2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

An Immersive Motor Imagery Training System for Post-Stroke Rehabilitation Combining VR and EMG-based Real-Time Feedback

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Abstract— **Motor imagery combining virtual reality (VR) technique has recently been reported to have an increasingly positive impact on post-stroke rehabilitation. However, there is a common problem that the engagement of patients cannot be confirmed during motor imagery training due to a lack of effective feedback control. This paper proposes a VR-based motor imagery training system for post-stroke rehabilitation, using surface electromyographic (EMG)-based real-time feedback to enable the personalized training and quantitative assessment of participation degree. Three different experiments including assessment experiment, action observation (AO), combined motor imagery and action observation (MI+AO) experiment were performed on 4 post-stroke patients to verify the system. The immersive scenario of the VR system provides a shooting basketball training for bilateral upper limbs. The EMG data of assessment of each participant was collected to calculate the thresholds, which was utilized in the subsequent experiments based on real-time feedback of EMG. The result reveals significant differences of the muscle strength between AO and MI+AO experiments. This demonstrates that the EMG-based feedback is effective to be of use in assessment of participation degree. The primary application shows that VR-assisted motor imagery system has potential to provide personalized and more engaged training for post-stroke rehabilitation.**

Keywords— surface-electromyographic, real-time feedback, motor imagery, virtual reality, stroke rehabilitation.

I. Introduction

Stroke has become the leading cause of adult long-term disability in the world [1]. Commonly, patients with stroke suffer from severe limb impairment [2], have low quality of social interaction [3], and are limited in activities of daily living [4]. Rehabilitation following stroke is becoming considerably important. Conventional rehabilitation includes physical therapy and occupational therapy. Except for the monotonous training content, it is limited for those patients with low or no levels of motor control. Motor imagery has been demonstrated to be a kind of mental rehearsal of motor behavior in a cognitive way, which can activate the cerebral cortex to a certain extent [5]. Motor imagery has been reported to be effective for functional rehabilitation of both upper and lower limbs and the recovery of daily activities [6].

Recently, virtual reality (VR) has been incorporated in the rehabilitation system of motor imagery [7]. For example, Sollfrank et al. [8] demonstrated that VR-feedback, which is consistent with the participant's motor imagery, should be well suited and helpful for accomplishing successful motor imagery. Athanasios et al. [9] developed a motor imagery paradigm for post-stroke rehabilitation to investigate the efficacy of a BCI-VR system. The results revealed that the VR-based system can be used in rehabilitation for chronic stroke.

However, one issue in motor imagery-based rehabilitation concerns the engagement of patients in motor imagery training. So far, the absence of effective methods of quantitative assessment makes it difficult to confirm the patients could focus themselves on completing motor imagery as instructed. Electromyographic signal has been adopted in robotic prosthesis serving as real-time feedback to help a paralyzed hand with rehabilitation training [10], [11]. Besides, combined EMG and virtual reality rehabilitation system can assist to increase volitional muscle activity and induce changes in corticospinal communication [12]. Since the motor imagery involves the muscle activity, EMG may have the potential to be of use in VR-based motor imagery training to provide a real-time feedback, which may function as a quantitative method for assessment of patient's engagement during training.

In this manuscript, we developed a VR-based motor imagery training system for post-stroke rehabilitation. The VR scenario of the system was designed to provide shooting basketball training for bilateral upper limbs with enhanced immersion. The EMG-based real-time feedback was adopted to access the participation degrees of participants during motor imagery training. To verify the feasibility of the setup, four post-stroke patients were instructed to perform the experiments. The result demonstrates that the VR-based motor imagery training system combining EMG-based real-time feedback enables the personalized training and quantitative assessment of participation degree.

II. Experiment

A. Participants

In total, there are 4 post-stroke patients participating in the study which was approved by the Ethics Committee of Jiaxing 2nd Hospital Rehabilitation Center and was compliant to Helsinki Declaration. Each participant was informed about the purpose of the study and signed informed consent prior to participation. All participants had normal or corrected-to-normal vision. And all participants experienced the

Research supported by the National Key R&D Program of China (2018YFC2001600) and 2020 Li Ka Shing Foundation Cross-Disciplinary Research Grant (2020LKSFG07C).

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assessments based on Brunnstrom stages. Table I shows the basic information of the 4 participants.

Table I. Basic information of the participated stroke patients

	Participant 1	*Participant 2*	*Participant 3*	*Participant 4*
Gender	male	male	male	male
Age	72	46	70	71
Affected Side	right	right	left	left
Time after stroke (month)	70	5	1	1
Brunnstrom stage	II	III	II	II

B. Experimental Setup

The VR scenario was constructed based on HTC VIVE PRO EYE with the helmet-mounted display (HMD) of 1440×1600 resolution per eye and 110° Field of View. A g.HIamp (g.tec, Australia) with 80 channels was used to acquire the surface electromyogram signal data. To perform experiments, the participants were asked to wear head-mounted display and lie on a bed that was placed at the center of virtual reality environment built by using two laser locators. EMG electrodes of 7 channels were used to record EMG signal from upper limb muscles including musculi flexor pollicis longus, flexor digitorum superficialis and flexor carpi radialis with the sampling rate of 1200 Hz.

C. Experimental Protocol

The VR scenario provides a shooting basketball training for bilateral upper limbs rehabilitation. When the participants are associated in the training scenario, they can see the virtual hands from first-person perspective and imagine from their own view. The shooting basketball training consists the following main procedure: reaching forward for the basketball, bending the arms, raising the arms, and throwing the basketball. Meanwhile, the corresponding voice instructions were optional during the entire procedure.

Each participant was asked to perform three ordered experiments: the assessment experiment, the action observation (AO) experiment, the experiment combining motor imagery (MI) and AO. The detailed procedure for each experiment is shown in Fig.1.

In the assessment experiment, each participant was required to relax for two minutes and subsequently make a fist 5 times with the healthy side and 5 times with the affected side. The EMG data of each participant was collected for further analysis.

In the AO experiment, participants wearing the HMD, which can display the animation of shooting basketball by the virtual hands, were instructed to only observe the execution of shooting basketball 5 times without imagery involved. And there was no voice instruction during the process. Also, the EMG data from musculi flexor pollicis longus, flexor digitorum superficialis and flexor carpi radialis of each participant was collected, like the assessment experiment.

In the experiment consisting of MI and AO, the HMD can show the virtual scenario with the corresponding instruction in voice. Participants were asked to observe the action and engage in motor imagery simultaneously. Each participant completed consecutive shooting by 5 times. The EMG data of each participant was recorded.

D. Data Processing

The surface EMG has been used to estimate the muscle strength as well as to evaluate the stroke recovery stages [13]. We used the root-mean-square (RMS) to extract the EMG feature in different time periods of different experiments, to indicate the current muscle strength of the participant. In equation (1), x_i represents the EMG signal value at each sampling moment.

$$M = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}} \qquad (1)$$

In the assessment experiment, we calculated the root-mean-square of the EMG signal of the healthy upper limb and the affected upper limb for relaxed time and for 5 fisting times, so as to respectively obtain the relaxed muscle strength and the maximum muscle strength of the patient's healthy and affected side. Finally, the relaxed comprehensive muscle strength was calculated by averaging the relaxed muscle strength of the healthy side and the affected side, as in (2). And the maximum comprehensive muscle strength was obtained by averaging the maximum muscle strength of both sides, as in (3).

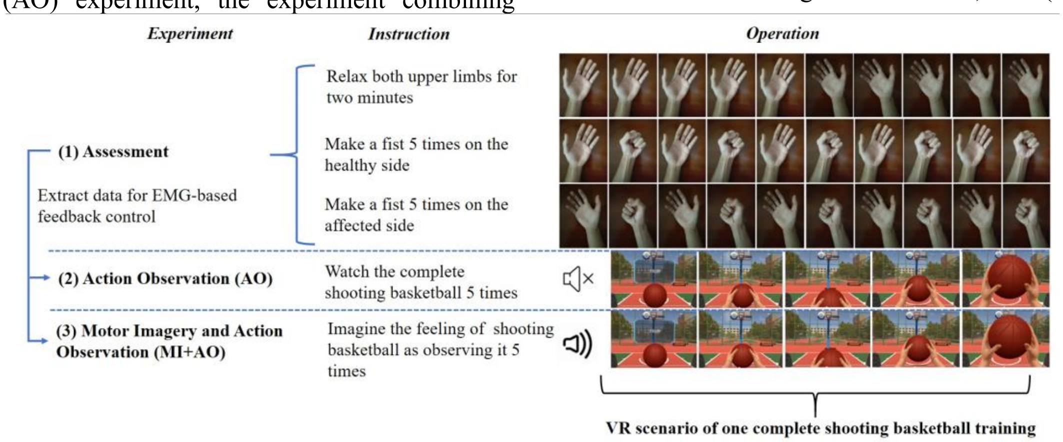

Figure 1. A schematic representation of the three experiments

$$M_{relax} = (M_{healthy\_relax} + M_{affected\_relax}) / 2 \quad (2)$$
$$M_{max\_muscle} = (M_{healthy\_max} + M_{affected\_max}) / 2 \quad (3)$$

To provide personalized training for participants according to their own condition, we calculated two parameters of M_{th1} and M_{th2} based on the M_{relax} and M_{max_muscle} for each participant. The values of M_{th1} and M_{th2} were used to set thresholds in both AO and the MI+AO experiments with EMG-based real-time feedback. Specifically, the EMG data was collected and compared to M_{th1} and M_{th2} in real time and the different comparison results lead to different scores of shooting basketball. Participants can get three kinds of scores according to their performance. When their muscle strength in the current training is less than M_{th1}, they will get one point. When their muscle strength is not less than M_{th1} and less than M_{th2}, they will get two points. The last condition that their muscle strength is greater or equal to M_{th2}, they finally will get three points.

$$M_{th1} = M_{\max\_muscle} \times 0.2 \quad (4)$$
$$M_{th2} = M_{\max\_muscle} \times 0.6 \quad (5)$$

In the other experiments, since a complete shooting basketball consists of four parts and lasts for 51 seconds, we took the sampling time of 3 seconds for each part (as shown in Fig. 2) and obtained the RMS value, which represents the comprehensive muscle strength in the current training.

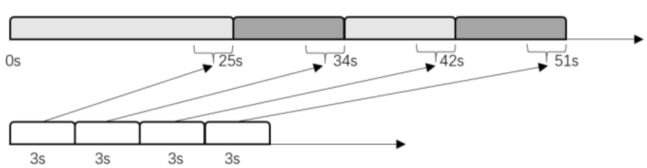

Figure 2. The periods of extracted sampling time

III. EMG Feature Analysis

In order to provide a personalized training for each participant, we used EMG-based real-time feedback to assess their own performance of shooting basketball, and we also recorded participants' EMG in the assessment experiment, and then extracted feature value of EMG. Table II shows muscle strength values of the both upper limbs of 4 patients in relaxed and clenched state.

Table II. The muscle strength in relaxed and clenched state on both sides for 4 participants

Muscle Strength	*Participant 1*	*Participant 2*	*Participant 3*	*Participant 4*
Healthy Side - Relax	2.57045	2.6258	3.6183	6.2528
Affected Side - Relax	2.44095	18.8543	3.45115	11.6316
Healthy Side - Fist	487.0497	68.1234	70.3016	132.9792
Affected Side - Fist	71.9314	17.4232	11.4072	10.38

Since the experiment involved shooting basketball with both hands in different conditions, we considered muscle strength values of both the healthy and affected upper limb so as to obtain the comprehensive muscle strength to access the performance of training and degree of participation. Fig. 3 shows the comparison results of muscle strength in 4 post-stroke patients under three different experiments. As expected, the trend is relatively steady in the AO experiment for 4 participants in comparison to the MI+AO case. Moreover, the curves of the muscle strength in the relaxed state and the AO experiment are very closed, this is reasonable because less muscle activation is involved for participants instructed to perform AO experiment. Compared with AO experiment, the average of muscle strength from MI+AO experiment is greater and the overall trend of the curve changes more pronouncedly. Furthermore, this difference also varies with participants. The result demonstrates that the EMG-based feedback can be employed to access the participation degrees of participants during motor imagery-based rehabilitation.

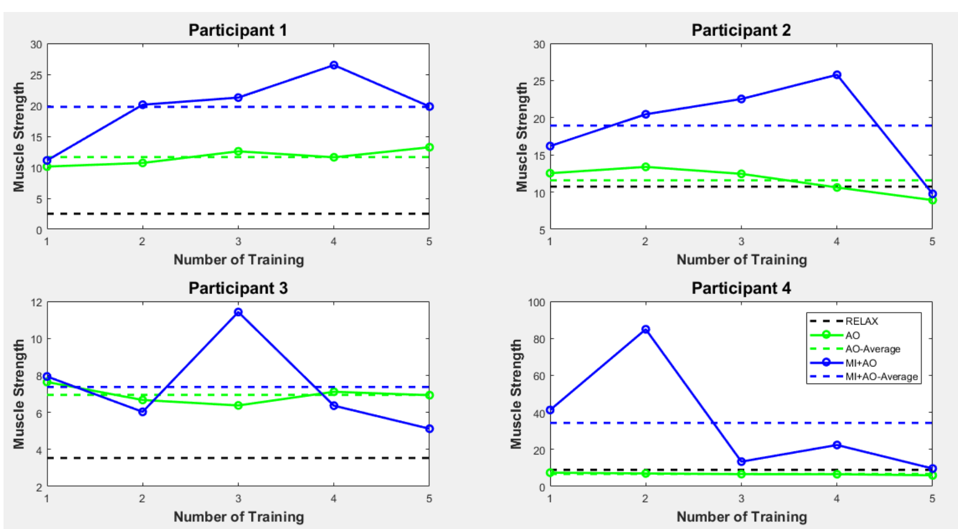

Figure 3. The trend of muscle strength of 4 participants in three different experiments

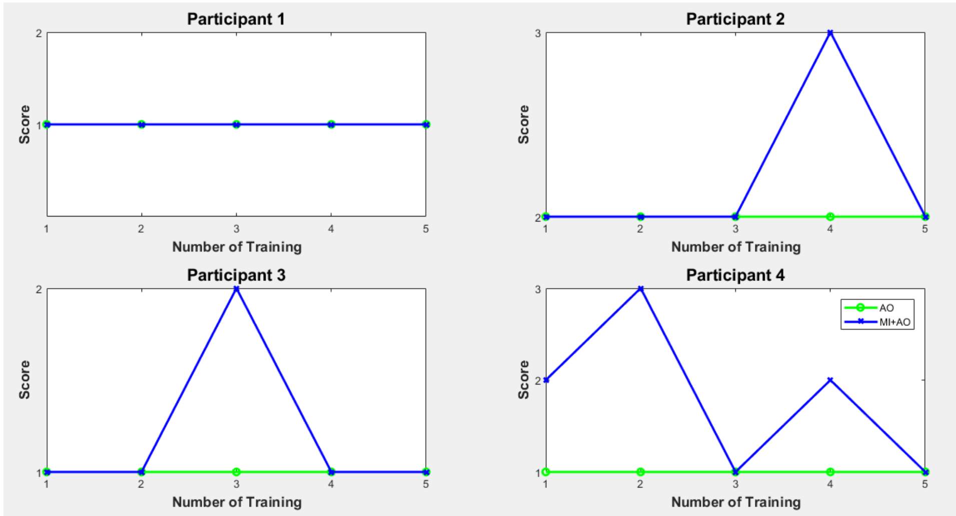

Figure 4. The scores of 4 participants in the AO and MI+AO experiments

Fig. 4 shows the scores of 4 patients in the AO and MI+AO experiments based on real-time feedback of EMG. It is obvious that the performance in MI+AO experiment is better than that in AO experiment. Our result suggests that the developed VR-based motor imagery training system with EMG as real-time feedback is feasible and has the ability to provide personalized training for stroke patients.

Experiments involving EMG collection when patients participated in motor imagery have also been reported by several group recently. Mattia et al. collected EMG from the extensor digitorum and flexor digitorum superficialis muscles of the upper limbs, in order to monitor that no actual movement is performed [14]. Moreover, Oh et al. measured the EMG data in the knee extensor and the results show that motor imagery training can promote the symmetrical use of knee extensors during sit-to-stand and stand-to-sit tasks. Therefore, EMG can be used as a method to monitor or assess the training performance of patients. However, these experiments don't use EMG as a kind of feedback to promote training [15].

IV. Conclusion

Here we have proposed a rehabilitation system of VR-based motor imagery for stroke patients, which is expected to provide EMG-based real-time feedback with the aim to promote patients' participation. Moreover, we have extracted different comprehensive muscle strength for each patient to enable a personalized training. By comparing the change trend of muscle strength in three different sub-experiments, we conclude that the VR-based action observation can facilitate the ability of motor imagery and EMG-based real-time feedback can be used as a way to access the patients' involvement in motor imagery.

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