, the conditions that included 80% SOL contractions generated peak amplitude responses to an equal or higher level of maximum contractions. Although the variability between subjects for this comparison was substantial, the prevailing conclusion is that the peak magnitude of the SOL reflex response to foot stimulation is comparable to moderate or upper level voluntary SOL contractions. This implies that dynamic mechanical foot stimulation has the ability to activate a substantial number of motor units of the plantar flexor musculature. Thus, these results support the use of mechanical foot stimulation for individuals that struggle to produce voluntary contractions of the lower limb, whether requisite for generating moderate level contractions in a passive muscle or for enhancing voluntary contractions to obtain higher peak amplitudes.

Voluntary activation of the homonymous muscle is expected to facilitate the response observed in this study in two ways—First, by exciting the soleus motorneuron pool thresholds with descending commands, lowering thresholds, and creating an excited spinal environment for subsequent sensory inputs. This concept is in agreement with the attribution of greater cortical activity, creating larger long latency cutaneous reflex responses during voluntary muscle contractions rather than similar levels of posturally driven contractions.[19] Second, isometric voluntary contractions elevate muscle spindle output during a maintained contraction,[31] which may contribute to a facilitating spinal environment for additional afferent input.

In addition to the enhanced response to foot stimulation, another feature of the response waveform pattern was identified during the presence of background contractions, that being a post response inhibition period with a duration of ~55 ms. This inhibition may result from *Ib* inhibitory afferents or recurrent inhibition triggered from the initial response. Interestingly, visual inspection of individual stimulations revealed the occasional stimulation that failed to produce a clear response but still exhibited notable inhibition. This suggests that the inhibition was not generated by negative feedback loops from the responding muscle, but rather from sensory afferents directly associated with the stimulation.

Remote contractions in the form of Jendrassik-like contractions yielded no change to the neuromuscular response to foot stimulation; nor did they affect the facilitated response created by the background *triceps surae* contraction when both local and remote contractions were simultaneously performed. This was unexpected because Jendrassik contractions provide a strong potentiation for stretch and H-reflexes. Thus, the results of this study suggest that a global excitation of the *triceps surae* motorneuron pools is not generated by a remote Jendrassik-like contraction,[25] for enhancement of the response to the stimulation would have been expected were this the case. This also indirectly implies that *Ia* input is not a primary contributor to the mechanically-induced response from the plantar surface, as *Ia* afferents are potentiated by Jendrassik maneuvers.[25]

Conclusion

Overall, the findings in this study support the idea of dynamic foot stimulation as a viable method for creating and enhancing neuromuscular activity of the SOL and GA. The stimulation could be used in conjunction with guided movements to help insert a contraction-inhibition pattern that may otherwise be missing, or the simulation could be simply employed as a facilitator to achieve higher peak amplitude responses. Thus, mechanical foot stimulation could provide a rehabilitation approach for encouraging sensory motor interactions of the lower limbs, stimulating the spinal cord, and attenuating muscle atrophy and neuromuscular degradation. Individuals prone to muscle atrophy stand to benefit the most from such an approach, through both the treatment and attenuation of muscle atrophy. Independent of the potential use, however, this study demonstrated the value of lateral foot stimulation as a non-invasive, non-noxious method for generating neuromuscular activity.

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Publications

Forth, K. E. and C. S. Layne. "Background Muscle Activity Enhances the Neuromuscular Response to Mechanical Foot Stimulation" (2006). (*In review*.)

Presentations

Forth, K. E. and C. S. Layne. "Neuromuscular Response to Context-Specific Foot Stimulation," Annual meeting of the Society for Neuroscience, Washington D.C., Nov. 2005.

Kyparos, A., D. L. Feeback, C. S. Layne, D. A. Martinez, and M. S. F. Clarke. "Dynamic Foot Stimulation as a Potential Countermeasure to Muscle Atrophy," 4th Symposium of Aerospace Medicine and Space Research, Oinouses, Chios, Greece, Sept. 2005.

Funding and Proposals

Clarke, M. S. F., C. S. Layne, and W. Boling. "Development of New Technologies for Assessing the Effects of Physical Activity on Skeletal Muscle Function and Physical Fitness in Field-Based Situations," Grants To Enhance and Advance Research, University of Houston, May 2003, $23,284.

Incidentals

During the previous reporting period, ISSO-supported student, Katharine E. Forth obtained her Ph.D. in Motor Control from the Department of Health and Human Performance, University of Houston. She is continuing in her role as a postdoctoral fellow in the Neurosciences Laboratory at NASA-Johnson Space Center.

During the reporting period, Andrew Abercromby, who previously worked on the project (see publications and presentations), obtained his Ph.D. degree in Motor Control from the Department of Health and Human Performance, University of Houston. Dr. Abercromby is now employed in the Anthropometrics Laboratory at the NASA-Johnson Space Center.