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A hybrid brain computer interface system based on the neurophysiological protocol and brain-actuated switch for wheelchair control

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HIGHLIGHTS

- A MI and SSVEP-based hybrid brain computer interface is first proposed to control a real wheelchair.
- A novel neurophysiological protocol is used for direction and speed control simultaneously and improve the effectiveness.
- A hybrid modalities-based control switch is first designed to start and stop the control system for the control safety.
- The threshold strategy provides the reliability of classification result and safety of wheelchair control.

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ABSTRACT

Background: Brain Computer Interfaces (BCIs) are developed to translate brain waves into machine instructions for external devices control. Recently, hybrid BCI systems are proposed for the multi-degree control of a real wheelchair to improve the systematical efficiency of traditional BCIs. However, it is difficult for existing hybrid BCIs to implement the multi-dimensional control in one command cycle.
New method: This paper proposes a novel hybrid BCI system that combines motor imagery (MI)-based bio-signals and steady-state visual evoked potentials (SSVEPs) to control the speed and direction of a real wheelchair synchronously. Furthermore, a hybrid modalities-based switch is firstly designed to turn on/off the control system of the wheelchair.
Results: Two experiments were performed to assess the proposed BCI system. One was implemented for training and the other one conducted a wheelchair control task in the real environment. All subjects completed these tasks successfully and no collisions occurred in the real wheelchair control experiment.
Comparison with existing method(s): The protocol of our BCI gave much more control commands than those of previous MI and SSVEP-based BCIs. Comparing with other BCI wheelchair systems, the superiority reflected by the index of path length optimality ratio validated the high efficiency of our control strategy.
Conclusions: The results validated the efficiency of our hybrid BCI system to control the direction and speed of a real wheelchair as well as the reliability of hybrid signals-based switch control.

1. Introduction

In the field of rehabilitation engineering, Electroencephalogram (EEG)-based BCIs for wheelchair control have attracted great attention because of their convenience, non-invasion and low expense (Tanaka et al., 2005; Nijholt and Tan, 2008; Rebsamen et al., 2010; Sellers, 2011; Lin et al., 2011). It is helpful for the paralyzed to improve the independence in the daily life (Rebsamen et al., 2010; Millán et al., 2010; Sellers, 2011). The EEG signals applied to control a wheelchair include the P300 potential (Rebsamen et al., 2007; Iturrate et al., 2009), SSVEPs (Middendorf et al., 2000; Muller-Putz et al., 2006; Müller et al., 2010; Stamps and Hamam, 2010) and event-related desynchronization/synchronization (ERD/ERS) produced by MI tasks (Leeb et al., 2007; Ferreira et al., 2010; Tsui et al., 2011; Huang et al., 2012).

Up to now, synchronous and asynchronous protocols have been presented for BCI-based wheelchair control. Typically, the synchronous protocol was proposed for BCI-based wheelchairs by Rebsamen (Rebsamen et al., 2006, 2010). Then, the P300 potential

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(Iturrate et al., 2009; Rebsamen et al., 2010) or SSVEP signal (Müller et al., 2010; Diez et al., 2013) evoked by visual stimuli, was used for selecting the pre-defined location of a destination. Moreover, an intelligent navigation system was employed to avoid obstacles by laser sensors and drive the wheelchair along the specific path (Iturrate et al., 2009). The user couldn't modify the designated trajectory. The synchronous protocol showed high accuracy and safety (Rebsamen et al., 2006). However, low response efficiency and inflexible path option were unacceptable for wheelchair control in the real environment.

Meanwhile, the asynchronous protocol was used for controlling the brain-actuated wheelchair by the independent manipulation (Leeb et al., 2007; Tsui et al., 2011; Hema et al., 2011). A representative MI-based control system was developed by Galán et al., to control a real wheelchair (Galán et al., 2008). In the system, the asynchronous protocol was applied to realize the real-time directional control. Recently, several BCI systems using the asynchronous protocol had been developed for commercial applications (Blatt et al., 2008; Carrera et al., 2011). Nevertheless, the available control commands from a single modality were not enough to meet the criteria of multi-dimensional control.

In recent years, hybrid BCIs were proposed for multi-dimensional control. It combined different EEG signals to produce multiple control commands simultaneously or sequentially for applications. It was demonstrated that hybrid EEG signals, such as SSVEP and MI, could improve the classification accuracy of BCIs (Allison et al., 2010; Brunner et al., 2010). Lately, Li et al. incorporated the P300 potential and MI or SSVEP to control the 2-D cursor and brain-actuated wheelchair (Li et al., 2010, 2013; Long et al., 2012, 2013). This system provided multiply commands to realize multi-dimensional control (e.g., direction and speed). Simultaneously, the hybrid BCI combined MI and SSVEP signals had been developed for control engineering (Pfurtscheller et al., 2010; Horki et al., 2011; Allison et al., 2012; Choi and Jo, 2013). In these BCIs, the control commands were limited by a small number of classification categories. Moreover, Pfurtscheller et al. firstly designed a MI-based brain switch for activating and deactivating their hybrid BCI system (Pfurtscheller et al., 2010). These MI and SSVEP-based hybrid BCIs achieved the good control effect for external devices control. However, it was a challenge that hybrid BCI system was designed for high-efficiency wheelchair control.

In this paper, we proposed a hybrid modalities-based and self-paced BCI system for wheelchair control. A novel neurophysiological protocol provided eight commands for sophisticated multi-dimension control. This protocol gave much more control commands than those of previous MI and SSVEP-based BCIs (Pfurtscheller et al., 2010; Horki et al., 2011; Allison et al., 2012; Choi and Jo, 2013). And a reliable hybrid modalities-based brain switch was developed for a real wheelchair firstly. In our system, left- and right-hand imageries were used for adjusting the direction of the wheelchair. The idle state without mental activities was decoded to keep the wheelchair moving at the straight direction. Synchronously, SSVEP signals induced by gazing specific flashing buttons were used to accelerate or decelerate the wheelchair according to actual conditions. Moreover, the control switch was triggered by hybrid signals (MI and SSVEP), as well a threshold strategy was provided for obtaining available classification results. Our study contained two experiments. First, a virtual wheelchair training task was conducted for evaluating the performance of our proposed hybrid BCI. Second, a real wheelchair was controlled for performing the assigned task by our hybrid BCI system. The efficiency of our methodology was demonstrated by our experimental results and data analysis.

The rest of the paper is organized as follows: The methodology, including the system paradigm, neurophysiological protocol, classification algorithm and threshold strategy, is presented in Section 2. Experimental and result analysis are declared in Section 3. Further discussion is given in Section 4. Section 5 concludes the paper.

2. Methodology

2.1. System paradigm

We propose a hybrid BCI system based on a novel interactive paradigm for wheelchair control. As shown in Fig. 1, the system is composed of a signal acquisition device, a stimulus panel, a BCI module, a wireless communication module and a wheelchair. A suitable EEG cap is used for data acquisition from 15 Cu electrodes. A high-performance bio-signal amplifier translates the raw signal into the computer-sensible data. On the stimulus panel, 4 flashing buttons are used to produce SSVEP signals. And MI is spontaneously carried out by the user simultaneously. Then the BCI module decodes EEG signals into control commands. These control commands are finally transmitted to control the wheelchair by the wireless communication module.

2.2. Neurophysiological protocol

In our system, the user is able to manipulate the direction, speed and switch synchronously. Three options, straight driving, left turn and right turn, are available for directional control. As long as the speed is controlled within the limited range, the user could accelerate, decelerate or drive the wheelchair at the uniform velocity. In addition, the control switch is utilized for starting or stopping the wheelchair. In order to accomplish these functions, the hybrid BCI system provides eight commands in total: turn left, turn right, drive forward, accelerate, decelerate, drive at the uniform velocity, turn on and off the switch. As shown in Table 1, these commands are used for constructing the neurophysiological protocol to control the wheelchair effectively.

The neurophysiological protocol for wheelchair control is illustrated in Fig. 2. When the control switch is turned on by the specific hybrid EEG signals, the BCI system starts to acquire EEG data for controlling the speed and direction of the wheelchair. The single control command is transmitted by sliding 2 s window with an 1.5-s overlap between consecutive computations (regulating the state of the wheelchair every 500 ms). During the driving process, the speed and direction are simultaneously modulated by our control strategy. The control switch will not be turned off to stop the wheelchair until the corresponding hybrid EEG signals are detected by our system.

First, left-hand imagery and the specific SSVEP signal are concurrently detected to turn on the control system. Then the user can steer the wheelchair by using the direction and speed control commands simultaneously as follows:

(1) Left- or right-hand imagery is detected to make a left or right turn respectively. The directional command triggers

Table 1
The control command and their corresponding mental tasks (MI: motor imagery).

Control commands	Mental tasks
Left turn	Left-hand MI
Right turn	Right-hand MI
Driving forward	Idle state without MI
Acceleration	Focusing on the button flashed in the 11Hz
Deceleration	Focusing on the button flashed in the 9Hz
Driving at the uniform velocity	Ignoring flashing buttons
Turning on the switch	Focusing on the button flashed in the 8Hz and left-hand MI
Turning off the switch	Focusing on the button flashed in the 7Hz and right-hand MI