

Haptic Device System for Upper Limb Motor and Cognitive Function Rehabilitation: Grip Movement Comparison between Normal Subjects and Stroke Patients

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Abstract—We have developed a rehabilitation system utilising a haptic device. This system aims to integrate motion and sensory therapy ensuring that the patient's interest is maintained and to establish a quantitative assessment of the level of disorder. This system consists of a haptic device, a computer and a LCD monitor. The user moves the grip of the haptic device according to the training program, which is displayed on the computer screen. The haptic device provides a virtual force to the grip. Various types of force can be applied, e.g. resistance, assistance, viscosity and friction. The basic and applied training programs are prepared for training and evaluation including training with simple motion and games. Suitable training can be chosen from the different types of training programs according to the patient's disability. An experiment was carried out with normal healthy subjects and patients who have upper limb dysfunction. The results indicated that this system could be used for quantitative assessment and provide tailor-made training programs for individual patients.

I. INTRODUCTION

IN the present aging society, the number of patients with brain and nervous disorders such as stroke, intracerebral hemorrhage (ICH), chronic subdural hematoma (CSH), Parkinsonian syndrome and Guillain-Barre syndrome, is increasing. These diseases exhibit symptoms of motor disability and upper limb disorder. Compensation and rehabilitation of their impairments helps to improve a patient's level of activity of daily living and could develop a patient's quality of life and help them on the road to an independent life. Current relevant research is focused on providing effective rehabilitation using robotics and computer technology. Above all, robotic therapy and the use of virtual reality (VR) are found suitable for solving the problems associated with conventional training. The rehabilitation system using computers can provide a simple and flexible environmental setup, exact recursive training and can gather the training data at the same time. It can also

provide interactive therapy to engage the patient's interest. Various kinds of research have been conducted so far in this field. For example, MIT-MANUS [1], MIME (Mirror Image Movement Enabler) [2], Assisted Rehabilitation and Measurement (ARM) Guide [3] and rehabilitation training system using electrorheological actuator [4], all employ robotic therapy to recover motor function. VR systems using a haptic glove [5], with a web-based Java application for controlling the joystick [6] is used for post-stroke hand rehabilitation.

However, almost all conventional rehabilitation programs are monotonous. Ranges of motion and muscle coordination exercises are carried out with therapists or by the patient her/himself. In self-training, the patient slides her/his hand on the table and picks up a peg and inserts it into target holes repeatedly. This makes it difficult to stay motivated to recover and improve the impaired functions.

On the other hand, there are several methods available to evaluate the level of the motor function, e.g. manual muscle testing, stages by the Brunnstrom method, stroke impairment assessment set. These assessments are largely based on therapist's observations. Sometimes the result depends on the quality of therapy and experience of the therapist. Therefore, it is necessary to measure, analyse and evaluate the patient's performance in objective and quantitative terms.

To solve these problems and meet requirements, we have developed a rehabilitation system using a haptic device integrating both motion and sensory therapy. The new system is designed in such a way that the patient's interest is maintained during the rehabilitation activity [7]. To evaluate the system and gather the basic data for quantitative evaluation of the level of the disorder, we carried out experiments with young and middle-aged subjects, elderly subjects and patients with upper limb impairment afflicted with a brain or neurological disease.

II. SYSTEM DESIGN

The haptic device in the system for upper limb motion function and cognitive function rehabilitation was designed on the assumption that it would mainly be used by a patient under the supervision of a therapist. This system also aims to be used by the patients by themselves. In order to carry out suitable training of every individual patient, this system should be designed so that the therapist can set up individual

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environmental condition data for each training program. The system is needed to make it possible to easily save and load the individual training environments to and from the hard disk. The evaluation of the disorder and the improvement level traditionally depend on a therapist's subjective decisions. Therefore, an objective quantitative analysis is a good and useful supplement. A rehabilitation tool using a computer can record the training data and evaluate the level of recovery and improvement of patients using this analysis. It is based on the recorded training data, which is currently under development. To avoid distracting the patient, everything except the training program is hidden from display including the detail of the system's control menu, during training. We have tried to develop a rehabilitation system for both the motor function and cognitive function disorder rehabilitation. In addition, to realise the therapy without the patients losing interest, we have prepared the therapeutic application with interaction that can be fun. It is similar to a computer game.

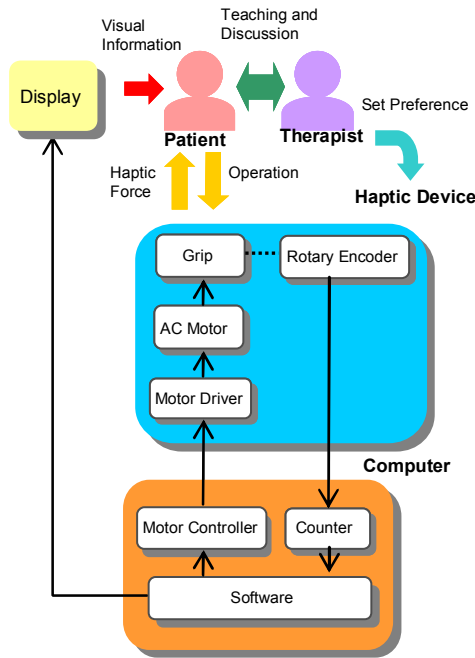


Fig. 1. Schematic of Haptic Rehabilitation System.

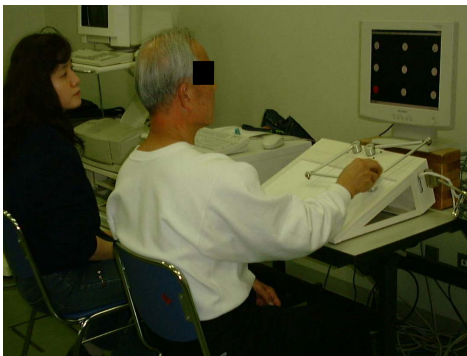


Fig. 2. Using Haptic Rehabilitation System.

III. HAPTIC DEVICE SYSTEM

A. Hardware System

Fig. 1 shows the schematic of the haptic device system for upper limb rehabilitation. This consists of a haptic device, a display and a computer. The haptic device comprises two servomotors with reduction gears, link rods, a grip and a flat panel. The grip and servomotors are connected by the link rods. Patients can move the grip on the surface of the flat panel and train their upper limb movements in two dimensions.

The range of movement is 400 mm in the lateral direction and 250 mm in the longitudinal direction. The servomotors can apply a maximum force of 30 N to the grip. There are optical encoders attached to the servomotors. The position of the grip can be calculated by the encoder pulse count and the lengths of the link rods. The 15-inch LCD is used as a display and it shows visual symbols of the training programs. The aspect ratio of the work field on the display is in proportion to the actual flat panel. The computer is a Windows PC with a Pentium III 700 MHz CPU. An analogue output board for controlling servo amplifiers and a pulse counter board are installed. For ease of handling and portability in a hospital and at home, a haptic device using a USB interface has also been developed. In this model, the user only needs to plug in the USB connector to the PC and run the training program. The computer executes the following functions:

- Controlling the haptic device
- Displaying the training program
- Acquiring the training data
- Evaluating the training result

B. Haptic Forces

Six types of haptic forces can be provided on this rehabilitation system. These are load, assistance, spring, viscosity, friction and special effect force. Therapists can change the type of haptic force and magnitude according to the disorder level of the user. Details of each force are given below.

1) *Load*: The load force is generated in the opposite direction to the grip velocity vector. The magnitude of the force is increased in proportion to the distance between the current grip and target positions. The load force F_l is given as shown in (1), where the grip position is (x, y) , the target position is (x_0, y_0) and the gain is K_l .

$$F_l = \begin{bmatrix} F_{lx} \\ F_{ly} \end{bmatrix} = K_l \left(\begin{bmatrix} x_0 \\ y_0 \end{bmatrix} - \begin{bmatrix} x \\ y \end{bmatrix} \right) \quad (1)$$

2) *Assistance*: The assistance force is generated in the same direction as the grip velocity vector. The magnitude of the force is increased in proportion to the distance between the current grip and target positions. The assistance force F_a is given as in (1), where the gain is replaced by K_a .

3) *Spring*: The spring force is generated in the direction of the initial grip position. The magnitude of the force is increased in proportion to the distance between the current and initial positions of the grip. The spring force F_s is given as in (1), where the gain is replaced by K_s . This force is only applied in the game program.

4) *Viscosity*: The viscosity force is generated in the opposite direction to the grip velocity vector. The magnitude of the force is increased in proportion to the velocity of the grip. The viscosity force F_v is given as shown in (2), where the velocity of the grip is (\dot{x}, \dot{y}) and the gain is K_v .

$$F_v = \begin{bmatrix} F_{vx} \\ F_{vy} \end{bmatrix} = K_v \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} \quad (2)$$

5) *Friction*: The friction force is generated in the opposite direction to the grip velocity vector. The magnitude of the force is constant. The friction force F_f is given as shown in (3), where the gain is K_f .

$$F_f = \begin{bmatrix} F_{fx} \\ F_{fy} \end{bmatrix} = K_f \begin{bmatrix} \frac{\dot{x}}{|\dot{x}|} \\ \frac{\dot{y}}{|\dot{y}|} \end{bmatrix} \quad (3)$$

6) *Special effect*: In order to provide special effects in the game program, e.g. contact force of the wall of the maze, reaction force when hitting some object, the special effect force F_e is generated.

The total haptic force F on the grip is the sum of (1) to (6) as shown in (4).

$$F = F_l + F_a + F_s + F_v + F_f + F_e \quad (4)$$

Modifying a program can easily generate a haptic force different from the above.

IV. SOFTWARE FOR TRAINING AND EVALUATION

The software has three functions: training, data acquisition and evaluation. The training program consists of five different programs for basic training. It also contains two other programs for applied training. When moving the grip, a cursor on the display moves with the grip simultaneously, and the haptic device provides a force that can either assist or resist the movement of the patient's arm. The level and direction of the force are also adjustable. Moreover, the patients can sense haptic perceptions such as contact force, viscosity and surface friction. The data acquisition program stores the training data such as time and grip position. This data can be used in the quantitative analysis for motor control as well as in cognitive function rehabilitation. The evaluation program is currently being developed.

A. Basic Training Programs

In the basic training programs, the patients are urged to move their arms along straight, circular, wave-like and voluntary paths. Screenshots are shown in Fig. 3. Details of the programs are as follows.

1) *POINT*: Nine circles are shown on the display and patients try to move the cursor from circle to circle. The displacement and radius of the circles can be changed.

2) *LINE*: Nine small circles and lines connecting the circles are shown on the display. Patients try to move the cursor from circle to circle while staying on the lines. The displacement and radius of the circles are changeable in the same way as in the POINT program.

3) *CIRCLE*: Four concentric rings are shown on the display. Patients try to move the cursor while staying on the rings. The radius and width of the rings are changeable.

4) *WAVE*: Two small circles and a sine wave shaped line are shown on the display. The circles are connected with the wavy line. Patients try to move the cursor from one circle to the other while staying on the line. The amplitude and cycle of the wave can be changed.

5) *TILE*: Square-shaped coloured tiles are shown on the display. Patients try to move the cursor over all tiles. When the cursor is over a tile, the colour of the tile is cleared and a hidden picture appears. Pictures of interest to the patient can be displayed to maintain their concentration during training. Prepared arbitrary picture files can also be used for the hidden pictures.

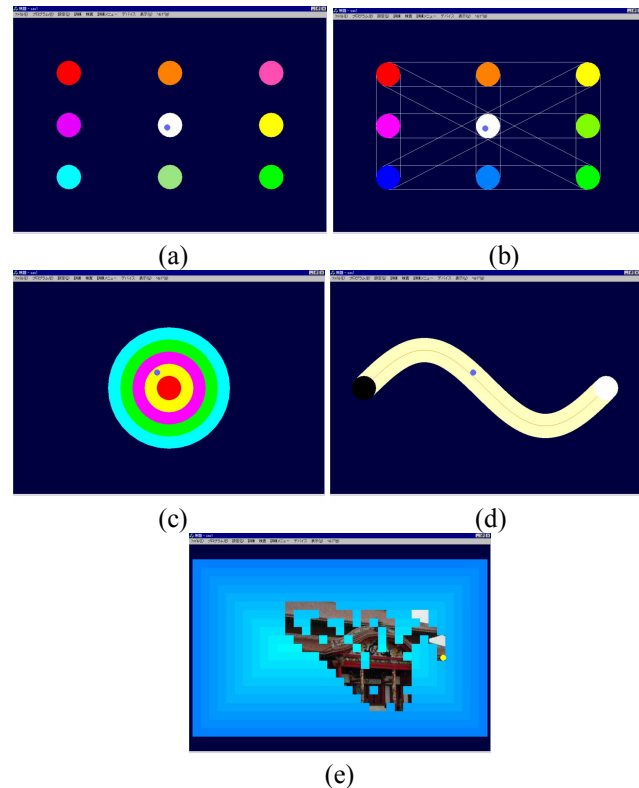


Fig. 3. Basic Training Programs: (a) POINT, (b) LINE, (c) CIRCLE, (d) WAVE, (e) TILE.

The number of tiles is changeable. The magnitude and direction of the virtual force in the training is also adjustable.

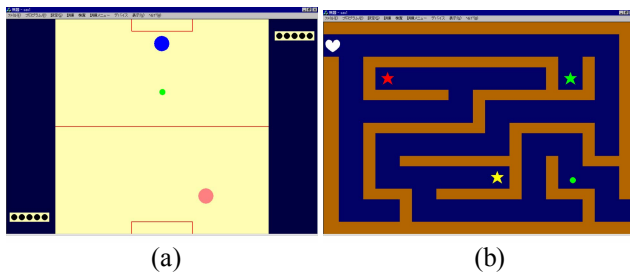


Fig. 4. Applied Training Programs: (a) HOCKEY, (b) MAZE.

B. Applied Training Programs

In the applied training programs, the patients can play hockey and maze games. This helps them to train without losing motivation. It also helps them to maintain their concentration during training. Screenshots are shown in Fig. 4. Details of these programs follow.

1) *HOCKEY*: Patients try to hit a puck and score against the computer program. It is similar to table hockey. Various haptic forces can be felt when moving the grip such as impact force, viscous force and spring force. The velocity of the puck and the virtual force are adjustable.

2) *MAZE*: Patients try to move the cursor from the start to the goal through an intricate network of passages. Somewhere in the maze, the therapist can deploy symbols, which the patient can try to pick up. Various haptic forces can be felt when hitting the walls on different special parts in the maze. The magnitude and direction of the virtual force in the training programs are adjustable. This program could be used for cognitive function rehabilitation.

C. Data Acquisition and Evaluation Programs

The time series training data such as a grip position, a grip velocity, can be stored related to individual patients every 100 ms. The data can be loaded for evaluation at any time the therapist wishes. The evaluation program could be used to analyse and evaluate the relearning degree using the quantitative analysis software programs for motion and cognitive function rehabilitation.

V. MATERIALS AND METHODS

The aim of the experiment was to confirm the difference in the upper limb motor function ability between normal subjects and patients. In total, 133 subjects were enrolled in this experiment and they were categorised into three groups: a young and middle-aged group, an elderly group and a patient group. The young and middle-aged group consisted of 40 females and 40 males, with ages ranging from the 20s to 50s. They were normal healthy volunteer subjects without any neurological or muscle disorders. The elderly group consisted of 46 elderly subjects, 24 females and 22 males, with ages ranging from the 60s to 80s. Five subjects had a previous history of diseases associated with paralysis or controlling motor behaviour of upper limb, stroke and CSH. The patient

group consisted of seven subjects; four with stroke, one with ICH and two with Guillain-Barre syndrome. The informed consent for this experiment was obtained from all subjects.

For young, middle-aged subjects and elderly subjects, the experiment included 30 tasks. Six were trial tasks and 24 were experimental. These tasks are variations of three basic and one applied training program. For the patients group, the experiment was carried out with a therapist. They tried as many of the same tasks as the other groups as they could. Before the experiment, a supervisor explained how to move the grip, moving fast and accurate as possible as they can. The supervisor guided the operation of the tasks and gave a cue when starting the tasks. In this study, we focused on the WAVE program. The WAVE program is one of the basic training programs. Patients try to move the cursor from one circle to another while keeping on the line. The height and cycle of the wave are changeable. We measured the position and velocity of the grip when different types of force were applied. The cycle of the wave was set to two and load, assistance, viscosity and friction forces were applied. The origin of the X-Y coordinate system was set in the centre of the display image, with the lateral axis being X and the longitudinal axis being Y.

VI. RESULTS

Typical results of each subject group are shown in Figs. 5 to 10. The example from the young and middle-aged group is a 42-year-old male, the elderly subject is a 77-year-old female and the patient is a 59-year-old male. The patient had suffered a stroke and his left side is paralysed. He does not have a higher brain function disorder.

Fig.5 shows the trajectory of the grip movement as a top view of the flat panel. The figure confirms that the middle-aged subject could move the grip along the sine wave line. In the case of the elderly subject, the trajectory is not so stable as with the middle-aged subject. The stroke patient could not move the grip along the sine wave line and the trajectory is unstable.

Figs. 6 to 8 show the grip position and velocities of each subject with no force applied. In these figures, all lateral axes show time. They are normalised with respect to the greatest obtained value. The longitudinal axis of the upper graph shows the position of the grip in the Y-axis, the middle graph shows the velocity of the grip in the X-axis and the bottom graph shows the velocity of the grip in the Y-axis. The position and velocities are rectified and normalised.

The top graph of Fig. 6 shows a repetition of similarly shaped convex curves, which means that the grip was moved with an equal time frame and magnitude periodically. The middle and bottom graphs show the velocities of the grip motion; the velocities of the grip were very uneven. However, the velocity on the Y-axis did not drop down to zero during the grip movement.

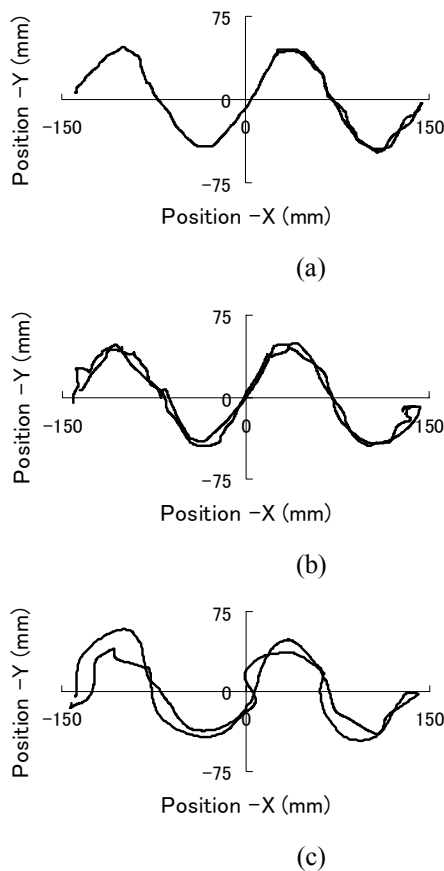


Fig. 5. Trajectory of the Grip Movement: (a) Middle-Aged Subject, (b) Elderly Subject, (c) Stroke Patient.

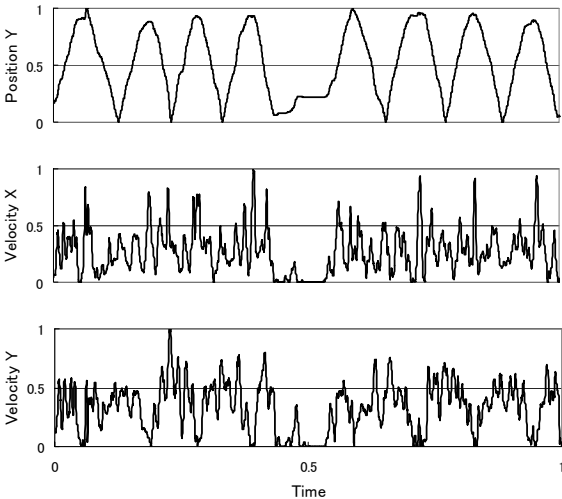


Fig. 6. Position and Velocities of the Grip: Middle-Aged Subject.

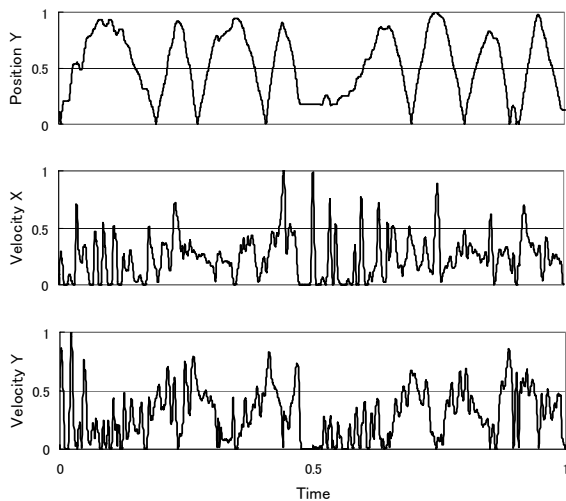


Fig. 7. Position and Velocities of the Grip: Elderly Subject.

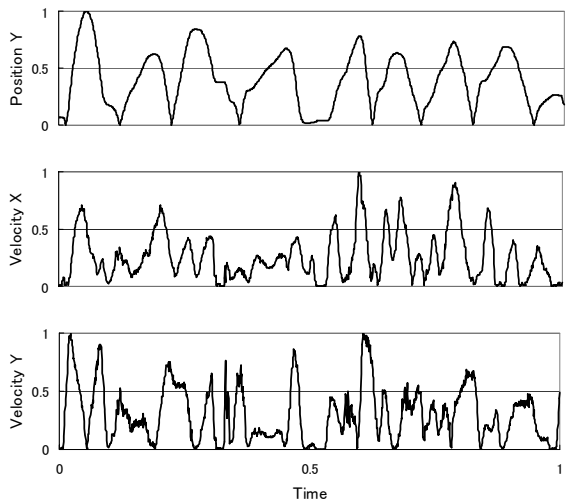


Fig. 8. Position and Velocities of the Grip: Stroke Patient.

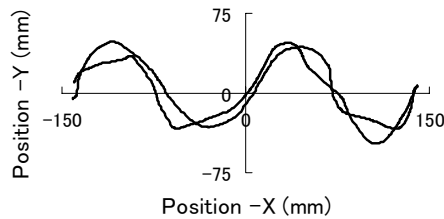


Fig. 9. Trajectory of the Grip Movement: Stroke Patient with Viscosity Force Applied to the Grip.

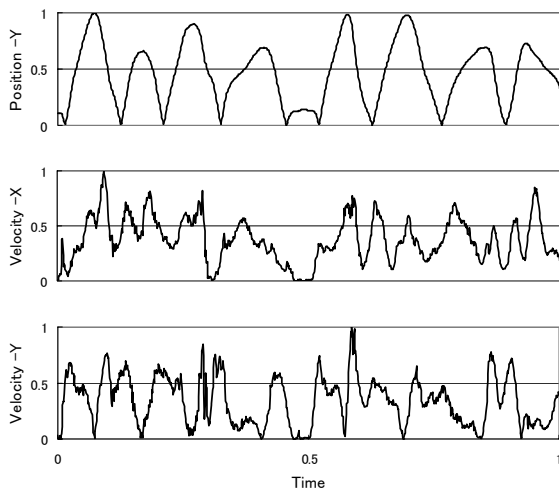


Fig. 10. Position and Velocities of the Grip: Stroke Patient with Viscosity Force Applied to the Grip.

This suggests that the grip moved with an approximately constant velocity between the peaks of the sine wave. In the case of the elderly subject and stroke patient (Fig. 7 and Fig. 8), the shapes of the curve in the top graph are different. The time frame of each convex curve and magnitude is also different. Moreover, they could not move the grip with a constant velocity. The grip velocities were uneven and came down to zero several times, indicating that the grip was moved intermittently. This confirms that the grip velocities of the stroke patient changed more smoothly compared with other subjects. This may be caused by his motor function disability; he could not move the grip and correct the motion quickly.

Fig. 9 and Fig. 10 show the results for the stroke patient when viscosity force was applied. The trajectory seems to be closer to the sine wave than when no force was applied (Fig. 5 (c)). In addition, in the graph of the Y-axis position, the magnitude and shapes of the convex curves become more similar to each other. The velocities did not come to zero when no force was applied and the intermittent action was improved. This confirms that applying the haptic force affects the upper limb movement.

VII. DISCUSSIONS

The periodical pattern of the grip movement and continuity of velocity could be used to evaluate the level of disorder and the effect of rehabilitation training. It could establish new indices of user performance, based on the above-mentioned results.

Applying viscosity force to the grip could improve the stabilisation of the grip movement, meaning that the apparent motion ability level can be improved. This exercise could then be used for upper limb dysfunction patients to keep up their motivation for training.

VIII. CONCLUSIONS

We have developed a haptic device system for upper limb motor and cognitive rehabilitation, which is capable of keeping up the interest of patients during rehabilitation. The experiments were carried out with a young and middle-aged group, an elderly group and a patient group with upper limb dysfunction. The experimental results show that this system could be used for effective training of patients and the data could be used to evaluate the effectiveness of the training program and the level of disorder.

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