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Soleus H-reflex phase-dependent modulation is preserved during stepping within a robotic exoskeleton

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HIGHLIGHTS

• The soleus H-reflex is modulated in a phase-dependent manner during stepping within a robotic exoskeleton in healthy humans.
• Body unloading and decreased EMG amplitude of ankle extensors are not key factors for the soleus H-reflex phasic excitability to be manifested.
• Spinal interneuronal circuits involved in the phasic H-reflex excitability are engaged in a physiological manner during robotic assisted stepping.
• Robotic assisted stepping utilized for rehabilitation of walking in neurological disorders will not engage locomotor spinal circuits in a pathological manner.

ABSTRACT

Objective: To investigate to what extent the phase-dependent modulation of the soleus H-reflex is preserved when bilateral leg movements are electromechanically driven by a robotic exoskeleton at different levels of body weight support (BWS) in healthy subjects.
Methods: The soleus H-reflex was elicited by posterior tibial nerve stimulation with a 1-ms single pulse at an intensity that the M-waves ranged from 4% to 9% of the maximal M-wave across subjects. Stimuli were randomly dispersed across the step cycle which was divided into 16 equal bins. At each bin, a maximal M-wave was elicited 100 ms after the test H-reflex and was used to normalize the associated M-wave and H-reflex. Electromyographic (EMG) activity from major hip, knee, and ankle muscles was recorded with surface bipolar electrodes. For each subject and muscle, the integrated EMG profile was established and plotted as a function of the step cycle phases. The H-reflex gain was determined as the slope of the relationship between the H-reflex and soleus EMG amplitudes at 100 ms before the H-reflex for each bin.
Results: During robotic assisted stepping, the phase-dependent soleus H-reflex modulation pattern was preserved and was similar at 25% and 50% BWS, a linear relationship between soleus H-reflex amplitude and background activity was found, and the reflex gain did not change with alterations of the BWS level. EMG amplitudes were smaller at 50% compared to 25% BWS.
Conclusions: Body unloading, decreased EMG amplitude of ankle extensors, and reduced ankle movement are not key factors for the soleus H-reflex phasic excitability to be manifested.
Significance: Robotic devices are utilized for rehabilitation of gait in neurological disorders. Based on our findings, spinal interneuronal circuits involved in the phase-dependent modulation of the soleus H-reflex will be engaged in a physiological manner during robotic assisted stepping in neurological disorders.

1. Introduction

During rhythmic motor tasks, sensory afferent feedback refines motor output to suit environmental demands. A plethora of studies have provided evidence towards a sensory, reflex-mediated, regulation of locomotion that involves largely extensor muscle and

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plantar cutaneous afferents mediating load, and muscle afferents mediating changes of muscle length (see reviews of Dietz and Duysens, 2000; Rossignol et al., 2006; Grillner, 2006; Knikou, 2010a). In decerebrate acutely spinalized cats, stimulation of group I ankle extensor afferents during fictive locomotion prolonged extensor nerve activity when delivered during an extensor burst and terminated flexor nerve activity when delivered during a flexor burst (Conway et al., 1987). It was later shown that the locomotor rhythm could be entrained by rhythmic contractions of ankle extensor muscles, hip extension and unloading are necessary for swing phase initiation while excitatory actions of group I afferents are distributed to all extensor muscles (Angel et al., 1996; Grillner and Rossignol, 1978; Guertin et al., 1995; Pearson et al., 1992; Whelan et al., 1995). In addition, cutaneous nerves and afferents of the foot were shown to have similar effects to those described for group I afferents promoting correct foot placement and weight bearing during the stance phase (Bouyer and Rossignol, 2003).

Ample evidence suggests that spinal reflex circuits integrating information from receptors registering stretch or load regulate human locomotion. Their behavioral relevance is supported by their susceptibility to a task-, phase-, and use-dependent modulation (Zehr and Stein, 1999). In particular, the short latency ankle or quadriceps extensor reflexes (stretch or H-reflex) are progressively increased from mid to late stance and significantly depressed or even abolished during the swing phase of gait (Sinkjær et al., 1996; Mrachacz-Kersting et al., 2004; Capaday and Stein, 1986; Crenna and Frigo, 1987; Larsen et al., 2006; Dietz et al., 1990). The reflex facilitation during the stance phase may be partly related to group I facilitatory actions exerted between ankle extensors (Faist et al., 2006). Given that the amount of loading and/or unloading is directly related to the motor output amplitude (Fouad et al., 2001; Sinkjær et al., 2000; Dietz and Colombo, 1996) and that the soleus H-reflex amplitude changes in parallel with the soleus EMG activity, one would expect that under conditions of reduced loading the soleus H-reflex modulation will be altered. However, a phase-dependent modulation of the soleus H-reflex has been reported during robotic air stepping (Kamibayashi et al., 2010), at 0%, 25% and 50% body weight support (BWS) treadmill walking without robotic or manual leg guidance (Knikou et al., 2009), rhythmic one-legged step ascending and descending (Knikou, 2011), passive stepping movements (Brooke et al., 1995), and active pedalling (Boorman et al., 1992). Under these conditions, hip proprioceptors mediating muscle stretch might have provided the gating mechanism for adaptation of the synaptic efficacy of the soleus Ia afferents (Knikou and Rymer, 2002a,b).

Body weight supported treadmill walking was introduced as a means of rehabilitation of human walking after spinal cord lesions (Barbeau et al., 1987; Dobkin et al., 2003), based largely on evidence from spinalized cats (Barbeau and Rossignol, 1987; Edgerton et al., 1997; Belanger et al., 1996; Rossignol et al., 1999). During this therapeutic intervention, BWS and manual assistance is provided by therapists based on patient's needs. This led to the development of a sophisticated exoskeleton system (Lokomat®), where manual assistance by therapists is replaced by electromechanically driven bilateral leg braces, leg movement patterns occur in a pre-determined trajectory (Colombo et al., 2000), the ankle movement is assisted by the foot lifters, and trunk rotations are minimal. Accordingly, the objective of this study was to establish the modulation pattern of the soleus H-reflex across multiple phases of the step cycle in healthy humans during robotic assisted stepping at BWS levels commonly utilized for rehabilitation of walking in neurological disorders while carefully controlling for changes in the amplitude of the maximal M-wave across the step cycle. Part of this study has been published in abstract form (Smith et al., 2011).

2. Materials and methods

The experimental protocol received Institutional Review Board (IRB) approval from the Northwestern University and CUNY College of Staten Island IRB committees. All procedures were conducted in compliance with the Declaration of Helsinki and a written consent was obtained from each subject prior to study participation. Thirteen healthy subjects (5 male, 8 female) with ages ranging from 21 to 51 (30.5 ± 11.4) years participated in the study. Their daily physical activities ranged from moderate to vigorous. No subject reported low back pain or any other type of neuromuscular disorder.

2.1. EMG recordings

In all subjects, following standard skin preparation procedures, bipolar differential surface electrodes of fixed inter-electrode distance (MA-411-002, Motion Lab Systems Inc., Baton Rouge, LA, USA) were used to record EMG activity from the soleus (SOL), medial gastrocnemius (MG), tibialis anterior (TA), peroneus longus (PL), medial hamstrings (MH), vastus lateralis (VL), rectus femoris (RF), and hip adductor gracilis (GRC) muscles from both legs. All EMG signals were filtered with a cut-off frequency of 10–1000 Hz and sampled at 2000 Hz using a data acquisition card (NI PCI-6225, National Instruments, Austin, TX).

2.2. Robotic assisted stepping

A driven gait orthosis (DGO) system (Lokomat®, Hocoma, Switzerland) was utilized in this study for robotic assisted stepping. In-depth details on the Lokomat can be found elsewhere (Colombo et al., 2000; Jezernik et al., 2003). Briefly, the hip, knee, and ankle joint movements of each leg were assisted through separate position controllers implemented in a computer-based real time system while stepping on a moving treadmill (ADAL, Andrezieux Boutheon, France). Subjects were fixed into the DGO using straps at the waist, thighs, and shanks, which were adjusted at different body segments, allowing for adaptable fitting. Both feet were enclosed in foot lifters (using elastic straps and springs), which promoted ankle dorsiflexion during the swing phase of gait. The DGO system was fixed to the treadmill through a parallel frame, while compensation for the weight of the DGO was also provided. Body weight was removed through an upper body harness that was connected to the orthotic system. Subjects were instructed to walk with the robotic device, and not to oppose the leg guidance provided by the DGO.

2.3. Elicitation and recording protocol of the soleus H-reflex during robotic assisted stepping

The soleus H-reflex was evoked according to methods previously employed in healthy subjects during walking on a motorized treadmill at different BWS levels without leg assistance (Knikou et al., 2009). Square pulse stimuli of 1-ms duration were delivered by a custom-built constant current stimulator to the right posterior tibial nerve. With subjects seated, a stainless steel plate of 4 cm^2 in diameter was secured proximal to the patella. A hand-held monopolar stainless steel head electrode was used to establish the most optimal stimulation site for the posterior tibial nerve, and corresponded to the site that the M-wave had a similar shape to that of the H-reflex, and at the lowest stimulus intensity an H-reflex could be evoked without an M-wave. The hand-held electrode was then replaced by a pre-gelled disposable electrode (N-10-A; Medicotest, Ølstykee, Denmark), which was maintained under constant pressure throughout the experiment.