Long-Term BCI Training for Grasp Restoration in a Patient Diagnosed with Cervical Spinal Cord Injury

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Abstract

Increasing the independency and quality of life of cervical spinal cord injured persons by restoring grasping function using a BCI-controlled hand neuroprosthesis is one of the recent goals in research. The aim of this study is to evaluate the changes of motor cortical patterns, which could be used for controlling such a device, in the course of a long-term BCI training in a 20 year old SCI patient. The patient was regularly trained for 17 months, with different BCI paradigms. The activation patterns of the motor cortex changed over time and got stable after 18 feedback sessions and she reached classification accuracies up to 85% already at the third session. Although such a performance is acceptable, it is still a long way towards a useful and reliable signal for controlling a hand neuroprosthesis to restore grasp.

1 Introduction

A cervical spinal cord injury (SCI) at a high level leads to a loss of motor, sensory, and autonomic functions and therefore to a life-long dependency on carers. Increasing the patient’s independency and quality of life by restoring grasping function is one of the goals in research at our lab. Ten years ago, Pfurtscheller et al. [1] already proposed to use brain oscillations to control a hand orthosis with a brain-computer interface (BCI). A strategy to voluntarily modulate brain oscillation is the imagination of limb movements. This motor imagery (MI) induces a relative decrease in band power, known as event-related desynchronization (ERD), which can be measured with electroencephalography (EEG) of the motor cortical areas [2]. In healthy persons these patterns are usually quite prominent and easy to classify. In SCI patients the patterns of motor cortex activation are altered in dependence of the severity of the paralysis (level of injury; complete or incomplete; time since injury) [3, 4], which makes a training of distinguishable patterns necessary. The aim of the present study is to evaluate the changes of motor cortical patterns in the course of a long-term BCI training using the example of a single SCI patient. We expected to find distinguishable activation patterns over the course of time resulting from regular BCI training.

2 Methods

2.1 Patient

The 20 years old female patient was diagnosed with tetraplegia of C4/C5 (ASIA, A) since a traumatic event in January 2009. Besides the loss of functionality of the lower extremities, as well as the loss of vegetative functions below the lesion, she has lost motor and sensory function of the hand and parts of the arm. Residual muscle activity is restricted to muscles controlling the shoulder and partly to muscles controlling the elbow joint.
2.2 EEG Recordings and Data Processing

The EEG was recorded from 15 channels (C3, Cz, C4, each surrounded by 4 electrodes). Reference and ground electrode were placed on the left and right mastoid. The signals were acquired with a g.USBamp amplifier (Guger Technologies, Austria) with 512 Hz sample rate, 0.5 Hz high-pass and 100 Hz low-pass filter and an additional 50 Hz notch filter. To assess changes in the frequency domain for each class, ERD maps for frequency bands between 4 and 40 Hz were calculated, using overlapping frequency bands with 2 Hz band width and 1 Hz step size [5]. The statistical significance of the ERD values was determined by applying a t-percentile bootstrap algorithm [6] with a significance level of $\alpha = 0.01$. Based on this data 1-3 relevant band power features were selected by checking for relevant ERD patterns in the time-frequency maps. These features were used to train linear discriminant analysis (LDA) classifiers to discriminate between two different classes (2-MI-class BCI: right hand MI vs. feet MI; 1-MI-class BCI: right hand MI vs. rest). Classifiers provided feedback for the training sessions and were updated after every session.

For evaluating performance, classification accuracies were calculated for every feedback session. In case of the 1-MI-class BCI training with continuous feedback the number of true (TP) and false positives (FP) per minute and the ratio between TP and FP per minute were calculated. In addition a t-test for dependent measures was performed to check for significant differences between the number of TP and FP per minute.

2.3 Training procedure

The training started in October 2009 and is still ongoing. It started with nine screening sessions without feedback (right hand vs. feet MI), twelve 2-MI-class BCI training sessions with feedback (right hand vs. feet MI), again four screening sessions without feedback (right hand MI vs. rest) and 14 1-MI-class BCI training sessions with feedback (right hand MI vs. rest).

A training session usually took place once a week in the patient’s home and consisted of 8 runs with 15 trials per class, one trial lasting 7 s. According to the needs of the patient the interval between the sessions was sometimes more than one week (longest interval between sessions 6 weeks) and some sessions were terminated with less than 8 runs (minimum 6 runs).

In the course of the training different kinds of visual feedback were given, due to new developments and to avoid tediousness and keep motivation high (see Figure 1). For the 2-MI-class BCI training at first feedback was given in form of the basket game [7] (see Figure 1.A). Here, a ball falls downwards with constant speed and its horizontal alignment is controlled by the LDA distance. The task was to guide the ball into a basket on the left (feet MI) or right (right hand MI) bottom of the screen. Due to a clear drop in performance after six sessions, feedback was changed to a fluid cursor (see Figure 1.B). Here, the classifier distinguished between right hand MI and feet MI by generating an output of positive or negative classlabels with a continuous distance value that was proportional to the probability of the actual classification belonging to one class. The fluid cursor could change color (right hand MI = green, feet MI = blue), intensity (continuous distance value) and direction (right hand MI = right, feet MI = down; integrated classifier output). The task was to move the cursor in the cue-guided direction.

For the 1-MI-class BCI training feedback was given in form of a car, driving along a two-lane street with obstacles appearing on the left lane and coins appearing on the right lane (see Figure 1.C). The task was to avoid the obstacles and collect as many coins as possible. The car stayed on the left lane if rest was detected and changed to the right lane if right hand MI was detected. This paradigm was a first step towards asynchronous control, as in this case feedback was given constantly, meaning throughout the whole run the car could drive to the left or the right lane, depending on which state was detected (rest or right hand MI).

In addition to the BCI training, the patient was provided with a functional electrical stimulation (FES) device (MotionStim8, KRAUTH+TIMMERMANN GmbH, Germany) to preserve and build up the muscles of the upper extremities. This FES training started after eight months of BCI training and is needed to obtain a reasonable grip strength for using a hand neuroprosthesis.
3 Results

3.1 2-MI-class BCI

The patient showed ERD from 15 to 25 Hz over Cz and C4 during MI right from the beginning of the training, but the pattern for feet and right hand MI did not differ from each other. In the course of the screening sessions this pattern changed to ERS at 25 to 30 Hz over C3 for right hand MI and ERS at 10 to 12 Hz over C3 and C4 for feet MI. Both MI were accompanied by an ERD at 20 to 25 Hz over Cz. With these patterns, after five months of screening, a reasonable differentiation of the two classes was possible, so in the following sessions feedback was given. The left part of Figure 2.A shows the classification accuracies for the 2-MI-class BCI sessions with feedback. The interval between session 5 and 6 was six weeks, which resulted in a clear decrease in classification accuracy, due to a change in the ERD/ERS pattern. The ERS at C3 and C4 did not appear anymore. As the performance did not reach the level it had before this long interval, in further sessions the training paradigm was changed from two MI classes to one MI class (right hand MI) against rest.

3.2 1-MI-class BCI

After four screening sessions for right hand MI against rest a weak ERD from 15 to 20 Hz appeared over C3, Cz and C4. In the course of the following feedback sessions this pattern turned out to be unstable and appeared in variable strength at the different channels. After eight feedback sessions (session 19 in Figure 2.A) an ERD at 15 to 20 Hz appeared over Cz, which stayed stable over the following sessions, only varying in strength. The right part of Figure 2.A shows the classification accuracies for the 1-MI-class BCI sessions with feedback. Performance varied between 70 and 80% accuracy. Figure 2.B shows the true (TP) and false positives (FP) per minute and the ratio between them for all 1-MI-class BCI sessions. The results of the t-test showed that the number of TP per minute ($M = 6.85$; $SD = 0.51$) is significantly higher ($t_{(13)} = 21.88; p < .0001$) than the number of FP per minute ($M = 4.18; SD = 0.73$). The ratio between TP and FP per minute is quite stable in the course of feedback training.

4 Discussion

BCI training in patients is challenging. Although the patient’s SCI was only nine months before start of the BCI training, it took about five months of screening to find distinguishable MI patterns. Due to altered motor cortex activation patterns found in SCI patients [3, 4] it seems to be harder to establish discriminative patterns. After starting feedback training a clear increase in performance, accompanied by a prominent ERS during MI, occurred after only three sessions. After a long interval between session 5 and 6, due to illness of the patient, the performance dropped down to chance level, which shows that the pattern was not stable. Nevertheless, performance increased again in the course of training but did not exceed 85% by now. Although the performance is acceptable and the number of TP per minute is significantly higher than the number of
FP per minute, it is still a long way towards a useful and reliable signal for controlling a hand
neuroprosthesis to restore grasp. Motor cortical activation in SCI patients seems to change with
BCI training, but only short-termed. Enzinger et al. [8] reported on an SCI patient who per-
sistently trained MI via BCI over 8 years and established a stable activation pattern, which is
similar to the pattern observed with actual movement in healthy controls. To achieve this goal,
a regular training, perhaps with shorter session intervals, is needed. As patients do have a life
beside supporting BCI research, this is not easy to realize. Longer session intervals, or shorter
sessions due to discomfort or a conflicting schedule can not be avoided. In addition to a regular
training, the use of additional information, e.g. error potentials, might increase performance to a
reasonable level.
Also the design of feedback is important. Although the patient always reported to be highly moti-
vated, she started to get bored by playing the same game over and over again and got confused by
the amount of information of the fluid cursor feedback. An appealing and entertaining feedback,
which is adapted to the needs of the patient is necessary to avoid tediousness and frustration.
Concluding we can state that if we want to design tools to improve motor functions and quality of
life in SCI patients, we should be aware that gaining a reasonable control of the BCI takes longer
as in healthy subjects.

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