Current Study on Brain Computer Interface with Virtual Reality in Upper Limb Rehabilitation

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Abstract. Cerebral stroke has been a great issue in the world due to its high mortality rate and disability rate. Rehabilitation for stroke patients has been a hot research field. However, conventional therapies for disabled patients depend mainly on medication and rehabilitation therapist, which is a painful and time-consuming process. Besides, the rehabilitation process requires volitional movement, which is a challenge for severe stroke patients. Therefore, researchers came up with an approach to combine brain-computer interface (BCI) with traditional therapies. Through brain-computer interface technology, researchers collect brain signals to strengthen the motor pathway. Virtual reality (VR) is also a new technique that can be utilized in rehabilitation. This paper studied research from several teams. A research team came up with a hybrid VR-BCI system and designed a classification model based on neural network. Another research team introduced an experiment on a VR- BCI combined platform called REINVENT. The team assessed the feasibility and effect of the platform by analyzing data collected during the study. In addition, A VR game was developed for mild patients. Current studies on VR-BCI combined system have proved its feasibility. However, more clinical data and further research are also needed to assess its effect on rehabilitation.

Keywords: Cerebral stroke, brain-computer interface, virtual reality.

1. Introduction

Cerebral stroke occurs when a blood vessel in the brain is blocked by a clot or burst. The incidence of stroke is rising year by year. It has become the leading cause of death in the United States and the main cause of disability for adults [1]. Though cerebral stroke is treatable, traditional therapy for disabled patients is a painful and time-consuming process. To restore the lost motor and cognitive function of human body, researchers have introduced several rehabilitation strategies, including mirror therapy [2], motor imagery [3], repetitive motor training [4], and action observation [5]. However, conventional therapies require volitional movement from patients. For those with severe motor inability, conventional therapies are relatively challenging.

Brain Computer Interface (BCI) system is a technology transferring information between humans and computers. It can acquire signals from human brain and strengthen the motor pathways[6], which may be used for the rehabilitation of cerebral stroke patients. Besides, BCI does not require volitional movement. Patients are not required to perform active motor activities, which may benefit those with great severe motor inability. Researchers have proved the feasibility of combining BCI with conventional therapies. For example, motor imagery (MI) is a mechanism in which the subject tries to carry out movement through cognitive process without actually moving the limbs. researchers have combined BCI with motor imagery to achieve the recovery of upper limb motor function.

Virtual reality (VR) technique has developed rapidly recently and has shown positive signals in the rehabilitation process for stroke patients [7]. It can create a virtual environment for rehabilitation in which the patients can immerse themselves in the recovery process. VR effectively promotes the duration and efficiency of conventional therapies [8]. Combining BCI with VR, researchers can provide an immersed environment where the severe patients can interact with virtual avatar and do not require a violation motor control [9].

This paper is intended to show that combining BCI with VR is feasible in the therapy process of stroke patients. Several VR-based platforms have been established to study the effect of BCI-VR-based therapy on individuals with different degrees of disability and symptoms. The research team conducted comprehensive clinical research on the VR systems and drew some encouraging conclusions [10, 11], which show the great potential of merging VR with BCI. However, researchers also indicate that current VR-based therapies have defects. The rehabilitation effects for certain patients remain unclear.

2. Related Works

2.1. A Hybrid BCI and VR System

2.1.1 Structure of the System

The traditional training process for post-stroke patients consists of multiple procedures to strengthen the pathway between the brain and the muscle. Different kinds of therapies and techniques are included in the rehabilitation process to provide effective treatment to patients with different symptoms.

However, the traditional process is relatively boring and time-consuming. Patients tend to lose motivation and get tired, which will lead to reduced effectiveness. Research has shown that motivation is one of the key factors that influence the plasticity of Central Nervous System (CNS) and therefore influences the result of the recovery process [12]. Researchers are trying to offer novel techniques to improve the motivation of patients during the training process.

Action Observation (AO) is a process in which the patients are requested to observe certain actions and then imitate them to strengthen the corresponding motor region of the brain. Motor imagery (MI) is a training therapy in which the patients imagine performing certain movements without actually moving the body. It has been demonstrated that MI can activate the motor cortex similar to the actual movement. Researchers believe that the combination of AO and MI has great potential in the rehabilitation process which will be more effective in motor learning. During AO+MI, patients, especially those with severe motor impairment will observe the motor movements and perform them mentally.

2.1.2 BCI in the Hybrid System

Furthermore, brain-computer interface (BCI) and virtual reality (VR) can improve the effectiveness of AO+MI therapy. Therefore, researchers have come up with a hybrid system combining BCI and VR for AO+MI therapy.

BCI in the hybrid system is used to establish a pathway between the brain and the virtual image in VR environment. MI signals from the post-stroke patients are acquired and pre-processed by the BCI device. Then, the pre-possessed signals are sent for feature extraction and signal classification. The possessed signals are sent to the VR training device to control the virtual image (e.g., virtual avatar).

The classification model in BCI system is a very important part of MI signal processing. Neural network has been widely used to classify and analyze signals. In this study, researchers designed a neural network shown in Figure 1. The network consists of two hidden layers with 50 and 20 neurons respectively. A public MI recording database [13] was used to train and test the network. 228 groups of data were randomly selected and the rest 50 groups were the testing set.

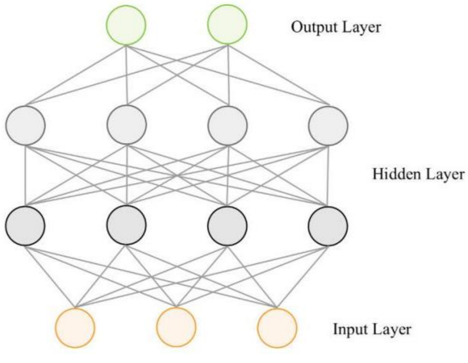

Figure 1. The structure of the neural network

2.1.3 VR in the Hybrid System

VR in the hybrid system provides an environment for action observation and motor imagery. The patients can observe the movements of virtual avatar and imitate the action through motor imagery. Visual feedback will also be provided to the patient in real-time.

Researchers designed a virtual reality game for training. The game contains multiple training programs. Participants can choose different programs for training. Virtual coins and rewards will be provided to enhance the motivation of users. In AO training program, the users can see a virtual person in the head-mounted display (HMD). The virtual person will perform swimming movement with the upper limbs which will activate the corresponding area for swimming movement (see Figure 2, Left). In the MI training program, two virtual persons are shown in the HMD. One of them will perform the swimming movement same as the AO program. The other person represents the movements of the user through MI signal (see Figure 2, Right).

Figure 2. The training program for AO and MI [14]

2.2. A Research based on REINVENT

REINVENT is designed for people with severe motor impairments. The system collects the motor signal from a stroke patient to control the virtual avatar through VR device [15]. The system can provide EEG-based neurofeedback or EMG-based neurofeedback to individuals. Researchers assess the effect of the therapy process by analyzing clinical measures, for example, Transcranial Magnetic Stimulation (TMS) and Magnetic Resonance Imaging (MRI).

In this study, REINVENT system was applied to the rehabilitation of three kinds of patients: (1) patients without active movement, researchers use EEG signals to interact with virtual avatar, (2) patients with weak muscle activation, researchers use EMG signals for interaction with virtual avatar, (3) substantial active movement. The research team acquired electrophysiological signals from the patients with hardware. After acquiring the interfacing process, EEG or EMG signals were sent to a processing module for feature extraction and signal processing. The processed signal was then sent to a VR system where the individuals were able to control the virtual avatar to perform multiple tasks. Visual and vibrotactile feedback was sent back to the patient (see Figure 3).

The research team includes 4 stroke patients with upper limb impairment (subject S01 has severe motor impairments, S02, S03, and S04 have volitional movements). During the training process, the patients were trained over 8 sessions (patient S01 asked for a second-round training session). The patients were asked to complete a series of training tasks in a virtual environment where they needed to control a set of virtual hands from a first-person perspective. The virtual hand can perform movements including wrist and elbow extension toward the target.

The researchers then analyzed multiple parameters to assess the feasibility and effects of the VR system. EEG bands, surface EMG signals, and event-related synchronization/desynchronization (ERS/ERD) were extracted and calculated. The team also measured the TMS and MRI before and after the training process for comparison. The researchers marked each patient according to the following formula:

$$Score=\frac{1}{n}\left(\sum_{i=1}^{n} x_i\right) \times 100 \quad (1)$$

n represents the total number of trials and x_i represents the number of successful motor actions (the virtual hand successfully reached the target).

The training scores of four participants are shown in Figure 4. The score of subject S01 showed a slit increase by 7.3% between the first and the last session. The score of S02, S03, S04 decreased by 37.1%, 5.4%, and 32.5% respectively.

Researchers extracted ERDs from four individuals and compared them with healthy people [16, 17]. Figure 5 shows a great difference between the ERDs for stroke patients and that of healthy ones.

To assess the experience and attitude of four patients, they were asked to complete a set of questionnaires. The Simulator Sickness questionnaire was also provided to the patients to evaluate the simulator sickness during the VR training, which is often a key concern when combining VR devices with the therapy process.

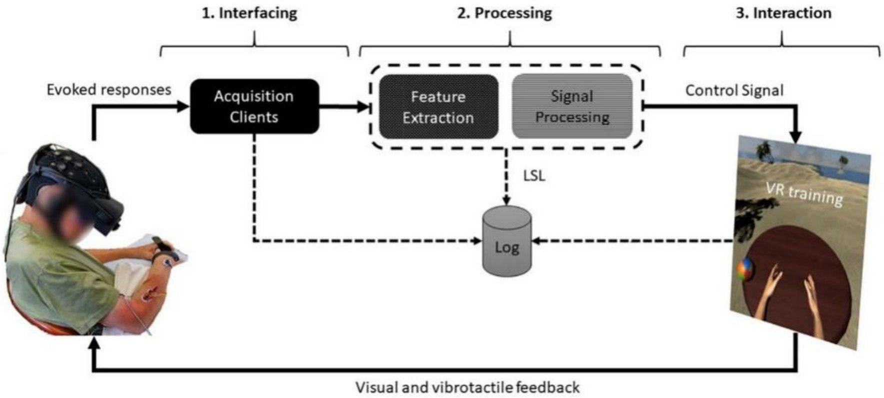

Figure 3. The structure of a neurofeedback loop [15]

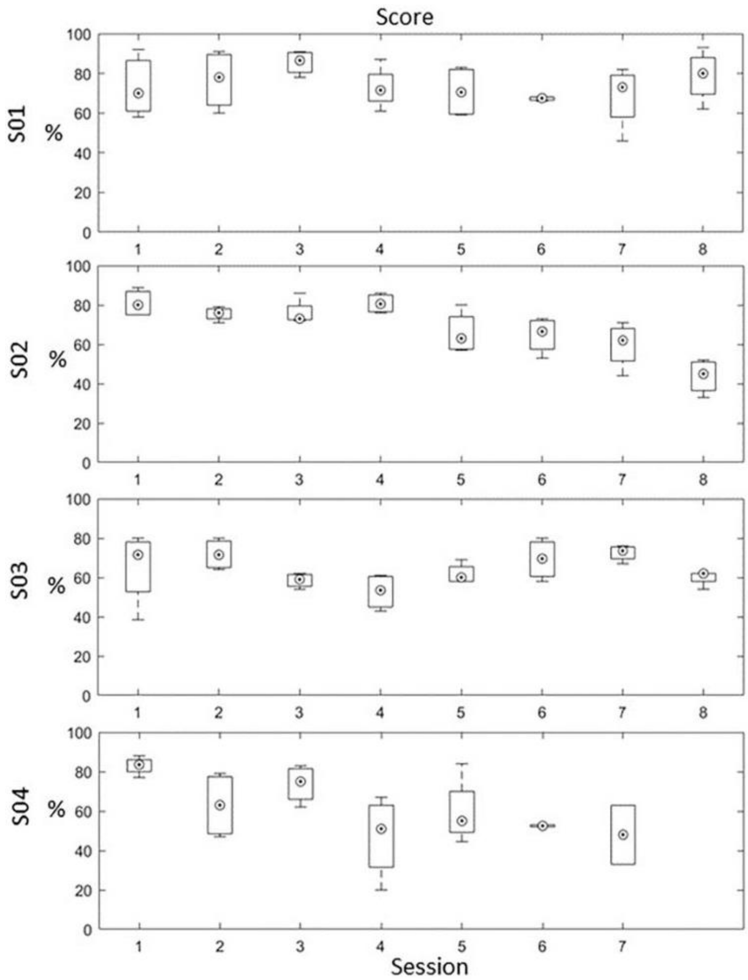

Figure 4. Four patients with average scores of 8 sessions [15]

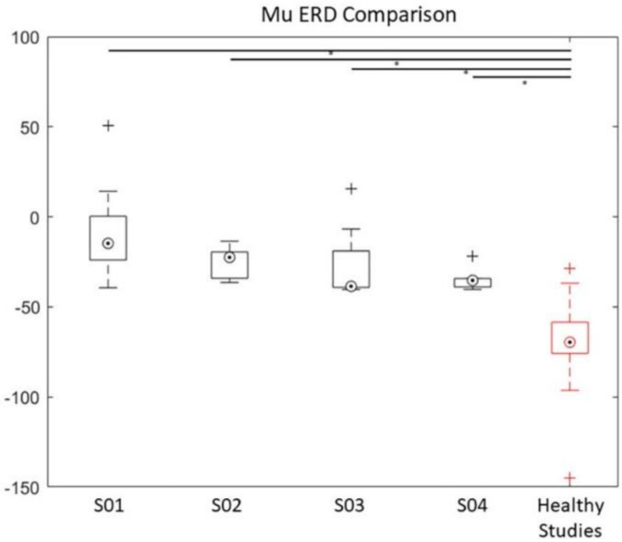

Figure 5. ERDs of 4 subjects and healthy people [15]

2.3. VR Games for Post-stroke Patients

VR-BCI combination systems have shown potential in the rehabilitation process of post-stroke patients. VR games can be also used in the recovery of post-stroke with mild stroke.

Motion Rehab AVE 3D (software registration number: BR 51 2016 001373 7, INPI-Brazilian Patent and Trademark Office) is a serious game that can be applied to the rehabilitation process of post-stroke patients. The developers of this game intend to combine it with rehabilitation to enhance the motivation of post-stroke patients. It can be used in the upper limb and balance rehabilitation of patients with mild stroke. Patients engaging in the game are requested to complete different exercises in a virtual 3D space, including flexion, abduction, shoulder adduction, horizontal adduction and abduction, elbow extension, wrist extension, keen flexion, and hip flexion and abduction [18].

The whole process of the game can be divided into several sessions. In the first step, the users access a menu to select the level of difficulty. The system will customize certain levels of training for different patients. In the following step, the participants will perform shoulder abduction movements along with elbow and wrist extension to strengthen the upper limb function and participate in games to improve the balance of the lower limbs. The performance of the patients will be evaluated by the score during the game. Virtual feedback such as scores, the movements of patients, and suggestions will be displayed in the HMD.

Researchers assumed that the VR-based system could be used for post-stroke patients if healthy people were comfortable with it. Based on the assumption, a study was conducted to test its feasibility.

The team chose 10 healthy people and asked them to play the game through HMD and Smart TV 3D. After the interaction, a set of questionnaires was proposed to evaluate the comfort level of the game.

3. Discussion

3.1. Validation of the Neuro Network

After 37 epochs of training for the neural network. The best validation performance is 0.60096 at epoch 31. Among 50 testing groups of data, the accuracy rate reached 97% (see Figure 6). The result demonstrates that the designed network for the classification of MI signal is feasible for the public dataset.

The proposed hybrid VR-BCI system combines AO and MI therapy and provides a novel training process for post-stroke patients. The system is specially designed for those with severe motor impairments, promoting the motivation of the training without actual body movement.

However, the neural network still needs further research on clinical data to test its validation. The proposed system lacks clinical application to requires more data to assess its effectiveness and for improvement.

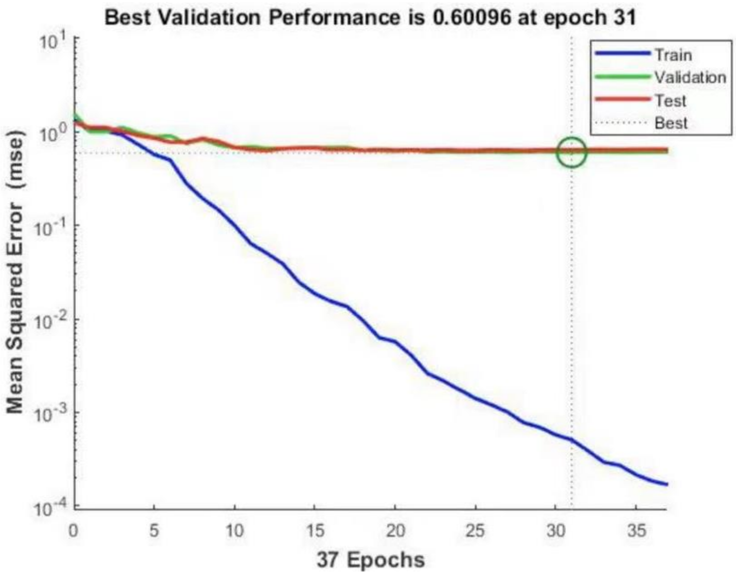

Figure 6. Mean Square Error of the neural network [14]

3.2. EEG and EMG Feedback Analyses

The team analyzed EEM data and EMG data. The scores were recalculated based on EMG data. Researchers compared the performance of EEG neurofeedback and EMG neurofeedback (see Figure 7). The EEG-based score for subject S01 is higher than the EMG-based score. By contrast, the EMG-based scores for subjects S02, S03, and S04 are higher than EEG-based scores, which indicates that EEG neurofeedback performs better for those who have severe motor impairments.

By analyzing data collected in the training process, the researchers demonstrated that combining BCIs with VR system (REINVENT) is feasible for the rehabilitation of stroke patients with motor impairments. It is also suggested that the effect is variable associated with the degree of disability of the subject and the source of neurofeedback.

Overall, EEG-BCI tends to have better performance in rehabilitating stroke patients with severe motor impairments. The team came up with a hypothesis that the motor cortex in severe stroke patients tends to be less active compared to those with volitional movement. Therefore, these regions are more flexible to neurofeedback and more likely to learn new patterns through EEG neurofeedback since these damaged regions are not engaged in other tasks. Patients with volitional movement may benefit more from EMG neurofeedback. EEG-based feedback can strengthen the existing pathways from the brain to muscle. Therefore, a flexible BCI that acquires both EEG and EMG and provides a suitable neurofeedback signal may benefit patients with different degrees of motor impairments.

However, though this study did prove that the VR-BCI-based training process is feasible, no significant clinical improvement was detected, and the patients had limited improvement in motor ability. One possible reason is that 8 sessions of training are too few to have a notable change in motor performance, which suggests a longer duration of training for further study. Another reason is that the BCI-based training process is affected by multiple variables, such as environment, motivation, and state of mind, which can lead to different results across individuals and sessions. Hence, more variables should be taken into consideration in the treatment process to have a better clinical effect.

The study contained four subjects including one individual with severe motor impairment (S01), therefore it was limited by its sample size. Statistical results from the study are relatively inconclusive and have much randomness. Further experiments should contain a wider population of stroke patients. Training sessions in this study are also relatively insufficient, which may not be able to reach a confirmative outcome.

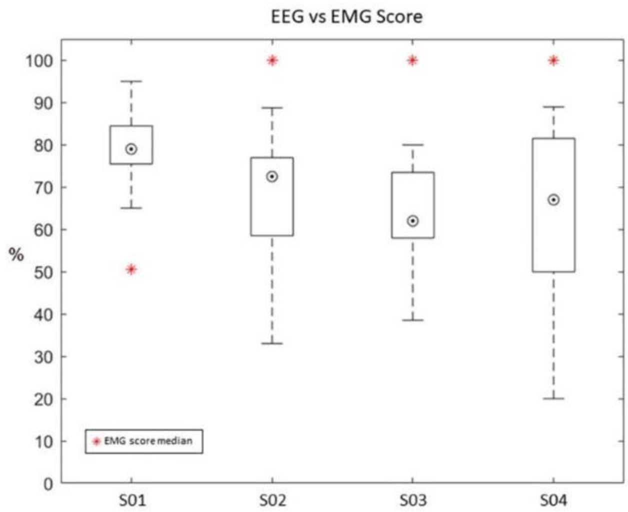

Figure 7. The average score from EMG data compared to the average EEG score [15]

3.3. Feasibility of Motion Rehab AVE 3D

The result from the questionnaire shows that there is no significant difference between HMD and Smart TV 3D devices. Of 10 participants, 20% had difficulty in capturing the object during the task. Another 20% of participants had the same difficulty in the beginning but were able to complete the task as the experiment went on.

3.4. Further Experiment for VR-BCI System

Current studies on VR-BCI-based systems mainly focus on their feasibility, which demonstrates that the system has an advantage in improving the motivation and sense of embodiment during therapy. However, there is no sufficient evidence to prove the clinical effect of the system.

Future research can study the effect of the combined therapy on post-stroke patients with mild disability and severe impairments respectively. More subjects with different symptoms should be included in the experiment. Besides, most of the current studies are based on a public database, which is not able to represent the complex clinical environment. Researchers believe that it is possible to combine the VR-BCI system with other rehabilitation devices such as rehabilitation robots and functional electrical stimulation. Single VR-based therapy may have a limited effect on post-stroke patients, combining them with such equipment can greatly promote the effect of rehabilitation therapy, which is a potential research field for further study.

4. Conclusion

This paper studied the research of VR-BCI combined therapy from different teams. The first team designed a novel hybrid BCI and VR system to provide various training programs to post-stroke patients. Of the proposed system, researchers also designed a classification model for MI signal based on neuro network, which eventually presented a relatively high accuracy rate on a public database. In the study on REINVENT, researchers carried out studies on four post-stroke patients with different degrees of impairments. During the experiment, researchers collected EEG signals and EMG signals from four post-stroke patients. Researchers believe that EEG-based feedback has better performance on patients with severe motor impairments, while EMG-based feedback performs better on those with volitional movement. Motion Rehab AVE 3D is designed for those with mild motor impairment. During the game, participants can choose tasks based on their abilities. Visual feedback such as the score and suggestions on better movements will be provided in real time to participants. Developers believe that the game is feasible for post-stroke patients and promote the motivation and embodiment of participants without significant side effect. However, the current VR-BCI-based system has only been proven feasible, there is still not enough data especially clinical data to prove its effect on rehabilitation. Besides, the recovery of post-stroke patients is a complex training process with high variability, it is relatively hard to exclude other factors and evaluate the actual performance of VR-BCI system across the whole session.

Therefore, further study should focus on the clinical effect of VR-BCI combined system on various patients. The system also has the potential to be combined with other rehabilitation devices to improve the effect. The rehabilitation of post-stroke patients is a complex research field involving neuroscience, physiology, and studies on neuron, and muscle movement, which is an interdisciplinary area requiring deeper and further research.

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