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Changes in movement-related β-band EEG signals in human spinal cord injury

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ABSTRACT

Objective: The purpose of this study was to characterize differences in movement-related β-band signals of the brain between people with chronic spinal cord injury (SCI) and neurologically intact volunteers.
Methods: A 64 channel EEG system was used to record EEG while subjects attempted brisk toe plantar flexion in response to auditory cues. Change in amplitude in β-band frequencies during times of event-related desynchronization and synchronization (ERD and ERS) and topography of ERD and ERS were compared across groups and correlated to ASIA motor and sensory impairment scores for SCI subjects.
Results: ERS amplitude immediately following the movement attempt was significantly smaller (*t-test;* $p < 0.001$) in SCI subjects as compared to controls. The ERD change tended to be greater and the topography was more widespread in SCI subjects. Incomplete SCI subjects with more severe neurological injury (lesser ASIA motor score) had lower peak ERS amplitude and a significant correlation was observed between sensorimotor impairments and ERS amplitude ($r^2 = 0.79$; $p = 0.02$).
Conclusions: Our results suggest that motor processing in the brain is altered after SCI, and that it occurs in proportion to the severity of neurological injury.
Significance: These results are important for brain computer interface applications that rely on ERD and ERS pattern recognition.

1. Introduction

Brain signals obtained by electroencephalography (EEG) have potential as control sources for computers or prosthetic devices for people with spinal cord injury (SCI). In particular, changes in EEG signal power in the β frequency band (13–35 Hz) are of particularly high interest because of their strong association with motor commands (Pfurtscheller and Lopes da Silva, 1999). The potential of these signals as controller commands for brain computer interfaces (BCIs) relies on the continued association of β-band amplitude modulation with motor commands after spinal injury (Pfurtscheller and Neuper, 2006). However, the fluctuations in β-band power associated with motor commands in SCI subjects with a complete injury differ from noninjured subjects (Muller-Putz et al., 2007), possibly due to cortical plasticity and/or loss of sensory feedback to cortical structures. Thus, our objective was to compare the motor command β-band power fluctuations in sensory incomplete SCI subjects to similar measurements in subjects with complete injury and in noninjured controls. We hypothesized that retention of sensory tracts in incomplete SCI would partly normalize the fluctuations in β frequency associated with motor commands, compared to complete injury.

Motor commands produce characteristic fluctuations in EEG recordings over the sensorimotor cortices in the α (8–13 Hz) and the β frequency bands. During the preparation and execution of voluntary movements, the β-band oscillations are desynchronized (decreasing β-band power) followed by a rebound resynchronization (β-band power increase) after movement offset (for review see (Neuper and Pfurtscheller, 2001)). The event-related desynchronization (ERD) is postulated to represent the electrophysiological correlate of activated motor networks in the brain, while the subsequent event-related resynchronization (ERS) is believed to represent inhibition of these networks (Pfurtscheller and Aranibar, 1977; Pfurtscheller and Lopes da Silva, 1999; Neuper et al., 2006). Because of their association with motor commands, ERD and ERS are potentially useful indicators of cortical sensorimotor function.

ERD and ERS patterns can be detected in single trials (Bai et al., 2008; Pfurtscheller and Solis-Escalante, 2009; Solis-Escalante et al., 2008) and thus, are a potential signal source for BCIs that utilize intentional motor control commands to control computers or other assistive technologies. Further, when ERD/ERS is combined with detection of movement related potentials, there is a significant improvement in the detection rate of control commands with

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minimal subject training (Fatourechi et al., 2008; Fatourechi et al., 2007). Therefore, it is postulated that BCI control structures based on ERD/ERS will be especially useful for patients with severe movement disorders including those with SCI (Pfurtscheller and Neuper, 2006; Pfurtscheller et al., 2006). A critical factor in the applicability of ERD/ERS to chronic SCI is that reliable signals are still available, and relatively unchanged by the loss in sensation and cortical plasticity that accompany SCI.

There is evidence that injury to the spinal cord changes the EEG patterns associated with motor commands (Green et al., 2003; Castro et al., 2007; Muller-Putz et al., 2007; Mattia et al., 2006), which could affect the use of EEG signals for BCI applications. While the EEG associated with motor commands of the leg (i.e. below the level of injury) demonstrate a spatiotemporal pattern that resembles the pattern of noninjured subjects, there are some notable differences. The spatial topography of the movement-related brain potentials is altered (Castro et al., 2007), with a posterior shift in the readiness and motor potentials (Green et al., 2003; Green et al., 1999; Green et al., 1998; Castro et al., 2007). Interestingly, the amplitude of these potentials is not significantly changed. In contrast, the magnitude of ERD/ERS is reduced significantly (Muller-Putz, et al., 2007) in complete SCI, and models of functional connectivity based on β-band signals indicate an increase in connections, particularly for brain regions that integrate sensory and motor functions (Mattia et al., 2009). These changes in topography and functional connectivity suggest that the loss of sensation might play an important role in the EEG signals associated with motor commands.

The purpose of this study was to characterize the alterations in β-band ERD and ERS that occur in people with chronic complete and incomplete SCI. We hypothesized that ERD/ERS amplitudes and spatial patterns would vary with the extent of neurological impairment after SCI.

2. Methods

2.1. Subjects

Eight chronic (>2 years post injury) SCI subjects, with a range of neurological impairments (ASIA impairment scales (AIS) A to C (American Spinal Injury Association, 2006)) and 8 noninjured (NI) volunteers participated in this study. Two additional SCI subjects with AIS D were also included in this study, but data collected from them were used only to enable a correlation between ERD and ERS parameters and the whole spectrum of impairments (A to D) as per the AIS. A description of the study participants is provided in Table 1. Inclusion criteria included traumatic SCI of duration > 2 years, medically stable, the ability to give written informed consent and the ability to sit still for at least 10 min. Exclusion criteria included a history of concomitant central or peripheral neurological impairment (for example traumatic brain injury or peripheral neuropathy), severe hearing impairment and presence of unhealed decubitus ulcers. The study protocol was approved by the Institutional Review Board at Marquette University. Written informed consent was obtained from all participants prior to enrolling in the study.

2.2. EEG recording

EEG recording was done using the 64 channel Synamps2 EEG system and the Scan 4.3 EEG acquisition software (Compumedics Neuroscan, El Paso,TX). Subjects wore the QuikCap (Compumedics Neuroscan) electrode cap, which has 64, pre-positioned electrodes arranged according to the modified combinatorial 10–20 system of electrode placement (American Clinical Neurophysiology Society, 2006). EMG was simultaneously recorded from the short toe flexors to detect the onset of movement (if any). The skin over the short toe flexors (on the medial half of the sole, anterior to the heel) was lightly abraded and cleaned with alcohol. Two disposable, self-adhesive surface electrodes were placed over this area, while the ground electrode was placed over the tibial tuberosity. Electrodes were connected to an amplifier to amplify the EMG signals (X1000) and route them to a data acquisition card attached to a personal computer (PC). Custom LabVIEW (National Instruments, Austin, TX) software running on the PC was used to collect the EMG data, along with the time marks for the auditory cues. The auditory stimulus consisted of a "click" generated by a 100 ms 5 volt monophasic pulse supplied to the speakers. Subjects reclined on a dental chair and continuous EEG was recorded during the following trials:

Trial 1: This trial was used to determine the evoked response due to the auditory cue alone. The subjects listened to an auditory cues presented at pseudo-random intervals (detailed below) without attempting any movement.

Trials 2 through 4: The next 3 trials recorded the movement-related brain potentials (MRBPs) generated by an auditory-cued toe plantar-flexion movement. A custom LabVIEW (National Instruments) program was used to generate a 5 V electrical pulse via a data acquisition card on a personal computer. The pulse was generated at a pseudo-random interval varying between 5 and 7 s. This same pulse was routed simultaneously to the EEG and EMG amplifiers and a pair of portable speakers. Thus, the EEG and EMG signals were time-locked to the auditory cue.

Table 1
Demographic characteristics and American Spinal Injury Association (ASIA) (American Spinal Injury Association, 2006) scores of SCI subjects included in the study.

Subject	Level of injury	ASIA Impairment scale	ASIA motor score	ASIA motor score in the tested leg	ASIA sensory score	ASIA sensory score in the tested leg	Years since injury
1[*]	T1	D	55[**]	22	122	20[**]	7
2	T10	C	73	11	148	0	6
3	C7	C	43	10	144	20	26
4	T8	A	50	0	120	0	14
5	C7	C	35	7	144	20	20
6	C8	A	14	0	40	0	5
7[*]	C4	D	78	20	132	20	5
8	T1	A	32	0	79	0	9
9	T10	A	50	0	144	0	16
10	C8	A	14	0	56	0	27

[*] AIS D subjects had ERD/ERS characteristics very similar to NI subjects, they were not included in the group of SCI subjects (AIS A, B or C; $n = 8$) initially studied to highlight the differences in ERD/ERS patterns between NI subjects and subjects with SCI.
[**] This subject had a below knee amputation. The ASIA motor and sensory scores for the absent muscles and dermatomes were taken as the same as that in the corresponding muscles and dermatomes in the opposite side.