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RESEARCH ARTICLE | *Control of Movement*

Effect of standing posture on inhibitory postsynaptic potentials in gastrocnemius motoneurons

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Garland SJ, Gallina A, Pollock CL, Ivanova TD. Effect of standing posture on inhibitory postsynaptic potentials in gastrocnemius motoneurons. *J Neurophysiol* 120: 263–271, 2018. First published April 4, 2018; doi:10.1152/jn.00555.2017.—This study examined the task dependence of sensory inputs on motoneuron excitability by comparing the inhibitory postsynaptic potential (IPSP) evoked by stimulation of the sural nerve between a standing postural task (Free Standing) and a comparable voluntary isometric contraction performed in a supine position (Lying Supine). We hypothesized that there would be a smaller IPSP in standing than in the supine position, based on the task dependence of the ankle plantarflexor activity on the standing task. Ten healthy participants participated in a total of 15 experiments. Single motor unit (MU) firings were recorded with both intramuscular fine-wire electrodes and high-density surface electromyography. Participants maintained the MU discharge at 6–8 Hz in Free Standing or Lying Supine while the right sural nerve was stimulated at random intervals between 1 and 3 s. To evaluate the reflex response, the firing times of the discriminated MUs were used to construct peristimulus time histograms and peristimulus frequencygrams. The sural nerve stimulation resulted in weaker inhibition in Free Standing than in Lying Supine. This finding is discussed in relation to the putative activation of persistent inward currents in standing posture and the task-dependent advantages of overriding inhibitory synaptic inputs to the plantarflexors to maintain the standing posture.

NEW & NOTEWORTHY The task-dependent modulation of sensory inputs on motoneuron excitability in standing is not well understood. Evoking an inhibitory postsynaptic potential (IPSP) resulted in a smaller IPSP in gastrocnemius motoneurons in standing than in the supine position. Mildly painful sensory inputs produced weaker motoneuron inhibition in standing, suggesting an imperative to maintain ankle plantarflexion activity for the task of upright stance.

motor unit; peristimulus time histogram; postsynaptic inhibition; standing posture

INTRODUCTION

Standing posture involves bilateral activation of the ankle plantarflexor musculature. According to the "inverted pendulum" model of standing posture (Winter et al. 1998), the central nervous system adjusts the center of pressure (COP) to maintain upright stance through activation of soleus (Masani et al. 2003) and gastrocnemius (Gatev et al. 1999; Masani et al. 2003) muscles. Previous work in our laboratory investigating the control of motor units (MUs) in quiet stance revealed a significant amount of common modulation of MUs in soleus (Mochizuki et al. 2006). Possible sources of the common drive in standing included ionotropic inputs, generated by sensory inputs and descending commands, such as proprioceptive (Mochizuki et al. 2007) and vestibulospinal (Monsour et al. 2012) inputs.

Evidence is mounting for the participation of the cortex in postural control whereby sensorimotor responses to postural perturbation are adapted in a task-dependent manner (Jacobs and Horak 2007). There is also considerable evidence supporting cortical involvement in sensory gating during posture (Saradjian 2015). Sensory gating, a process whereby the inflow of somatosensory information is suppressed, is prevalent in movement, possibly serving to reduce redundant information reaching the cortex (Song and Francis 2015). Movement-related sensory gating at the spinal level is context dependent (Confais et al. 2017). Less is known about the presence of sensory gating in the spinal cord during postural tasks.

We examined the task-dependent modulation of gastrocnemius motoneuron excitability in standing vs. lying supine. To do so, we compared the inhibitory postsynaptic potential (IPSP) evoked by stimulation of the sural nerve between a standing postural task and a comparable voluntary isometric contraction performed while lying supine. We hypothesized that the task of standing would result in a smaller IPSP in the standing position than in the supine position.

METHODS

Participants. Ten healthy participants (aged 22–56 yr; 4 women, 6 men) with no known neuromuscular disorders participated in a total of 15 experiments after providing informed written consent. All experimental procedures were approved by the University of British Columbia Clinical Research Ethics Board and conformed to the standards established by the Declaration of Helsinki (2008).

Electrical stimulation and electromyography. Sural nerve stimulation has evoked a robust IPSP in gastrocnemius in past studies (Brooke et al. 1997; Khan and Burne 2010; Rogasch et al. 2012). In this study, the sural nerve of the right foot was stimulated through bipolar electrodes (1 cm^2, 3 cm apart) positioned below the lateral malleolus over the sural nerve trunk. Single square-pulse stimuli of 500-μs duration were delivered by a constant-current stimulator DS7

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(Digitimer, Welwyn Garden City, UK) triggered through Power 1401 with Spike2 software (Cambridge Electronic Design, Cambridge, UK). Perceptual threshold (PT) was determined by increasing the stimulator intensity in 1-mA increments until the participant reported sensation. Stimulator intensity was then reduced until the participant reported no sensation; the last intensity that the participant could perceive was taken as threshold. Reflex stimulation intensity was set at 7 × PT; at this intensity, subjects reported mild pain sensation (3 out of 10).

Single MU firings were recorded with both intramuscular fine-wire electrodes and high-density surface electromyography (HDsEMG). Fine-wire electrodes consisted of three insulated Teflon-coated stainless steel wires (50-μm diameter; California Fine Wire) bonded together and passed through a 25-gauge hypodermic needle (Becton Dickinson, Franklin Lakes, NJ). A small hook at the terminal end of the fine-wire electrode held the electrode in place after the needle was removed. The exposed tips of two of the three wires formed a bipolar electrode that recorded MU action potentials from the medial gastrocnemius muscle. The third wire provided freedom to configure the bipolar electrode differently should the first configuration yield an undesirable signal. The signal was band-pass filtered (10–10,000 Hz), differentially amplified (common-mode rejection ratio > 90 dB at 60 Hz, input impedance 10 MΩ; Coulbourn Instruments, Allentown, PA), and sampled at 25,000 Hz. Single MU action potentials were discriminated online with Spike2 software with a template-matching algorithm.

The HDsEMG grid (semidisposable adhesive matrix; OTBioelettronica, Turin, Italy) consisted of 64 electrodes spaced 8 mm apart, arranged in 5 columns and 13 rows (an electrode missing in 1 of the corners). Electromyographic signals were collected in monopolar modality with a HDsEMG amplifier (128-channel EMG-USB; OTBioelettronica). Signals were amplified 2,000 times, sampled at 2,048 Hz, and stored for off-line MU action potential extraction. The positions of the fine-wire electrode in the right medial gastrocnemius muscle and the HDsEMG grid are depicted in Fig. 1*A*.

Experimental protocol. Participants were positioned on a tilt table, a standing frame that is used in clinical practice to enable supported stance, which allowed us to move the participant easily between standing and supine positions with minimal changes in body position. A force platform (AccuGait; Advanced Mechanical Technology, Watertown, MA) was secured to the base of the tilt table to measure either *1*) the plantarflexion forces exerted by an isometric contraction in the supine position or *2*) the postural sway in standing.

Two conditions were tested in each experiment: Free Standing and Lying Supine. The order of the testing conditions (Free Standing or Lying Supine) was randomized. In the Free Standing condition, the tilt table behind the participant was vertical, with the foot support parallel to the floor (Fig. 1*B*). In the Lying Supine condition, the tilt table supporting the participant was horizontal and the foot support was vertical (Fig. 1*C*). Before the tilt table was transitioned from Free Standing to Lying Supine, supports were placed between the participant and the table to avoid a change in body position (Fig. 1*C*). If Lying Supine was performed first, the straps and supports were removed for the Free Standing condition after transitioning slowly from supine to standing.

Before the experiment started, the participant stood in a comfortable position to determine whether the intramuscular electrode was collecting single MUs in the standing position. Intramuscular MUs were more difficult to isolate in standing than in the supine position, and we wanted to ensure that MU activity could be observed in both conditions before starting the experiment. The single MU was discriminated online with a template-matching algorithm (Spike2 v.6; Cambridge Electronic Design), and the acceptance pulses were displayed for the participant as instantaneous firing frequency on a screen. The audio signal associated with the acceptance pulses served as auditory feedback of MU discharge. Once we were sure of the quality of the intramuscular MU recording, the experiment began according to the randomized order of conditions.

In the Free Standing condition, participants stood on the force platform without touching the tilt table, which allowed for natural body sway. In the Lying Supine condition, ankle plantarflexion results in movement of the body along the tilt table. To prevent this movement, the participant's heels were placed on a rigid support and noncompliant straps, which were attached between the foot support of the tilt table and a belt on the participant's waist, maintained the position of the legs and feet similar to that in standing. In Lying

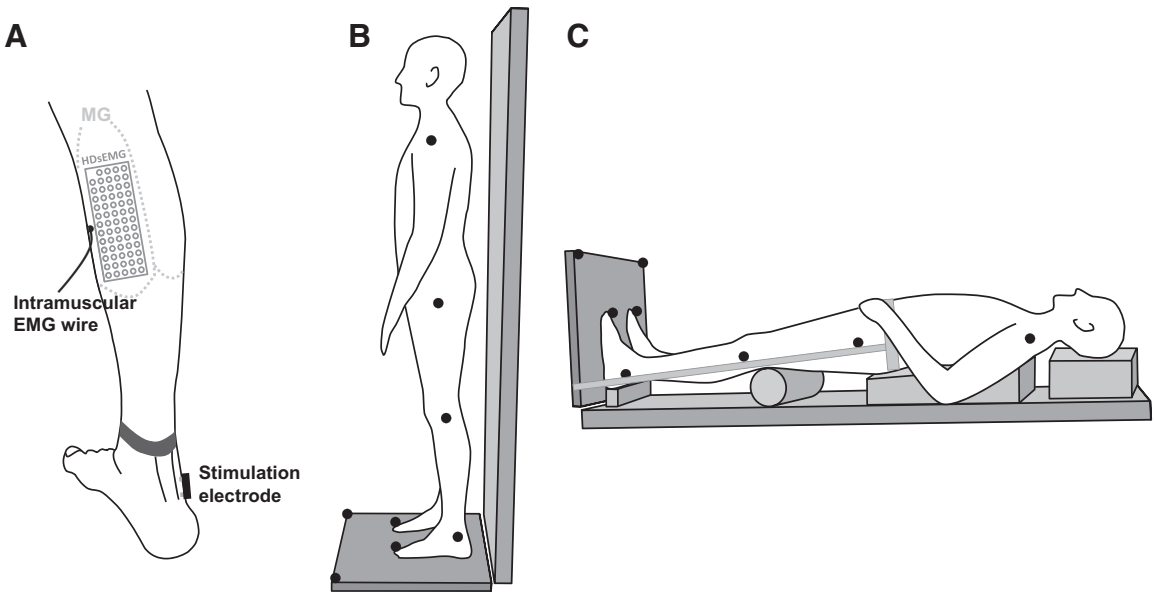

Fig. 1. Experimental setup. Positioning of high-density surface electromyography (HDsEMG) electrode grid and intramuscular fine-wire electrode with respect to medial gastrocnemius muscle (MG; shown with dotted line) on the participant's right leg. *A*: the electrode ground strap around the ankle and the bipolar stimulating electrode are shown. *B* and *C*: position of the tilt table with the mounted force platform for Free Standing (*B*) and Lying Supine (*C*) conditions. Reflective markers (black dots) were placed on the force platform and bilaterally on the participant's body (13 markers; not all visible). During Lying Supine (*C*), rigid supports enabled the same relative position of the participant's body and the table as in Free Standing. A waist belt and rigid straps anchored the participant to the force platform. All supports and restraints were removed for Free Standing (*B*).

Supine, participants were asked to produce isometric contractions of the plantarflexors of the right leg (the side that was stimulated). Participants performed two ramp-and-hold voluntary ankle plantarflexion contractions in Lying Supine; the force was gradually increased until MUs were recruited in the intramuscular recording, held for 5 s, and then gradually lowered. The force associated with the first firing of the MU was deemed the recruitment threshold (RT). Subsequently, a low-force contraction sufficient to recruit a MU on the intramuscular wire was performed. Participants tried to maintain the MU on the intramuscular wire that was active in the first testing condition throughout the transition between conditions and during the second task.

In both conditions, participants maintained the MU discharge at 6–8 Hz (in standing or a low-force isometric contraction) while the right sural nerve was stimulated at random intervals between 1 and 3 s (see *Electrical stimulation and electromyography*). On average, 380 stimuli were delivered (minimum of 300; maximum of 500) that were used to evaluate the reflex response. At the end of each experiment, participants performed two maximal voluntary contractions (MVCs) in Lying Supine by pressing as hard as they could against the force platform. If the two MVCs were not consistent, participants performed a third one. The peak force from all contractions was taken as MVC.

To assess the effect of standing without postural sway, a subset of four participants returned on a separate day to repeat the experiment. In these experiments, rather than Free Standing participants remained strapped onto the tilt table in standing (Supported Standing condition) to remove the postural sway component from the standing task.

Kinetic and kinematic data. Reflective markers were affixed to allow for motion capture of the ankle and knee joints bilaterally (Fig. 1). Ten high-speed digital cameras (Motion Analysis, Santa Rosa, CA) sampled the movement of the reflective markers at 100 Hz. Kinematic and kinetic data were analyzed with a custom-written program in postprocessing software (MATLAB; MathWorks, Natick, MA). The calculated angles were within 0.51° of known angles collected with markers on a goniometer.

Kinetic data were collected with a force platform (AccuGait; Advanced Mechanical Technologies) sampled at 1,000 Hz. Anterior-posterior COP displacement was calculated in the standing condition. Reflective markers affixed to the force platform ensured that calculations of anterior-posterior COP were relative to foot and ankle position of participants.

Data analysis. Identification of MU action potentials from the intramuscular EMG was repeated off-line with the same template-matching algorithm (Spike2) on a file where recordings from both conditions were spliced together. The classified MU action potentials were inspected manually to resolve interpolation issues. The firing characteristics of the MUs were evaluated by calculating the mean interspike interval (ISI) for the 1-s period immediately before each stimulus. Epochs from interstimulus intervals smaller than 1.5 s and with fewer than four ISIs were not included in the mean calculation.

For HDsEMG recordings, the single MU action potentials were obtained by decomposition of the EMG signal with DEMUSE software (Holobar and Zazula 2007). MU firing rate (Holobar et al. 2010) and reflex inhibition/facilitation (Yavuz et al. 2015) estimated with this method were shown to be valid when compared to gold-standard intramuscular recordings. To identify the MUs that were active in both conditions, epochs from the recordings during each condition were spliced together and decomposed as a single recording and a procedure based on the spatial representation of the MU action potential (Dideriksen et al. 2016) was used to verify the correct matching of MUs. With spike-triggered averaging, the spatial representation of the action potential of each MU was obtained for Free Standing and Lying Supine conditions separately. The channels with amplitude higher than 70% of the peak amplitude were identified (Vieira et al. 2010), and the median value of their proximal-distal coordinate was considered to represent the MU position. The properties of the action potential identified in both testing conditions were assessed by comparing its spatial representation by calculating the R value of the two-dimension correlation between the average rectified value (ARV) map of the MU action potential in Free Standing vs. Lying Supine. As a first step, MUs identified from intramuscular and HDsEMG electrodes were analyzed separately. MUs were pooled together for further analyses, as there was no difference in their firing behavior between the recording methods.

To assess medial gastrocnemius activation, single differential signals were calculated from the monopolar recordings along the columns of the HDsEMG (now 12×5 channels). The differential signals were then filtered with a band-pass filter (Butterworth, 4th order, 10–400 Hz) and full-wave rectified. Epochs of 250 ms before the stimulus were extracted from each differential signal and averaged across the channels. Average rectified amplitude of all the channels of the grid was calculated subsequently as the mean of the 250 ms to represent the global surface EMG for the medial gastrocnemius muscle as a whole. The mean value across participants was compared between conditions.

To evaluate the reflex response, the firing times of the discriminated MUs were used to construct peristimulus time histograms (PSTHs) and peristimulus frequencygrams (PSFs) with a bin size of 0.5 ms around the time of the stimulus (±250 ms). For both PSTHs and PSFs, the value of each bin was normalized with the average prestimulus bin value (calculated from −250 ms to 0 ms). PSTH and PSF cumulative sums (CUSUMs) were then constructed from the normalized data (Ellaway 1978). From the prestimulus period of each CUSUM, maximum and minimum deflections from the prestimulus average were obtained. The larger of the two CUSUM values was then used to make a symmetrical "error box" (Türker et al. 1997). Signif-

Table 1. *Reflex parameters and MU firing characteristics during Free Standing and Lying Supine*

Parameter	Motor Units	Intramuscular Free Standing	Intramuscular Lying Supine	HDsEMG Free Standing	HDsEMG Lying Supine
Reflex amplitude, % max amplitude (from PSTH CUSUM)	All	−53.1 ± 26.9	−66.9 ± 37.3†	−40.0 ± 23.3	−54.4 ± 25.8*
	Active in both conditions	−47.3 ± 36.8	−57.0 ± 32.7*	−32.8 ± 13.9	−54.6 ± 26.1*
Reflex latency, ms (from PSTH CUSUM)	All	95.0 ± 12.2	89.1 ± 11.7	96.8 ± 14.8	98.5 ± 13.8
	Active in both conditions	87.9 ± 10.5	87.0 ± 14.3	96.1 ± 14.1	98.7 ± 8.9
Reflex duration, ms (from PSTH/PSF CUSUMs)	All	77.8 ± 22.7	89.1 ± 24.6	81.1 ± 27.3	83.2 ± 19.5
	Active in both conditions	81.6 ± 20.0	83.6 ± 25.2	78. ± 26.3	73.8 ± 20.4
Mean ISI, ms	All	133.9 ± 16.9	130.7 ± 19.1	120.2 ± 15.2	123.4 ± 14.6
	Active in both conditions	128.9 ± 18.9	124.0 ± 16.9	112.0 ± 15.2	114.1 ± 14.1
CV of ISI, %	All	28.0 ± 9.1	20.6 ± 5.4*	27.1 ± 7.7	21.2 ± 5.4*
	Active in both conditions	25.7 ± 7.3	19.4 ± 5.3†	24.3 ± 7.1	20.6 ± 3.9*

Values are means ± SD. MU, motor unit; HDsEMG, high-density surface electromyogram; PSTH, peristimulus time histogram; PSF, peristimulus frequencygram; CUSUM, cumulative sum; ISI, interspike interval; CV, coefficient of variation. *$P < 0.05$, †$P < 0.1$, comparisons within each MU recording method.

Table 2. *Number of motor units identified in Free Standing and Lying Supine conditions*

Motor Units	All			Active in Both Conditions		
	Total no.	No. with inhibition	Inhibition present, % total	Total no.	No. with Inhibition	Inhibition present, % total
Intramuscular Free Standing	17	15	88	9	7	78
Intramuscular Lying Supine	17	15	88	9	8	89
HDsEMG Free Standing	99	76	77	27	17	63
HDsEMG Lying Supine	123	103	84	27	22	81

HDsEMG, high-density surface electromyogram.

icant changes in the MU firing after the stimulus were determined by comparing deflections in the CUSUM with the error box, with deflections in the CUSUM greater in size than the error box considered a significant reflex response (Türker and Powers 2003). If such large deflections were up-going they were classified as "excitation" and if they were down-going as "inhibition."

The inhibitory reflex parameters were measured with the combined PSTH-PSF method (Rogasch et al. 2011; Türker and Powers 2003). The inhibitory reflex latency was taken as the time between 0 ms (initiation of the stimulus) and the first turning point of significant PSTH CUSUM, as it better represents the latency of the very first reflex (Todd et al. 2012). Similarly, the end point of the reflex was determined as the second turning point of significant PSF CUSUM. Following the recommendations of Rogasch et al. (2011) and Todd et al. (2012), the duration of the inhibition was calculated as the time between the latency (determined by PSTH method) and the end point of the reflex (determined by PSF method). The amplitude of the reflex was determined as the vertical size of the PSTH CUSUM between the first and second turning points divided by the number of stimuli used for that experiment. This value was then normalized to the maximal possible inhibition (i.e., no spikes in any of the bins throughout the duration of the reflex) calculated with the formula (Brinkworth and Türker 2003)

$$100\%\ \text{reflex amplitude} = (k \times \text{reflex duration in bins})/\text{no. of stimuli}$$

where k is the average prestimulus bin value.

This approach provides the strength of the reflex responses independent of the number of stimuli used and the duration of the reflex. The strength of the reflex is presented as a negative number indicating inhibition.

Statistical analysis. After significant reflex responses were determined with the error box approach, further statistical analysis was performed only on the significant responses. Data from Free Standing-Lying Supine experiments were analyzed separately from data obtained during the subset of experiments with Supported Standing-Lying Supine. Paired *t*-tests were used to compare the stimulus intensity and perceived pain as well as the global HDsEMG and joint positions of the ankle and knee between Free Standing (or Supported Standing) and Lying Supine conditions. For single MU analysis, the comparisons of the mean ISI, reflex strength, latency, and duration (estimated by PSTH and PSF methods) between Free Standing (or Supported Standing) and Lying Supine were performed with an independent Student's *t*-test when all MUs were considered. For analysis of MUs that were active in both conditions, paired *t*-tests were used.

A secondary analysis was performed to evaluate the influence of MU firing rate on reflex strength. A subgroup of MUs with comparable firing rates in both Free Standing and Lying Supine tasks (or Supported Standing and Lying Supine tasks) was selected. For each experiment, the mean ISIs of MUs from both tasks were compared and assembled in pairs or small groups having a mean ISI difference of <5 ms (~0.5-Hz difference in firing rate). Student's *t*-tests were

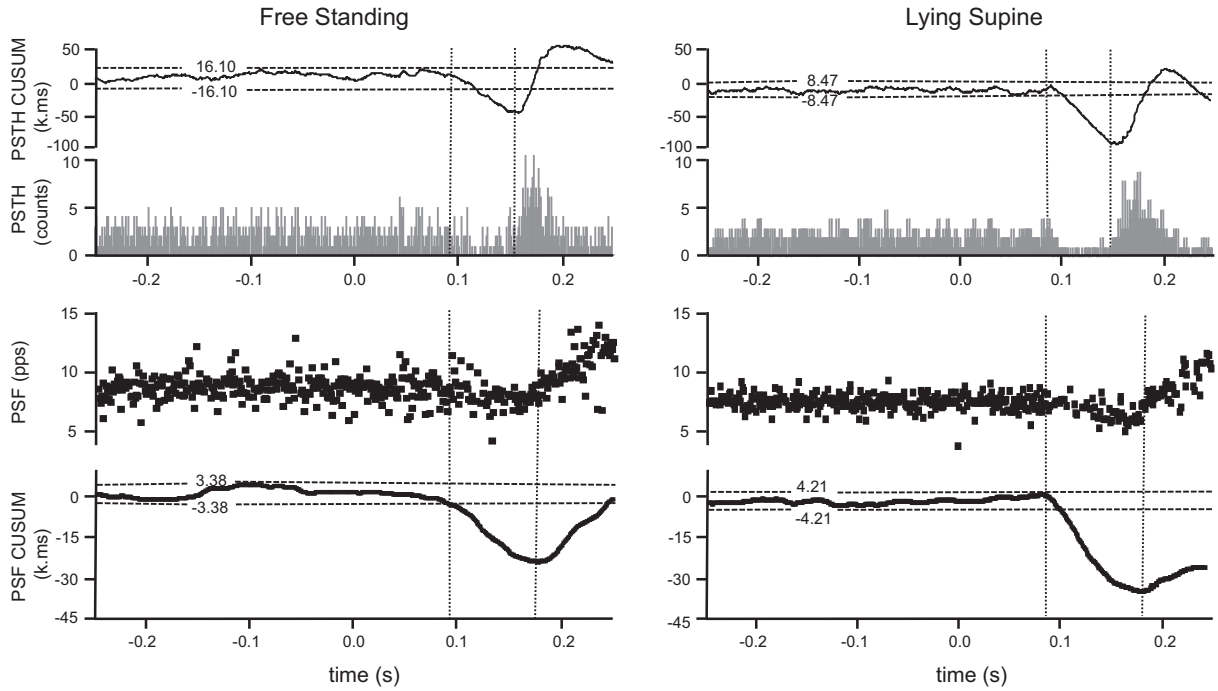

Fig. 2. Peristimulus time histograms (PSTHs) and their cumulative sums (CUSUMs) (*top*) and peristimulus frequencygrams (PSFs) and corresponding CUSUMs (*bottom*) for the same motor unit decomposed from high-density surface electromyography in Free Standing (*left*) and Lying Supine (*right*) conditions. Note the larger inhibition in the Lying Supine condition.

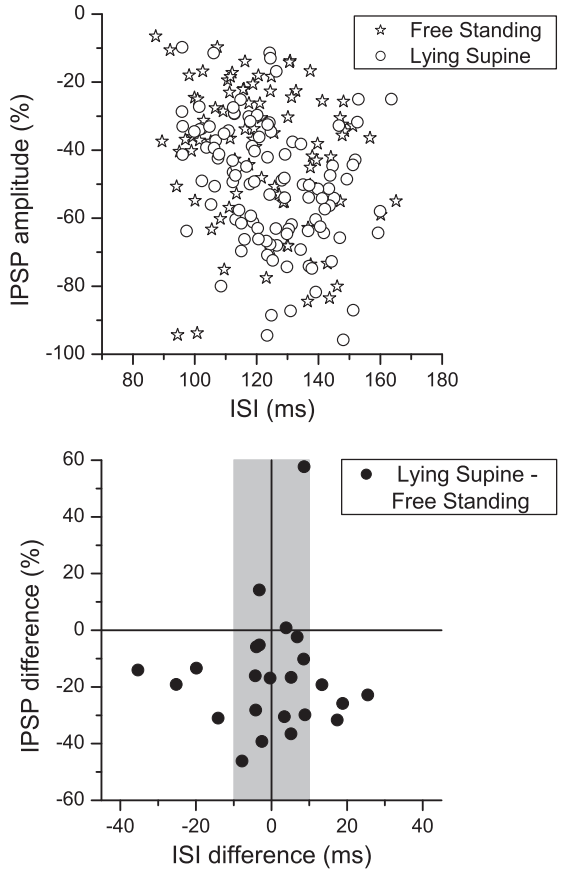

Fig. 3. Inhibitory postsynaptic potential (IPSP) amplitude and mean interspike interval (ISI) during Free Standing and Lying Supine conditions for all motor units (MUs) identified with intramuscular and high-density surface electromyography recordings. *Top*: there is no relationship between the IPSP amplitude and the ISI. *Bottom*: for MUs that were active in both conditions, the difference (Lying Supine – Free Standing) of the IPSP amplitude vs. the difference in mean ISI is presented. MUs with very similar mean ISIs in both conditions (±10 ms) are in the gray shaded area. There is a predominantly negative IPSP amplitude difference for the MUs active in both conditions, suggesting larger inhibition during Lying Supine despite the difference in the firing frequency for some MUs.

used to compare reflex strength and mean ISI of selected MUs between tasks.

The relationships between IPSP amplitude and mean ISI and IPSP amplitude and MU RT were assessed by calculating the lines of best fit. The level of significance was set at 0.05. The data are presented as means ± SD.

RESULTS

Medial gastrocnemius activation was similar in both conditions (Free Standing: 13.5 ± 3.5 μV, Lying Supine: 13.4 ± 6.3 μV; $n = 15$; $P = 0.94$ or Supported Standing: 16.1 ± 11.0 μV, Lying Supine: 15.1 ± 7.4 μV; $n = 4$; $P = 0.63$) The stimulus intensity (Free Standing: 40.2 ± 6.4 mA, Lying Supine: 40.5 ± 7.4 mA; $n = 15$; $P = 0.70$ or Supported Standing: 45.7 ± 8.9 mA, Lying Supine: 45.6 ± 8.8 mA; $n = 4$; $P = 0.59$) and pain ratings (Free Standing: 3.2 ± 0.8 out of 10, Lying Supine: 3.5 ± 1.1 out of 10; $n = 15$; $P = 0.19$ or Supported Standing: 3.5 ± 1.3 out of 10, Lying Supine: 3.3 ± 1.3 out of 10; $n = 4$; $P = 0.39$) were similar in both conditions.

Before the successful development of various surface electromyography decomposition techniques, intramuscular recordings (needle or fine wire) were the only means to collect single MU potential trains and, as such, are considered a "gold standard" in MU research. We analyzed the behavior of the MUs collected with intramuscular electrodes as a way of validating the responses observed in MUs decomposed from the HDsEMG signals.

MU firing characteristics were similar between the intramuscular and HDsEMG recordings (Table 1). Whereas only one or two MUs were collected per person on the intramuscular fine-wire electrodes, an average of 7 ± 4 MUs were decomposed from the HDsEMG per condition per person. There was no difference in the mean ISI in both conditions (Table 1). The coefficient of variation (CV) of the ISI in the Free Standing condition (27.3 ± 7.9%), however, was significantly larger ($P < 0.001$) than in Lying Supine (21.1 ± 5.4%), despite the same firing rate (see also Table 1). The MUs that were active in both conditions had a high median correlation coefficient of the ARV map of the MU action potential between Free Standing and Lying Supine (0.94; 25th–75th percentiles: 0.89–0.96), confirming that the same MU was being recorded in both conditions.

The mean number of sural nerve stimuli delivered was 380 ± 75, with a minimum of 300 and a maximum of 500 stimuli per condition per experiment. The sural nerve stimuli resulted in significant inhibition in the majority of MUs recorded with both the intramuscular fine wire and the HDsEMG (84% of the 220 single MUs identified in Free Standing and Lying Supine conditions; see also Table 2). Figure 2 depicts PSTH and CUSUM (Fig. 2, *top*) and PSF and CUSUM (Fig. 2, *bottom*) for a single MU decomposed from the HDsEMG in Free Standing (Fig. 2, *left*) and Lying Supine (Fig. 2, *right*). Both the PSTH and PSF CUSUMs reveal clear inhibition in both conditions, with the Lying Supine condition having stronger inhibition than the Free Standing condition. Both MU recording methods (intramuscular and HDsEMG decomposition) rendered the same results when the Free Standing and Lying Supine conditions were compared (Table 1). Across all the MUs, the latency and duration of the reflex were not significantly different between conditions but the strength of inhibition for Lying Supine was greater than in Free Standing

Table 3. *Reflex amplitude and motor unit interspike interval for motor units with comparable firing rate*

Parameter	*Experiment 1*		*Experiment 2*	
	Free Standing	Lying Supine	Supported Standing	Lying Supine
Number	66	78	14	15
Reflex amplitude, % max	−42.0 ± 20.3	−59.0 ± 29.1*	−39.7 ± 23.9	−60.4 ± 31.6*
Mean ISI, ms	123.8 ± 16.8	125.0 ± 16.3	131.5 ± 13.1	131.3 ± 12.8

Values are means ± SD. Note that only motor units with inhibition are included. ISI, interspike interval. *$P < 0.05$.

Table 4. *Ankle and knee joint angle during Standing and Lying Supine conditions*

Test	Mean		SD	
	Ankle	Knee	Ankle	Knee
Free Standing				
Free Standing	98.1 ± 5.7*	175.2 ± 2.4	0.7 ± 0.5	0.6 ± 0.5
Lying Supine	109.3 ± 4.1	174.4 ± 2.3	0.7 ± 0.5	0.5 ± 0.4
Supported Standing				
Supported Standing	109.8 ± 3.2	174.0 ± 3.8	0.3 ± 0.2	0.3 ± 0.2
Lying Supine	113.4 ± 3.5	172.7 ± 2.6	0.6 ± 0.5	0.2 ± 0.1

Values (in °) are means ± SD. Mean, mean joint angle position; SD, SD of the right leg joint position (describing amplitude of joint movement). *$P < 0.05$.

(−42.7 ± 24.0% and −56.0 ± 27.7% for Free Standing and Lying Supine, respectively; $P < 0.001$).

To explore possible explanations for this finding, we sought to determine whether differences in MU firing rate between the two conditions might influence the results. There was no significant relationship between the strength of the inhibition and the mean ISI for all MUs, during both Free Standing and Lying Supine conditions ($r = -0.09$; $P = 0.3$ and $r = -0.06$; $P = 0.5$, respectively; Fig. 3, *top*). To eliminate the possibility that small differences in firing rate could affect the strength of the inhibition, for MUs that were active in both conditions we plotted the difference in IPSP amplitude against the mean ISI difference between Lying Supine and Free Standing conditions (Fig. 3, *bottom*). Figure 3 shows that the strength of inhibition was unaffected by ISI ($r = 0.03$, $P = 0.8$). Whether the mean ISI was within 10 ms between conditions (shaded region, Fig. 3, *bottom*), higher or lower, the IPSP was larger in Lying Supine by a comparable amount. Similar results were obtained when the strength of inhibition was compared in a subgroup of MUs with virtually identical firing rates in both tasks (Table 3). For both Free Standing-Lying Supine and Supported Standing-Lying Supine experiments the IPSP was larger in the Lying Supine task.

We also compared the mean joint angles of the ankle and knee between Free Standing and Lying Supine conditions to determine whether body position affected the results. While there was no difference in the knee angle between conditions, the ankle joint angle was 11.2 ± 4.6° more plantarflexed in the Lying Supine than the Free Standing condition (Table 4). The postural sway also introduced a larger CV of the ISI in Free Standing compared with Lying Supine. We therefore performed an additional experiment with four of the original participants. In this case, the participants repeated the experiment in the opposite order, with the postural sway component removed (Supported Standing). Eliminating the postural sway, the difference in the ankle joint angles between Supported Standing and Lying Supine was only 3.6 ± 1.8° and the CV of ISI was comparable (19.5 ± 4.8% and 17.8 ± 2.9% for Supported Standing and Lying Supine, respectively, $P = 0.14$; see also Table 5). The pattern of reflex response was the same in Supported Standing as in Free Standing, in that Lying Supine had significantly larger IPSPs than Supported Standing (−58.6 ± 30.3% and −39.7 ± 20.7% for Lying Supine and Supported Standing, respectively; $P = 0.02$; see also Table 5).

In the Lying Supine condition, the strength of the IPSP was associated with the MU RT such that the IPSP amplitude was less in the earliest-recruited MUs than the later-recruited MUs. This is seen in Fig. 4*A*, where a ramp-and-hold contraction from a single subject is shown with the firing times of the recruited MUs. It was also found that most MUs were identified from the distal electrodes of the grid (Fig. 4*B*; lower leg schematic; median position: 10, 25th–75th percentiles: 8–11.25). For all MUs with an identifiable RT (54 of 103 MUs during Lying Supine condition), there was a moderate correlation ($r = -0.37$; $P = 0.005$) between the strength of the inhibition (negative number to indicate inhibition) and the RT (Fig. 4*C*).

DISCUSSION

This study has demonstrated that stimulation of the cutaneous sural nerve evoked less inhibition in the standing position than in the supine position, potentially reflecting a task dependence of the influence of cutaneous sensory inputs onto the motoneuron.

One concept in motor control, as reviewed by Prochazka (1989), is that "the goal of a motor act crucially determines its planning and performance" (p. 301). The task dependence of postural responses to perturbations is well known. In the seminal study by Nashner (1976), adaptive changes to the muscle activation associated with postural perturbations were found on the basis of whether the response would be useful or not to maintain postural stability. Considerable research has been performed over the last decade or two to uncover the cortical and subcortical mechanisms involved in sensorimotor modulation in posture and locomotion. Altenmüller et al. (1995) showed modulation of the somatosensory evoked po-

Table 5. *Reflex parameters and motor unit characteristics for motor units identified during Supported Standing and Lying Supine*

MU Parameter	All		Active in Both Conditions	
	Supported Standing	Lying Supine	Supported Standing	Lying Supine
No. of MUs	28	27	12	12
MUs with inhibition	21	23	10	11
Inhibition present, % total	75	85	83	92
Reflex amplitude, % max (from PSTH CUSUM)	−39.7 ± 20.7	−58.6 ± 30.3*	−34.3 ± 18.5	−56.0 ± 30.4*
Reflex latency, ms (from PSTH CUSUM)	95.8 ± 15.4	100.0 ± 20.6	98.2 ± 19.1	102.3 ± 22.8
Reflex duration, ms (from PSTH/PSF CUSUMs)	75.6 ± 17.4	78.8 ± 18.6	72.5 ± 14.3	72.9 ± 19.4
Mean ISI, ms	131.3 ± 10.9	138.1 ± 15.0	128.1 ± 13.9	137.6 ± 12.7
CV of ISI, %	19.6 ± 4.8	17.7 ± 2.9†	18.7 ± 4.1	16.8 ± 3.6*

Values are means ± SD. Note that these motor units (MUs) are from the intramuscular wire and high-density surface electromyogram recordings combined. PSTH, peristimulus time histogram; PSF, peristimulus frequencygram; CUSUM, cumulative sum; ISI, interspike interval; CV, coefficient of variation. *$P < 0.05$, †$P < 0.1$.

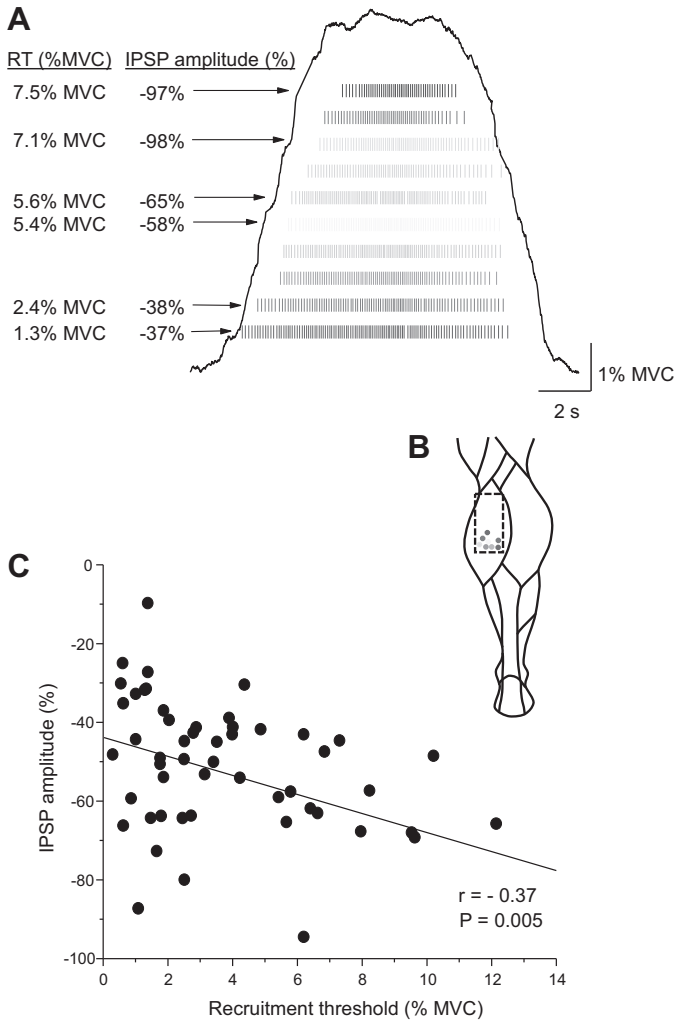

Fig. 4. *A*: ramp-and-hold contraction during the Lying Supine condition from a representative subject. The firing times of the single motor units (MUs) are presented with vertical bars. On *left*, the recruitment threshold (RT) and the inhibitory postsynaptic potential (IPSP) amplitude are shown for the MUs (arrows). The MUs that were recruited earlier (had lower RT) experienced less inhibition than later-recruited MUs. *B*: MUs were recorded from the lower part of the medial gastrocnemius as shown on the lower leg schematic. *C*: relationship between the IPSP amplitude and the RT for all MUs with the line of best fit. Note that not all MUs that were analyzed for IPSPs were recruited during ramp-and-hold contractions; hence only 54 of 103 MUs are plotted. MVC, maximal voluntary contraction.

tentials produced by sural nerve stimulation between stance and different phases of gait. Saradjian (2015) suggested that the central modulation of sensory input is evidence that the central nervous system can modify incoming information based on its relevance to the task. This study adds to this body of literature by showing that sensory inputs that inhibit the motoneurons in the supine position produce less inhibition in stance, a task that requires ankle plantarflexion activity not only to maintain the MU firing but to maintain upright standing.

The lower IPSP amplitude in the standing position to the same mildly painful cutaneous stimulation as in the supine position suggests that sensory inputs are gated in standing. Even when the postural sway component of standing was eliminated (Supported Standing condition), the pattern for a smaller IPSP in supported standing than in the supine position remained. This suggests that vestibulospinal inputs may be involved. Differences in the sources of central drive to the motoneuron during standing vs. supine position may influence the strength of inhibition. Mochizuki et al. (2006) found differences in common drive in the soleus MUs between standing and sitting, suggesting more common drive when standing vs. performing an isometric voluntary contraction while sitting. While anecdotal, it is worth commenting on the difficulty some participants had in maintaining the same MU discharging on the intramuscular wire between conditions despite minimal change in the body position and the audio feedback of the discharge of the MUs in the transition between conditions. This suggests that different sources of central drive, e.g., vestibulospinal inputs (Grillner et al. 1970), may influence the recruitment of a single MU.

Brain stem-derived neuromodulatory inputs produce dendritic persistent inward currents (PICs) that control the state of excitability of the motoneuron (Heckman et al. 2005). PICs have been theorized to be functionally useful in postural activities such as stance to promote self-sustained firing of motoneurons (Elbasiouny et al. 2010). In mammalian models, the PIC renders the motoneuron less sensitive to excitatory inputs and highly sensitive to inhibitory inputs (Heckman and Enoka 2012). During standing, excitatory inputs to the human ankle plantarflexors imposed by external perturbations resulted in only modest increases in MU discharge rate (Pollock et al. 2014); a finding consistent with the presence of a PIC in standing that would reduce the response of the active MUs to excitatory inputs. In a recent study by Revill and Fuglevand (2017), the high sensitivity of the PIC to synaptic inhibition was exploited to blunt the steep increase in MU firing rate upon recruitment, suggesting that the presence of a PIC contributes to the nonlinear firing rate increases during ascending ramp contractions. Because PICs are highly sensitive to synaptic inhibition, one might have expected a larger IPSP in the standing position than in the supine position. Instead, we found that the same sural nerve stimulation resulted in weaker inhibition in standing than in the supine position.

We do not think the relatively flexed ankle joint angle in standing was the explanation for the smaller IPSP amplitude in Free Standing because the IPSP was less in Supported Standing than in Lying Supine when the ankle joint angles were similar. However, in standing reciprocal inhibition is present and is modulated by concurrent facilitatory corticospinal inputs (Hanna-Boutros et al. 2015). We were not able to measure the amount of reciprocal inhibition between the Standing and Lying Supine conditions, so we are unable to speculate on the potentially complex interactions between synaptic and neuromodulatory inputs at the segmental level between these conditions.

We tried to keep the overall level of central drive similar between conditions by asking participants to control the discharge rate of the intramuscularly recorded MU between 6 and 8 Hz (ISI 125–166 ms). On average, the MU ISI recorded from the HDsEMG grid was slightly faster than 8 Hz—an ISI of ~120 ms in both Free Standing and Lying Supine for all units. Overall the MUs recorded during Lying Supine were not significantly slower than the Supported Standing condition, and Fig. 3 shows no relationship between firing rate and IPSP strength from both intramuscular and HDsEMG recordings. This, along with the additional analysis in Table 3, suggests

that IPSP strength is not solely a function of MU discharge rate.

In human experiments, we only have a proxy of central drive in the recordings of net MU discharge rate. In mammalian preparations, Berg et al. (2007) showed a balance of excitatory and inhibitory inputs in spinal motoneurons; that is, as excitation was increased, so was inhibition. Therefore it is possible that similar MU firing rates in both standing and supine conditions are due to increased excitation in standing accompanied by increased inhibition. In cortical neurons, neurons experiencing greater synaptic activation were in a higher conductance state (Bernander et al. 1991; Destexhe et al. 2003). This high conductance state could result in shunting of additional inhibitory currents presented by the sural nerve stimulation in the Standing conditions that was not seen in Lying Supine.

The observation of a larger IPSP amplitude in the earliest-recruited MUs is consistent with the finding of larger IPSP in slow-twitch vs. fast-twitch motoneurons (Burke et al. 1970), albeit that all MUs would be considered to be of low threshold in the present experiment. Although we could not compare the RTs between Standing and Lying Supine conditions, the difference in IPSP strength between standing and supine positions was observed in the same MUs and therefore the lower IPSP amplitude in standing could not be attributed to a sampling bias.

The main finding of this study was that the strength of IPSPs in MUs of the gastrocnemius evoked by stimulation of the sural nerve was less in a standing postural task than in a supine position. Our data reveal that there is less sensitivity to synaptic inhibition in the standing position than in the supine position. While speculative, it may be more advantageous to override inhibitory synaptic inputs to the plantarflexors to maintain the standing posture.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

S.J.G., A.G., C.L.P., and T.D.I. conceived and designed research; A.G., C.L.P., and T.D.I. performed experiments; A.G., C.L.P., and T.D.I. analyzed data; S.J.G., A.G., C.L.P., and T.D.I. interpreted results of experiments; T.D.I. prepared figures; S.J.G. drafted manuscript; S.J.G., A.G., C.L.P., and T.D.I. edited and revised manuscript; S.J.G., A.G., C.L.P., and T.D.I. approved final version of manuscript.

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