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Neural coupling between the upper and lower limbs in humans

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Abstract

The aim of this study was to establish the effects of active sinusoidal ipsilateral and contralateral upper limb flexion, extension, abduction, and adduction with elbows extended on the right soleus H-reflex with subjects seated and standing. Reflex effects were also established when both arms moved synchronously in a reciprocal pattern with elbows flexed in seated and standing subjects. Sinusoidal arm movements were timed to a metronome and performed at 0.2 Hz. Soleus H-reflexes were elicited only once (every 4 s) in every movement cycle of the upper limbs. Position of arms, and activity of shoulder muscles were recorded through twin-axis goniometers and surface electromyography (EMG), respectively. We found that in seated subjects, regardless the direction of the active movement or the upper limb being moved, the soleus H-reflex was depressed. In standing subjects, a reflex depression was observed during extension, abduction, and adduction of the ipsilateral and contralateral upper limbs. Muscles were active during arm flexion and abduction in all directions of arm movement with subjects either seated or standing. It is suggested that arm movement might be incorporated in the rehabilitation training of people with a supraspinal or spinal cord lesion, since it can benefit motor recovery by decreasing spinal reflex excitability of the legs in these patients.

Keywords: Arm movement; H-reflex; Crossed interlimb connections; Inhibition; Posture

Long propriospinal neurons (LPNs) originate in the cervical (C) enlargement (C3-C5), travel in the ventral and lateral funiculi, and terminate in the ventral horn of the lumbosacral enlargement [1,2,12,17]. These neurons are involved in the neural coupling of arms and legs during rhythmical movements [13], and contribute to limb coordination during locomotion. LPNs couple the cervical and lumbar enlargements in lower vertebrates [18,20] and in humans [19], through connections with alpha motoneurons and inhibitory interneurons projecting to motoneurons [13].

Coordination of the arms and legs during rhythmic movements is evident in humans [8,21]. Cutaneous and H-reflexes of the upper limb muscles during arm cycling are modulated in a phase and task dependent manner [22,24], with cutaneous reflex reversals to be present [23], corresponding to the phase and task dependency of the leg reflexes during human walking [4,26]. These findings suggest of similar control mechanisms in the reflex modulation of upper and lower limbs, which might be represented by a system of two coupled oscillators like the one underlying quadruped locomotion [7,21].

Changes in static positioning of the shoulder modulate the Achilles, quadriceps, and biceps femoris tendon reflexes as well as the soleus H-reflex [5,6]. The effects were expressed in a reciprocal pattern, e.g. ipsilateral arm flexion and contralateral arm extension facilitated the Achilles, the quadriceps tendon and soleus H-reflexes and depressed the biceps femoris tendon reflex. The modulation pattern of these reflexes was reversed when the position of the ipsilateral and contralateral shoulder was switched. In contrast, in seated subjects the soleus H-reflex size is decreased during bilateral arm cycling when compared to reflexes recorded with the arms held statically in flexion or extension [9]. Although it is apparent that interlimb reflex connections are present in humans and affect motor output promoting human upright posture and balance, it is currently not known if active movement of both upper limbs in various planes at different body postures affect differently lower limb spinal reflex excitability. Thus, the objectives of this study were to establish whether active ipsilateral and/or contralateral upper limb movement in different directions and active movement of both arms in a reciprocal pattern (mimicking the movement pattern observed during human

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walking) affect the soleus H-reflex size in seated and standing human subjects.

Fourteen subjects (six men and eight women) aged 23–41 (29 ± 5) years participated in the study. The experimental protocol was approved by the Institutional Review Board (IRB) of the College of Staten Island (IRB No. 48-N-06), all procedures were conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki, and each subject gave a written consent before testing. None of the subjects reported any neurological deficit, low back pain, or other musculoskeletal disorder.

In all subjects, the H-reflex was elicited and recorded according to procedures described previously in detail [14,15]. Briefly, the H-reflex was elicited on the ascending part of the recruitment curve by stimulation of the posterior tibial nerve using a single pulse of 1 ms, the reflexes were 15–30% of the maximal M-wave (Mmax), and the corresponding M-waves (which were monitored online) were below 5% of the Mmax. H-reflexes were recorded from the right soleus muscle via a single differential electrode (Delsys Inc., Boston, USA) having established the correct site of stimulation by using a stainless steel monopolar electrode as a probe (see more details in Refs. [14,15]).

The ipsilateral and the contralateral active upper limb movement included flexion/extension (0–90°) in the sagittal plane, and abduction/adduction (0–90°) in the frontal plane with elbows extended. In addition, alternated flexion/extension of both upper limbs in a reciprocal pattern with elbows flexed was tested. The frequency of the movement was set by a digital metronome and was equivalent to 0.2 Hz. The subject matched the sound of the metronome with the movement of the arm, while each movement cycle lasted 4 s.

Soleus H-reflexes during ipsilateral and contralateral upper limb movement (conditioned reflexes) were recorded with subjects seated and standing, and were elicited only once in every movement cycle of the upper limbs. The stimulus to the posterior tibial nerve was sent at the beginning of the sinusoidal active arm movement (see top traces of Fig. 3). In each subject, at least three control reflexes for each testing condition (seated and standing) were randomly recorded with the conditioned reflexes. For every control and conditioned reflex 15 sweeps were recorded. M-wave amplitudes were continually monitored to ensure stability in the stimulation and recording procedures. The M-wave size was used for screening conditioned H-reflexes during active movement of the upper limbs. Experimental data were rejected when a significant difference between the M-wave of the conditioned and the control reflexes was established.

Surface electromyograms (EMG) were recorded via single differential electrodes (Bagnoli System, Delsys Inc., Boston, MA) from the ipsilateral and contralateral anterior deltoid (AD), middle deltoid (MD), posterior deltoid (PD), triceps (Tric), and biceps brachii (Bic) muscles following standard procedures. The arm position during each sinusoidal movement was recorded through twin-axis goniometers (World Precision Instruments Inc., FL, USA). All signals were amplified and band-pass filtered (10–500 Hz) before being sampled at 2 kHz (1401 plus running Spike 2 software, Cambridge Electronics Design Ltd., Hertfordshire, England, UK).

The soleus M-wave and H-reflex of the control and conditioned reflexes were full-wave rectified and their sizes were measured as the area under the respective waveforms (Spike 2, CED Ltd., UK) [15]. For each subject, the conditioned reflexes (all 15 sweeps) recorded during active movement of either upper limb in all directions were expressed as a percentage of the mean size of the control reflex collected with the subject seated. A one-way analysis of variance (ANOVA) and post hoc Bonferroni tests were applied to the experimental data sets for each subject to establish statistically significant differences between the control and the conditioned H-reflexes and across the conditioning trials. This analysis was also conducted for conditioned reflexes recorded with subjects standing, while in this case the control reflex was recorded with subjects standing.

The mean size of each subject's conditioned H-reflex was then grouped based on the upper limb being moved (ipsilateral or contralateral) and the direction of the movement (flexion, extension, abduction, and adduction). An ANOVA for repeated measures (2×4) was applied to the data sets to determine changes in the size of the conditioned reflexes across different experimental conditions investigated for the subject group. This analysis was performed separately for tests conducted with subjects seated and standing. Lastly, an ANOVA for repeated measures (2×4) was also applied to the conditioned reflexes in order to establish whether the conditioned H-reflexes were modulated differently with subjects seated and standing.

For each subject, the M-waves of the control and conditioned H-reflexes were expressed as a percentage of the maximal M-wave. A one-way ANOVA with post hoc Bonferroni tests was used to test for differences between the M-waves of the reflexes recorded under control conditions and during upper limb movement. When significant differences were encountered the trial was rejected. Each EMG recording was full-wave rectified, smoothed, and averaged over the 15 consecutive arm movement cycles. Then, the average EMG signal for each muscle was plotted as a function of time. In all tests, statistically significant differences were established at 95% of confidence level. Results are presented as mean values along with the standard error of mean (S.E.M.).

Ipsilateral and contralateral upper limb movement induced significant changes in the magnitude of the soleus H-reflex with subjects seated. Representative examples of these effects are illustrated for two subjects in Fig. 1. The right soleus H-reflex was significantly depressed when either upper limb moved in flexion, extension, abduction, and adduction. The reduction in the H-reflex occurred without any apparent changes in M-wave characteristics demonstrating that the stimulus conditions were not altered.

The population data for the conditioned H-reflex following ipsilateral and contralateral upper limb movement in the frontal and sagittal planes with subjects seated are illustrated in Fig. 2A. Ipsilateral arm flexion and extension as well as abduction and adduction with elbows extended resulted in a significant depression of the soleus H-reflex across subjects with the reflex reaching overall amplitudes that ranged from 80 to 85% of control reflex values ($P < 0.05$). Similarly, the soleus H-reflex was signif-