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ARM SWAY HOLDS SWAY: LOCOMOTOR-LIKE MODULATION OF LEG REFLEXES WHEN ARMS SWING IN ALTERNATION

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Abstract—It has been argued that arm movements are important during human gait because they affect leg activity due to neural coupling between arms and legs. Consequently, one would expect that locomotor-like alternating arm swing is more effective than in-phase swing in affecting the legs' motor output. Other alternating movements such as trunk rotation associated to arm swing could also affect leg reflexes. Here, we assessed how locomotor-like movement patterns would affect soleus H-reflexes in 13 subjects performing arm swing in the sagittal plane (ipsilateral, contralateral and bilateral in-phase versus locomotor-like anti-phase arm movements) and trunk rotation with the legs stationary, and leg stepping with the arms stationary. Findings revealed that soleus H-reflexes were suppressed for all arm, trunk or leg movements. However, a marked reflex modulation occurred during locomotor-like anti-phase arm swing, as was also the case during leg stepping, and this modulation flattened out during in-phase arm swing. This modulation had a peculiar bell shape and showed maximum suppression at a moment where the heel-strike would occur during a normal walking cycle. Furthermore, this modulation was independent from electromyographic activity, suggesting a spinal processing at premotoneuronal level. Therefore, trunk movement can affect legs' output, and a special neural coupling occurs between arms and legs when arms move in alternation. This may have implications for gait rehabilitation. © 2014 Published by Elsevier Ltd. on behalf of IBRO.

Key words: H-reflex, arm movement, locomotion, central pattern generators.

INTRODUCTION

''Why do quadrupeds move their legs crisscross?'' This fundamental question was already raised by Aristotle in the first known manuscript on locomotion (Aristotle, 350 BC). Indeed, the diagonal nature of interlimb coordination is striking even in free-arm bipedal gait of humans (Grillner, 1975). Some authors have suggested that alternated arm swing may enable humans to save energy while others debated that it can affect gait stability (Ortega et al., 2008; Bruijn et al., 2010). This arm swing could be a passive reaction to the leg motions (Gerdy, 1829; Pontzer et al., 2009) or rather a manifestation of an active control by the neural system because arm muscles contract rhythmically even if arm swing is prevented (Elftman, 1939; Ballesteros et al., 1965). However, it is not obvious what purpose this alternated rhythmic muscle contraction serves, in fact it could be regarded as wasteful (Jackson, 1983).

This neural control could be an evolutionary remnant of quadrupedal locomotion where movements in the upper limbs are partly coordinated with the hindlimbs through propriospinal pathways that connect cervical and lumbar spinal circuits such as central-pattern-generators (CPGs) activated rhythmically in alternation (Dietz, 2002; Juvin et al., 2012). If this is still the case in humans, one would expect that connections between the circuits involved in arm and leg movements would favor conditions that are ''locomotor-like'' (i.e. alternating or anti-phase arm swing). However, the arms have become specialized to perform skilled movements in humans, and in-phase movements such as hand clapping are usually more accurate and stable (Swinnen, 2002).

Soleus H-reflexes have been used to investigate interlimb connections. Reflex changes during a given task (task-dependent modulation), or during a movement phase within this task (phase-dependent modulation), were used to probe a possible CPG's contribution when this modulation was independent from the electromyographic (EMG) background activity (Burke, 1999; Zehr and Duysens, 2004). Previous studies showed that soleus H-reflex decreased during all rhythmic arm movements, such as arm swing or cycling, indicating a persistence of neural coupling between upper and lower limbs (Hiraoka, 2001; Hiraoka and Iwata, 2006; Knikou, 2007; De Ruiter et al., 2010). However, phase-dependent modulation was not always assessed during arm swing, and methodological concerns were raised in some of the previous studies because EMG background was not always controlled. Furthermore, since some features of leg movements are mainly controlled by the spinal automatism of the stepping limb movement whereas others depend on other limb movements (Shik and Orlovsky, 1976), it remained unclear if locomotor-like alternated arm movements would induce similar soleus H-reflex

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Abbreviations: CPG, central-pattern-generator; EMG, electromyography; M-max, maximal M-wave; RMS, root mean square.

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modulation as during walking or stepping in place. Another limitation was that the former studies did not sufficiently consider that alternated trunk rotation is closely associated to arm swing during walking (Bruijn et al., 2008). Therefore, the question emerges whether trunk movement may also determine leg motor output. Trunk movements could be important as soleus H-reflexes are not anymore significantly depressed during arm cycling if the head and trunk are immobilized (Hiraoka and Taniguchi, 2010).

We investigated the modulation pattern of the soleus H-reflex during rhythmical anti-phase arm movements versus unilateral, bilateral in-phase arm movements and trunk rotation while the legs were stationary. In addition, leg stepping movements were tested while the arms were stationary. We hypothesized that soleus H-reflex modulation would be more pronounced during anti-phase arm movements. This modulation should contribute to the well-known soleus modulation previously described during walking if connections between the circuits involved in arm and leg movements would favor conditions that are ‘‘locomotor-like’’.

EXPERIMENTAL PROCEDURES

Subjects

Thirteen subjects (six men and seven women) aged 25 ± 3 years (mean ± SD) participated in the present study. None of the subjects reported any neurological deficit, low back pain, or other musculoskeletal disorders. All the subjects were right-handed and right-footed. The experimental procedures were approved by the Ethics Committee of Biomedical Research at the KU-Leuven University (Leuven, Belgium). Informed consent was signed by every participant prior to testing. The experiments were conducted in accordance with the Helsinki Declaration.

Apparatus and task

The subjects were instructed to perform rhythmic movements with their upper limbs, lower limbs or trunk (Fig. 1).

The H-reflex was elicited by stimulating the tibial nerve of the right leg in the following test conditions: (1) ipsilateral right arm flexion/extension in the sagittal plane, (2) contralateral left arm flexion/extension, (3) anti-phase flexion/extension of both arms, (4) in-phase flexion/extension of both arms, and (5) trunk rotation in the transverse plane. Data collection was conducted while the subjects performed these five conditions in a sitting position. In standing condition, only one condition was performed where H-reflex was elicited during stepping in place (6). During all trials, subjects were asked to look straight ahead and to restrain from unwanted head, trunk or leg movements during a given trial of the experiment. During the sitting position, the subjects had their back supported and their hip, knee, and ankle angles were set at approximately 90°, 110°, and 90°, respectively, and they were asked to maintain the legs stationary and produce a controlled activation of the right soleus by constantly pushing the right foot onto a pedal to produce low-level tonic contractions (around 10% maximum voluntary contraction) using an online visual feedback of their EMG on an oscilloscope. This minimal voluntary sustained contraction of the homonymous muscle is a way to maintain stable motoneuron excitability and minimize postsynaptic effects (Stein and Thompson, 2006; Knikou, 2008). Indeed, the state of excitability of the motoneuron pool plays a significant role in determining the H-reflex magnitude which may vary within and across subjects. The chair and foot pedal were fixed in a similar position during all movements and the subjects were asked to press the pedal while keeping the same position so that the segment positions of their lower limbs remain stable, which was continuously verified by the experimenter. The maximum voluntary contraction was determined by asking the seated subject at the beginning of the experiment to perform a maximum tonic contraction of the soleus while pushing on the pedal three times for 5 s and the average of the muscle contraction amplitude during these three trials was calculated.

For arm flexion/extension conditions, participants were asked to move the arms in the sagittal plane and maintain the elbows comfortably extended and to perform a movement as large as possible from maximum possible extension up to around 70–80° flexion. These positions were chosen because previous studies demonstrated significant effects of similar shoulder positions on reflex excitability in the legs (Delwaide et al., 1973, 1977; Eke-Okoro, 1994; Frigon et al., 2004; Knikou, 2007). For trunk rotation, the subjects were asked to cross their arms on the chest and perform a rotation movement of the trunk with the head looking straight ahead and not rotating along with the trunk. For the ‘stepping in place’ condition, the subjects were asked to make walking movements in place with the legs and without changing the position of the body in space. An alternated flexion of the hips and knees in the sagittal plane was then performed. We visually verified that the movement amplitudes were not exaggerated with the feet stepping in the same place and the arms relaxed along the body. During a given movement the subjects heard double-tone auditory signals (high versus low pitch), which provided pacing for the movements at a frequency of 1 Hz (i.e. a full movement cycle beginning and ending at the same position was performed during the period of 1 s separating two consecutive high pitch sounds). This frequency was chosen as it is close to that seen during gait at common intermediate speeds of 4 km/h (Donker et al., 2001, 2005; Huang et al., 2010). The subjects were asked to match the high pitch sound either with the maximum extension position of their right arm for the ipsilateral flexion/extension arm movement (condition 1 in Fig. 1), or the maximum flexion position of the left arm for contralateral, anti-phase and in-phase flexion/extension arm movements (conditions 2–4), or with the maximum rotation position of the trunk to the right for the trunk rotation (i.e. left shoulder forward)