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A NOVEL SELF-ASSISTED REHABILITATION SYSTEM FOR THE UPPER LIMBS BASED ON VIRTUAL REALITY

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We propose a novel self-assisted rehabilitation system for the upper limbs of stroke patients. The system mainly includes two haptic devices (PHANTOM Omni), an advanced inertial sensor (MTx) and a computer. The inertial sensor is used to get the real-time orientation of one of the manipulator's hands, and the haptic devices are used to get the real-time positions of the manipulator's two hands and generate the appropriate forces that act on the two hands. We have built a virtual force model to get the accurate magnitude and orientation of the forces. With the change of the position and orientation of the manipulator's hands, the magnitude and orientation of the forces will change accordingly. The manipulator operates the styluses of the two haptic devices to control the position and orientation of the virtual object m, so that it can track the virtual object m', which moves and rotates randomly in 4 degree-of-freedoms (DOF). It is expected to improve the agility and strength of manipulator's hands in this way. Furthermore, one hand can be used to assist the other one in the rehabilitation, so the self-assistance character is included in the system. The advantages of high safety, compaction and self-assistance will make the system suitable for home rehabilitation.

Keywords: Self-assisted rehabilitation; haptic device; inertial sensor; virtual reality.

1. Introduction

Stroke is a leading cause of permanent disability. According to figures from the National Stroke Association (NSA), in 1993, there were 550 000 patients with stroke in the United States. The consequences were devastating, 150 000 died (the third leading cause of death), and there were 350 000 disabled survivors. The estimated cost of care was $30 billion [Krebs *et al.*, 1998]. In fact, stroke patients have become a burden for many countries, it is urgent to find a good way to solve the problem. The application of novel rehabilitation approach and novel rehabilitation system is regarded as the best way to solve it.

A therapist is necessary in the conventional rehabilitation for one stroke patient. The patient's limbs are moved by the therapist in different tracks and velocities, which is called passive rehabilitation. On the other occasion, the patient moves his own limbs by himself under the therapist's instructions, which is called active rehabilitation [Laura *et al.*, 2004;

Czell *et al.*, 2004]. Both are testified to be effective to improve the performance of Activities of daily living (ADL) [Suzuki *et al* 2004; Seaton *et al.*, 2005] for stroke patients.

Robotics has been widely used in the industrial field. It has also been used in the biomedical field in recent years, such as surgical operation, stroke rehabilitation etc. Robotics is testified to be useful in neurological rehabilitation for people who have suffered neurological injuries resulting in impaired motor ability in the lower and upper limbs [Reinkensmeyer *et al.*, 1999; Pan *et al.*, 2005]. Until now, many rehabilitation systems based on robotics have been developed successfully [Kahn *et al.*, 2004; Boian *et al.*, 2004]. In 1995, a rehabilitation system named MIT-MANUS has been developed by Massachusetts Institute of Technology, Cambridge [Hogan *et al.*, 1995; Krebs *et al.*, 2004]. In 1997, with the cooperation of Stanford University and Rehabilitation Research and Development Center, another rehabilitation system named MIME has been developed [van Vliet & Wing, 1991; Lum *et al.*, 1995]. For hand rehabilitation, sensor gloves have been comprehensively used in the past [Bonato, 2005; Simone & Kamper, 2005]. In recent years, the virtual reality technology has increasingly been used in the rehabilitation of upper limbs and lower limbs [Ring, 1998; Jones, 1998; Brewer *et al.*, 2005].

In robotics rehabilitation, the repeated movement of limbs is testified effective for the recover of stroke limbs. For the passive rehabilitation approach, the movement trajectory of robot is predefined, and the patient's limbs move repeatedly with the movement of the robot. The passive rehabilitation approach is effective to some extent for the neurological patients, but it is not so obvious on some occasions. So, the active rehabilitation approach has been introduced into rehabilitation system. But the active rehabilitation is mainly fit for mild stroke patients.

The aim of the rehabilitation for stroke patients is to increase the strength, agility and range of movement (ROM) of the limbs [Wolf *et al.*, 2002]. In this paper, we propose a novel active rehabilitation approach for the recovery of the stroke upper limbs. In our study, we suppose the positions of both the elbows are unchangeable, but the forearms can rotate around the elbows in 3 DOF respectively, and we mainly consider the rotation of the elbows and the wrists. During the rehabilitation process for the elbows and the wrists, we suggest that both of the two hands participate in the rehabilitation practice, instead of one hand only, so that the patient can perform self-assisted rehabilitation practice [Danek *et al.*, 2005].

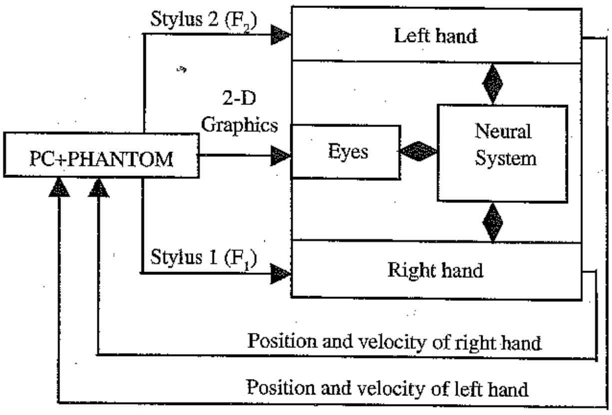


Fig. 1. The schematic diagram of the original system.

Our exploration of the self-assisted rehabilitation idea begins with the development of a rehabilitation system based on virtual reality [Song & Guo, 2006]. Figure 1 shows the schematic diagram of the original system, the various power and information pathways available are depicted in the system. In the figure, the neural coupling between two hands through his neural system is illustrated. The proposed additional mechanical coupling between the two hands through the haptic devices and the computer is also illustrated. Through the combined efforts of two hands, the exchange of haptic information between the left hand and the virtual environment and between the right hand and the virtual environment can be realized. We hypothesize that the combination of mechanical and neural coupling during the completion of a single task will promote motor recovery.

2. The Original Prototype of the System

At the first step, we have proposed an original prototype of the rehabilitation system, which includes two haptic devices and one computer. The manipulator's hands can move in 3 dimensions, but only the position in x-axis is used in the display interface.

2.1. *The apparatus of the original system*

The original system consists of two haptic devices (PHANTOM Omni) and one computer. To get the continuous output of force on the styluses, high performance of the computer is necessary. In the system, the CPU is Pentium 4 (3.40 GHz), random memory is 1GB, and display memory is 256MB. The operating system of computer is Windows XP, the program of the system is developed with Microsoft Visual Studio.NET and OPEN GL. The apparatus of the system is shown in Fig. 2.

PHANTOM Omni is a kind of haptic device, the stylus 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. Figure 2 shows the apparatus of the original system. Manipulator operates one stylus with left hand, and operates the other one with right hand. From Fig. 2, we can see that each hand is put on a soft cushion, which will make the manipulator operate the haptic device more comfortably and easily.

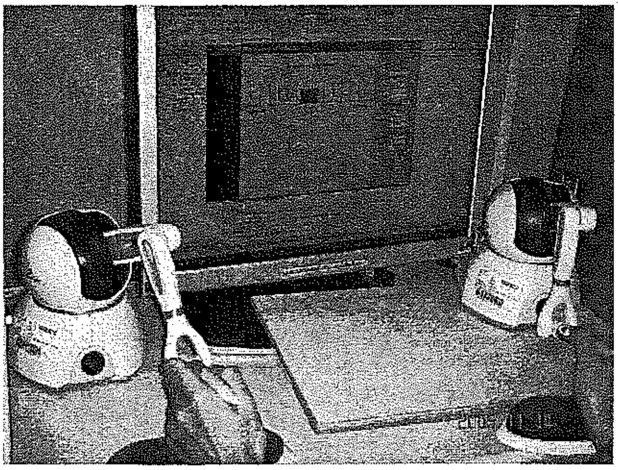


Fig. 2. Apparatus of the original system.

2.2. *The virtual force model*

We have designed a virtual force model for the original system, it is shown in Fig. 3. Based on the virtual force model, the kinematics equation is shown in (1).

$$\begin{aligned} m\ddot{x}_m + (b_1 + b_2)\dot{x}_m + (k_1 + k_2 + k)x_m \\ = k_1x_1 + b_1\dot{x}_1 + k_2x_2 + b_2\dot{x}_2. \end{aligned} \tag{1}$$

In (1), x_m is the displacement of object m, x_1 and x_2 are the displacement of objects 1 and 2, $\dot{x}_1$ and $\dot{x}_2$ are the velocity of objects 1 and 2, k_1, k_2 and k are the stiffness constants of the springs, b_1 and b_2 are the damping constants of dampers 1 and 2. With the scheduler of the haptic devices, the displacement and velocity of the styluses can be sampled by computer every one millisecond, so the displacement, velocity and acceleration of object m can be calculated with (1).

With the calculated velocity and displacement of object m, the output force on two effectors can be calculated with (2) and (3). From (1)–(3), we can see that the displacement and velocity of manipulator's hands determine the output forces on the styluses.

$$F_1 = b_1(\dot{x}_1 - \dot{x}) + k_1(x_1 - x). \tag{2}$$

$$F_2 = b_2(\dot{x}_2 - \dot{x}) + k_2(x_2 - x). \tag{3}$$

The display interface is shown in Fig. 4. In the experiment, the virtual object m will track the virtual object m', which moves randomly in x-axis. In this way, the agility of the manipulator's hands is expected to be improved.

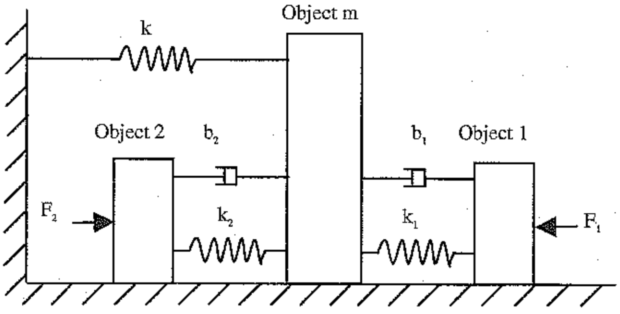
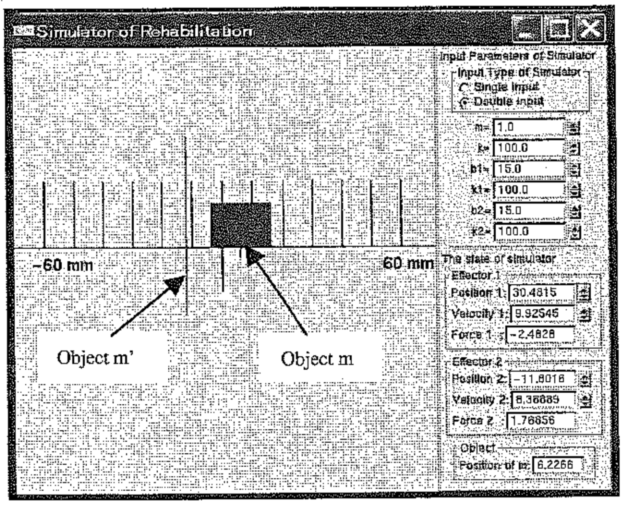


Fig. 3. The virtual force model of the original system.



Input Parameters of Simulator
Input Type of Simulator
○ Single input
● Double input
m= 1.0
k= 100.0
b1= 15.0
k1= 100.0
b2= 15.0
k2= 100.0

The state of simulator
Effector 1
Position 1: 30.4815
Velocity 1: 9.92545
Force 1 : -2.4828
Effector 2
Position 2: -11.8016
Velocity 2: 8.36889
Force 2 : 1.76856
Object
Position of m: 6.2266

Fig. 4. The display interface of the original system.

3. Improvement of the Original System

In the original rehabilitation system, there are some problems have not been solved yet. At first, the position in x-axis is only considered in the display interface, so the evaluation parameter is not enough for the rehabilitation. Secondly, the visual feedback in the original system is not 3D, it is 2D instead, while 3D visual feedback is expected to make the subject interested in the rehabilitation more, and the better training effect can be obtained in this way.

To improve the performance of the original system, an inertial sensor (MTx) is added to the system [Tao *et al.*, 2005]. The inertial sensor can get the gesture of manipulator's hand in real-time when it is equipped on the back of manipulator's hand. The schematic diagram of the improved system is shown in Fig. 5. Figure 6 shows the flow to get the Euler angles for MTx sensor, Fig. 7 shows the relation between the MTx coordinates M and the reference coordinates R. The profile of the improved system is shown in Fig. 8.

In this part, we have analyzed the kinematics model of the upper limb at first. Then we have built the virtual force model of the improved system, with which the exerted forces on the two styluses of the haptic devices can be calculated.

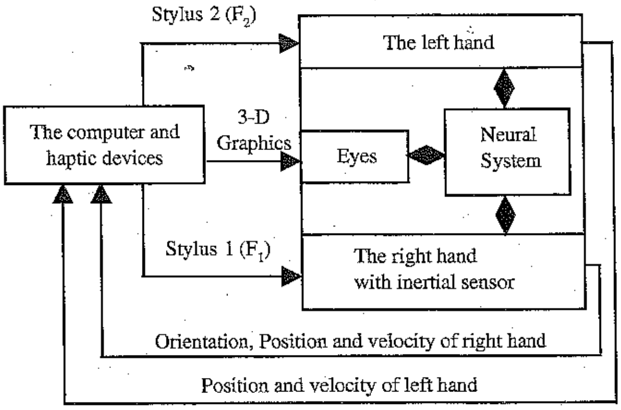


Fig. 5. The schematic diagram of the improved system.

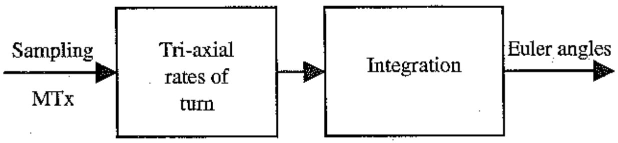


Fig. 6. The flow to get the Euler angles for MTx sensor.

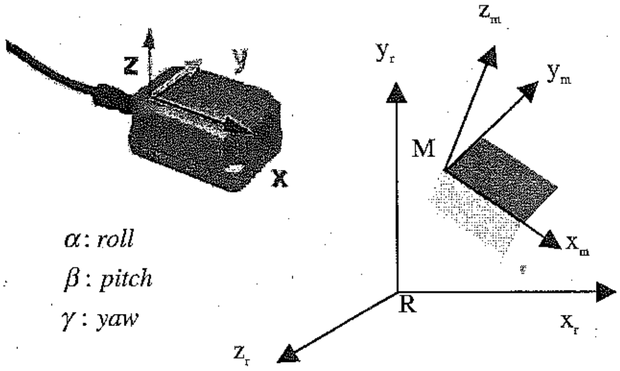


Fig. 7. MTx coordinates M relative to the reference coordinates R.

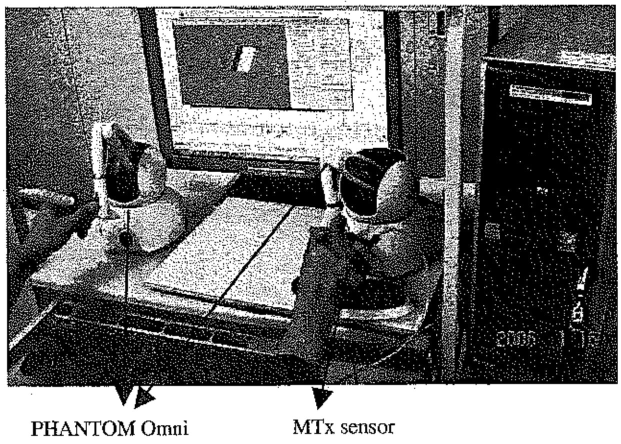


Fig. 8. The profile of the improved system.

The task for manipulator is to change the position and orientation of the two hands to control the position and orientation of a virtual object m, so that it can track a virtual object m', which moves and rotates in 4-DOF randomly. At the end of this part, it is explained how to generate the tracked random signals, including the position and the orientation signals.

3.1. *The kinematics model of upper limb*

In our study, the elbow of the subject is fixed, but the forearm can rotate around the elbow in 3-DOF. At the same time, the hand can rotate around the wrist in 1 DOF. So, there are 4 DOF for the kinematics model of the upper limb, which is shown in Fig. 9. In the figure, point E stands for the elbow, point W stands for the wrist, and point F stands for the fingertips when the fingers grasp the stylus of the PHANTOM haptic device. The real-time 3D position of point F can be sampled by the PHANTOM haptic device. To simplify the kinematics model, we suppose there is no movement among the fingers during rehabilitation training, so the distance between the point W and the point F is a constant. We can get the position of the wrist from (4). In the equation, the position vector of $\overrightarrow{EF}$ can be obtained with the PHANTOM haptic device, the position vector of $\overrightarrow{WF}$ can be obtained with the MTx sensor:

$$\overrightarrow{EW} = \overrightarrow{EF} - \overrightarrow{WF}. \tag{4}$$

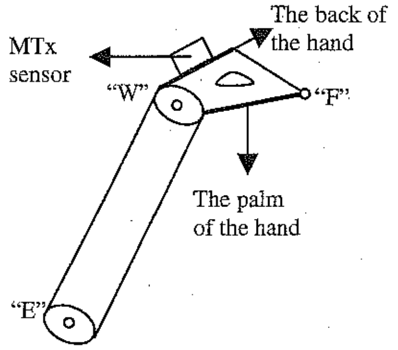


Fig. 9. The kinematics model of upper limb.

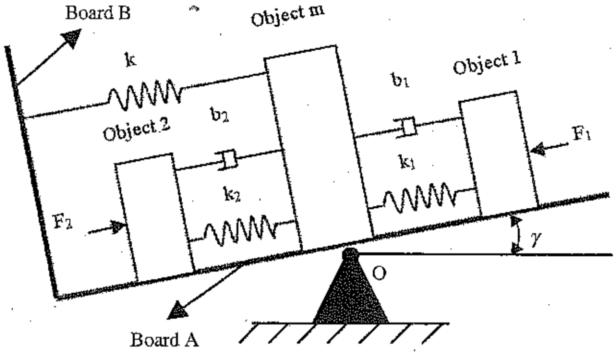


Fig. 10. The virtual force model of the improved system.

3.2. *The virtual force model of the improved system*

The virtual force model of the improved system that we have built is shown in Fig. 10. In this virtual force model, we make four hypothesises to simplify the model.

(i) Objects 1, 2 and m can only move along with board A, and board A can rotate around linkage "O" in 3 DOF. Board B is vertical to board A.

(ii) The magnitude of the velocity and the displacement of objects 1 and 2 are equal to the velocity and the displacement of styluses 1 and 2 in x-axis respectively.

(iii) The orientation of board A is decided by the Euler angles of the MTx inertial sensor, which is fixed on the back of the manipulator's right hand. The orientation of the exerted forces on styluses 1 and 2 are parallel, both of them are parallel to board A.

(iv) Because the styluses are light enough, we suppose the mass of objects 1 and 2 are zero, and we suppose there is no friction for all of the objects.

According to these hypothesises, the kinematics equation of the virtual force model is depicted as (5). In the equation, x_1 and x_2 are the displacement of objects 1 and 2 respectively, $\dot{x}_1$ and $\dot{x}_2$ are the velocity of objects 1 and 2 respectively. The displacement and velocity of the virtual object m can be calculated with (5), and the orientation is accordance with the orientation of board A.

When there is no rotation for the hand, the exerted forces on the styluses are accordance with x-axis. In (6) and (7), F_1 and F_2 are the forces that the subject acts on styluses 1 and 2 respectively. With these two equations, F_1 and F_2 can be calculated. Actually, F_1 and F_2 are equal to the exerted forces on styluses 1 and 2 respectively, but the orientation is just the opposite. If we change the spring constant and damper constant, F_1 and F_2 can be changed easily:

$$m\ddot{x}_m + (b_1 + b_2)\dot{x}_m + (k_1 + k_2 + k)x_m = k_1x_1 + b_1\dot{x}_1 + k_2x_2 + b_2\dot{x}_2 - mg\sin\gamma, \tag{5}$$

$$F_1 = b_1(\dot{x}_1 - \dot{x}_m) + k_1(x_1 - x_m), \tag{6}$$

$$F_2 = b_2(\dot{x}_2 - \dot{x}_m) + k_2(x_2 - x_m). \tag{7}$$

When there is no rotation for the MTx sensor, the force vector $\vec{F_1'} = (F_1,\ 0,\ 0)$, $\vec{F_2'} = (F_2,\ 0,\ 0)$. After the rotation, the force vectors become to $\vec{F_1}$ and $\vec{F_2}$ respectively, we suppose $\vec{F_1} = (F_{1x},\ F_{1y},\ F_{1z})$, $\vec{F_2} = (F_{2x},\ F_{2y},\ F_{2z})$. So, $\vec{F_1}$ and $\vec{F_2}$ can be calculated with (8) and (9):

$$\vec{F_1} = B \times \vec{F_1'}, \tag{8}$$

$$\vec{F_2} = B \times \vec{F_2'}, \tag{9}$$

and

$$B = \begin{bmatrix} c\gamma c\alpha - s\gamma c\beta s\alpha & c\gamma s\alpha + s\gamma c\beta c\alpha & s\gamma s\beta \\ -s\gamma c\alpha - c\gamma c\beta s\alpha & -s\gamma s\alpha + c\gamma c\beta c\alpha & c\gamma s\beta \\ s\beta s\alpha & -s\beta c\alpha & c\beta \end{bmatrix},$$

where c and s stand for the cosine and sine functions respectively.

3.3. *The tracked random signals of the virtual object m'*

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 ($x_{m'}$) is the sum of five cosine waves, which can be calculated with (10):

$$x_{m'} = \sum_{i=1}^{5} A\cos(\omega_i t + \phi_i). \tag{10}$$

With the same principle, we can get the random orientation signal of the virtual object m'.

4. Experimental Results

The rehabilitation's aim for the stroke patients is to increase the strength, agility and ROM of limbs. In our study, five healthy subjects have participated in the experiments. At first, we have performed the self-assisted experiment with the system that we have proposed. The further experiment has been performed to testify that the agility of the subjects' upper limbs can be improved with the rehabilitation system.

There are six parameters (m, b_1, b_2, k, k_1 and k_2) in the virtual force model. The parameters can be decided according to the following discuss.

(i) To decide the parameter of m. We suppose the maximum of the generated force is 0.1 N because of the acceleration of object m, and we suppose the acceleration of object m is 1 m/s^2 on this occasion. According to the equation $F = ma$, we can get: $m = 0.1$ kg. Of course, we can change the mass to get a different experiment difficulty.

(ii) To decide the parameters of b_1 and b_2. In the virtual force model, we suppose there is no spring, that means $k = k_1 = k_2 = 0$. To simplify the calculation, b_1 and b_2 are set to be equal. We suppose the maximum speed of subject's hand is 50 mm/s, and the velocity of object m is supposed to be 45 mm/s on this occasion. Based on the virtual force model, we can get the maximum damper constant: 10 Ns/m.

(iii) To decide the parameters of k, k_1 and k_2. In the virtual force model, we suppose there is no damper, that means $b_1 = b_2 = 0$. To simplify the calculation, k, k_1 and k_2 are set to be equal. When the displacement of objects 1 and 2 is the maximum: 80 mm (because the workspace of PHANTOM haptic device is 160 mm in x-axis), we suppose the displacement of object

m is 70 mm. Based on the virtual force model, we can get the maximum spring constant: 20 N/m.

So, we can choose the spring constant in (0, 20 N/m) and the damper constant in (0, 10 Ns/m). Based on the spring constant and damper constant, the sum of virtual spring force and virtual damper force should not over 3.3 N (it is the maximum exertable force of PHANTOM haptic device). In our experiment, the initial parameters are set as: $m = 0.1$ kg, $k = k_1 = k_2 = 10$ N/m, $b_1 = b_2 = 5$ Ns/m.

In the virtual force model, the mass of object m mainly affects the experiment difficulty of the rehabilitation tracking experiment; b_1 and b_2 mainly affect the agility improvement of upper limbs; k, k_1 and k_2 mainly affect the strength and ROM improvement of upper limbs.

With the increase of mass, it is more difficult to change the position and orientation of the virtual object m. So, it gets more difficult for a subject to complete the same tracking task. With the increase of b_1 and b_2, the forces on the styluses will change more quickly, so the better agility of upper limb is necessary to complete the same tracking task. In the virtual force model, the forces on the styluses get bigger with the increase of k, k_1 and k_2. So, these three parameters mainly affect the strength and ROM improvement of upper limbs. According to the force model, the natural frequency of no input (ω_0), one hand input (ω_1) and two hands input (ω_2) can be calculated with (11)–(13) respectively.

$$\omega_0 = \sqrt{k/m} = 10 \text{ rad/s}, \tag{11}$$

$$\omega_1 = \sqrt{(k + k_1)/m} = 14.1 \text{ rad/s}, \tag{12}$$

$$\omega_2 = \sqrt{(k + k_1 + k_2)/m} = 17.3 \text{ rad/s}. \tag{13}$$

To avoid the resonance, the maximum frequency of the tracked random position and orientation signals are set to less than half of the natural frequency of the virtual force model. In our experiments, as (10) shows, A = 20 mm, ω is a random value in (0, 5), and ϕ is a random value in (0, 2π). At the same time, the maximum rotation angles of the virtual object m' is set as 30°.

4.1. *The self-assisted experiment*

In this part, five healthy subjects have participated in the experiments. The characters of the subjects are depicted in Table 1. Among the subjects, two of them are aged (over 50 years old) and the other three are young (under 30 years old); one is female, the other four are male, and all of them have not been injured on the upper limbs before.

In the experiment, the MTx inertial sensor is fixed on the back of the subject's right hand, and the subject grasps the styluses of the two haptic devices and manipulates it. Figure 8 shows the experiment apparatuses, and Fig. 11 shows the display interface of the system. In the display interface, the 3D virtual object m stands for the virtual object m in the virtual force model, which is shown in Fig. 10. The path of the virtual object m' rotates in 3 DOF, and the 3D virtual object m' can move along the path. The position and orientation signals of the 3D virtual object m' are random, which are generated from computer in real-time.

The subject's task is to control the position of the styluses of the PHANTOM haptic devices

Table 1. The characters of the subjects.

Subject	No. 1	No. 2	No. 3	No. 4	No. 5
Sex	Male	Male	Female	Male	Male
Age	52	55	24	26	25

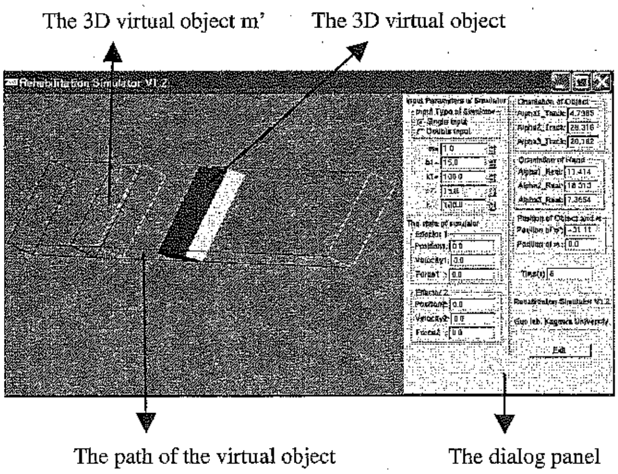


Fig. 11. The display interface of the improved system.

and the orientation of the MTx sensor, in order to control the position and orientation of the 3D virtual object m to track the virtual object m'. Before the recorded experiment, every subject is given 5 min to practise and get familiar with the system. After that, the recorded experiments have been performed. The tracking performance can be evaluated with the square error between the track of object m' and object m, and the agility of the subjects' upper limbs can be evaluated with the square error too, which is calculated with (14). In the experiment, the position and the orientation of the subject's hands are sampled once a millisecond:

$$\delta = \sum_{i=1}^{N} (x_{m'} - x_m)^2 / N. \tag{14}$$

For every subject, the experiment is performed on two different conditions. One is to control the virtual object m with right hand only, the other is to control it with the combined efforts of two hands. Every subject performs the tracking experiment for ten times, five times for right hand operation and five times for two hands operation, and it takes 1 min for once. After the experiment, the tracking performance is simulated in the software of MATLAB.

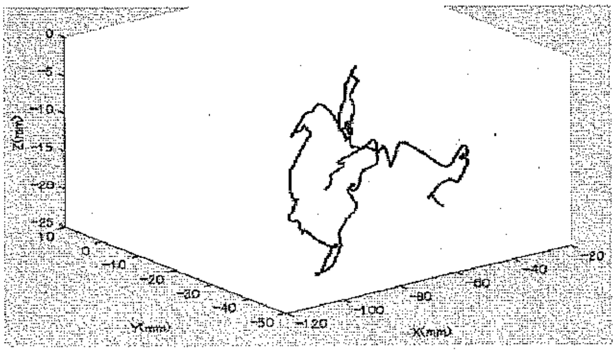


Fig. 12. The typical 3D track of the right hand for subject No. 1.

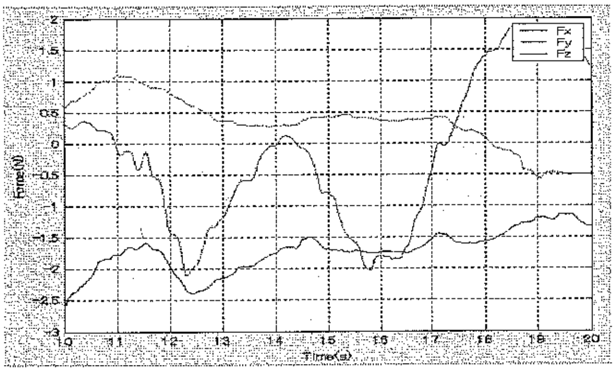
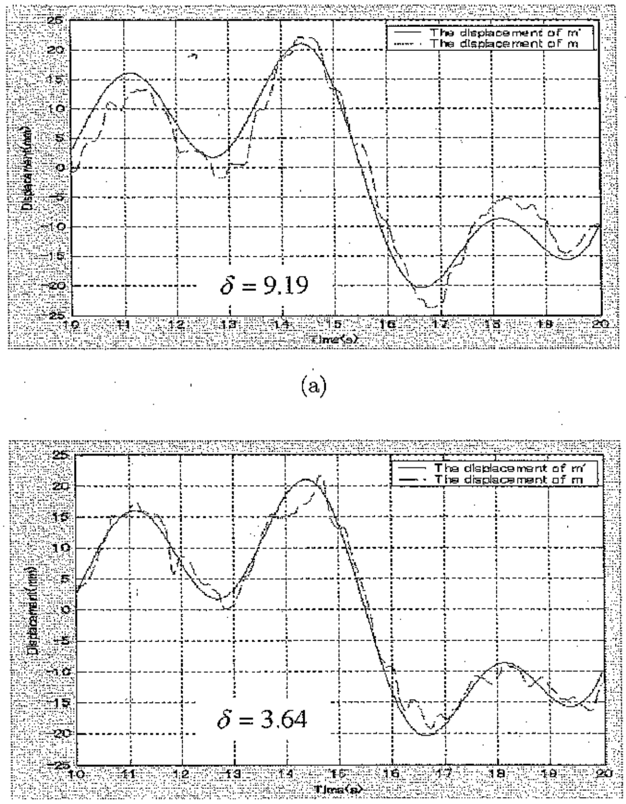


Fig. 13. The typical exerted force on stylus 1.



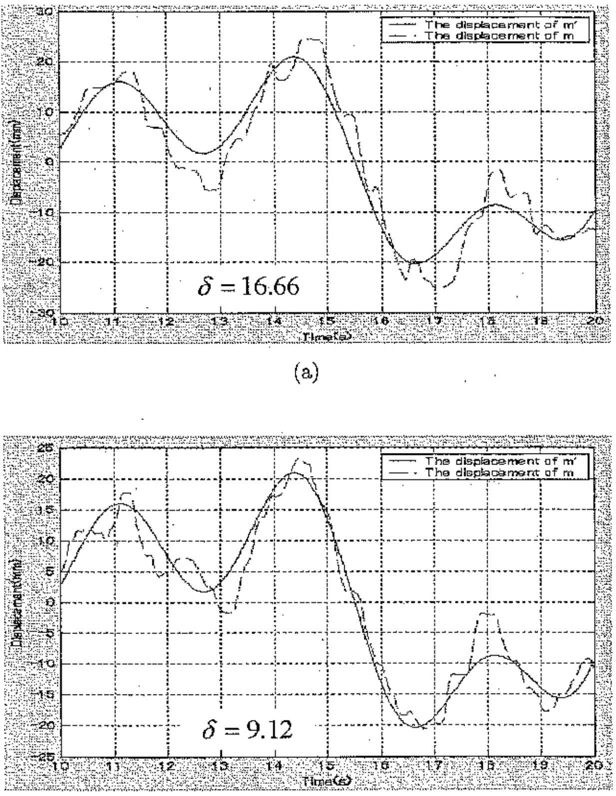
(a)

(b)

Fig. 14. The typical tracking result of a young subject (subject No. 4). (a) With the right hand. (b) With the combined efforts of two hands.

The typical position tracking performance from 10th second to 20th second of subject No. 4 is shown in Fig. 14. Figure 15 shows the typical position tracking performance of subject No. 1. The mean square errors of the position tracking experiment for every subject are listed in Table 2.

From Table 2, we can see that the agility of the old subjects' hands is not as good as that of young subjects' hands, which means the agility of the old people's hands has decreased. For both the aged and the young groups, the tracking performance of two hands combined efforts is better than that of one hand. In this opinion, when



(a)

(b)

Fig. 15. The typical tracking result of an old subject (Subject No. 1). (a) With the right hand. (b) With the combined efforts of two hands.

one of the subject's hands is injured, the other intact one can be used to assist the injured hand, two hands combined efforts are used to complete the tracking task, until there is no assistance from the intact hand. At last, the injured hand recovers gradually and it can complete the tracking task alone. The proposed system is an active rehabilitation system, so it is mainly fit for mild stroke patients. In self-assisted rehabilitation, the worst occasion is that the injured hand can hardly move, only the intact hand can move actively. On this occasion, the MTx sensor is equipped on the back of intact hand. According to the proposed virtual force model (see Fig. 10), when the intact hand moves and rotates in the tracking task, there will be a corresponding force act on the injured hand to make it move in the expected direction. In this way, the self-assisted rehabilitation can be realized.

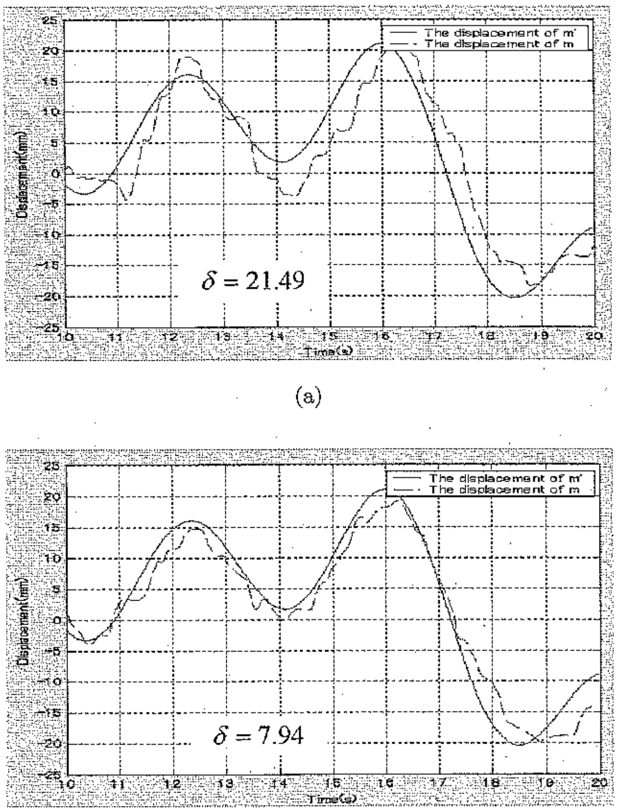
4.2. *Improving the agility of the upper limbs*

With the increase of age, the agility and strength of upper limbs decrease. Especially, it is obvious for the aged people (over 50 years old) [Matsudo & Matsudo, 2003]. In some sense, this character is just like the mild stroke patients, who have lost some agility and strength on their upper limbs. Therefore, two aged subjects (see Table 1, subject No. 1 and subject No. 2) have participated in the rehabilitation experiment for two continuous months in our initial research. The mild stroke patients will participate in the further experiments in our future research. In fact, it is the most important object for a mild stroke patient to improve the agility of upper limbs. So, we mainly performed the position tracking experiment and orientation tracking experiment to evaluate the agility of upper limbs. With these tracking results (square error), we can evaluate the agility of mild stroke patients' upper limbs accurately. For each old subject in this experiment, he always performs the rehabilitation with two hands combined efforts, and the rehabilitation continues for 30 mins every day, 15 mins in the morning and the other 15 mins in the afternoon.

Figure 12 shows the typical 3D track of the right hand for subject No. 1 from 10th second to 20th second. From the figure, we can see the ROM of the old subject's right hand is 100 mm in x-direction, 60 mm in y-direction and 25 mm in z-direction. According to the virtual force model, the exerted force on styluses 1 and 2 can be calculated, and the orientation of the

Table 2. The mean square error of the position tracking experiment.

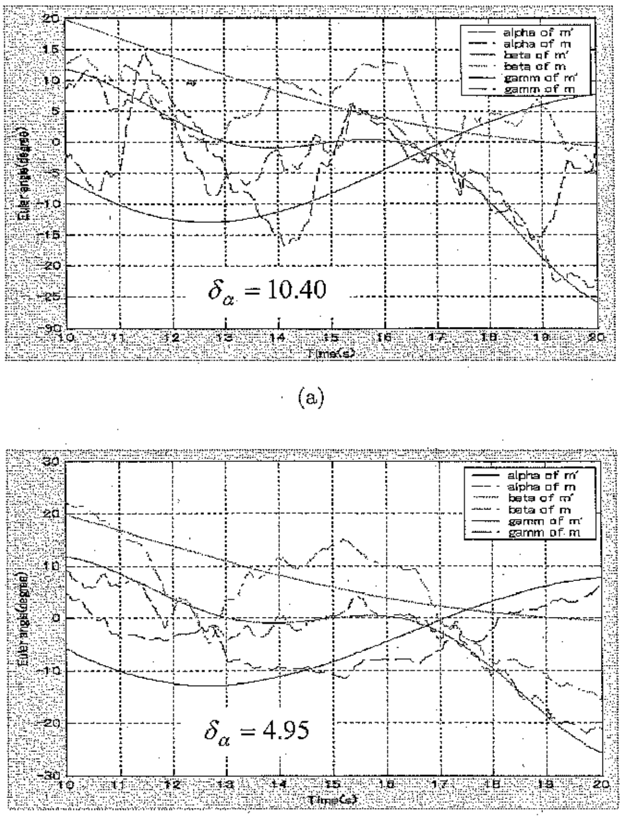
Subject	No. 1	No. 2	No. 3	No. 4	No. 5
With right hand only	16.5	17.3	9.4	8.8	10.2
With two hands efforts	9.6	10.1	5.1	4.5	5.4



(a)

(b)

Fig. 16. The position tracking result of subject No. 1. (a) Before the rehabilitation. (b) After two months rehabilitation.



(a)

(b)

Fig. 17. The orientation tracking result of subject No. 1. Before the rehabilitation. (b) After two months rehabilitation.

forces are decided by the rotation of the MTx sensor. The typical exerted force on the stylus 1 is shown in Fig. 13. The force range is from −3 N to 2 N for each of the three axis.

At last, the tracking results of position and orientation for subject No. 1 are shown in Figs. 16 and 17 respectively. For the tracking performance of orientation, we mainly analyze the tracking performance of the roll Euler angle (α). From Figs. 16 and 17, we can see the tracking performance of position and orientation has been improved greatly after two months rehabilitation with the system, that means the upper limbs' agility of the old subject have been improved greatly.

5. Conclusions

We have developed a self-assisted active rehabilitation system for upper limbs, especially for the wrists and elbows. It is easy to change the stiffness of the system through changing the parameters of the virtual force model. The system has the characters of high safety, compaction and self-assistance, which make the system suitable for home rehabilitation.

The advanced haptic devices and the inertial sensor have been used in the system, so the accurate position and orientation of the subject's hand can be obtained in real-time, which are most significant for the rehabilitation of upper limbs. According to the comparison of the tracking performances, we can see the agility of the old subjects' hands have been improved greatly after two months rehabilitation with the system.

The system is not only fit for one hand rehabilitation, but it is also fit for two hands rehabilitation. On the latter occasion, the intact hand can be used to assist the injured one in the rehabilitation. When the injured hand has recovered gradually, the assistance from intact hand can be decreased gradually, until there is no assistance. In general, the stroke patients are divided into four categories: mild, moderate, severe, and fatal [Solomon *et al.*, 1994]. The proposed system is an active rehabilitation system, so it is not fit for severe stroke patients (such as the patients with hemiplegia). It is mainly fit for mild stroke patients.

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. In the future, we will enlarge the work space of the system, so that it can be suitable for the rehabilitation of the elbows. Furthermore, we will develop a new system include the passive rehabilitation function, which can improve the strength and ROM of severe stroke patients' upper limbs.

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