

A VR-based Self-rehabilitation System

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Abstract – This paper proposed a VR-based self-rehabilitation system which utilizes the virtual training model rendered by OpenGL and collects electromyography (EMG) signals from the subjects to perform hand motion recognition. EMG signals are biomedical signals generated in muscles and can be applied in many fields such as clinical diagnosis and biomedical applications. The subjects were asked to manipulate a haptic device (Phantom Premium) to operate a virtual hand to catch a ball in the virtual environment which displayed on the computer's screen. A dry electrode was attached on the subject's skin to collect sEMG signals and recognize the action of grasping. Once caught by subjects, the virtual ball will appear in another location at random on the computer's screen. Therefore, the subject needs to manipulate the Phantom to the new destination and catch the ball once again. Combining sEMG with VR Technology, the proposed self-rehabilitation system could provide enhanced visual feedback about movement trajectory, which is beneficial to improve motor function task learning and execution compared with traditional therapy. By this method, stroke patients can realize self-rehabilitation exercise of upper limb at home. The effectiveness of the proposed rehabilitation system has been verified by experiments.

Index Terms – Self-rehabilitation, Virtual Reality, Surface electromyography, Butterworth filter, OpenGL

I. INTRODUCTION

Stroke, is a sudden ischemic or hemorrhagic disturbance in the blood supply to brain tissue that results in partial loss of brain function [1]. There are approximately 795,000 people who suffered from stroke annually in the United States [2]. As a leading reason of disability, stroke always causes partial destruction of cortical tissue and leads to a disorder of neural system. After the outbreak of the disease, professional and prompt rehabilitation treatment is essential and necessary for patients to prevent muscle atrophy and joint contracture. However, a long rehabilitation training cycle with therapists, who are actually relative shortage, is not always available. To relieve the burden of therapists, many robotic rehabilitation systems have been developed. A number of clinical studies have examined the effect of post-stroke rehabilitation with robotic devices on hemiparetic arm function [3]-[10]. Krebs et al developed MIT-MANUS which was used for upper limb rehabilitation [11]. The equipment can follow predefined task-oriented training orders to achieve the movement of upper

limbs including shoulder, elbow and wrist movement. It has improved motor function in the hemiparetic upper limb of acute and chronic stroke patients in clinical trials [12]. Another typical system which called Mirror-image motion enabler was developed by Stanford University and Rehabilitation Research and Development Centre [13]. This equipment could follow the predetermined trajectories by operating the intact arm which is called active movement to drive the impaired arm which is called passive movement to realize bilateral rehabilitation. In recent years, the virtual reality technology has been applied on robotics for realizing better rehabilitation. Studies have demonstrated that VR technology could provide sensible movement features to strengthen feedback in healthy subjects compared with conventional rehabilitation training [14]. And some concerned researches have also been published in these years. Song et al. [15] presented an upper limb rehabilitation system in which the patients can operate a haptic device to carry out the tracking task in the virtual environment. Kawasaki et al. [16] proposed a hand rehabilitation support system which realized a master-slave motion assistant with the application of VR technology. In those researches, force sensor is applied to measure force or torque in order to assess the rehabilitation effects. However, compared with conventional force prediction, sEMG signals can provide directly “look” into the muscles and allows measurement of muscular performance. When an extra effort was made, the subjects could briefly increase their force accompanied by a proportionately greater increase in sEMG activity [17]-[19]. Therefore, sEMG signals which are generated in muscles are more immediate approach to evaluate the muscle strength.

In the proposed rehabilitation system, hence, sEMG signals generated by the flexor digitorum profundus (FDP) were collected by a dry electrode attached on the subject's skin to measure muscle's strength and recognize the subject's action of grasping the ball. And movement trajectory was recorded by the haptic equipment (Phantom Premium) to evaluate the achievement of rehabilitation. A training system based on virtual reality (VR) has been presented to assist patients to carry on rehabilitation training by manipulating the haptic device (Phantom Premium) to control the virtual hand in the virtual environment rendered by OpenGL. Training classification corresponded with different intensity was

considered into the proposed rehabilitation system for satisfying the requirements of patients with different motor function loss.

The structure of this paper is organized by the following parts. The relative researches and the purpose of the research are represented in the first section. Then a rehabilitation training model and relevant signal filter method have been proposed in the Section II. Experimental setup and results can be shown in the Section III. Finally, conclusions are given in Section IV.

II. PROPOSED TRAINING SYSTEM

A. The framework of the proposed system

The hardware of the system consists of a haptic device (Phantom Premium), an EMG collector, an A/D board and a computer. The data of sEMG collected by the Personal-EMG (Oisaka Electronic Equipment Co. Ltd, Japan) and recorded by an analog/digital (A/D) board (USB4716, Advantech Co. Ltd, Taiwan) were transmitted to the computer. The computer received and processed those data to recognize the action of grasping the ball. Besides, the Phantom Premium (3D systems, Co. Ltd, U.S.A) can be used to operate the virtual hand on the computer's screen to catch the ball and record the movement trajectory. The schematic of the proposed system was shown in Fig. 1.

In the proposed rehabilitation system, surface EMG signals generated by FDP were collected by a dry electrode which was attached on the subject's skin. The manipulator operated the handle of Phantom Premium to control the virtual hand rendered by OpenGL and displayed on the computer's screen to reach the target's position and implemented the action of grasping the ball. The subject exerted the force which would reflect the sEMG signals variation of concerned muscles to hold on the ball. The virtual hand close or open can be recognized by monitoring the sEMG signals which collected from the manipulator and processed by Butterworth filter. Virtual reality has been applied in the proposed rehabilitation system for the purpose of enhancing the sense judgement and raising training interest. The procedure of the proposed training system is described in Fig. 2.

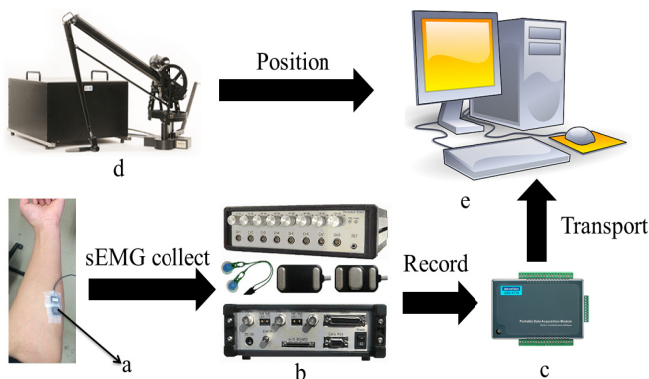


Fig. 1 Schematic of the proposed rehabilitation system

(a: dry electrode; b: signal acquisition device and filter box; c: A/D board; d: a haptic device called Phantom Premium; e: computer)

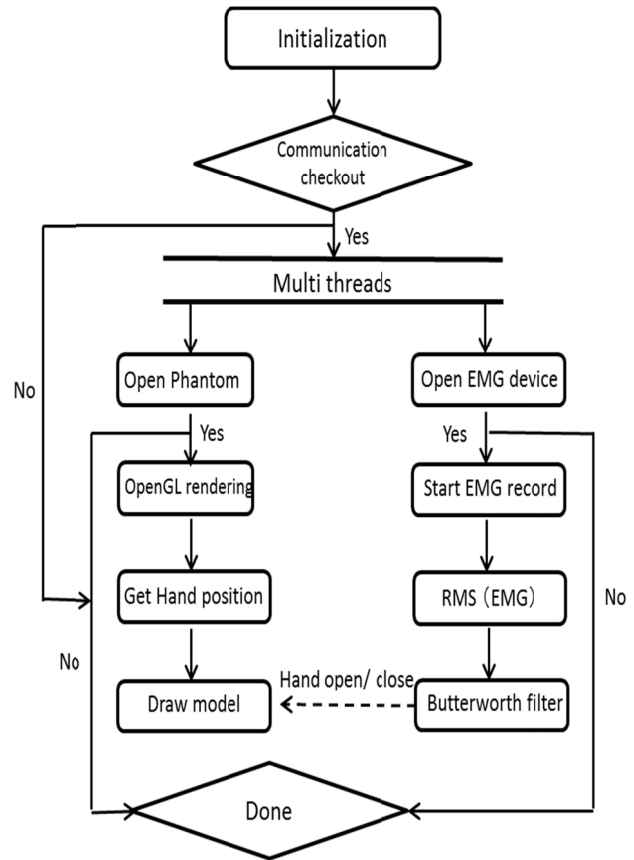


Fig. 2 Flow chart of hand motion in VR environment

B. Raw sEMG signals process

The main application field for the sEMG analysis is in clinical diagnosis and biomedical applications, where EMG signals can be used for force estimation and rehabilitation assessment.

The EMG signals which are controlled by the nervous system are correlated with the physiological properties of concerned muscles. When collected the sEMG signals, the noise is inevitable while travelling different tissues and would be mixed with the raw EMG signals. Moreover, the EMG detector, particularly if it is attached at the surface of the skin, collects mixed raw signals from different motor units at a sampling period which may contaminate the purity of signals. The contaminated signals are not beneficial for subsequent motion recognition. Therefore, powerful detection and filtering methodologies of EMG signals are fairly significant in biomedical application, and once the sEMG signals are processed appropriately, we can acquire the most immediate inherent characteristics of the biomedical signal and then various EMG signal related applications could be implemented by hardware system [20].

Surface EMG is a method of recording the action potentials of muscles. When detecting and collecting the EMG signals, there are mainly two concern factors that impact the fidelity of the collected signals: the signal-to-noise ratio and the distortion of the collected signals. The first one means the ratio of the energy in the EMG signals to the energy in the

noise signal. In this experiment, noise is defined as those signals that not belong to our desired EMG signals. The second one means that the corresponding composition of EMG signals in frequency component may be transformed.

Therefore, it is necessary to choose a powerful electric filter to realize the function of rejecting the noise and remaining the high fidelity of the sEMG signals. The Butterworth filter is a typical signal processing filter, the most important feature of which is that the frequency response is maximally flat in the passband and falls towards zero in the stopband. Compared with other filters such as a Chebyshev Type I/Type II filter or other filters, the Butterworth filter has a slower roll-off. Hence the Butterworth filter would require a higher order to implement a particular stopband specification. Nevertheless, Butterworth filters have a more linear phase response in the passband than other electric filters. Given cut-off frequency $\omega_c=1$, the normalized Butterworth polynomials can be generalized by the following form.

when n is even,

$$B_n(s) = \prod_{k=1}^{\frac{n}{2}} [s^2 - 2s \cos\left(\frac{(2k+n-1)\pi}{2n}\right) + 1] \quad (1)$$

when n is odd,

$$B_n(s) = (s+1) \prod_{k=1}^{\frac{n-1}{2}} [s^2 - 2s \cos\left(\frac{(2k+n-1)\pi}{2n}\right) + 1] \quad (2)$$

where n is the order of filter.

In the experiment, considering the balance between time lag and smoothness, a fourth-order high pass Butterworth filter was implemented in the software. An electrode was attached on the subject's skin to collect the sEMG signals generated by the FDP which controls hand close.

The sEMG signals filtered by Butterworth can be seen in Fig. 3. The red curve described the filtered signals processed by Butterworth filter. The peak of the signals is connected with the action of grasp.

C. Training classification

In order to satisfy patients with different motor function loss, diverse patterns with different training intensity have been developed. In the proposed system, sEMG signals generated by FDP were applied to recognize the action of grasp. A threshold has been set to distinguish hand close or open. Once the detected sEMG signals surpassed the threshold, the system will predicate the patient close his hand to grasp the ball. Otherwise, the system will predicate the

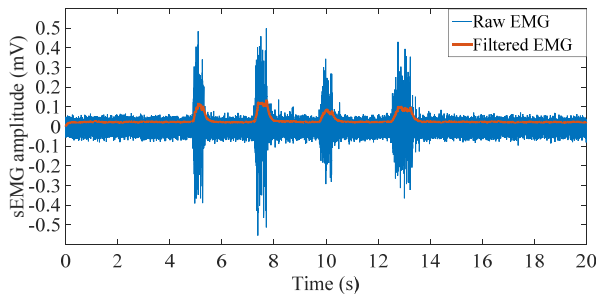
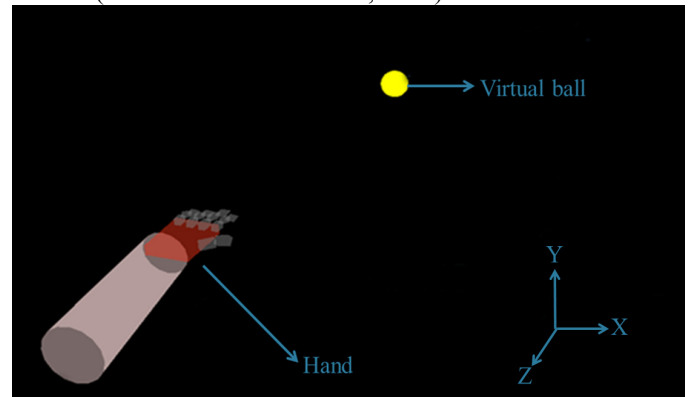


Fig. 3 sEMG signals filtered by Butterworth

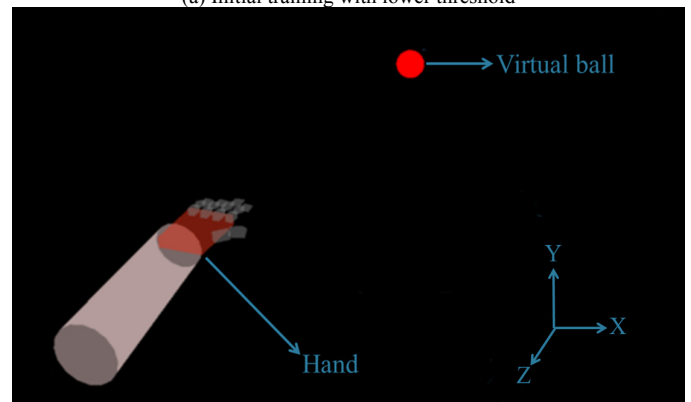
patient maintain to open his hand. For those patients who are in the initial stage of recover, the sEMG signals which could be used for force estimation and muscle strength assessment may be weak. Therefore, a lower threshold was set to recognize his action. For those who suffered from a mild stroke or received the initial training for a period of time, an intensive training with a higher threshold was preferred in the further treatment. Moreover, a mix mode including lower threshold and higher threshold has been developed. In this mode, the yellow and red virtual ball which represented lower threshold and higher threshold respectively will appear at random after completing each action of grasp, which is beneficial to improve the rehabilitation effect. The different training modes of the proposed system were shown in Fig. 4.

III. EXPERIMENTS AND RESULTS

Five healthy male volunteers (average age: 25.2 years; average weight: 74.4 kg; average height: 177.8 cm) participated in the experiments. The dry electrode which was aligned parallel to the muscles fibers was chosen and attached on the skin to collect sEMG signals. In purpose of reducing skin impedance, the body hair of the participants would be shaved and their skins will be cleaned with the alcohol. In the experiment, the sampling rate was 1000 Hz with differential amplification (gain: 1000) and common mode rejection (104 dB). A MFC dialog was built as the user interface by Visual Studio (Microsoft Co. Ltd, USA). The data of sEMG was recorded by an analog/digital (A/D) board and processed by Matlab (The MathWorks Co. Ltd, USA).



(a) Initial training with lower threshold



(b) Intensive training with higher threshold

Fig. 4 Different training models with diverse intensity

Considering the impact of individual difference, maximum voluntary contraction (MVC) tests have been performed to record sEMG data for the flexor digitorum profundus (FDP) before carrying out the experiment. In the MVC test, the subject was asked to grasp a real ball whose radius is 7.5mm with maximum force and maintain that maximum level of force for 5 seconds. By recording the sEMG data, the MVC values for the FDP of the subject can be obtained. Each test was carried out for five times and there are 5 minutes for relaxation between two tests. The highest value for each test was regarded as the MVC value with respect to the subject. The MVC value can be as a reference when we set the different threshold concerned with sEMG signals according to different subjects

After those trials for each subject, the experiments of grasping the ball were performed. At the beginning of the rehabilitation training, every subject would perform the path tracking freely without the limitation of position for the purpose of learning how to manipulate the equipment. In the proposed rehabilitation system, a three-dimensional virtual environment rendered by OpenGL has been developed aimed at enhancing the stroke patients' sense judgement and training interest. The subject manipulates the handle of Phantom to control a virtual hand to reach the target position in which there is a virtual ball and completes the action of grasping the ball. A dry electrode was attached on the subject's skin to collect the surface EMG signals generated by FDP. The action of grasping and holding the ball conducted by the subject would reflect the sEMG signals variation of concerned muscles. The virtual hand close or open can be controlled by monitoring the sEMG signals which collected from the manipulator and processed by a fourth high pass Butterworth filter. Once the action was recognized by the method of sEMG analysis, the virtual ball will appear in another position at random. The rehabilitation training will not be completed until ten times of grasping. The details of experimental setup were shown in Fig. 5.

When the subject carried out the experiments, the corresponding data of sEMG signals and handle position for the manipulator would be recorded by A/D board and Phantom respectively. In order to obtain an intuitive comparison, we have plotted the desired and experimental trajectory of grasping the ball for one time for Subject A in

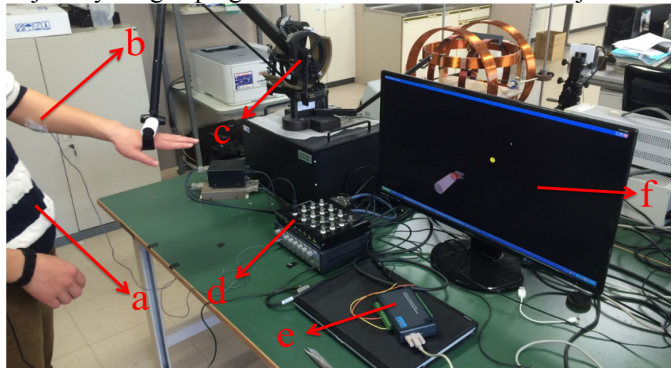


Fig. 5 Experimental process of the proposed system
(a: the manipulator; b: a dry electrode; c: Phantom Premium; d: signal acquisition device; e: A/D board; f: virtual environment)

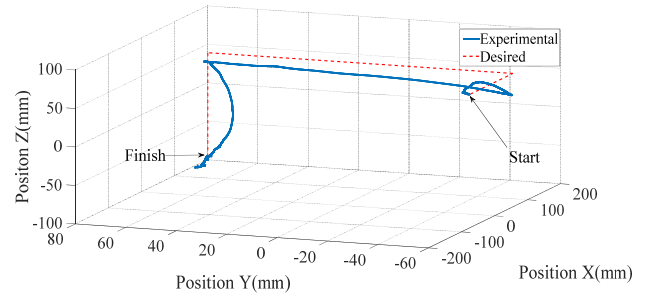
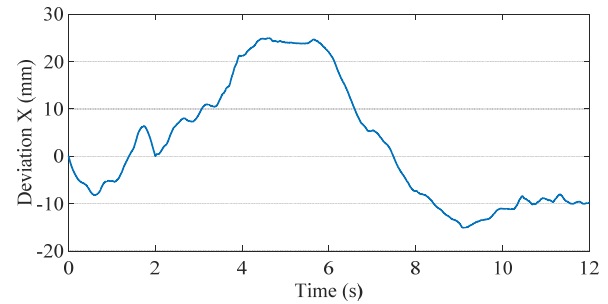


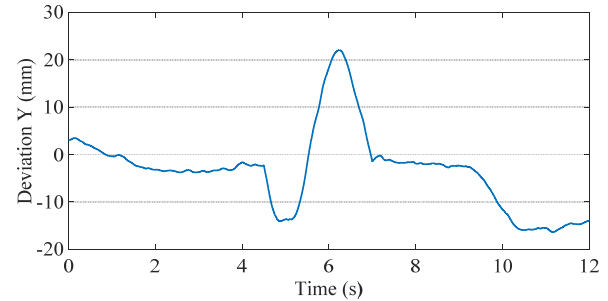
Fig. 6 The position tracking result for Subject A (one time)

Fig. 6. The red dashed curve in the figure stands for desired trajectory while the blue solid curve represents the experimental trajectory.

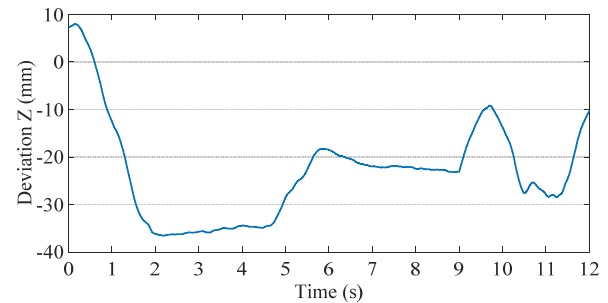
After the subject completed the experiments for ten times, we calculated the deviation along three directions separately between the desired trajectory and experimental trajectory. The details of deviation along three directions for Subject A before carrying out the rehabilitation training were plotted in Fig. 7.



(a) Deviation along X direction before the training



(b) Deviation along Y direction before the training



(c) Deviation along Z direction before the training

Fig. 7 Deviation along 3 directions before the training for Subject A

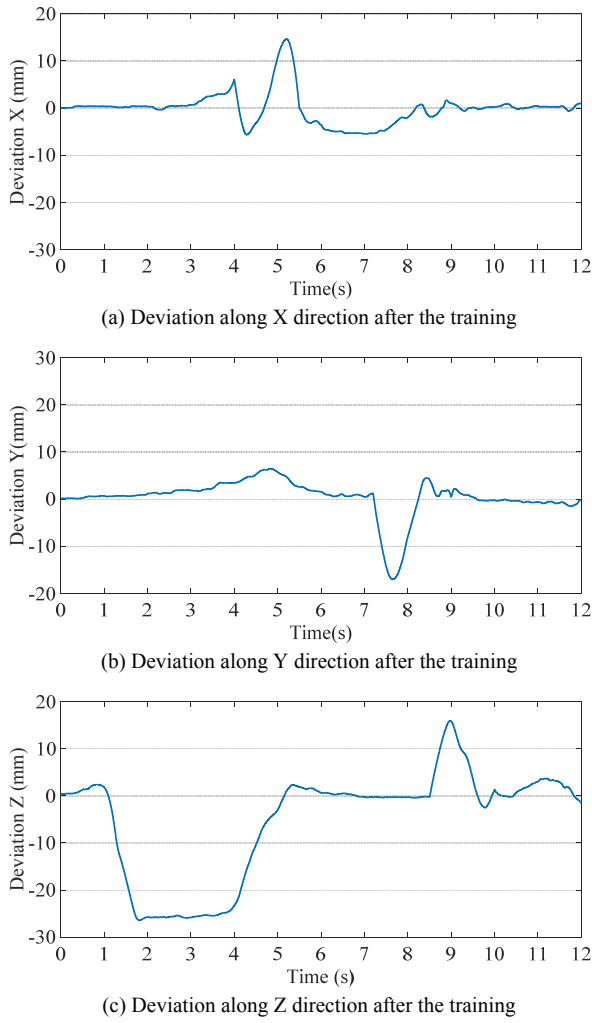


Fig. 8 Deviation along 3 directions after the training for Subject A

After finishing the collection of the initial data, we asked each subject to perform the proposed rehabilitation training for 10 times in the morning everyday (before breakfast) and the training cycle is a period of 20 days. When the training plan was finished, the experimental results were recorded for one more time. The deviations along X, Y and Z respectively for the same subject (Subject A) after the rehabilitation training were plotted in Fig. 8. Compared with the deviations at the beginning of the training, it is obvious that the deviations have been decreased and the smoothness of the curves has been improved which means the manipulation dexterity of the subject has been increased.

In purpose of further assessment for the rehabilitation effect trained by the proposed rehabilitation system, we calculated the absolute value of deviations between the desired and experimental trajectories for each subject. The subject was asked to complete the path tracking and the action of grasping the virtual ball for ten times before the rehabilitation training and after the rehabilitation training respectively. The absolute deviations along three directions of ten times for each subject were calculated and averaged. The results can be shown on the Table I.

TABLE I
ABSOLUTE DEVIATIONS BETWEEN THE DESIRED AND EXPERIMENTAL TRACK

Subject		Deviation X (mm)	Deviation Y (mm)	Deviation Z (mm)
A	Before	19.1	16.9	22.9
	After	9.7	9.1	14.3
B	Before	24.2	24.6	26.8
	After	16.1	15.6	19.7
C	Before	17.9	20.4	21.6
	After	13.4	12.9	15.2
D	Before	20.6	19.2	24.3
	After	16.2	12.1	16.8
E	Before	18.6	17.7	21.9
	After	12.5	13.1	14.7

TABLE II
THE RATIO OF DECREASE

Ratio \ Subject	A	B	C	D	E
K_x	49.2%	33.5%	25%	21.3%	32.8%
K_y	46.1%	36.6%	36.8%	37.0%	26.0%
K_z	37.6%	26.5%	29.6%	30.9%	32.9%

We define the decrease Δ as

$$\Delta = R - R' \quad (3)$$

Where R is the deviation before the training, R' is the deviation after the training.

Furthermore, the ratio of decrease K can be described as

$$K = \frac{\Delta}{R} \quad (4)$$

The decrease K for each subject can be shown on Table II, where K_x , K_y and K_z represent the ratio of decrease along X, Y and Z direction separately.

As demonstrated by the Table I and Table II, though the decrease of deviation and the ratio of decrease varied from person to person, it is not difficult to observe that the deviation of path tracking has been decreased and operation dexterity has been improved after a period of training by the proposed rehabilitation system.

IV. CONCLUSIONS

In this paper, a novel rehabilitation training system based on virtual reality which can implement self-assisted training was proposed. Compared with traditional rehabilitation system, sEMG signals which are biomedical signals generated

from the relative muscle were applied in the proposed system to recognize the action of grasp as well as evaluate the patients' recovery. Besides, VR technology has been utilized to enhance sense judgement and raise training enjoyment. Five subjects who have no disability are invited to participate in these training, the proposed system has been proved effective in those subjects.

Five healthy volunteers took part in the experiment. Considering the sEMG signals of patients maybe different with those of healthy subjects due to the inherent characteristic of vulnerability, hence, the effectiveness of the proposed rehabilitation system maybe not convinced without patients' participation. Besides, the haptic feedback has not been included in this system, and only one task was considered to train the patients which may limit the application of this system.

In the future, post-stroke patients who have remained partial motor function are expected to participate in these experiments to obtain more detailed and effective information for further research. Furthermore, a bilateral training system with coordinative motion of two limbs will be considered for meeting the requirements of those patients with hemiplegia.

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