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A Novel Motor Function Training Assisted System for Upper Limbs Rehabilitation

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Abstract—**In this paper, we propose a novel task-oriented motor function training and assistance of upper limbs system after brain injured such as stroke based on Virtual-Reality. In this system, two kinds of training approaces are developed. One is tracking training with path-unlimited based on a mass-spring-damper force model, and the other is tracking training with path-limited based on a compound force model. Both of training approaches are same that coordination motion of two hands is needed. We want to re-examine how effective the haptic sensory and visual sensory are in training of upper limbs. Further, we enhance the effect of system through adding assistance in order to help mild stroke patients to recovery. This system is convenient and compact so that it is suitable for home-based rehabilitation.**

I. Introduction

Stroke is the leading cause of disability in the U.S. Approximately 700,000 people experience a stroke each year. There are an estimated 5 million stroke survivors living in the United States. Stroke places a financial burden on our society with the projected cost of stroke care in 2007 approaching 62 billion dollars [1]. The most significant physical impact on stroke survivors is long term disability. In the stroke survivor population, 50% have some level of hemiparesis. These stroke patients needed locally based multi-disciplinary assessments and appropriate rehabilitative treatments after they were dismissed from hospital. The conventional rehabilitation for stroke patients which relies on the use of physiotherapy and the therapists training and experience is called passive rehabilitation. Meanwhile there is another method called active rehabilitation that patients can restore their motor function through using certain system by themselves [2], [3]. This method is mainly used in home-rehabilitation. Therefore, we chose cabinet and light devices as experiment tool and develop a system used in home-rehabilitation for mild stroke patients.

The benefit of coordinated interdisciplinary stroke care has been shown to reduce mortality, reduce the percentage of patients requiring institutionalization and reduce dependency in mobility and self-care skills [4]. With the development of robotics technology, robot-assisted systems for physical and neurological rehabilitation for patients who have suffered physical or neurological injuries have been developed. They are also candidates as tools in other neurological conditions characterized by motor deficits, such as multiple sclerosis or spinal cord injury, as well as for training healthy subjects to perform skilful movements, such as those required for surgery, writing, or athletics[5]-[7]. Some results of research have indicated the robot-assisted movement has an effect on patients' recovery [8]-[10]. Work done at MIT-MANUS[11]-[14] on the development of a new robot that allowed the patient to exercise against therapist nominated stiffness and damping parameters uses a different approach from the systems. The device assisted planar pointing and drawing movements with an impedance controller. In 1997, with the cooperation of Stanford University and Rehabilitation Research and Development Centre, another rehabilitation system named MIME (Mirror-image motion enabler) has been developed [15], [16]. In the MIME workstation, the robot is a Puma-560, the paretic limb mobile arm support is eliminated, and a six DOF position digitizer replaces the contra-lateral support. The Puma-560 facilitates unilateral therapeutic exercises in 3 modes and 12 trajectories. A computer controls movement of the robot, with specific preprogrammed tasks tailored to the subject's level of recovery and therapeutic goals. The ARM Guide is a singly-actuated, four DOF robotic device that consists of a hand piece attached to an orientable linear track and actuated by a DC servo motor. [17]. Gentle/s was a three year project funded by the European Commission to develop machine mediated therapies for neurorehabilitation of people with stroke. Gentle/s had the aim to improve quality of treatment and reduce costs [18]. These systems have some advantages and are good for rehabilitation, but large robotic devices are used so that it is not convenient for home-rehabilitation. Further more, there are still disputations on the effect of rehabilitation. In recent years, the virtual reality technology has increasingly been used in the rehabilitation of upper limbs and lower limbs [19]-[21].

The intense and repetitive motion of limbs is considered to be effective by current theory of rehabilitation; however, it has been indicated that simply repetitive execution may not be more effective than the motion involved deeply cognitive processing [22], [23]. Recently, an execution-observation system called Mirror Neurons has been found and it has been proved that action observation may also induce cortical plasticity [24]-[26]. Maybe observation stimulates patient's cognitive processing and strengthens patient's recovery. And then we design a task-oriented and visible experiment. We hope the ability of motor function of patients can be improve through doing some training which needs strength and dexterity. We put emphasis on motion coordination rather than muscle activation, which is the same with [27], however, considering that 50% of stroke patients have some level of hemiparesis, the system is designed to be manipulated with two hands, which one hand is impaired and the other hand is

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intact, more over, the intact hand can supply assistance to the impaired hand. In order to absorb subjects' attention, subjects should coordinate the motion of their two hands to track a moving virtual object randomly.

This paper is organized as follows. It first introduces the relative research and proposed rehabilitation system briefly. In Section 2, the proposed rehabilitation system is presented in detail. In this part two kinds of training approaches are introduced, namely path-unlimited training based on mass-spring-damper force model and path-limited training based on compound force model. Experiments and results are presented in Section 3. The last section presents paper conclusion.

II. PROPOSED REHABILITATION SYSTEM

A. Description of the system

A novel haptic device and an inertial sensor are used in the training. Fig. 1 shows the schematic diagram of the proposed system. In order to enhance the effect of rehabilitation and validate the advantages of improving restriction and impressing subjects, two kinds of training pattern are developed. One is tracking training with path-unlimited based on a mass-spring-damper force model, and the other is tracking training with path-limited based on a compound force model.

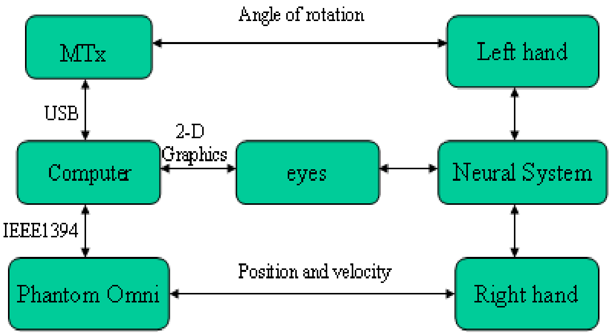

Fig. 1. The schematic diagram of the system

B. Apparatus used in the system

The components of system comprise one haptic device (PHANTOM Omni), an advanced inertial sensor (MTx) and a computer. To make sure that haptic device can work smoothly, the performance of computer should be good. The CPU of the computer is Pentium 4 (3.40 GHz), random memory is 1GB. The operating system of computer is Windows XP, the program of virtual simulator is developed with Visual C++ and OPENGL. PHANTOM Omni is a kind of haptic device, the effector can move in 3 degree of freedoms, the maximum exertable force at nominal position is 3.3N. PHANTOM Omni is connected to computer through IEEE-1394 FireWire port (Fig.2). The MTx is complete miniature inertial measurement unit with integrated 3D magnetometers (3D compass), with an embedded processor capable of calculating roll, pitch and yaw in real time, as well as outputting calibrated 3D linear acceleration, rate of turn and magnetic field data(Fig.3).

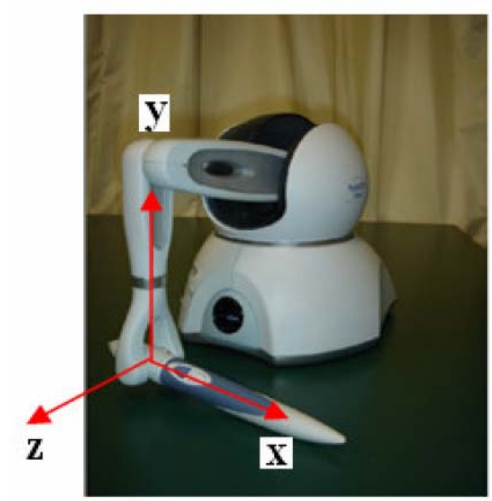

Fig. 2. Phantom omni

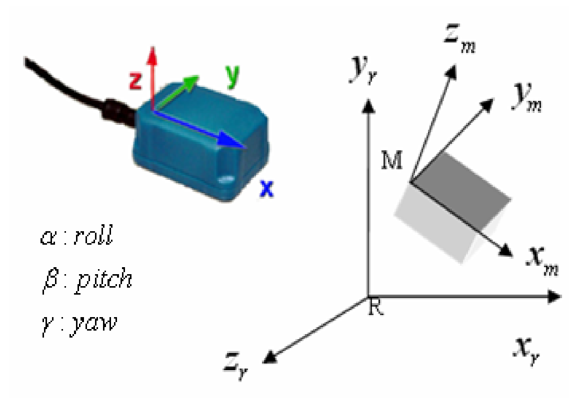

Fig. 3. MTx coordinates M relative to the reference coordinates R

C. Path-unlimted training based on the force model of mass-spring-damper

On two dimension virtual environment, a lathy rectangle virtual object (m) is created. In the experiment, subjects manipulate the stylus of haptic device to control the translation of virtual object (m) with dominant hand and rotate the inertial sensor MTx to control the posture of virtual object (m) with non-dominant hand. The angle of virtual object (m) on the interface of manipulation is the same as the roll angle of MTx. The other virtual object (m') keeps moving randomly. The shape of m' is the same with m , but the color is different. What should subjects do is to track the virtual object (m'). In detail, the tracking is manipulating the object m to realize superposition with the other object m' including the position and posture.

It is the same as research on active rehabilitation; the impedance is used in this system. A mass-spring-damper force model is used to simulate impedance in the process of training. The midpoint of virtual object m is connected to A, B, C and D with springs separately. The elastic coefficient of springs can be set easily on the dialog panel separately. The points A, B, C and D are positioned on the coordinating sides of the rectangle. The force exerted on the stylus of haptic device is set to 0 where the object m is on the initial position as shown in Fig.4. On the other hand, damping force is adopted in the force model. There are four dampers linking the virtual object m and four points separately. Subject manipulates the stylus of haptic device to control the translation of virtual object m as if he holds the stylus and move it on a plane where is of spring and viscous damping net. The forces exerted on the stylus of haptic device are the composition of elastic force and damping force. The dynamics formulation is shown, as in (1).

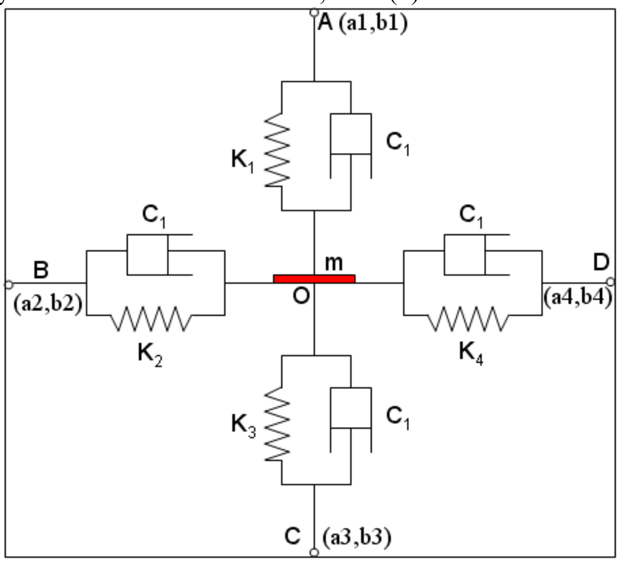

Fig. 4. The mass-spring-damper force model

$$\begin{aligned}\vec{F} &= m\vec{\ddot{p}} + k_1\Delta\overrightarrow{OA} + k_2\Delta\overrightarrow{OB} + k_3\Delta\overrightarrow{OC} + k_4\Delta\overrightarrow{OD} \\ &+ c_1\vec{\dot{p}}\overrightarrow{OA} + c_1\vec{\dot{p}}\overrightarrow{OB} + c_1\vec{\dot{p}}\overrightarrow{OC} + c_1\vec{\dot{p}}\overrightarrow{OD}\end{aligned} \tag{1}$$

Where $\vec{F}$ is forces exerted on the stylus of haptic device. m is the mass of virtual object. $\vec{\ddot{p}}$ is the acceleration of the midpoint of virtual object m ; $\vec{\dot{p}}$ is the velocity of the midpoint of virtual object m ; c_1 is the damping coefficient. k_1, k_2, k_3 and k_4 are the elastic coefficients of springs. This formulation is realized through calculating force along x axis and y axis separately in program.

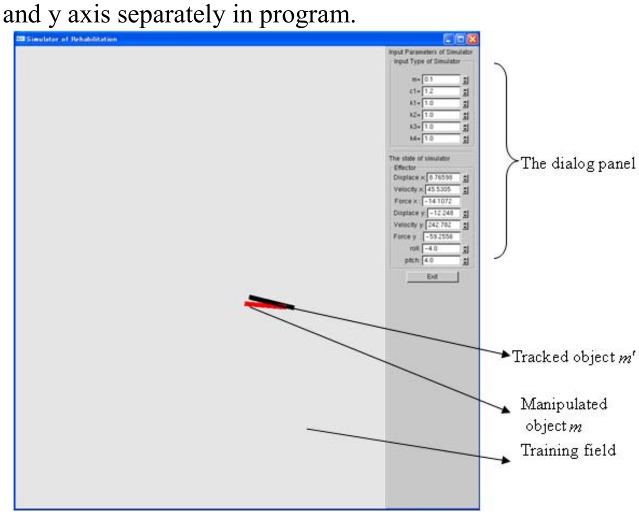

Fig. 5. The interface of path-unlimited training

In this model, the target object m' moves on the training field randomly, and it rotates between -60°—160°, so that subject can easily rotate inertial sensor with non-dominant hand. In our experiments, the position and orientation signals of the tracked virtual object m' are generated by computer, which are random values generated from the seed of the computer's system clock. The random displacement signal ($x_{m'}$), ($y_{m'}$) is the sum of five cosine waves and sine waves, which can be calculated with (2) and (3). With the same principle, we can get the random orientation signals of the virtual object m'.

$$x_{m'} = \sum_{i=1}^{5} A\cos(\omega_i t + \phi_i) \tag{2}$$

$$y_{m'} = \sum_{i=1}^{5} A\sin(\omega_i t + \phi_i) \tag{3}$$

D. Path-limited training based on compound force model

Path-unlimited training based on mass-spring-damper force model has supplied a large-scale to subjects. Though the mass-spring-damp force model generates high fidelity haptic stimuli to subjects, there is still not enough scene to impress subjects. Because of these, we develop path-limited training based on compound force model. The training interface is made up of two parts of deep blue area in order to impress patients. A curve path is formed between the boundaries of these two parts and the boundaries can be felt when subject control object (n) touching it as if he touched wall. The virtual object (n) is also a lathy rectangle which can be manipulated by stylus of PHANTOM Omni and the inertia sensor MTx. n can not rotate freely in the path because of limitation of the path's width. Another object (n') has been created in black color and with the same size of n shown as in Fig.6. n' moves along the predefined path at variable speed which is generated by pseudo-random variable in program. The task is to manipulate n to track n' and we can learn that it is also a cognitive processing. It is the same as path-unlimited training, there is also force exerted on the stylus of haptic device. Therefore, a virtual force model of the system is built after analyzing the kinematics model of the upper limb [28]. Another aspect is the same as path-unlimited training that subjects' two hands should be coordinated in performance. It is different from path-unlimited training that this kind of training supply assistance to subjects allowing for stroke patients' hemiparesis. In that process, subject rotates the inertial sensor and adjusts the pitch angle in reference coordinate. With this system, patients can use their intact hands to assist impaired hands and coordinated manipulation of two hands is benefit for patients' neurorehabilitation. There are some parameters which can be changed in order to increase system levels such as the width of predefined path and coefficient of dynamics.

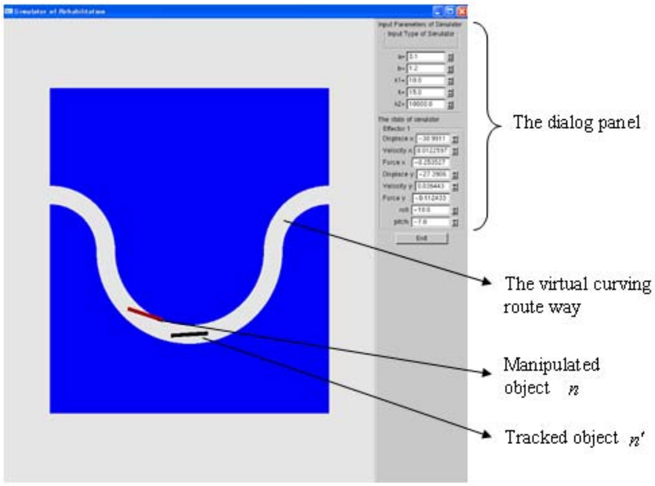

Fig. 6 The display interface of the system

The proposed virtual force model is called compound force model, because it has two parts. One part is called $\lambda-$ *model* which is created in order to augment the strength of upper limb, and the other part is called $\gamma-$ *model* which mainly simulates boundary of curve path.

In $\lambda-$ *model*, the forces exerted on stylus of haptic device along y and x axis are used to augment the strength of patients' upper limb as impedance, but when the force become too strong that patients can not move the stylus of haptic device, an assistance is needed, and then, he will get help from manipulation of their intact hands. We create this force model with the formulation (4), (5) and (6). The impedance is stronger in the main direction of motion. In this model, we hypothesize that the virtual stick has no weight, which is calculated by some formulations.

$$F_y = k\alpha v_y (|P_y| - a)/(3|\beta| + b) \quad (4)$$

Where F_y is the force exerted on the stylus of haptic device along y axis in $\lambda-$ *model*; P_y is the coordinate of midpoint of virtual object n along y axis; v_y is the velocity of midpoint of virtual object n along y axis. α is the roll angle of MTx sensor, and β is the pitch angle of MTx sensor. a has the meaning illustrated in Fig.7. b is used to adjust the value of force. k is the coefficient to adjust the stiffness of system.

When $P_x <= x_1$,

$$F_x = -k_1' |\alpha| v_x (P_x - x_2)/(3|\beta| + b) \quad (5)$$

When $P_x >= x_1$,

$$F_x = -k_1' |\alpha| v_x \frac{x_1 - x_2}{x_1 - x_3} (P_x - x_3)/(3|\beta| + b) \quad (6)$$

F_x is the force exerted on the stylus of haptic device along x axis in $\lambda-$ model; P_x is the coordinate of midpoint of virtual object n along x axis; v_x is the velocity of midpoint of virtual object n along x axis. α, β and b are the same as above; x_1, x_2 and x_3 are illustrated in Fig.7. k_1 is the coefficient like k.

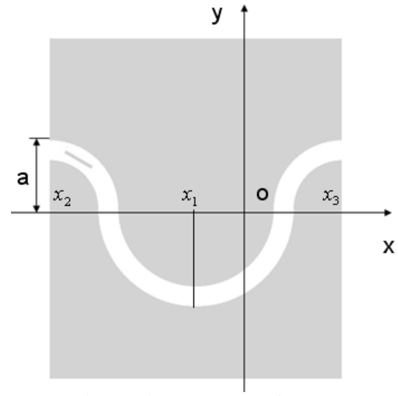

Fig. 7. The parameter of scene

P_x, P_y, v_x and v_y can be obtained by the servo loop and α and β can be obtained by MTx sensor. The call of sampling of MTx sensor is also under the servo loop, so one group of data are recorded in every 0.02 seconds. The forces exerted on the stylus of haptic device are the composition of F_x and F_y when virtual object n does not touch the boundary of curve path.

The $\gamma-$ *model* is designed to simulate the virtual environment, which provides subjects the feeling of touching path boundary. We suppose the boundary was of elasticity which can be set by changing the elastic coefficient. If the virtual stick does not touch the boundary, the $\gamma-$model will not work. The force against path boundary is at normal orientation of boundary direction. The times of touching boundary will be recorded. The resultant of two kinds of force model will be exerted in experiment.

III. Experiments and Result

Subjects are seated in a height adjusted chair in order to manipulate haptic device expediently. We had conducted two experiments to evaluate the proposed system with path-limited training model and with path-unlimited training model. In the first experiment (E1), the subjects were required to try to control the object m to track the object m'. In the second experiment (E2), subjects were required to control the object n to track the object n'.

There are six parameters (m, c_1, k_1, k_2, k_3 and k_4) in the mass-spring-damper model in E1.There are five parameters (a, b, k, k_1' and k_2') in the virtual force model in E2. In our experiment, in order to make it possible to compare the results of two models, through checking the force exerted on the same point of interface many times, the initial parameters can be set as: $m = 0.5\text{kg}$, $k_1 = 5.0\text{N/m}$,

$k_1 = 5.0\text{N/m}$, $k_2 = 12.0\text{N/m}$, $k_3 = 22.0\text{N/m}$, $k_4 = 12.0\text{N/m}$, $k_2 = 12.0\text{N/m}$, $a = 40\text{mm}$, $b = 12\text{mm}$, $k = 10.0\text{N/m}$, $k_1' = 20.0\text{N/m}$, $k_2' = 100.0\text{N/m}$. In the virtual force model, the width of curving route way depended on the parameter of a , and the size of virtual stick can be set to the parameter of b . k_2' mainly affects the rigidity of virtual boundary in $\gamma -$ model.

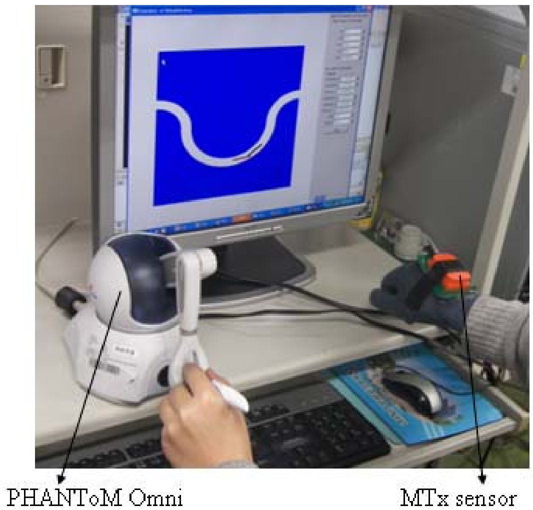

Fig. 8 The profile of the system

In this part, four healthy participants took part in the experiments that were described above. They are studying in our lab and all of them are young (under 30 years old). They have not been injured on the upper limbs before and all of them were right-handed. The MTx inertial sensor is fixed on the back of the subject's right hand that is dexterous for controlling the posture of virtual object and supplying assistance to left hand. The subjects grasp the stylus of the haptic device in left hand and manipulate it to imitate impaired hand. Before the recorded experiment, every participant is given five minutes to practice it. After that, the recorded experiments have been performed. Every participant performed the task 50 times for every experiment.

In E1, subjects manipulate object m to track the object m' on the interface. The mean square error is adopted to assess the effect of the performance in this paper. The performance can be recoded by 0.02 seconds as form of data. The value of mean square errors can be gained according to (7) and (8). δ_p is the mean square error of the position of midpoint of n , and $p_1 - p$ is the distance between the midpoint of n and n'. δ_a is the square error of the posture of n . α_1 is the roll angle of inertial sensor. $\alpha_1 - a$ is the intersection angle between two virtual object. k' is the speed coefficient. $|\dot{p}|$ is the absolute value of tracked objects' speed. N is recorded times.

In E2 the target object n' moves along the predefined curve path randomly, and it movement has the character that its midpoint is always on the center curve of two boundaries of curve path that we call it standard trajectory. Meanwhile its orientation is always parallel to the normal of standard trajectory, which is called standard posture. Both of them are defined to evaluate subjects' performance.

$$\delta_p = k'|\dot{p}|\sqrt{\sum_{i=1}^{N}(P_1 - P)^2 / N} \qquad (7)$$

$$\delta_\alpha = k'|\dot{p}|\sqrt{\sum_{i=1}^{N}(\alpha_1 - \alpha)^2 / N} \qquad (8)$$

In Fig.9, the purple zone is the mean square errors of the posture and the green zone is the mean square errors of the position. A, B, C and D have participated in E1 and E2 and do the experiments 50 times separately at 10 times per day. Before recording the training, subjects were given 3 minutes to adapt it. We represent the average result of first 10 times and last 10 times in Fig.9, which is shown using arrowheads. The starts of arrowheads stand for the average data of mean square errors of first 10 times, and the ends of arrowheads are the average data of last 10 times. From Fig.9, all arrowheads point adown obviously, which means subjects' mean square errors of position and posture are decreased. Meanwhile, we can know that the arrowheads in E2 are longer than them in E1 in results of four subjects. Therefore, path-limited training is more effective. In E2, there are more haptic and visual stimuli than in E1. In addition, non-dominant hand could be assisted through rotating dominant hand and changing pitch angle of MTx sensor. This contrastive experiment indicate that E2 provides more space for improving motor function, and generally it is more effective for patients' neurorehabilitation. Accordingly we can use this to help patients following stroke to recovery by him, and self-rehabilitation can be realized.

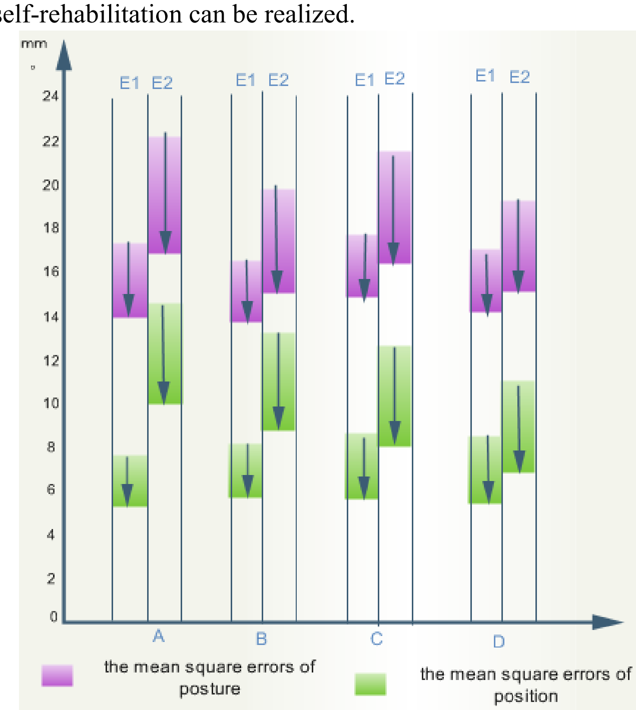

Fig.9 The decreasing mean square errors of position and posture

IV. Conclusion

We have developed a new task-oriented motor function training assisted system for people who injured on upper limbs based on Virtual-Reality. There are two kinds of training pattern which is path-unlimited training and path-limited training. Both of them are tracking training. The former is easy to manipulate, and the result of experiment has been improved. The latter provides more haptic and visual stimuli to participants, and the mean square errors decreased more than the former through 50 times practice. Otherwise, this system has the characters of high safety, compaction and self-assistance, which make the system suitable for home rehabilitation.

Though this system can provide certain assistance to impaired upper extremity, certain motor function is required for subject, that is to say, this system is not suitable for sever stroke patients. In the future, we will conduct experiments above to mild stroke patients. Otherwise the work space of the PHANTOM haptic device is not large enough for the free rotation of the elbow, although it is enough for the free rotation of the wrist, so the system is mainly fit for the rehabilitation of the wrist. And force of output is not strong enough, which is not perfect in improving strength. In the future, we will enlarge the work space of the system and make sure it is not heavy, so that it can be suitable for the rehabilitation of the elbows.

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