Different Uses of Non-invasive BCI for Controlling Neuroprostheses: Case Studies with End-Users

A. Kreilinger[1], M. Rohm[2], V. Kaiser[1], R. Rupp[2], G. R. Müller-Putz[1]
[1]Graz University of Technology, Austria; [2]Spinal Cord Injury Center, Heidelberg University Hospital, Germany

Correspondence: G. R. Müller-Putz, Graz University of Technology, Austria. E-mail: gernot.mueller@tugraz.at

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Abstract. This work introduces two strategies of how to use a non-invasive brain-computer interface (BCI) for controlling upper extremity neuroprostheses customized for end-users with varying degrees of impairment. One strategy employs a hybrid-BCI for end-users who have remaining muscular functions at shoulder level; the other one uses a control purely based on BCI. We demonstrate the two different BCI-controlled neuroprostheses with case studies, recorded in two spinal cord injured end-users.

Keywords: Electroencephalogram (EEG), Brain-Computer Interface (BCI), Functional Electrical Stimulation (FES)

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1. Introduction

Spinal cord injured (SCI) people can benefit from assistive devices including brain-computer interface (BCI) [Wolpaw et al., 2002]. Depending on the level of impairment, BCI can be combined with other signals based on residual movements or muscular activity measured by electromyography (EMG). However, with a more severe impairment, these signals may no longer be available or cause early fatigue. In this case, a BCI system without any other control signals can offer an alternative. Neuroprosthesis users primarily want to control their hand to grasp objects but with reduced elbow function the restoration of elbow flexion/extension is a prerequisite for adequate use of the grasping function. In this work we show two case studies. Both apply BCI to control a neuroprosthesis based on Functional Electrical Stimulation (FES). The first one is designed for end-users who still have elbow and shoulder functions. Shoulder movements are used to control the grasp strength and a motor imagery (MI)-based BCI to switch between two grasp patterns. The second type uses only a MI-BCI as a control method: depending on the length of delivered MI commands—time-coded MI [Müller-Putz et al., 2010]—either discrete commands like opening/closing the hand or continuous commands like moving the arm upward/downward can be elicited.

2. Material and Methods

Two tetraplegic male end-users, both diagnosed with complete SCI at C4/C5, tested the systems. End-user ES, 31 years old, used both systems. End-user TS, 37 years old, only tested the system for switching between grasp patterns. Both had long-term BCI experience and underwent BCI training to set up individual classifiers based on linear discriminant analysis (LDA) for distinguishing between imaginations of feet movements versus rest.

2.1. BCI to switch between grasp patterns

A 2-axis position sensor was placed on the shoulder to use shoulder movements for modulation of the pulse width of FES in a proportional control scheme and thereby modulate the grasping of the hand. The FES electrodes were placed on different positions on the forearm which allowed the user the execution of palmar and lateral grasps, depending on which electrodes were used to stimulate the underlying motor points [Rupp et al., 2011]. BCI was used in a time-coded manner: short or long commands were generated by imagination of feet movements, as trained beforehand. The paradigm consisted of three states: palmar grasp, lateral grasp, and pause. Short commands (1.5-3 s) allowed the user to toggle between the grasp patterns or exit pause mode. Pause mode could be entered via long commands (>3 s). Additionally, the shoulder position was constantly monitored and used to prevent unwanted switches during ongoing shoulder movements. The two end-users were asked to perform two tasks. Each task started in pause mode. Task A required them to exit the pause mode by switching to the first grasp pattern. Using this pattern they should try to move as many objects—fitting to the current grasp pattern—as possible within 120 s. After this time period, they should switch to the second grasp pattern, move objects for 120 s, switch once again back to the first pattern, move objects, and finally return to the pause state. Task B was different: after exiting pause mode, they had 180 s to alternately move one object and switch to the other grasp pattern.

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2.2. BCI for continuous and discrete control of a neuroprosthesis

The end-user was asked to perform 10 sequences in order to simulate eating food with a hybrid orthosis [Rohm et al., 2011] (open hand→close hand→move arm up→open hand→return to starting position), each within 180 s. The used BCI was again a time-coded MI, however, now the long commands served as continuous commands: as soon as a long command was detected, the elbow started to flex or extend for as long as the long command remained active. The elbow movement was generated by FES electrodes on the upper arm and by equipping the end-user with an orthosis that facilitated stabilization of the elbow joint and provided a control loop to automatically reach desired angles by changing the pulse width of the electrical stimulation. When the target angle was reached, the elbow joint of the orthosis was mechanically locked to avoid fatigue due to continuous stimulation. Short MI commands were only used as discrete commands: these discrete commands were either used to open/close the hand in maximum and minimum angle positions or used to move the arm to the nearest end position.

3. Results

3.1. BCI to switch between grasp patterns

Both end-users tested this system, end-user ES twice. This end-user needed on average 16.9±12.2 s to switch between grasp patterns, 51.3±59.1 s to switch to pause mode; he transferred 215 objects within 24 min during tasks A and 31 objects during the 12 min of tasks B; 53 switches were rejected in total. End-user TS needed 26.2±27.9 s for grasp toggles and 9.0±1.4 s to enter pause mode. He transferred 138 objects during the 12 min of tasks A and 16 objects during the 6 min of tasks B and had 25 switches rejected.

3.2. BCI for continuous and discrete control of a neuroprosthesis

End-user ES achieved a rate of 73.7% true positive commands, depending on the current position of the arm and hand. Eight of ten sequences could be finished within the time limit. During additional non-control states he triggered 2 false commands/min in contrast to 6.9 commands/min during the active sequence periods.

4. Discussion

Both systems were tested successfully in the two tetraplegic end-users. The high variance of switching times is caused by the necessary switches to revoke false commands. Control for both grasp patterns was improved strongly, for the fine-tuned movements were not possible without the neuroprosthesis. In this first system, BCI is only used as an additional control signal; the main control signal is based on shoulder movements. Negative effects of unwanted BCI switches can be strongly reduced due to the rejection of switches during ongoing shoulder movements. The second system uses the BCI signal as the main component. Additional sensory signals are merely used to allow the system to control the angle of the arm. The BCI task itself is more demanding since performing mental tasks over different time periods can be very difficult. Yet, end-user ES is a very good BCI performer and for him it was possible to successfully control the system and complete most of the required sequences. In conclusion, an exclusive BCI control is feasible in severely disabled people but the performance, e.g. the time needed to move objects, is lower than in the hybrid BCI where BCI is combined with other signals controlled by the user.

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