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Does the force level modulate the cortical activity during isometric contractions after a cervical spinal cord injury?

Sylvain Cremoux [a,*], Jessica Tallet [b], Eric Berton [a], Fabien Dal Maso [b], David Amarantini [b,c]

[a] ISM, Aix-Marseille Université, Marseille, France
[b] PRISSMH, Université Paul Sabatier Toulouse 3, Toulouse, France
[c] Département de kinésiologie, Université de Montréal, Montréal, Québec, Canada

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HIGHLIGHTS

- We compared the modulation of the cortical activity depending on the force level in participants with a cervical spinal cord injury (SCI) during intact or altered isometric contractions in comparison to able-bodied participants.
- The cortical activity of the participants with a cervical SCI was comparable to that of able-bodied participants whatever the integrity of the force production capacity.
- The cortical activity was modulated with the intent to modulate the force level.

ABSTRACT

Objective: This study investigated the effects of a cervical spinal cord injury (SCI) on the modulation of cortical desynchronization (ERD) during isometric contractions at different force levels.
Methods: For 8 able-bodied (AB) and 6 cervical SCI participants, the net joint moment and electroencephalographic activities were recorded during isometric contractions of the right elbow in flexion and in extension at 3 force levels, that is, during intact and altered muscle contractions for SCI participants. The mean net moment and ~20 Hz ERD from C3 electroencephalographic electrode were compared between AB and SCI participants.
Results: In flexion, that is, during intact contractions for all participants, the mean net moment and the ERD increased with the required force level. In extension, that is, during altered contractions, the mean net moment increased for 3 SCI participants while it was almost zero for 3 other SCI participants. The associated ERD increased with the required force level for all participants.
Conclusion: The cortical desynchronization was modulated by the intent to modulate the force level rather than the actual modulation of the force production.
Significance: These results provide a better understanding of the modulation of the cortical desynchronization following SCI. Potential applications could include the control of neuroprostheses.

1. Introduction

Following a spinal cord injury (SCI), the preservation or reorganization of the cortical activity involved in motor control is still an active debate (for a review, see Kokotilo et al., 2009). Many electroencephalographic (EEG) studies have focused on the level of cortical activity during attempted muscle contractions (Halder et al., 2006; Gourab and Schmidt, 2010) but few studies have investigated the level of cortical activity during actually realized voluntary muscle contractions (Mattia et al., 2006). Further investigations are especially needed to improve understanding of influence of the force level during actual muscle contractions, whether intact or altered by the SCI.

In healthy participants producing a motor task, the level of cortical activity can be characterized by the cortical desynchronization, that is, a decrease of the ~20 Hz spectral amplitude of the oscillatory EEG activity recorded over the primary motor cortex (Salmelin and Hari, 1994; Salmelin et al., 1995; Crone et al., 1998; Pfurtscheller and Lopes Da Silva, 1999). Previous EEG studies have also shown that the level of cortical desynchronization is influenced by the magnitude of the produced force (Pfurtscheller and Lopes Da Silva, 1999). More precisely, the cortical desynchro-

* Corresponding author. Address: CP 910, 163, Avenue de Luminy, 13288 Marseille Cedex 09, France. Tel.: +33 (0) 4 91 17 04 10; fax: +33 (0) 4 91 17 04 12.
E-mail address: sylvain.cremoux@univ-amu.fr (S. Cremoux).

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nization increases as force increases (Stančák et al., 1997; Mima et al., 1999; Siemionow et al., 2000; Chakarov et al., 2009).

In SCI participants, recent EEG studies have revealed distinct patterns of cortical activity associated to motor tasks. On one hand, studies showed that, in comparison to healthy participants, the modulation of the spatiotemporal pattern of cortical activity was preserved in SCI participants during attempts to move paralyzed foot/toes (Halder et al., 2006; Castro et al., 2007; Hotz-Boendermaker et al., 2008) or during realized intact movements of the lips (Mattia et al., 2006). On the other hand, studies revealed no pronounced or exacerbated cortical desynchronization during attempts to move paralyzed foot/toes (Müller-Putz et al., 2007; Gourab and Schmidt, 2010). However, to our knowledge, no study has taken into consideration the influence of the force level on the cortical desynchronization during voluntary muscular contractions, whether intact or altered by the SCI.

This study was designed to investigate the modulation of cortical desynchronization associated to intact and altered voluntary isometric contractions at different force levels in SCI participants compared with healthy participants. First, our aim was to confirm whether the modulation of cortical desynchronization is associated to increasing force level in SCI participants performing intact muscle contractions. Second, we investigated the modulation of cortical desynchronization during altered muscle contractions, hypothesizing that the integrity of force production capacity would be associated to the modulation of cortical activity. Based on the clinical literature, we considered that isometric contractions around the elbow joint in flexion and in extension are particularly appropriate for this purpose. Indeed, the musculotaneous nerve innervates the elbow flexors with fibers originating from the C5 and C6 spinal nerves, while the radial nerve innervates the elbow extensors with fibers originating from the C6, C7 and C8 spinal nerves (Hislop and Montgomery, 2007). It follows that an injury localized above the C8 spinal nerves does not affect the ability to contract the elbow flexors while it affects the ability to contract the elbow extensors (Maynard et al., 1997).

2. Methods

2.1. Participants

Fourteen men volunteered in this experiment. All participants were right-handed as assessed by the Edinburgh handedness inventory scale (Oldfield, 1971; mean laterality quotient: 0.67 ± 0.21). None of the participants had suffered from a brain lesion. They were assigned to two groups matched for age, weight and height (Student's *t*-tests, all $t_{12} < |2.03|$; $p > 0.05$). The AB group was composed of 8 able-bodied and healthy participants without any neuromusculoskeletal or sensory disorder (age: 28.14 ± 3.98 years, mass: 71.57 ± 8.02 kg, height: 1.75 ± 0.05 m). The SCI group was composed of 6 participants with chronic SCI (age: 31.00 ± 4.10 years, mass: 60.33 ± 9.00 kg, height: 1.78 ± 0.08 m, time since injury: 10.50 ± 3.73 years, physical activity: 6.17 ± 1.32 h/week). A manual muscle testing (MMT) was carried out on the right arm to clinically assess the performance of elbow flexors and extensors (Hislop and Montgomery, 2007). For each SCI participant, the MMT score from the elbow flexors was 5, whereas it ranged from 0 to 5 for the elbow extensors. As shown in Table 1, SCI and AB participants had homogeneous force production capacity in flexion and heterogeneous force production capacity in extension. Other characteristics of the SCI participants were obtained from a chart review (time since latest exam: 4.00 ± 1.67 years) (Table 1).

The experimental procedure was approved by the local ethics committee of Paul Sabatier Toulouse 3 University, and all participants gave informed consent in accordance with the Helsinki convention for the investigation with human participants.

2.2. Materials

The net moment (i.e., the sum of the individual moments created from the forces developed by muscles and other structures crossing a joint, Zajac et al., 2002) was recorded around the right elbow joint at 1 kHz using a calibrated dynamometer (System 4 Pro, Biodex Medical Systems, Shirley, NY, USA).

After suitable skin preparation (Hermens et al., 2000), electromyographic signal (EMG) was recorded on the right upper limb with a MP 150 system (Biopac Systems Inc., Goleta, USA) at 1 kHz using Ag–AgCl bipolar surface electrodes (EL503, Biopac Systems Inc., Goleta, USA) with a 2 cm inter-electrodes distance. The biceps brachii (BB) and the brachioradialis (BR) were chosen to represent the elbow flexors, while the long head and the lateral head of the triceps brachii (TBlh and TBlt, respectively) were chosen to represent the elbow extensors (Bouisset et al., 1976; Buchanan et al., 1989). The reference electrode was placed on the head of the ulna of the left arm.

EEG was recorded at 1024 Hz from 64 active electrodes mounted on a cap using the international 10–20 system (Active II, Biosemi Inc., Amsterdam, The Netherlands).

The electro-oculogram was recorded from the left eye to locate movements or blinks.

Time synchronization of data acquisitions was achieved offline using a TTL pulse.

2.3. Experimental setup

In a dimly lit room, participants comfortably sat on the chair of the dynamometer with their trunk and their right upper limb firmly strapped. The right arm was positioned along the trunk. The forearm was supinated and 90° flexed, that is, in a favorable

Table 1
Clinical characteristics and performance during MVC for the SCI participants.

Participant *n*	Years since injury	AIS[a]	Right motor neurological level of injury	Flexion		Extension	
				MMTS[b]	MVC (Nm)	MMTS[b]	MVC (Nm)
1	13	D	C5	5	45.98	5	−55.70
2	11	A	C5	5	51.39	0	0.15[†,*]
3	19	A	C7	5	79.96	5	−54.49
4	10	A	C5	5	57.28	2	−3.58[*]
5	10	A	C7	5	53.34	5	−45.27
6	7	A	C6	5	66.01	1	0.77[†,*]

[a] AIS: ASIA Impairment Scale.
[b] Muscles were graded on a six-point ordinal scale and a score upper or equal to 3 indicated that a muscle can contract in the full range of motion, at least, against the resistance gravity (Hislop and Montgomery, 2007).
[†] Values within the margin of error of the dynamometer used for net joint moment measurement ([−1.35 1.35 Nm]).
[*] Values significantly different from the AB group ($p < 0.05$).