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A brain–computer interface for single-trial detection of gait initiation from movement related cortical potentials

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HIGHLIGHTS

- Accurate single trial detection of the intention of step initiation from scalp EEG.
- Independent component analysis (ICA) preprocessing helps to automatically remove EEG artifacts and enhances detection performance.
- All participating subjects were BCI/EEG naïve subjects, implying general applicability of the proposed approach.

ABSTRACT

Objective: Applications of brain–computer interfacing (BCI) in neurorehabilitation have received increasing attention. The intention to perform a motor task can be detected from scalp EEG and used to control rehabilitation devices, resulting in a patient-driven rehabilitation paradigm. In this study, we present and validate a BCI system for detection of gait initiation using movement related cortical potentials (MRCP).
Methods: The templates of MRCP were extracted from 9-channel scalp EEG during gait initiation in 9 healthy subjects. Independent component analysis (ICA) was used to remove artifacts, and the Laplacian spatial filter was applied to enhance the signal-to-noise ratio of MRCP. Following these pre-processing steps, a matched filter was used to perform single-trial detection of gait initiation.
Results: ICA preprocessing was shown to significantly improve the detection performance. With ICA preprocessing, across all subjects, the true positive rate (TPR) of the detection was 76.9 ± 8.97%, and the false positive rate was 2.93 ± 1.09 per minute.
Conclusion: The results demonstrate the feasibility of detecting the intention of gait initiation from EEG signals, on a single trial basis.
Significance: The results are important for the development of new gait rehabilitation strategies, either for recovery/replacement of function or for neuromodulation.

1. Introduction

Neurological conditions, such as stroke, spinal cord injury or Parkinson's disease, often result in impaired motor control and consequent difficulty of the patient to perform activities of daily living. One of the goals of rehabilitation is to promote the patient's independency with the aim of restoring the loss of movement ability.

Conventional approaches of rehabilitation promote motor recovery through a "bottom-up" approach, focused on peripheral training, often with robotic trainers. Robotic training has several advantages (a reduction of the effort of physical therapists per patient, the possibility to objectively quantify rehabilitation parameters and training output) (Pennycott et al., 2012) and allows for peripheral activity compatible with unconstrained tasks (Gizzi

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et al., 2012). However its effectiveness may also be reduced by the autonomous ability of the robot to complete the movement without the need for patient involvement. Active participation of the patient has been demonstrated to be crucial in improving the outcome of rehabilitation (Pennycott et al., 2012; Duff et al., 2013).

As a complementary and promising branch within motor rehabilitation and assistance are brain–computer interfaces (BCI). BCI technologies provide the means for conveying control commands directly from the brain and can be used either for directly controlling rehabilitation devices (function recovery or replacement) or to provide feedback to the patient based on his/her brain activity (neuromodulation). In the latter case, the patient is actively involved in the rehabilitation process. The feedback is provided by the action of rehabilitation devices (e.g., the movement of an orthotics system) triggered by the brain activity (brain switch).

When the brain activation related to motor intention is measured using non-invasive EEG, the information carried in different frequency bands may be extracted, interpreted and used as the command signal to external devices. These strategies include sensory motor rhythms (SMR), on which most past studies on BCI for neuromodulation have focused (Neuper et al., 2006; Kaiser et al., 2011; Ramos-Murguialday et al., 2013). A disadvantage of this approach, however, is the need for numerous training sessions until the user is able to control the signal adequately. Alternatively, movement related cortical potentials (MRCP) have also been proposed for detecting motor intention from EEG. MRCP is a slow cortical potential that occurs naturally as a person commences or imagines the start of a movement (Gangadhar et al., 2009; Niazi et al., 2011; Garipelli et al., 2013; Xu et al., 2014). The advantage of this approach is that no extensive prior training of the user is required. Moreover, MRCPs can also be used to discriminate between different types of tasks as well as the way a task is executed (Do Nascimento et al., 2008; Gu et al., 2009). One potential confounding factor is that the size of the MRCP is relatively small ($\sim$10 μV) and is prone to many movement artifacts that influence the EEG measures.

MRCPs have been studied during gait initiation, with focus on Parkinsonian patients (Vidailhet et al., 1995; Shoushtarian et al., 2011). Moreover, the study by Do Nascimento et al. (2005) on healthy subjects demonstrated that MRCPs contain rich information regarding gait initiation, which made a strong case for utilizing MRCPs for detecting the intention of gait initiation. However, the ability to detect MRCPs depends on the signal quality and the presence of artifacts, such as due to eye movements or to facial muscle contractions that can significantly affect the performance and robustness of a BCI detection system. This study aims at investigating the possibility of detecting the intention of gait initiation from MRCPs after artifacts were removed in a semi-automatic way. We focused on the step initiation in the forward direction, as it is most relevant for the targeted application. The main objective is to develop and test a brain switch based on the intention to initiate locomotion and, in future developments, to integrate this brain switch into non-ambulatory robotic systems for rehabilitation of walking to promote plasticity in stroke patients (Belda-Lois et al., 2011).

2. Methods

2.1. Subjects

Nine subjects (M6, F3, 21–38 yrs), denoted by SUB1–SUB9, participated in the experiment. No subject had any known neurological disorders. Except for SUB5, all other subjects had no prior experience with BCI systems before the experiment, and were thus considered as naïve BCI subjects. The experiment protocol was approved by the research ethics committee of the University Medical Center Göttingen.

2.2. Experimental protocol

An active EEG electrode system (activCap, Brainproducts GmbH) was used in all the experiments. The EEG electrodes were placed at the International 10–20 system locations Fz, FC1, FC2, C3, Cz, C4, CP1, CP2, Pz, T7, T8 and Fp2. The right ear lobe was used as the reference, and the nasion was used as the ground. The activCap system was connected to a 16-channel gUSBamp EEG amplifier (Guger Technologies OG). The EEG was sampled at 1200 Hz with 50 Hz notch filter enabled. The acquired EEG was then sent to a custom-built Matlab program on a PC through the gUSBamp Matlab API. This Matlab program would display the raw EEG data for the experimenter and store the data for offline processing. Two 6-axial force plates, connected to a Qualisys motion capture system, were also used. The two plates were placed on the ground such that the subjects would be able to step from one plate to the other at their normal strides. The ground reaction forces during the experimental session of the two force plates were recorded by the Qualisys system. To synchronize the EEG recordings and the force recordings, one of the force channels was also connected to the last channel of the gUSBamp system, via a custom-made optical isolator.

During an experimental session, the subjects were asked to perform three recording runs. At the beginning of each recording run, the subject stood on the force plate A. Following a vocal prompt ‘BEGIN’ by the experimenter, the subjects would step from the force plate A to the second plate (force plate B), and remain standing on plate B until stepping back to plate A. The pace at which the steps were taken was completely controlled by the subjects, without any external cues. The only external command the subject received was the ‘BEGIN’ prompt at the beginning of the run. This protocol is a completely self-paced BCI protocol. The only restriction was that the standing time on each plate between the forward and backward steps should exceed 4 s. Each run finished when the subjects completed 20 forward steps. The duration for each run usually lasted 6–7 min. This means that the average forward–backward trial interval was approximately 20 s. The subjects took a rest (3–5 min) between the runs.

2.3. Data analysis

The data from the three runs was used for a three-fold cross-validation. For each fold, the MRCP template was first extracted from one of the runs (training run), and the matched filter detection was done using the template on the other two runs (testing runs). The detailed processing procedure is described below.

2.4. Artifact rejection

In previous studies on MRCPs, the data contaminated by artifacts, such as motion artifacts, eye movements etc., was discarded during off-line processing. In this study, the fixed-point independent component analysis (ICA) (Hyvärinen, 1999) was used for semi-automatic artifact rejection for multi-channel EEG. The independent components (ICs) and the mixing matrix were estimated from the training run, and the ICs with artifacts were identified by visual inspection based on both the time course and the scalp maps of the ICs. Subsequently, the raw EEG data were transformed using the ICA mixing matrix, and the identified artifact ICs were rejected automatically, without further inspection. The remaining ICs were then projected back onto the original scalp channels, resulting in ‘cleaned’ EEG for further processing.