Feasibility Study of a Novel Rehabilitation Training System for Upper Limb Based on Emotional Control

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Abstract - This paper introduces a new way to help people who lose motor function regain their abilities of activities of daily living (ADL). As is proved, repeated training can help the paralytics rebuild the strength of muscles, while active participation of the patients will improve the outcome of rehabilitation than they barely assisted by robots. Brain-computer interface (BCI) technology brings paralytics a new way to join in the training process actively. The novel idea of our study is to treat the robot as a co-worker and the paralytic interacts in the training process with emotional states based on his satisfaction level of the robot's work. This system consists of two main parts: the robot and BCI. The robot can work in three different modes in training process. This paper focuses on the feasibility study of emotional control of the robot. Experiments were conducted with a healthy male subject. Brain signals of the subject were extracted by an electroencephalogram (EEG) headset. Four different mental states were detected and interpreted into control commands to start the robot, stop the robot, maintain training mode and switch training mode. Raw EEG data were recorded for off-line analysis. Powers of four frequency bands of EEG signals were analyzed to find their relationship with different emotional states. Experimental results proved the feasibility of our system and shown that it’s much easier to control the training process with the collaborating of the semi-autonomous robot. We also found that different EEG frequency bands carry important messages about different emotions, which may provide references for further study of emotional control.

Index Terms – Brain-Computer Interface, Emotional States, Upper Limb Exoskeleton Rehabilitation Device, Rehabilitation Training

I. INTRODUCTION

Rehabilitation methods for patients with motor impairment due to cerebrovascular brain damage have been studied for decades. Unlike chronic stroke patients, acute ones who suffer severe motor impairment are not included by current clinical therapies like constraint-induced movement therapy (CIMT) which relies on the residual physical movements of the patients [1]. And traditional therapies which require one-to-one treatment are limited by the time and capabilities of the therapists. So, alternative strategies are needed.

In recent decades, many therapeutic robots have been developed to enhance post-stroke rehabilitation of movement, such as MIT-MANUS developed by Krebs and Hogan in 1998 [2], MIME designed by Charles G. Burgar in 2000 [3], ARMin II [4], the second prototype of a robot for arm therapy applicable to the training of activities of daily living, and so many other rehabilitation robots. The application of these robots can save the therapists from intensive training with the patients and yields positive effects on neuromuscular function rehabilitation. However, no consistent improvement of the functional abilities provided by robot-assisted physical therapy has yet been found [5].

BCI technology brings new hope for rehabilitation medicine, which depends on decoding patients’ mental messages without requirement of any residual muscular movement. Logically, to combine BCI technology with robot-assisted physical therapy into an integrative rehabilitation strategy has become the focus of the attention of many researchers.

In 2009, Kai Keng Ang [6] and his team combined BCI and robotic arm for post-stroke rehabilitation exercises. Experimental results showed that most stroke patients are capable of operating the BCI effectively. Two years later (in 2011), K. Shindo and K. Kawashima [7] carried out an experiment in which a motor imagery BCI was studied. They found that BCI-based training method appears to have yielded some improvement in motor function and brain plasticity.

In recent years, more BCI-based rehabilitation robots have been presented. In 2012, Timm Meyer and Jan Peters [8] introduced a system that combines a Barret seven degree-of-freedom robot arm with neurophysiological recordings to conduct a study on motor learning during reaching movements. And in the same year, Antonio Frisoli [9] proposed a new multimodal architecture for gaze-independent BCI-driven control of a robotic upper limb exoskeleton for stroke rehabilitation to provide active assistance in the execution of reaching tasks in a real setting scenario.

Last year, MENRVA Group [10] in Canada presented a wearable system consisting of a Robotic Arm Orthosis (RAO),
a Functional Electrical Stimulation (FES) system, and a wireless BCI to assist individuals with neurological disorders to complete the task of independently drinking a glass of water.

Most of current researches about BCI-robot hybrid systems are staying in preliminary studies. The accuracy of recognition of brain activities and the instantaneity of signal transmission are always confusing problems in BCI-related systems. Moreover, most of the existing systems are so large that can’t be helpful in home rehabilitation. And MI [11, 12] is always used in modulating control signals, which is hard and boring for patients without long time exercises to accomplish. Though SSVEP is easy to generate and don’t need any exercise, an extra visual stimulating device is always required. Besides, patients need to be too much attentive and are easy to get tired [13].

Our study focuses on the rehabilitation of upper limbs because of their necessity in daily living. In this paper, a wearable and portable rehabilitation training system is proposed. Unlike other BCI-based systems, emotional states are used as control strategies. Three different emotional states (four different levels) are detected by an EEG neuroheadset. Powers of four frequency bands of the signals are analyzed to find the relationship with different emotional states. The robot is designed in a way that it can work in multiple modes which are predetermined by programming and can be reprogrammed according to the need of the training process. It collaborates with the subject to make the training job easy and comfortable. The robot runs the training process in a certain mode for a specific period of time as soon as the subject gives orders mentally. And during the training the subject can either join in by imaging the motion of the disabled upper limb or just keeping relaxed. The feasibility of the collaborative training method is investigated and the comfort of the training process is evaluated.

The rest parts of this paper are organized as follows: section II is devoted to the presentation of the whole system structure including both hardware and software; then, in section III, experiments are carried out with a healthy male and experimental results are demonstrated to verify the feasibility of the system; finally, conclusions and outlook of the novel system are drawn.

II. SYSTEM STRUCTURE

Like other BCI-robot hybrid systems this upper limb rehabilitation training system proposed here primarily consists of two subsystems: the rehabilitation robot subsystem and BCI.

A. Rehabilitation robot subsystem

The rehabilitation robot subsystem can be subdivided into three parts: the Upper Limb Exoskeleton Rehabilitation Device (ULERD), motor controller and mode selecting module (Fig. 1).

The ULERD (Fig. 2) designed by our team is based on the motivation that it can be taken out to do rehabilitation training at home to help impaired patients restore the motor function of the upper limb. It’s easily wearable and ergonomically comfortable with joints and segments corresponding to those of the person it is externally coupled with.

![Fig. 1 The upper limb rehabilitation training system block diagram](image1)

This exoskeleton device consists of three degree of freedoms (DOF) including the elbow flexion/extension, forearm pronation/supination and wrist flexion/extension, which generally cover the most important joins of the upper limb. During the training process, the exoskeleton is hard bound onto the upper limb of the subject to avoid unexpected movements. To make sure it’s portable and not a burden to the patient, main frames of this device are made of aluminum board [14]. Design process of ULERD can be obtained in detail from reference [15].

![Fig. 2 The upper limb exoskeleton rehabilitation device](image2)

The robot has three different modes of operation which are predefined by mode selecting module and can be reprogrammed according to the need of training process.

The three operating modes can be distinguished by the speed and times of the training procedure during which the motor controller ensures the precision of each step.

B. BCI

According to definition, a BCI is a communication and control system that provides an individual a new way to interact with the environment without depending on normal neuromuscular output channels [16]. The goal of any BCI system is to record the brain activities and translate them into messages and commands to fulfill communication purpose. In a BCI system, four processes are always consisted of: data
acquisition, feature extraction, feature translation, and device output [17].

In our study, a wireless and portable Emotiv EPOC headset [18] is used to capture EEG signals of the subject. After being interpreted mental states of the subject are translated in the form of commands to the robot to start, stop, maintain or change the training process.

The EPOC is a high resolution, multi-channel EEG system which features 14 EEG channels plus 2 references offering optimal positioning for accurate spatial resolution. Positions of electrodes are named according to the international 10-20 electrode location system [19], which are: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4, with references in the P3/P4 locations (Fig. 3). The EEG signals are recorded at a sampling rate of 2048 Hz and down-sampled to 128 Hz. The raw EEG data are preprocessed by a high pass filter with a cut off at 0.16Hz, a low pass filter with a cut off at 85 Hz, and a notch filter at 50Hz and 60 Hz to remove the main artifacts.

The software that comes with the Emotiv headset provides three different detection suits: Expressive Suit, Affective Suit and Cognitive Suit. The Expressive Suit uses the headset to collect EEG signals affected by intended action potentials of facial muscles and maps the expressions to the avatar. The Affective Suite extracts real time changes of the user’s emotional state and concentration levels from gathered EEG data. The Cognitive detection suite evaluates a user’s real time brainwave activity to discern the user’s conscious intent to perform distinct physical actions on a real or virtual object.

Researches have shown that frontal lobe activity characterized in terms of decreased power in certain frequency bands is associated with emotional states [20]. The best known correlates of emotionality found with EEG is that, a positive affect is associated with greater activity in the left prefrontal region than in the right side, and negative affect with the reverse [21].

In this paper, we use the Affective Suite (Fig. 4) to detect the emotional states of the subject in response to the robot’s behavior. The Affective detections look for brainwave characteristics that are universal in nature and don’t require an explicit training or signature-building step on the part of the user.

Brain signals of the subject are captured by the neuroheadset. After being converted to digital form, the signals are preprocessed, and the results are wirelessly transmitted to a PC (Fig. 1). A series of post processing are done on the PC to translate brain signals into control commands. An Emokey software (Fig. 5) is used to correspond classification results of four emotional states to four different sequences of keystrokes according to predefined rules. And a communication interface software named Uart-key (Fig. 6) is developed to translate the outputs of Emokey into control commands and send them wirelessly to the robot. Another
usage of Uart-key is to provide an auxiliary control strategy for the supervisor with an easy-to-operate interface.

III. EXPERIMENTS AND RESULTS

Primary experiments were performed with a healthy male on his right hand. In the paper, only elbow flexion and extension motion were focused on to test the feasibility of the novel emotional control-based rehabilitation training system.

During experiments the subject wearing EPOC headset tried his best to fall in specific emotional states. Some simple exercises had been down before experiments to ensure the subject to take his emotion under control easily. After the subject falling into a certain and right emotional state, the robot worn on his upper limb would receive messages from the computer which was used to translate brain signals into control commands almost in real-time. These messages would guide the robot to assist the subject to complete the training process. Fig.7 shows the upper limb rehabilitation training system and experimental environment.

To start the training process, the subject needs to be much more excited than normal state. When the instantaneous excitement level carried with brain signals is high enough, the training procedure is triggered. While, as the engagement level is reduced due to fatigue of the subject or emergencies, the training will be stopped. Otherwise, the current training mode will be maintained as long as engagement is kept in a certain level, or changed when the frustration level is high enough (Fig. 8).

In Fig.8 lines with different colours represent the level of different emotions. The black line represents the level of instantaneous excitement which controls the start of the training. The red line indicates the level of engagement which triggers both stopping and maintaining signals with different levels. The blue line shows the level of frustration which evokes changing signals. The green line drawn in the picture is not used in our experiments.

After a certain emotional level is triggered responsive commands are transmitted to the robot. After receiving commands from BCI, the robot needs to do a few judgements to confirm what messages are sent to it, thus makes movements accordingly.

![Fig.9](image)

**Fig. 9 The program flow chart of mode selecting module**
Fig. 9 shows the control strategies used in mode selecting module after receiving messages. When the starting message comes in, the robot starts training process and runs in mode 0. Afterwards, maintaining message does not change the current training mode, while changing message does (among mode 0, mode 1 and mode 2). As long as a stopping message is received, the robot will stop the training.

Three training modes are predefined by programming in the mode selecting module. Each type of training is under the precise position PID control mode to ensure the security of the subject. As long as one training mode is triggered, the subject can either stay rest while assisted by the robot, or follow the robot to do motor imagery, which does not disturb the training process but improves the outcome of motor rehabilitation remarkably.

![Fig. 10 Raw EEG data recorded at all channels by TestBench](image)

Raw EEG data (Fig. 10) were recorded by TestBench during experiments for off-line analysis. With the use of fast Fourier transformation, the power of four well-known frequency bands (Delta: 1-4Hz, Theta: 4-7Hz, Alpha: 7-13Hz and Beta: 13-30Hz) under four emotional states at channel F3 are displayed in Fig. 11. Graph (a) corresponds to the starting stage when the power of Theta is much bigger than other frequency bands. From experiments we can tell that Theta band makes a lot of contribution to instantaneous excitement emotion when the total power of EEG is much bigger than other frequency bands. While, graph (b) corresponds to the stopping stage when Alpha band takes the main parts of brain signals. Experimental results show that Alpha band power increases when the subject stays relaxed, especially when closing eyes, which is called the “Berger effect” in other researches [22]. Graph (c) and graph (d) present that during the maintaining stage power of EEG signals are distributed evenly between four frequency bands, and the increase of the power of low frequency Delta band helps in stepping into the changing stage. Due to the control of the engagement emotion is energy consuming the robot is designed as a collaborative partner that takes charge of control for a period of training time as soon as a training segment is triggered, which saves the subject much energy.

![Fig. 11 The power of four EEG frequency bands](image)

IV. CONCLUSIONS AND FUTURE WORK

In this paper, a novel rehabilitation training system for upper limb based on emotional control is proposed. We combined BCI with a wearable exoskeleton robot into a portable system. EEG signals of a healthy male were extracted by EPOC headset. Four types of mental states were analyzed and interpreted into commands to start, stop, maintain or change the training process. Conclusions can be drawn as follows:

1) Experiments proved the feasibility of our system and shown that it’s much easier to control the training process with the collaborating of the semi-autonomous robot.

2) In each training segment the robot ran the process autonomously, during which the subject could do either motor imagery or stay rest. After more than one hour training, the subject could still trigger a certain emotion without much effort.

3) It has been found that EEG frequency bands carry important messages about emotions, such as Alpha band power increment indicates low level of engagement while low frequency Delta and Theta bands are associated with some strong emotions like instantaneous excitement or...
frustration, which may provide references for further study of emotional control.

With its portable and easy-to-control characteristics, our system is very promising in home rehabilitation training. In future work, more experiments will be done to test the universality of its application.

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