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Brain-Computer Interfacing in Tetraplegic Patients with High Spinal Cord Injury

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Abstract. One basic rationale for Brain-Computer Interfaces (BCIs) is to enable severely paretic persons to interact again with their environment. While advancements of BCI techniques are significant in healthy volunteers, there are only few studies that investigated the applicability of BCIs in patients afflicted by spinal cord injury (SCI), and the spatiotemporal characteristics of sensorimotor cortical event-related potentials in these subjects is largely unknown. In this study we evaluated the feasibility and performance rate of the Berlin Brain-Computer Interface in a first-session setting in high-level SCI with tetraplegia.

In a one-dimensional online feedback four out of seven subjects were were able to control the BCI via attempted movements with their plegic limbs during the first session with a mean accuracy of 75%. Interestingly, subjects achieved an even higher perfomance rate of about 83 % (range: 74-95%) in a 'cursor off' mode, in which the feedback signal was provided only at the end of each trial. In contrast to a previous SCI-BCI study, topographical and temporal patterns of event related desynchronizations (ERDs) in the μ- and β-frequency bands were well distinguishable in these patients.
Keywords: Brain-Computer Interface, Spinal Cord Injury, Event-Related Desynchronization (ERD)

1. Introduction

Spinal cord injuries, e.g., due to accident, can lead to a complete loss of motor and sensory functions caudal to the lesioned myelon. Affected patients loose their ability to walk and – depending on SCI-level – to use their arms.

Brain-Computer Interfaces (BCIs) are a new option for severely disabled individuals to regain the ability to interact with their environment [Wolpaw et al., 2002]. Non-invasive BCIs use different types of internally or externally paced amplitude changes of brain potentials [Birbaumer, 2006]. Only few previous studies have investigated the applicability of BCI in severely disabled paretic patients [for a review see Kübler and Birbaumer, 2008], e.g., due to neurodegenerative diseases like amyotrophic lateral sclerosis, or SCI subjects [Krausz et al., 2003; McFarland et al., 2003]. There are some limits to generalize the results of these studies: lower limb paresis caused by SCI was often incomplete, upper limb functions were partly not affected, BCI training took place over weeks to months, and imagined movements rather than attempted movements were used to induce ERDs. To our knowledge there is only one BCI study investigating the applicability of ERDs using BCIs in complete tetraplegic patients [Kauhanen et al., 2007]. In this study, slow cortical potentials (0.5-3 Hz), i.e., lateralized readiness potentials (LRP), were used for the classifier since ERDs in the μ- and β-frequency bands were not sufficiently detectable. This finding is surprising since functional magnetic resonance imaging (fMRI) studies [Hotz-Boendermaker et al., 2008] could demonstrate preserved motor programs in the sensorimotor cortex in SCI patients, as related to attempted and imagined foot movements.

2. Material and Methods

2.1. Neurophysiology

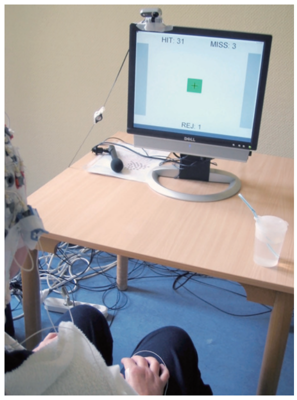
To detect and translate the users intent, the Berlin Brain-Computer Interface (BBCI) [Blankertz et al., 2007] utilizes modulation of sensorimotor rhythms (SMR) in the μ- (9-14 Hertz) and β-frequency range (14-30 Hertz) which are modulated, e.g., by executed and imagined movements [Pfurtscheller and da Silva, 1999] in the perirolandic sensorimotor cortices.

2.2. Subjects

Seven tetraplegic, BCI-naïve Patients (6m, 1f; mean age 36; measurement on average 11 month after SCI; all right-handed) participated in this one-session study after providing informed consent according to the guidelines of the local Ethics Commission. Subjects had complete motor and sensory loss below a cervical spinal cord lesion (Grade A or B ASIA Impairment Scale; [Maynard et al., 1997]) due to traumatic (5) or ischemic (2) cervical spinal cord injury (level C4 - C7).

2.3. Experimental Setup

According to the level of motor impairment and the subject's individual characteristic of kinetic experience (e.g., professional or sportive) prior to SCI, a movement simple and quick to perform was chosen (e.g., clench fist). All movements were accomplished as attempted, not imagined movements. Before measurement a detailed supervised training of a few minutes and instructions about the precise test procedure took place. During the measurement subjects were seated in a relaxed manner in their wheelchair with arms positioned in their lap. Brain activity was recorded from the scalp with 64-channel EEG amplifiers in an extended 10-20 system.



2.4. BBCI Feedback

Using data from an initial 30 minutes 'calibration measurement' the classifier was trained in a short break. Subsequently one to three runs of 'classic' feedback modus took place where subjects performed a one-dimensional feedback task moving a cursor from the center of a monitor to a randomly indicated horizontal direction. In a second part, one to three runs 'cursor off' were accomplished where the feedback signal was provided only at the end of each trial.

3. Results

3.1. Neurophysiological findings

In the majority of the patients, attempted foot movements were more distinctly detectable than attempted hand movements. In these subjects, topographical and temporal patterns of movement-related ERDs in the μ- and β-frequency bands were well distinguishable and located in a physiological appropriate anatomical location (Figure 1 and 2). In the present small group of patients we found no correlation between BCI-performance and duration and extent of motor disability.

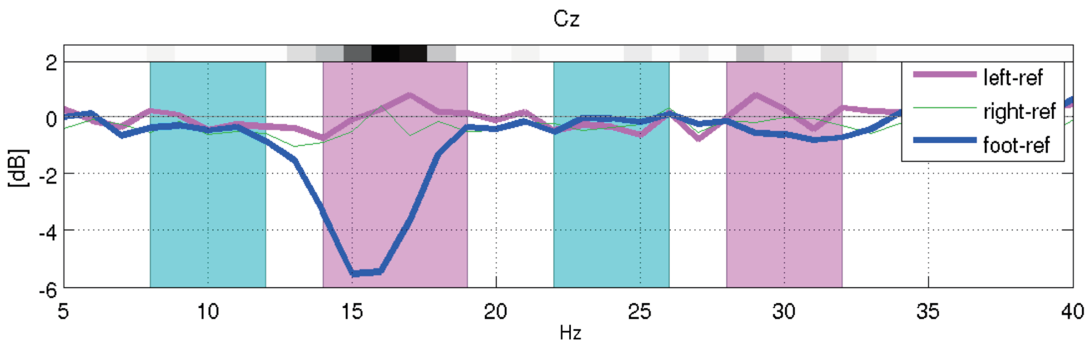


Figure 1. *ERD of subject VPgf for foot movement (blue line) in the lower β-frequency band (frequency at the abscissa in Hz) over the central foot area (ERD curve is shown for Laplace filtered channel at Cz electrode of the 10-20 system), induced by repetitive attempted foot movements. The green and pink lines show the log power during right and left hand attempted movments at the same electrode.*

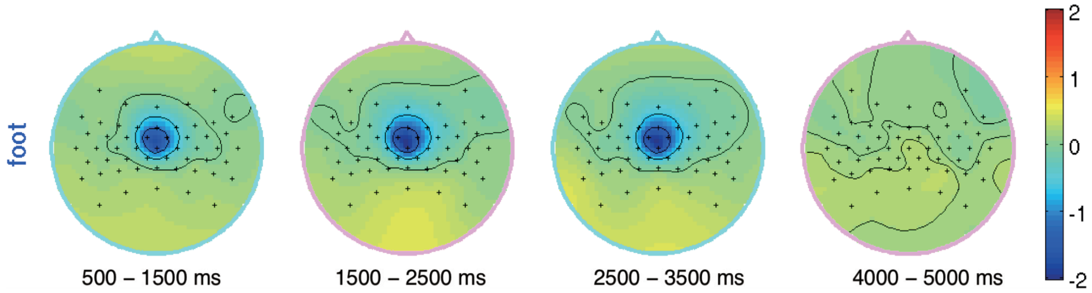


Figure 2. *Corresponding topographical map to figure 1 of the ERD for foot movement of subject VPgf with its temporal course. Blue indicates the log band power decrease (in db) within the chosen frequency band over the central foot area after a directional motor cue.*

3.2. Feedback Performance

In four out of seven subjects the classifier was able to distinguish two categories of attempted movements by means of their spatial and temporal distribution with an accuracy of 75% on average of all trials. Remarkably, all subjects were performing superior in the 'cursor off' feedback mode at a mean of 83 percent accuracy rate (range: 74-95%) in comparison to the preceding 'cursor on' runs (Table 1). Compared to slow cortical potentials in the form of LRPs, ERDs in the μ- and β-frequency bands showed far lower error probabilities in an offline analysis performed after the measurements (Figure 3).

Table 1. *Feedback scores of runs 1 to 6 (Number of trials in parenthesis). Run 1 to 3 in 'cursor on' modus, run 4 to 6 'cursor off' modus.*

Subject	*Run 1*	*Run 2*	*Run 3*	*Run 4*	*Run 5*	*Run 6*
VPga	71 % (55)	69 % (52)	56 % (18)	85 % (60)	95 % (58)	ø
VPgd	74 % (93)	84 % (96)	ø	86 % (98)	93 % (94)	81 % (94)
VPgf	70 % (87)	44 % (18)	64 % (84)	75 % (73)	ø	ø
VPgh	54 % (94)	64 % (96)	ø	74 % (97)	ø	ø

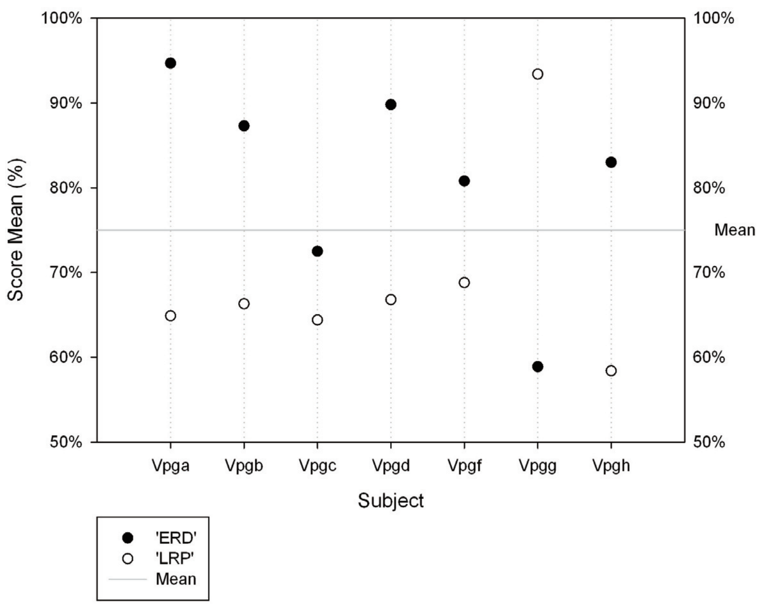


Figure 3. *Comparison of feedback scores using either LRP or ERD classifiers in an offline analysis. Except for VPgg the data of all subjects could be discriminated better using ERDs.*

4. Discussion

Our study demonstrates the applicability of an SMR-based BCI in for subjects with tetraplegia due to high-level SCI with good first-session performance rates up to 83%. Modulation of sensorimotor rhythms was generated through attempted (not imagined) movements in plegic hands and feet. Though a previous BCI study [Kauhanen et al., 2007] in tetraplegic SCI subjects failed to detect SMR in the μ- and β-frequency bands sufficient for BCI use, spatial and temporal patterns of ERD in our patients were similar to that of healthy subjects in anatomically appropriate areas. Furthermore, in our study an offline analysis showed clearly lower error probabilities for SMRs than for LRPs in six out of seven subjects, independently of the extent and duration of spinal cord injury. One explanation for this finding could be the relatively short duration of tetraplegia in our subjects. On the other hand a recent fMRI-study showed preserved motor programs in SCI patients, demonstrated by attempted and imagined foot movements [Hotz-Boendermaker et al., 2008] for measurements at about nine years after the SCI incident.

All subjects had higher performance rates in a 'cursor off' modus, where the feedback signal was provided only at the end of each trial. We introduced this modality after the observation that highly motivated subjects, eager to perform well in the feedback task, approached the feedback section more tensed, especially when the cursor moved in the wrong direction. Since these 'cursor off' feedbacks were realized after the classical 'cursor on' runs, this finding might be also be influenced in part by learning, though not in all patients a clear improvement by experience could be observed in this short one session study.

5. Conclusions

This study demonstrates the feasibility of the BBCI using physiological sensorimotor rhythms in the μ- and β-frequency bands in tetraplegic subjects after high-level spinal cord injury with high performance rates up to 84% that could be achieved in the first BCI-session.

Acknowledgements

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