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Voluntary ankle flexor activity and adaptive coactivation gain is decreased by spasticity during subacute spinal cord injury

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ABSTRACT

Although spasticity has been defined as an increase in velocity-dependent stretch reflexes and muscle hypertonia during passive movement, the measurement of flexor muscle paresis may better characterize the negative impact of this syndrome on residual motor function following incomplete spinal cord injury (iSCI). In this longitudinal study Tibialis Anterior (TA) muscle paresis produced by a loss in maximal voluntary contraction during dorsiflexion and ankle flexor muscle coactivation during ramp-and-hold controlled plantarflexion was measured in ten patients during subacute iSCI. Tibialis Anterior activity was measured at approximately two-week intervals between 3-5 months following iSCI in subjects with or without spasticity, characterized by lower-limb muscle hypertonia and/or involuntary spasms. Following iSCI, maximal voluntary contraction ankle flexor activity was lower than that recorded from healthy subjects, and was further attenuated by the presence of spasticity. Furthermore the initially high percentage value of TA coactivation increased at 75% but not at 25% maximal voluntary torque (MVT), reflected by an increase in TA coactivation gain (75%/25% MVT) from 2.5 ± 0.4 to 7.5 ± 1.9, well above the control level of 2.9 ± 0.2. In contrast contraction-dependent TA coactivation gain decreased from 2.4 ± 0.3 to 1.4 ± 0.1 during spasticity. In conclusion the adaptive increase in TA coactivation gain observed in this pilot study during subacute iSCI was also sensitive to the presence of spasticity. The successful early diagnosis and treatment of spasticity would be expected to further preserve and promote adaptive motor function during subacute iSCI neurorehabilitation.

Introduction

The development of spasticity following incomplete spinal cord injury (iSCI) has been operationally defined in the clinical setting as an increase in velocity-dependent tonic stretch reflexes (muscle tone) and exaggerated tendon jerks to passive movement (Lance, 1980), and has been demonstrated in more than one animal model (Taylor et al., 1999, 1997; Bose et al., 2002). However the functional impact of other clinical symptoms associated such as involuntary muscle contractions and excessive antagonist coactivation may equally contribute to the spastic syndrome (Taylor et al., 1997; Lance, 1980; Dimitrijevic and Nathan, 1967; Biering-Sorensen et al., 2006; Bennett, 2008) and to "spastic movement disorder" (Dietz and Sinkjaer, 2007; Biering-Sorensen et al., 2006). Furthermore analysis of ankle dorsiflexor muscle function in patients with multiple sclerosis and spasticity indicated that "phasic stretch reflex activity" was reduced or absent during a maintained contraction, in contrast to the increase in ankle extensor muscle activity (Toft et al., 1993) suggesting that the spastic syndrome may have specific muscle group effect.

Neurophysiological evidence in patients with SCI suggests that a deficit in corticospinal voluntary activation of ankle dorsiflexors (Diehl et al., 2006; Hansen et al., 2005; Wirth et al., 2008a) combined with the novel observation of a specific increase in ankle flexor reciprocal inhibition from spastic Triceps Surae (TS) muscles during movement (Yanagisawa and Tanaka, 1978; Ashby and Wiens, 1989; Okuma and Lee, 1996) could combine to promote Tibialis Anterior (TA) paresis during spasticity. Thus the measurement of ankle flexor muscle function during controlled movement could be important in determining the negative impact of spasticity on the recovery of residual motor function following iSCI (Biering-Sorensen et al., 2006; Nielsen et al., 2007).

Normal antagonist coactivation has been identified during several controlled movement conditions (Pierrot-Deseilligny and Burke, 2005; Hubley-Kozey and Earl, 2000). The role of ankle joint coactivity has been suggested to maintain the essential excitability of antagonist

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motoneurones and balance during movement (Nielsen and Kagamihara, 1992), but it is also prevalent during motor learning tasks (Llewellyn et al., 1990). Although increased ankle joint antagonist coactivation in patients with SCI during dynamic controlled movement (Knutsson and Martensson, 1980; Knutsson et al., 1997), or during gait has occasionally been identified (Dimitrijevic and Nathan, 1967; Dietz et al., 1994; Knutsson et al., 1997), it was not detected in an extensive study of spasticity in patients with several spinal pathologies, eventhough hyperactive tendon reflexes were present (Dietz et al., 1981). The prevalence of TA coactivation in patients with SCI with and without spasticity, compared to healthy subjects, is not known.

Antagonist muscle coactivation may also depend on the velocity and force of the movement testing conditions used. Although several studies have identified velocity-dependent coactivation in healthy subjects (Hubley-Kozey and Earl, 2000) and in patients with SCI spasticity (Knutsson et al., 1997; Knutsson and Martensson, 1980), the functional relationship of antagonist activity with the level of voluntary agonist contraction is unknown. Indeed the failure to observe antagonist coactivation in patients with a clear reduction in either reciprocal inhibition (Morita et al., 2001), which can be measured during dynamic contractions (Crone et al., 1987), or an increase in reciprocal facilitation (Crone et al., 2003) has been partially attributed to the limited range in which the muscle length was tested (Morita et al., 2001), further supporting the use of a wide range of contraction levels. The systematic analysis of antagonist muscle activity during ramp-and-hold controlled movement studies using a wide range of velocity and contraction levels could further clarify whether spasticity decreases TA coactivation in patients with SCI.

In this pilot longitudinal study of spasticity we show that a reduced but stable voluntary activation of the TA muscle combined with a decrease in contraction-dependent coactivation is present in patients with spasticity, characterized by the presence of hypertonia and spasms, compared to those without spasticity following iSCI. Furthermore, data from the small number of subjects presented in this study supports the hypothesis that analysis of ankle flexor coactivation gain over a wide range of ramp-and-hold plantarflexion forces could be instrumental as a measure of early adaptive or maladaptive spinally-mediated motor function during intensive neurorehabilitation of iSCI.

Materials and Methods

The experimental protocol was approved by the Toledo Hospital Clinical Research Ethical committee. Before inclusion into the study consent was obtained according to the Declaration of Helsinki.

Subjects

Patients within the age range of 18-65 years were recruited within 3 months of an incomplete SCI (ASIA C or D) as assessed by the medical staff with the ASIA scale (Maynard et al., 1997). Additional inclusion criteria were: injury in the range between C4 and L3 spinal levels, and a minimum score of 3 on the five point muscle scale for the dominant leg (Medical Research Council of the UK, 1976) for both ankle flexor and extensor muscles (where "3" represents motor activity just greater than resistance to gravity). A trained physiotherapist assessed hypertonia for muscles of the ankle joint with the Modified Ashworth Scale (Bohannon and Smith, 1987) and frequency of muscle spasms using the Penn scale (Penn et al., 1989). Patients were excluded from the study if in addition to the iSCI they had peripheral nerve damage, cerebral lesions or epilepsy. Initially 22 patients with iSCI were recruited to participate but 12 were excluded due to: weak voluntary TS or TA muscle score (n = 5), drop-out during the study (n = 2), early discharge from the hospital (n = 4), or the appearance of epilepsy during the study (n = 1). As such a total of 8 healthy subjects and 10 iSCI patients were tested according to the established criteria. There were four recording sessions, performed in general at approximately two week intervals. The exact start time for each subject was as follows: #1-16W, #2-19W, #3-11W, #4-11W, #5-13W, #6-13W, #7-21W, #8-15W, #9-14W, #10-15W. At the end of the study, data from the recruited patients were divided into two groups: those without (n = 5) and those with spasticity (n = 5)who presented or developed lower limb muscle hypertonia (one point or more on the Ashworth Scale) or spasms (one point or more on the Penn Scale, n = 5).

Experimental set-up procedure

During each testing session the subject was placed in a comfortable position in a chair or in the wheelchair, so that the dominant foot was positioned and fixed into a custom-built dynamometer (Cibertec, S.A., Spain) designed to measure only the plantarflexion torque (Nm) during different ramp-and-hold ankle joint displacement. In the testing position hip, knee and ankle joints were positioned at 90º of flexion. Subjects were initially asked to perform three consecutive maximal voluntary contractions (MVC) of ankle joint flexion, each of 5 s duration with a 15 s rest period between them. The subjects then performed the same protocol for ankle joint extension with the additional measurement of maximal plantarflexion voluntary torque (MVT). Dorsiflexion torque was not possible and as such electromyographic activity was recorded as the primary measure.

Following a rest period of 5 minutes, subjects were instructed to follow with the stronger leg a "ramp-and-hold" movement template presented on a monitor. This movement protocol was chosen based on the study of reciprocal Ia inhibition of ankle muscles during dynamic contractions (Crone et al., 1987). The movement protocol recorded the plantarflexion torque during the ramp phase and the hold phase (Fig. 1B). The target template was programmed to present six "ramp-and-hold" movements, with a 5 s initial resting period at the basal torque of 15% of the maximal voluntary plantarflexion torque, a 2 s ramp, and a 3 s hold phase followed by relaxation of the ankle extensor muscle to the initial condition for 2 s. The maximal hold phase was presented to reflect either 25%, 50% or 75% of the maximal voluntary recorded torque. Electromyographic activity from the TA and Gastrocnemius Medialis (GM) muscles were recorded with this protocol at 25, 50 and 75% of the MVT, in that order. An audible alarm was triggered if the produced torque fell outside of the desired target movement template.

Data recording and analysis

Electromyographic activity recorded from TA and GM was assessed during ramp-and-hold controlled plantarflexion at 25, 50 and 75% of the maximal voluntary torque measured previously. Muscle activity was recorded with bipolar silver chloride coated electrodes at a gain of 1KHz with an in-built filter bandwidth between 20-450 Hz, and low noise (Delsys Inc. Signal Conditioning Electrodes v2.3, USA), and referenced to a 2 cm square stainless steel electrode placed over the rotula. Electromyographic data were collected along with the target template and "ramp and hold" plantarflexion torque measure performed by subjects via a National Instruments analog-digital converter (National Instruments, Austin, Texas, USA) and stored on custom-built software (LabView Version 7, National Instruments, Austin, Texas, USA) for further off-line analysis with the Spike 2 software package (version 5.03, Cambridge Electronic Devices, CED, Cambridge, UK). Electromyographical coactivation was analyzed from the beginning of the plantarflexion up to the end of the isometric contraction, effectively measuring the "ramp-and-hold" ankle joint plantarflexion (Fig. 2B) as has been used in studies of reciprocal inhibition (Crone et al., 1987). Electromyographic data were digitized at 1 KHz and converted to Root Mean Square (RMS) signals, which is a measure of the magnitude of the varying signal, and