Development of an upper extremity motor function rehabilitation system and an assessment system

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Abstract: This paper presents a novel upper extremity motor function rehabilitation system and an assessment system. The rehabilitation system is an active rehabilitation that can be manipulated by patients through a haptic device and an inertia sensor to perform a tracking task in virtual environment with coordination training of bilateral upper extremity. The design of system aims to augment patients’ force exerted by theirs’ upper extremity and the ability of force control, namely, dexterity. The structure of rehabilitation system is compact and the inertia of the haptic device’s stylus is very small (only 45 g), which makes the system suitable for home-rehabilitation. Simultaneously, in order to assess the effect of rehabilitation, an assessment system has been developed using a 6-axis force sensor. The proposed rehabilitation system is testified experimentally for the upper limbs’ rehabilitation training.

Keywords: virtual reality; VR; path-unlimited training; path-limited training; position and posture tracking; home-rehabilitation.


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Shuxiang Guo received his PhD in Mechano-informatics and Systems from Nagoya University, Nagoya, Japan, in 1995. Currently, he is a Professor with the Department of Intelligent Mechanical System Engineering at Kagawa University. His current research interests include micro robotics and mechatronics, micro robotics system for minimal invasive surgery, micro catheter system, micro pump, and smart material (SMA, ICPF). He received research awards from the Tokai Section of the Japan Society of Mechanical Engineers (JSME), Best Conference Paper Award of IEEE ROBIO2004 and Best Conference Paper Award of IEEE ICAL 2008, in 1997, in 2004 and in 2008, respectively.
1 Introduction

Stroke can cause people’s neurological impairments. There are approximately 700,000 people suffer a first or recurrent stroke each year according to American Heart Association (2007). Traditional and occupational therapy provides a standard, effective treatment. However, it often needs one or a few therapists to recover each patient. Therefore it is a labour-intensive approach. Meanwhile the increasing in number of stroke patients increases the health care lost. Fortunately, with the development of robotics, some robots using for stroke patient emerged. In particular, robot-mediated neurorehabilitation is developing rapidly as an advancing and nascent field which involves robotics, virtual realities, haptic interfaces, theories in neuroscience and rehabilitation. In 1995, there is a rehabilitation system named MIT-MANUS developed by Massachusetts Institute of Technology, Cambridge (Boian et al., 2004; Hogan et al., 1995; Krebs et al., 2000). 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 was developed (Mahoney et al., 2003; Kahn et al., 2004; Lum et al., 2004). It is a 6-degree-of-freedom, industrial robot manipulator (PUMA 560 that applies forces to the paretic limb through a customised forearm splint. The ARM Guide (Kahn et al., 2006) 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. This research based on the increasing evidence that reorganisation motor cortex in patients with chronic impairments can be altered through the motor experiences (Ward and Cohen, 2004). This field aims to help patients to do some training such as motor control and motor learning so as to recovery internal model (Tee and Guan, 2008) and motor function. Earlier study showed that the highly repetitive training of constraint-induced movement therapy can induce improvement of motor function (Taub et al., 1999). Later research showed the repetitive movement of simple motor training may not be as effective as movement of more complex motor training that involves in-depth cognitive processing (Carey et al., 2005). The training improved patients function to a certain degree, in which visual and haptic feedback are provided to patients to enrich the sensorimotor experience (Lum et al., 2004). A common disability that results from stroke is paralysis on one side of the body, called hemiplegia. Most of current approaches for stroke patients’ upper limb function are focus on unilateral training. Few researchers engaged in bilateral movements and control of impaired and intact limbs. Bilateral symmetrical movements showed a reduction in movement time and increase of upper limb functional ability compared to unilateral training (McCombe Waller and Whitall, 2008). However, some researches on the dynamic theory of coordination patterns have been proposed (Cardoso de Oliveira, 2002). The purpose of this paper is to develop a system to improve motor function of upper extremity of mild stroke patients by coordination training of bilateral upper extremity and develop an assessment system to assess the effect of rehabilitation.

Rehabilitation training approach is mainly designed to track objective which is also involved in some other robot-mediated rehabilitation (Johnson et al., 2007; Baker et al., 2008; Goffredo et al., 2008; Song and Guo, 2006; Song and Guo, 2010). The rehabilitation system provide patients more sensorimotor stimulation and reasonable impedance to improve training effect of impaired upper extremity (Erol and Sarkar, 2007), in which not only the visual feedback is provided, but also the force feedback is involved. The proposed bilateral upper extremity motor function rehabilitation system, in this paper, consists of one haptic device (PHANTOM Omni) and an inertia sensor (MTx) which are accurate, compact and easy to be manipulated. Virtual objects and environment are rendered by using OpenGL. The manipulated object moved along with the end-effector of Phantom Omni and rotated along with inertia sensor (MTx). Patients manipulate two devices synchronously so as to realise bilateral training (Guo and Song, 2009). In addition, it is different from bilateral symmetrical training (Lum et al., 2006) that we put the emphasis on the bilateral coordination and control training. This kind of design can increase attention and motivation compared to bilateral symmetrical training. Proof from a neuroimaging research (Indovina and Sanes, 2001) indicated that attention during movement improves brain activity in some modes which were different from those without attention. Attention is necessary to monitor movements and evaluate errors when learning to perform a novel motor task or in presence of motor deficit (Lang and Bastion, 2002). This proposed rehabilitation system is compact and portable so that it is benefit for home-rehabilitation. In order to assess the effect of rehabilitation training, an assessment system of rehabilitation for upper extremity has been developed. This system consists of an inertia sensor and a 6-axis force sensor installed on a hand of 6-DOF robot. There are also an assessment system for rehabilitation developed (Song and Guo, 2009) based on a
force and moment tracking task. But interface created is 2D plane. The environment of this assessment system is 3D space.

The relative researches and motivation of this research are shown in introduction part. The second part presents rehabilitation training system design. Two kinds of experiments and their results are shown in this part, which are path-unlimited tracking experiment and path-limited tracking experiment. In third part, another experiment is presented to assess the efficiency of rehabilitation. Last part is conclusions and future work.

2 The proposed rehabilitation training system for upper extremity

2.1 The framework of system

Virtual reality (VR) was proved that it is benefit for neurorehabilitation. We used a commercial haptic device (Phantom Omni) to provide force to patients in this proposed rehabilitation system. Figure 1 shows the setup of the system proposed and Figure 2 shows the schematic diagram of the proposed rehabilitation training system. In order to recover the power and dexterity of impaired upper extremity, patients were required to manipulate the haptic device with impaired upper extremity and rotated coordinately with intact upper extremity in glove on which an inertia sensor was fixed.

![Figure 1](image1.png)

**Figure 1** The setup of the proposed rehabilitation training system (see online version for colours)

Notes: Haptic device is manipulated by subject’s left hand and MTx sensor detects the posture of subject’s right hand. Roll of MTx sensor is necessary in tasks and yaw of MTx sensor can assist subjects to finish tasks.

![Figure 2](image2.png)

**Figure 2** Schematic diagram of the proposed rehabilitation training system (see online version for colours)

Notes: With seeing the graphics generated on monitor, patients perform tracking task by manipulating haptic device and MTx sensor with impaired and intact hand respectively. The posture data of intact hand and position and velocity data of impaired hand are sampled at 1 kHz.

The hardware of the system consists of two haptic devices (PHANTOM Omni), an acceleration sensor (MTx) and a computer. The haptic device was connected to a computer through IEEE1394 FireWire port with a 1.2 metre cable. At the same time, an inertia sensor (MTx) was connected to the computer through a USB2.0 port with a 3 metre cable. More information about haptic device was shown in Table 1 and the coordinates of the inertia sensor were shown in Figure 3. In the figure, \((\theta, \phi, \psi)\) is Euler angle, which can be calculated with (1) and (2).

\[
\omega(t) = \int_0^t \alpha(t)dt \\
\theta(t) = \int_0^t \omega(t)dt
\]

where \(\alpha(t)\) is the rotation acceleration at a time \(t\). \(\omega(t)\) is the rotation velocity at time \(t\).

<table>
<thead>
<tr>
<th>Table 1 Parameters of the haptic device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force feedback workspace</td>
</tr>
<tr>
<td>Maximum exertable force</td>
</tr>
<tr>
<td>Stiffness</td>
</tr>
<tr>
<td>x-axis</td>
</tr>
<tr>
<td>y-axis</td>
</tr>
<tr>
<td>z-axis</td>
</tr>
<tr>
<td>Inertia (apparent mass at tip)</td>
</tr>
<tr>
<td>Force feedback</td>
</tr>
<tr>
<td>Position sensing</td>
</tr>
<tr>
<td>x, y, z (digital encoders) pitch, roll yall (±5% linearity potentiometers)</td>
</tr>
<tr>
<td>3D resolution</td>
</tr>
<tr>
<td>Backdrive friction</td>
</tr>
<tr>
<td>Nominal position resolution</td>
</tr>
<tr>
<td>~0.055 mm.</td>
</tr>
</tbody>
</table>
2.2 The design of rehabilitation training system for upper extremity

In our study, a curve path was designed in which a virtual object moved continuously with variable velocity and another virtual object was manipulated to track it by patients. The manipulated object cannot move out of the predefined path. When it penetrated into the boundary, simulating contact was exerted on haptic device stylus. Therefore it is necessary to test the degree of stroke and adapt patients to this system well. Another tracking training experiment has been developed without predefined path.

2.2.1 Path-unlimited training based on the force model of mass-spring-damper

In a two-dimension virtual environment, a lathy rectangle virtual object ($m$) moves along with the stylus of haptic device and rotates along with the roll angle of the inertia sensor. The other virtual object ($m'$) keeps moving randomly on the plane (Figure 4). The shape of $m'$ is the same as $m$, but the colour is different. What should patients do is to manipulate haptic device and inertia sensor to drive the object ($m$) to track the virtual object ($m'$). That is, patients manipulate haptic device with impaired upper extremity and inertia sensor with intact upper extremity. The task is to superpose the object $m$ onto the other object $m'$ including the position and posture as much as possible.

Similar as the research did by Richardson et al (2003) and Krebs et al. (1998), the impedance exits in this system. A mass-spring-damper force model (see Figure 5) is used to simulate impedance in the process of training. Haptic device can output force based on this force model. The midpoint of virtual object $m$ is connected to $A$, $B$, $C$ and $D$ with springs and dampers separately. The elastic coefficients of springs and the damper coefficients can be set easily on the dialog panel. The points $A$, $B$, $C$ and $D$ are positioned on the virtual plane (see Figure 5). We supposed that the force exerted on the stylus of haptic device was set to 0 when the object $m$ is on the initial position as shown in Figure 5. When patients manipulate the stylus of haptic device to move the object, the force generated according to formula (3)–(7) would exert on them.

$$ F = m\ddot{p} + k_1\Delta OA + k_2\Delta OB + k_3\Delta OC + k_4\Delta OD + c_1\dot{p}_{OA} + c_2\dot{p}_{OB} + c_3\dot{p}_{OC} + c_4\dot{p}_{OD} $$  \hspace{1cm} (3)

$$ \dot{p}_{OA} = \ddot{p} \cdot OA \cdot OA $$  \hspace{1cm} (4)

$$ \dot{p}_{OB} = \ddot{p} \cdot OB \cdot OB $$  \hspace{1cm} (5)

$$ \dot{p}_{OC} = \ddot{p} \cdot OC \cdot OC $$  \hspace{1cm} (6)

$$ \dot{p}_{OD} = \ddot{p} \cdot OD \cdot OD $$  \hspace{1cm} (7)

where $F$ is force exerted on the stylus of haptic device; $m$ is the mass of virtual object $m$; $\ddot{p}$ is the acceleration of the midpoint of virtual object $m$; $\dot{p}$ 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. Variations written in bold format stand for vectors. $\Delta OA$ stands for length variation of spring OA with the movement of object $m$.

The purpose of this experiment is to test the degree of stroke and make sure if the rehabilitation system is suitable to
patients. On the other hand, it is also an adaptive training for patients to perform following rehabilitation.

2.2.2 Path-limited training based on compound force model

The patients who have passed the experiment above can participate path-limited training. This experiment also requires patients’ bilateral coordination motion to track the moving object. It not only includes the reasonable impedance or assistance, but also shows patients the interaction with the virtual path. It makes patients to improve motor function of upper extremity under the VR environment. The training interface is made up of two parts of deep blue area in order to impress patients (Figure 6). 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 it knocked on a wall. The virtual object (n) is a lathy rectangle. Its centre position is decided according to the position of stylus of PHANTOM Omni and orientation is decided according to the posture of inertia sensor MTx. Therefore, its position and orientation can be controlled by manipulating the haptic device and inertia sensor. Another object (n’) has been created in black and with the same shape of n (see Figure 6). n’ moves along the predefined path at variable speed which is programmed as a pseudo-random variable.

**Figure 6** The display interface of the system (see online version for colours)

As an active rehabilitation system, programmable force model is involved after analysing the kinematics model of the upper extremity (Song and Guo, 2009). The force exerted on the haptic device mainly impedes movement of upper extremity. Otherwise, patients can be assisted to finish the task which can be implemented through decreasing the impedance by controlling the inertia sensor (MTx). The proposed virtual force model consists of two parts. One part is called λ-model which is created in order to provide impedance to patients and adjust the level of active rehabilitation, and the other part is called γ-model which mainly simulates boundary of curve path. There are some other parameters on the dialog panel (Figure 6) which can be changed such as the width of predefined path and coefficient of dynamics. Considering the movement trajectory of object on plane, the vertical and horizontal force components of impedance are created separately. Meanwhile, assistance can be provided to patients if it is needed through manipulating inertia sensor. A force model is built on the basis of mathematical formulations (8), (9) and (10).

\[ F_y = k \alpha \beta \gamma \left(\frac{b}{(c|\beta| + d)}\right) \]

\[ F_x = -k' \gamma \left| \frac{v_x (P_x - x)}{(c|\beta| + d)} \right| \]

where \( F_y \) is the vertical force component exerted on the stylus of haptic device; \( P_x \) is the position of midpoint of virtual object \( n \) along \( x \)-axis; \( v_x \) is the velocity of midpoint of virtual object \( n \) along \( y \)-axis; \( \alpha \) is the roll angle of MTx sensor, and \( \beta \) is the pitch angle of MTx sensor; \( b \) has the meaning illustrated in Figure 7; \( c \) and \( d \) are used to adjust assistance force, and \( k \) is the coefficient to adjust the stiffness of system.

Horizontal force component is calculated as the follows. When \( P_x < x_1 \),

\[ F_x = -k' \gamma \left| \frac{v_x (P_x - x_1)}{(c|\beta| + d)} \right| \]

when \( P_x < x_1 \),

\[ F_x = -k' \gamma \left| \frac{v_x (x_1 - x)}{(c|\beta| + d)} \right| \]

\( F_x \) is the horizontal force component exerted on the stylus of haptic device; \( P_x \) is the position of midpoint of virtual object \( n \) along \( x \)-axis; \( v_x \) is the velocity of midpoint of virtual object \( n \) along \( x \)-axis. \( \alpha, \beta, c \) and \( b \) are the same as (8); \( x_1, x_2 \) and \( x_3 \) are illustrated in Figure 7, and \( k' \) is the coefficient like \( k \).

**Figure 7** The parameters of scene (see online version for colours)

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 resultant of two force models is exerted in experiment. When the object (n) manipulated contacts with the boundary of path, impact force feedback stimulates patients and reminds them of adjusting performance. The path-limited training applies patients with more sensorimotor stimulation through visual and force feedback.
2.3 The position and posture tracking experiment

The parameters of force model are set as Table 2 after times of trials. We get the position and posture tracking results in MATLAB, and the position tracking result appraises with (11) and (12). With the same principle, the square error of posture tracking experiment can be calculated.

\[
\delta_p = k'\left| \sum_{i=1}^{N} \left( (P_{ix} - P_x) + (P_{iy} - P_y) \right)^2 \right| / N 
\]

\[
\delta_\alpha = k'\left| \sum_{i=1}^{N} (\alpha_i - \alpha) \right|^2 / N 
\]

(11)

(12)

where \(\delta_p\) is the mean square error of the position of tracking; \(k'\) is the parameter in relate to velocity; \(P_{ix}\) is the position component of object \(n'\) along \(x\) axis; \(P_x\) is the position component of object \(n\) along \(x\) axis; \(P_{iy}\) is the position component of object \(n'\) along \(y\) axis; \(P_y\) is the position component of object \(n\) along \(y\) axis; \(\delta_\alpha\) is the square error of the posture of tracking; \(\alpha_i\) is the angle between object \(n'\) and \(x\) axis; \(\alpha\) is the angle between object \(n\) and \(x\) axis and \(N\) stands for the number of sampling data.

Table 2 The parameters of the path-unlimited training

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m)</td>
<td>0.3 kg</td>
</tr>
<tr>
<td>(c_1)</td>
<td>0.5 N/(mm/s)</td>
</tr>
<tr>
<td>(k_1)</td>
<td>10 N/m</td>
</tr>
<tr>
<td>(k_2)</td>
<td>10 N/m</td>
</tr>
<tr>
<td>(k_3)</td>
<td>10 N/m</td>
</tr>
<tr>
<td>(k_4)</td>
<td>10 N/m</td>
</tr>
</tbody>
</table>

In the path-limited training, the parameters of force models are set as following: \(b = 4\) cm, \(c = 3\), \(d = 0\), \(k = 10\) N/m and \(k'_1 = 10\) N/m. The method of evaluation is also calculated by mean square error of position and posture of tracking as the above.

In our study, five elder subjects who have not injured on their arms participated in experiments. In order to simulate patient following stroke, subject manipulated haptic device with non-dominant hand instead of impaired hand and controlled inertial sensor with dominant hand instead of intact hand. The characters of the five subjects are shown in Table 3. Each subject first performs the path-unlimited training, until the mean square errors are up to certain level. The certain level is different from that is tested by patients with stroke. For every subject, the path-limited training was performed for 30 minutes everyday, and the experiment persisted for two months. Figure 8 and Figure 9 show the position and posture tracking result before and after two months’ training. The black curves in four figures below stand for desired position trajectory or posture curve.

Table 3 The characters of the five subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>M</td>
<td>54</td>
</tr>
<tr>
<td>B</td>
<td>F</td>
<td>56</td>
</tr>
<tr>
<td>C</td>
<td>M</td>
<td>61</td>
</tr>
<tr>
<td>D</td>
<td>M</td>
<td>57</td>
</tr>
<tr>
<td>E</td>
<td>M</td>
<td>58</td>
</tr>
</tbody>
</table>

Figure 8 The position tracking result at the start of training for Subject A (\(\delta_p = 7.71\) mm) (see online version for colours)

Figure 9 The position tracking result at the end of training for subject A (\(\delta_p = 5.31\) mm) (see online version for colours)

From Figure 8 and Figure 9 we can see, after two months’ training for Subject A, the typical square error of the position tracking experiment decreased from 7.71 mm to 5.13 mm. Meanwhile, Figure 10 and Figure 11 show the typical square errors of the posture tracking experiment decreased from 17.1° to 11.3°. The position and posture tracking results for all subjects are shown in Table 4. From the table, we can see that they have improved the manipulation dexterity and increased the tracking error in both position and posture tracking task.
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Figure 10  The posture tracking result at the start of training for Subject A (δ₀ = 17.1°) (see online version for colours)

Figure 11  The posture tracking result at the end of training for Subject A (δ₀ = 11.3°) (see online version for colours)

Table 4  The training results for the five subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Position (δ₀)</th>
<th>Posture (δ₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Pre</td>
<td>7.71</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>5.13</td>
</tr>
<tr>
<td>B</td>
<td>Pre</td>
<td>9.20</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>7.01</td>
</tr>
<tr>
<td>C</td>
<td>Pre</td>
<td>8.44</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>5.91</td>
</tr>
<tr>
<td>D</td>
<td>Pre</td>
<td>6.77</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>4.20</td>
</tr>
<tr>
<td>E</td>
<td>Pre</td>
<td>6.99</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>4.21</td>
</tr>
</tbody>
</table>

3  The assessment system for rehabilitation

3.1  The setup of assessment system

Because of the limit of output torque of Phantom Omni, this system cannot evaluate the efficiency of rehabilitation well, so that we developed another system for rehabilitation assessment, which consists of an inertia sensor and 6-axis force sensor installed on the hand of a 6-DOF robot. The force tracking experiment is shown in Figure 12. The signal of the force sensor is sampled by A/D board, and it is displayed on the monitor in real-time.

A 3D virtual room has been developed to augment patients’ sensorimotor gain (Figure 13). Patients manipulate a wood column which is fixed on the robot hand to control a virtual teapot (Q) to reach target teapot (Q') which is shown in a random position and posture in the virtual room. An inertia sensor (MTx) is utilised to control the posture of virtual teapot (Q). After reaching the target teapot and completing the superposition of posture, another target will come out randomly in another position and posture in the 3D virtual room. All training will be over after eight times of reaching.

The profile of the 6-DOF force robot is shown in Figure 14. Additionally, the force components, \( F_x \), \( F_y \), and \( F_z \) can be calculated using \( F = CV \), where \( C \) is the constant matrix of the force. The moment components, \( T_x \), \( T_y \) and \( T_z \) are not used. \( F \) is defined as (13).

\[
F = \begin{bmatrix} F_x & F_y & F_z \end{bmatrix}
\]

\( V = \begin{bmatrix} SG.0 \ SG.1 \ SG.2 \end{bmatrix} \) (14)

where \( V \) is the digital vector sampled with A/D board in the computer every millisecond (14). In this system, three force
components are used to calculate the position of teapot \((Q)\) according to formula (15).

\[
P = kF \cdot R
\]

(15)

where \(P\) is a position vector of teapot \((Q)\), \(R\) is transformation matrix and \(k\) is coefficient.

\[
R = \begin{pmatrix}
\cos \theta & -\sin \theta & 0 & 1 & 0 & 0 \\
\sin \theta & \cos \theta & 0 & 0 & \cos \phi & -\sin \phi \\
0 & 0 & 1 & 0 & \sin \phi & \cos \phi
\end{pmatrix}
\]

(16)

where \(\theta = \pi/2\), \(\phi = \pi/2\).

**Figure 14** Robot hand with the force sensor (see online version for colours)

A force transmission interface and a robot arm (Figure 15) are included in the force tracking experiment system. We designed the force transmission interface with a column wood which is grasped by robot hand during the experiment.

**Figure 15** Setup of the assessment system of rehabilitation (see online version for colours)

3.2 Experimental results

Considering what is needed to be evaluated is patients’ ability of reaching the target, we analysed the variation of force derived from patients’ upper extremities using MATLAB. The data of force variation on \(x, y\) and \(z\) axes are fitted with eight sine waves (formula 17) with 95% confidence bounds. Average sum of absolute value of eight amplitudes (AS) is calculated in formula (18).

\[
f(x) = a_1 \sin (b_1 x + c_1) + a_2 \sin (b_2 x + c_2)
+ a_3 \sin (b_3 x + c_3) + a_4 \sin (b_4 x + c_4)
+ a_5 \sin (b_5 x + c_5) + a_6 \sin (b_6 x + c_6)
+ a_7 \sin (b_7 x + c_7) + a_8 \sin (b_8 x + c_8)
\]

(17)

\[
SA = \frac{1}{N} \sum_{n=1}^{N} |b_n|
\]

(18)

The same five healthy subjects have participated in the experiment before and after two months’ rehabilitation training respectively. Each subject performed the assessment training five times. The SA results of all subjects before and after two month’s training are shown in Table 5, from which we can see SA has decreased through training. Time taken in the assessment is shown in Table 6. Figure 16 shows a typical example in one subject of component force exerted along \(x\)-axis at the start of treatment by means of bilateral upper extremity training system. The purple dots are sampling data of variation of force exerted. The red curve is sine wave fitted using MATLAB. Figure 17 shows a typical example in one subject of component force exerted along \(x\)-axis at the end of treatment by means of bilateral upper extremity training system. The time taken at the start of training is more than that taken at the end of training. Meanwhile, the former sine wave is more visible than later. Therefore, we consider that the subjects have improved control of force exerted on manipulator with upper extremity after two months’ training.

**Table 5** Average sum of absolute value of eight amplitudes

<table>
<thead>
<tr>
<th>Subject</th>
<th>AS Pre-training</th>
<th>Post-training</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23.39</td>
<td>10.13</td>
</tr>
<tr>
<td>B</td>
<td>24.13</td>
<td>12.02</td>
</tr>
<tr>
<td>C</td>
<td>22.42</td>
<td>9.43</td>
</tr>
<tr>
<td>D</td>
<td>23.33</td>
<td>11.21</td>
</tr>
<tr>
<td>E</td>
<td>25.24</td>
<td>13.12</td>
</tr>
</tbody>
</table>

**Table 6** Time taken of completing the task once

<table>
<thead>
<tr>
<th>Subject</th>
<th>Time(s) Pre-training</th>
<th>Post-training</th>
</tr>
</thead>
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4 Conclusions

In this paper, a novel rehabilitation training and assessment system for upper extremity is proposed. VR is applied in the training system which consists of a haptic device and an inertia sensor. Different from conventional rehabilitation system, the emphasis of this system is to augment patients’ sensorimotor gain through coordination training of bilateral upper extremity using VR. Two kinds of training strategies are proposed for different rehabilitation phases. Five old subjects participated in these training. Meanwhile, we have also developed an assessment system for training effect. Experimental results showed the proposed training approach was effective for the rehabilitation training of upper extremity. As hardware used in rehabilitation training is compact and software is programmable, this system is adaptable for home-rehabilitation.

In the future, stroke patients will participate in these experiments and some parameters of system should be adjusted to meet patients. In order to meet more patients, other commercial haptic device which is more functional will be used in experiments. More patients’ information will be obtained and analysed during rehabilitation.

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References


