



Review

Control of functional movements in healthy and post-stroke subjects: Role of neural interlimb coupling



Volker Dietz, Miriam Schrafl-Altermatt *

University Hospital Balgrist, Zürich, Switzerland

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HIGHLIGHTS

- A task-specific neural interlimb coupling mechanism underlies functional movements in humans.
- After a stroke, the neural coupling mechanism is preserved from the unaffected side but defective from the affected limb(s).
- Based on the knowledge of neural coupling, training of cooperative limb movements should be integrated into neuro-rehabilitation.

ABSTRACT

In recent years it has become evident that, in a number of functional movements, synergistically acting limbs become task-specifically linked by a soft-wired ‘neural coupling’ mechanism (e.g. the legs during balancing, the arms and legs during gait and both arms during cooperative hand movements). Experimentally this mechanism became evident by the analysis of reflex responses as a marker for a neural coupling. It is reflected by the task-specific appearance of reflex EMG responses to non-noxious nerve stimulation, not only in muscles of the stimulated limb, but also, with same long latency, in muscles of meaningful coupled (contralateral) limb(s). After a stroke, nerve stimulation of the unaffected limb during such cooperative tasks is followed by EMG responses in muscles of the (contralateral) coupled affected limb, i.e. unaffected motor centres support synergistically acting movements of the paretic limb. In contrast, following stimulation of the affected limb, no contralateral responses appear due to defective processing of afferent input. As a consequence, it may be therapeutically possible to strengthen the influence of unaffected motor centres on the performance of affected limb movements through training of cooperative limb movements required during activities of daily living.

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* Corresponding author at: Spinal Cord Injury Center, Balgrist University Hospital, Forchstrasse 340, CH-8008 Zürich, Switzerland. Tel.: +41 44 510 7212; fax: +41 44 386 3731.

E-mail address: mschrafl@paralab.balgrist.ch (M. Schrafl-Altermatt).

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1. Introduction

While close cooperation of muscle activation between the two legs during gait has been known for several years, only during recent years has it become evident that the mechanism of “neural interlimb coupling” plays a major role in the control of a number of functional movements. Neural interlimb coupling is defined as a flexible, task-specific, physiologically meaningful linkage of limbs during complex movements. Experimentally, this mechanism can be demonstrated through the analysis of reflex responses. Unilateral non-noxious stimulation (or mechanical displacement) is task-specifically followed by reflex EMG responses, not only in the stimulated limb but also in other, synergistically acting limb muscles as a marker for a neural coupling. This mechanism seems to be required for the effective performance of a number of functional movements. Thus, the neural coupling differs from interlimb reflex activity in so far that the latter was studied in a passive motor condition in healthy subjects (e.g. Gassel and Ott, 1973; Kearney and Chan, 1981; Piesiur-Strehlow and Meinck, 1980) or a condition of paralysis due to a cervical SCI (e.g. Calancie, 1991; McNulty and Burke, 2013).

Neural coupling as a task-specific control mechanism was first described for cooperation between the legs during balancing (Dietz and Berger, 1982) and locomotion (Dietz et al., 1989). Later on, a flexible, task-specific neural coupling between arms and legs was described for bipedal gait as a residual function of quadrupedal limb coordination (Dietz, 2002). Lastly, neural coupling was shown to be involved in the performance of cooperative hand movements such as opening a bottle, i.e. a task that is executed by one hand with the support of the contralateral hand (Dietz et al., 2015).

Neural coupling represents a task-specific neural mechanism involved in the control of fundamentally different complex functional movements. They are characterised by the fact that in all such tasks several limbs cooperate for effective movement performance. Although the mechanism is clearly defined, it is assumed to be mediated at different levels of the central nervous system during different movements, i.e. by a task-specific involvement of neural circuits within the spinal cord, the brainstem or cortical areas of both hemispheres, respectively.

After a stroke, neural interlimb coupling becomes re-organised in a specific way. Impaired processing of afferent input from the affected side prevents coupling, while a strengthening of pathways from the unaffected part of the brainstem/hemisphere to the affected limb(s) seems to play a major role in the compensation of the sensorimotor deficit. An increasing understanding of this neural re-organisation in the future might have an impact on neurorehabilitation procedures.

In the next section, the significance of neural coupling in movement control, the sensorimotor pathways possibly involved and the functional implications of this mechanism will be discussed. In a second section, the re-organisation of the neural coupling mechanism following a stroke will be established and the implications for neuro-rehabilitation will be discussed.

2. Physiology of neural coupling

Neural coupling during functional movements is reflected in the appearance of EMG responses to a non-noxious afferent volley

applied to a limb (in the form of electrical nerve stimulation or mechanical displacement), not only in muscles ipsilateral to the stimulated limb (Fig. 1A) but also, with the same long latency, in muscles of other limbs working in synergy during the specific task (Fig. 1B–D). It represents a flexible, i.e. not hard-wired, mechanism, that manifests only if required for optimal/effective performance of the task.

2.1. Neural interlimb leg muscle coupling: balancing and gait

In laboratory conditions, when a subject is sitting in a chair, non-noxious stimulation of the tibial nerve (e.g. train of 5 stimuli within 100 ms) leads to an ipsilateral EMG response in the anterior tibial muscle appearing with a latency of 65–75 ms, that corresponds to and is termed a ‘long latency reflex response’ (Fig. 1A). In contrast, during balancing on two separate balance platforms, a unilateral displacement (induced by a unilateral tibial nerve stimulation or by a brisk anterior tilt of one platform) leads to bilateral activation of tibialis anterior muscles with about the same latency (Fig. 1B). Through this muscle activation, the displacement becomes adequately compensated for (Dietz and Berger, 1982). However, leg muscles contralateral to the stimulated leg are not activated in such a task when they do not play a supportive/compensatory role, i.e. when they are not connected to a functionally meaningful ‘postural program’ (Horak and Nashner, 1986).

Similarly, a unilateral leg displacement during gait is automatically followed by a bilateral pattern of agonistic and antagonistic leg muscle activation appearing on both sides with the same latency (Dietz et al., 1986b). This bilateral response pattern of leg muscle activation depends on the phase of the gait cycle where the perturbation is induced (Dietz et al., 1984, 1986a,b) and is directed towards keeping the body’s centre of mass over the feet.

Such a neural postural control mechanism requires continuous appropriate information about the position of the body’s centre of gravity in space. Load receptor information seems to play an essential role in the provision and continuous updating of relevant information to spinal neuronal centres (Duysens and Pearson, 1980); for review Dietz, 2003). The onset latencies (65–75 ms) suggest that these bilateral EMG response patterns be most likely mediated by spinal neural circuits. These circuits are assumed to be connected with the central pattern generator (CPG) for locomotion that generates a leg muscle activation pattern according to the actual task conditions, i.e. requirements to maintain the body’s equilibrium (Grillner, 1981; Dietz, 2002).

2.2. Neural interlimb arm–leg muscle coupling: bipedal gait

Bilateral arm swing represents an integral part of bipedal locomotion (Elftman, 1939). During gait, arm swing is coordinated with leg movements, i.e. it depends, for example, on movement speed. It is required to compensate for torsional body movements and contributes to maintain body equilibrium. Arm swing during bipedal stepping is thought to represent a residual function of quadrupedal organisation of human locomotion (Dietz, 2002), i.e. interlimb coordination during bipedal gait appears to be organised in a similar way to that of the cat (Grillner, 1981). The frequency relationship characterising the coordination between arm and leg movements during bipedal locomotion (Wannier et al., 2001) corresponds to that of well-defined biological systems consisting of

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