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RESEARCH ARTICLE

Background Muscle Activity Enhances the Neuromuscular Response to Mechanical Foot Stimulation

ABSTRACT

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Objective: The aim of the present study was to determine the modulating effect of background muscle activity on enhanced neuromuscular responses to mechanical foot stimulation.

Design: A small solenoid embedded within a platform provided nonnoxious stimulation to the lateral portion of the sole for 100 msecs at a 3-mm protrusion. The stimulation was applied during different contraction levels of the homonymous muscle and of remote, Jendrassik-like contractions. Peak amplitudes of the neuromuscular responses were measured from the soleus and lateral gastrocnemius muscles using root mean square electromyography.

Results: Homonymous muscle contraction linearly increased peak amplitudes of the neuromuscular response induced by foot stimulation. Remote muscle contractions did not modulate the response. In all conditions, peak amplitudes of the reflex response reached 80–100% of maximal contraction levels. There was also a prolonged inhibition of homonymous contractions that lasted approximately 55 msecs after the excitatory neuromuscular response.

Conclusions: An application of mechanical foot stimulation enhanced neuromuscular activity of the triceps surae muscles; this enhancement was dependent on homonyomous background contraction levels.

Key Words: Task Dependence, Atrophy, Spaceflight, Sole

Muscle atrophy is a concern for many populations, including the elderly, bedridden patients, spinal cord–injured patients, and astronauts. Often, the environments or circumstances surrounding these individuals do not facilitate exercise volumes and/or magnitudes required to maintain muscle mass. Electric stimulation, sensory stimulation, and robotically driven movements are among the various stimulation techniques used in rehabilitation to counter muscle atrophy and to facilitate normal neuromuscular activation patterns.[1,2] Specifically, recent work has demonstrated that non-noxious cutaneous stimulation to the foot sole can modify neuromuscular activity,[3] alter postural responses,[4–7] and attenuate muscle atrophy.[8,9]

The integration of cutaneous stimulation into the motor system is widely accepted in the literature as task dependent and context specific.[10,11] 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 because these reflexes are only present in actively contracting muscles.[10,12] As a result, research into cutaneous reflex responses often involves a maintained level of background voluntary contraction.[12,13] A variety of voluntary contraction levels have been previously used, ranging from 1 to 50% of maximum voluntary contraction (MVC). However, few investigators have varied the level of contraction within a study.

Aniss et al.[12] compared single motor-unit responses in ankle muscles elicited from cutaneous stimulation of the foot, during both weak (5% MVC) and strong (30% MVC) contractions. They found that greater cutaneous reflex responses were associated with higher levels of background contractions.[12] 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 significantly enhanced when coupled with mechanical foot stimulation.[3] A passive response to mechanical foot stimulation has since been elicited by applying a 100-msec stimulation to the lateral side of the forefoot.[14] The response has been shown to be sensitive to static ankle angles and inhibited by soleus (SOL) stretch.[14] 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,[15,16] both of which are considered spinal reflexes. This potentiation has been attributed to the excitation of SOL motoneuron pools or reduction of presynaptic inhibition to enhance the reflex response.[17–19] Short-latency neuromuscular responses observed with mechanical foot stimulation are also suggested to be of spinal origin.[14] Therefore, it is reasonable to suggest that the Jendrassik maneuver might also facilitate neuromuscular responses to mechanical foot stimulation.

The aim of this study was to determine the modulating effect of background muscle activity on enhanced neuromuscular responses to mechanical foot stimulation. Specifically, this study investigated changes in the neuromuscular response evoked by mechanical foot stimulation during different levels of voluntary local, that is, 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. If our hypotheses were supported, a specialized boot providing mechanical stimulation to the foot might be used therapeutically to increase lower-limb neuromuscular activation. The benefits of this therapy would extend beyond muscle-atrophy attenuation to include an elevated use of sensory and neural apparatus that otherwise degenerates with disuse.[20] Such foot stimulations could be tailored to the need of the patient, including whether the boot is worn when passive or in combination with voluntary muscle activity.[21]

METHODS

Subjects and Experimental Design

The subjects were 15 right-handed healthy individuals (eight males, seven females) aged 25.5 ± 1.0 yrs (mean ± SE; height: 172.5 ± 2.3 cm; mass: 77.3 ± 4.2 kg). All were free of any known muscular or neurological medical conditions. Subjects were recruited from the university community and 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.

For all testing, subjects were seated with 100-degree ankle angle and 110-degree knee angle. Their right bare foot was secured in place with Velcro straps onto a platform that was used for dynamic foot stimulation (DFS; see Foot Stimulation section for more details). The subjects performed different levels of voluntary local contractions: homonymous (triceps surae) and remote (upper body) contractions. During these muscle contractions, the subjects received a non-noxious mechanical stimulus to the lateral portion of the sole of the foot, underneath the fifth metatarsal joint. The lateral foot stimulation was applied after 2 secs of maintained steady-state muscle activity (to ensure a stable contraction level) at 0, 40, or 80% MVC. The testing conditions were homonymous muscle contraction, remote muscle contraction, or both homonymous and remote muscle contractions. The experimental setups are shown in Figures 1 and 2, and Table 1 summarizes the experimental design. The order of the conditions was randomized for each subject to eliminate any order effect.

A computer monitor located a meter in front of the subject and a force dial in the subjects' hands within their line of sight provided visual feedback for maintaining background contraction levels required for triceps surae and Jendrassik-like contractions. For each trial, subjects were also required to read aloud a series of random numbers to control mental attention.[22] The random numbers were displayed on paper, 1 m in front of subjects at head height, partially covering the computer screen. The experimental environment minimized external stimulations such as noise, light, and distractions. Neuromuscular responses were measured with surface electromyography of the SOL and lateral gastrocnemius (GA).

Foot Stimulation

The DFS device contained one solenoid (surface area 2.5 cm), which was controlled through customized software (LabView, National Instrument Corp, Austin, TX). 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.

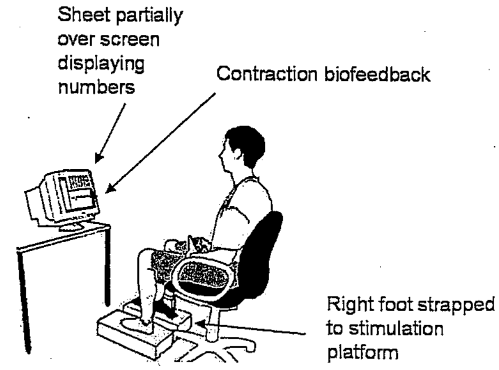

FIGURE 1 *The experimental setup.*

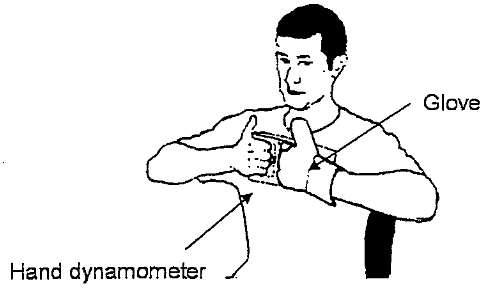

FIGURE 2 *The modified use of hand dynamometer for measuring Jendrassik-like contractions.*

Before testing, the subjects were familiarized with the DFS and experienced the stimulation. Each condition consisted of lateral sole stimulation applied for 100 msecs at 20 psi, to 3-mm protrusion, 16 times within a 50-sec period. A variable interstimulus interval and 2-min 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 five to seven stimulations, with rest periods in between.

Background Muscle Activity

The subjects performed isometric plantar flexion and Jendrassik-like contractions at maximal contraction, from which 40 and 80% of maximal effort contraction levels were calculated from SOL EMG (plantar flexion) and force levels (Jendrassik-like contractions). SOL maximal contraction levels were determined with a minimum of three isolated trials. A mean peak root mean squared EMG amplitude value was calculated from three separate 1-sec samples of the maximal-effort plantar flexion contractions. Contraction levels during isometric plantar flexions were controlled by subjects through visual feedback of the EMG associated with their SOL contraction from an oscilloscope. In all experimental conditions, EMG responses to foot stimuli were hidden from subjects by having only a limited viewing portion visible on the oscilloscope screen.

TABLE 1 Experimental conditions

Condition	Contraction	Contraction Level
Base	None	0%
TS 40	Triceps surae	40%
TS 80	Triceps surae	80%
Jend 40	Jendrassik	40%
Jend 80	Jendrassik	80%
Both 40	Both	40%
Both 80	Both	80%

Jendrassik-like contraction levels were determined with a modified use of a hand dynamometer (Lafayette Instrument, Lafayette, IN) (Fig. 2). 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 to not squeeze the hand dynamometer in the hand, but instead pull against the fingers, as an extension of force generated from the arms. A mean maximal force value for the Jendrassik-like contractions was calculated from at least three isolated maximal force attempts. Maintenance of background muscle levels was practiced at 40 and 80% of maximal effort levels with visual feedback of the hand dynamometer and, thus, force generated by the arms.

EMG Data Collection

Electrode sites were located and prepared, and electrodes were positioned over the belly of the SOL and GA. The skin was cleansed and abraised, and a silver–silver chloride preamplifier bipolar electrode (Therapeutics Unlimited, Iowa City, IA) was attached to the site with electrode gel and double-sided adhesive tape. Surgical tape ensured 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; the gain was 10K. Both the EMG root mean squared data from the SOL and GA (5.5-msec time constant) and solenoid activation signal were simultaneously collected by the enhanced graphics acquisition and analysis board (R.C. Electronics Inc., Santa Barbara, CA), to synchronize stimulus and EMG data waveforms for the analysis.

Data Analysis

A custom Excel program (Microsoft Corporation, Redmond, WA) identified a 300-msec period surrounding the stimulation: 100 msecs before stimulation, 100 msecs during stimulation, and 100 msecs after stimulation. Visual inspection of the 100 msecs before stimulation identified a consistent baseline level before stimulation. A 200-msec window of analysis for each stimulation was defined by the initiation of the stimulus and the following 200 msecs. 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 then determined for each condition for each subject. This method ensured the response peak amplitude was extracted rather than peaks associated with voluntary contraction, as 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 responses 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, including linear and repeated contrasts.

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, exhibiting minimal variation. The response latency was approximately 50 msecs and continued for approximately 20 msecs. The peak amplitude latency was typically positioned at 60 msecs (mean ± SD: SOL, 59.9 ± 3.9 msecs; GA, 56.6 ± 3.8 msecs); however, the amplitude of the response was highly variable. Figure 3 is an example of a typical response of the SOL during a single 100-msec stimulation.

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. 4).

Conversely, the conditions involving a remote contraction from the upper body, combined with

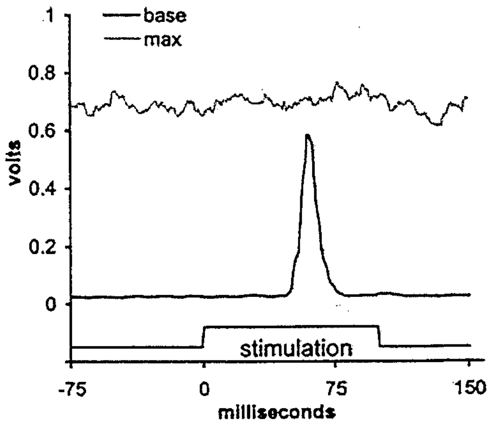

FIGURE 3 *A typical average waveform response of the SOL to lateral foot stimulation without any background contractions (base) and a maximal-effort isometric plantar flexor contraction with no stimulation (max).*

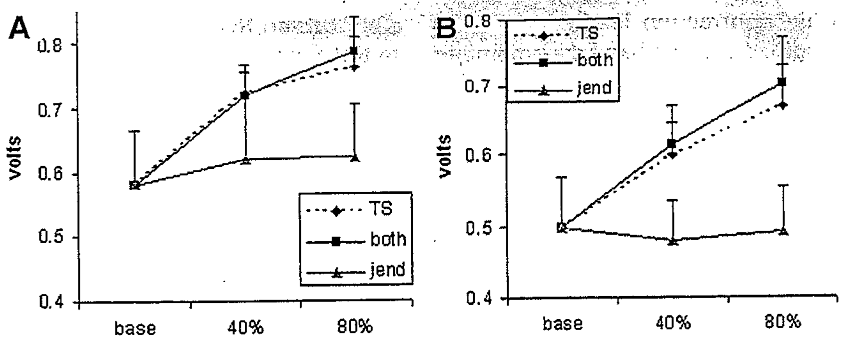

FIGURE 4 *The linear increase in peak amplitude response with voluntary background contraction levels of the TS and BOTH (TS + Jendrassik). a, SOL mean (+SE) amplitude response; b, GA mean (+SE) amplitude response.*

no voluntary triceps surae activation (jend 40 and jend 80), 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, because there was no difference between TS conditions (TS 40 and TS 80) and both conditions (both 40 and both 80).

Response *vs.* Maximum Contraction

Figure 5 represents the SOL reflex peak as a percentage of voluntary SOL maximal contraction. Peak reflex response amplitudes in the SOL reached similar levels as those measured during MVCs in a seated position. The 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.

Inhibition

For all conditions, including a voluntary background triceps surae contraction, an additional response waveform feature was observed: an inhibition for approximately 50 msec after response. This inhibition is observed in Figure 6 and is also maintained when a background Jendrassik contraction is added to the background triceps surae contraction.

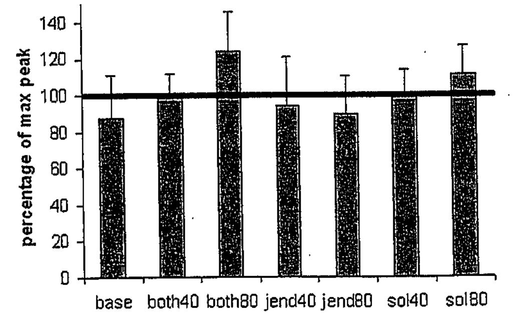

FIGURE 5 *The level of SOL peak amplitude reflex response as a percentage of SOL voluntary maximum contraction peak amplitude (+SE). The bold line represents the SOL voluntary maximal contraction peak amplitude.*

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 to mechanical foot stimulation. Sensory stimulation generated by lateral foot stimulation elicited a similar sharp neuromuscular response in both passive and active triceps surae musculature. The temporal features of the responses remained constant across all conditions, with variations only displayed in response peak amplitudes. The response latency was approximately 50 msecs, with a duration of approximately 20 msecs, which differentiated the response from monosynaptic reflexes at approximately 35- to 40-msec latencies.[23] This suggests that an oligosynaptic pathway, a pathway involving a few synapses, is the basis for the response to mechanical foot stimulation.[23]

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,[24] and may also stimulate muscle spindles of intrinsic foot muscles. The mechanical stimulation generated a response with a latency 20 msecs shorter than cutaneous reflexes elicited electrically,[13,25] 10–20 msecs longer than short-latency components, and 15–25 msecs shorter than medium-latency components of mechanically induced stretch reflexes.[26] 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.[10,12]

Regardless of the exact neurophysiological mechanisms, the presence of background volun-

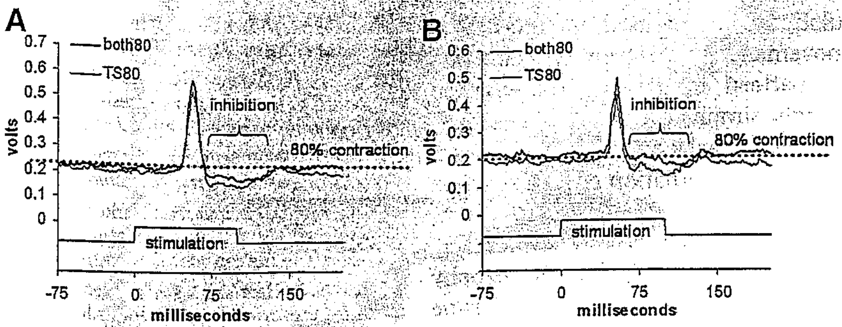

FIGURE 6 *The average response waveforms across all subjects for all conditions containing 80% background SOL contractions, and associated GA contractions. a, Average response waveform of the SOL; b, average response waveform of the GA.*

tary 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. The present findings are generally consistent with an increase in electrically elicited cutaneous responses with background contractions of the homonymous muscle from both non-noxious[12] and noxious foot stimulation.[27] The response to noxious stimulation with increasing background contractions demonstrated a linear trend until 30–40% maximal contraction, after which the response was saturated.[27]

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 and subjects may not have reached their true baseline maximal contraction level, the prevailing conclusion is that the peak magnitude of the SOL reflex response to foot stimulation is comparable with moderate- or upper-level voluntary SOL contractions. This implies that DFS 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 who struggle to produce voluntary contractions of the lower limb, whether 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. This occurs first by excitation of the SOL 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 than similar levels of posturally driven contractions.[13] Secondly, isometric voluntary contractions elevate muscle spindle output during a maintained contraction,[28] which may contribute to a facilitating spinal environment for additional afferent input.

In addition to the enhanced response to foot stimulation, the response waveform pattern also exhibited a postresponse inhibition period with a duration of approximately 50 msecs. 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 that still exhibited notable inhibition. This suggests that the inhibition was not generated by negative feedback loops from the responding muscle but, rather, 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,[19] because enhancement of the response to the stimulation would have been expected if this were the case. These results also indirectly imply that Ia input is not a primary contributor to the mechanically induced response from the plantar surface, because Ia afferent-driven responses (e.g., tendon jerk and H reflexes) are potentiated by Jendrassik maneuvers.[19]

Overall, the findings in this study support the idea of DFS 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 it might simply be 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 this potential therapeutic application, this study demonstrated lateral foot stimulation as a noninvasive, non-noxious method for generating neuromuscular activity.

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