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Quasi-3 DOF Rehabilitation System for Upper Limbs, “PLEMO”

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1. Introduction

The increasing numbers of the aged people and their physical deteriorations have become one of the most serious problems in many countries. Many stroke patients suffer from disabilities which restrict normal motions, e.g., locomotion, reaching, pointing and so on. Therefore, sufficient rehabilitative training is necessary for such patients. In general, therapists make rehabilitation programs based on their inspections and measurements of each patient. However, it is difficult to adopt appropriate rehabilitative programs for all patients, because the evaluation method is based on experiences of each therapist.

Nowadays, Evidence Based Medicine (EBM) is strongly required in the field of rehabilitation (Miyai et al, 2002). Therefore, rehabilitation systems using robotics technologies are expected for; 1) quantification of the effect of the rehabilitative training; 2) enhancement of the motivation for patients with creating new training methods (many patients are giving up rehabilitative training because of its boredom); 3) improvement of the efficiency of physical therapist's works.

Many robot systems for upper limbs rehabilitation have been suggested by researchers all over the world (Krebs et al., 2000; Loureiro & Harwin, 2007; Lum et al., 2004; Zhang et al., 2007; Perry et al., 2007; Wolbracht et al., 2006; Nef et al., 2007), and clinical tests have been conducted. Krebs et al. (Krebs et al., 2000) developed MANUS system, which has two degrees of freedom (DOF) for active control of force-feedback, and conducted clinical tests of exercises for shoulders and elbows. Many movements in daily activities, however, need to move arms in a vertical direction. Therefore, a system which enables exercise in three dimensions is effective for upper limbs training. Actually, in a sanding-training (woodworking as sanding long boards shown in Fig.1) (Trombly, 1982), which is one of the clinical training in the occupational therapy, the inclination of the sanding board can be adjusted. Patients tries to push up the sander higher and higher which provide some stretch to extensor muscles of the arm. Because the range of motion or muscles used in the training are different depending on the inclination, the therapists can gradually change the inclination as the patient improves.

Fig. 1. Sanding on an inclined plane (Trombly, 1982)

Although the MIME system (Lum et al., 2004) using PUMA-560 by VA and Stanford Univ. can perform three-dimensional training, the PUMA-560 is the robot originally developed for industrial use and not safe for human-interactive use.

In a current research, we developed 3-DOF rehabilitation system for upper limb "EMUL" (Furusho et al., 2005) and conducted clinical tests with several kinds of video game (Furusho & Kikuchi, 2007). "EMUL" adopted to use ER actuators (Furusho & Sakaguchi, 1999) and clutch mechanism as its actuation part. This mechanism makes EMUL so safe and back-drivable. However, EMUL has disadvantages in cost or ease of maintenance, because this system was enlarged to realize force-feedback in large 3-D space. Practical systems should be required to be more compact and better for maintenance.

To meet these demands above, we developed a new haptic device which has 2-DOF force-feedback function in working plane but its inclined angle of the working plane can be adjusted. We named this system "Quasi-3-DOF Rehabilitation System for Upper Limbs" or "PLEMO". PLEMO was developed to realize quantitative evaluation of rehabilitation training for hemiplegic patients or elderly persons. In this chapter, history, basic structure, properties, experimental results of clinical test and future works on PLEMO are presented.

2. History

In the Virtual Reality 2001 Conference, Sakaguchi et al. (Sakaguchi et al., 2001) presented a passive force display using ER brakes. By using ER brakes, which have quick response, low moment of inertia and good controllability of brake torque, the developed 2 DOF haptic device (Fig.2) has good properties as haptic devices. Passive force displays is inherently safe because it doesn't move actively.

By utilizing these good properties, i.e. safety and good controllability, we designed first prototype of passive force display for upper limbs rehabilitation with the quasi-3DOF configuration (Fig.3). This machine has two controllable DOFs in a working plane (working table) and one adjustable DOF for the inclined angle of the working plane. Haptic control is based on the passive haptic control with ER brakes. We can adjust the angle of the table depending on the training direction for patients. This configuration becomes a basic of the PLEMO mentioned following section.

Fig. 2. Passive force display using ER brakes [14]

Fig. 3. Quasi-3-DOF configuration: Horizontal state (left) and inclined state (right)

3. Core technology

3.1 ER Fluid

ER fluid is a fluid whose rheological properties can be changed by applying an electrical field (Winslow, 1949). By using the ER fluid as a working fluid, we can construct electrically controllable brake (ER brake) with high-performance (quick response and good repeatability of brake torque) (Kikuchi et al., 2003). We used this brake for force generators of a new rehabilitation system (force-feedback system).

3.2 ER Brake

Figure 4 shows a basic structure of a cylindrical-type ER brake. It consists of fixed cylinders and rotating cylinders with the ER fluid between them. These two cylinders also play the role of a pair of electrodes. The rotating cylinder is fixed to the output shaft and driven by external forces through this shaft. When a voltage is applied between the pair of cylinders, the electric field is generated within the ER fluid, and then the viscosity of the fluid increases. This increase of viscosity generates the braking torque and reduces the rotational speed.

Fig. 4. Basic structure of ER Brake

Figure 5 shows a sectional view and an appearance of the ER brake used in this chapter. As shown in the left hand of Fig.5, this brake consists of multi-layered disks. ER fluid is filled between these rotor-disks and stator-disks. As a result, six layers of ER fluid generate the brake torque with change of the fluid. Piston mechanism in this structure works for the prevention of liquid leakage depending on expansion of the fluid.

Fig. 5. ER Brake: Sectional view (left) and picture (right)

Table 1 shows basic characteristics of the ER brake. We can control the brake torque from 0.1 Nm to 4.0 Nm with the electric field from 0.0 kV/mm to 3.0 kV/mm, respectively.

Total weight	2.3 kg
Diameter	15cm
Height	4cm
Maximum brake torque	4.0Nm (at 3.0kV/mm applied)
Idling torque	0.1Nm (at 0.0kV/mm applied)
Num. of rotor disks	3
Disk gap	1mm
Time constant of response	2~3 msec

Table 1. Basic characteristics of ER brake

Left hand of the Fig.6 shows a step response of the ER brake. In this figure, a solid line is the torque response of the ER brake, and a dashed line is input signal of electric fields. As shown in this figure, time constant of the response is 2~3 ms (Kikuchi et al., 2003). Thanks to this rapidity, a haptic device using this ER brakes can realize a high frequency response (e.g. it can generate an impact force of virtual hockey clearly. Refer to Fig. 12.)

Right figure of Fig.6 shows static brake torques vs. the electric field applied to it. The static torque has good repeatability and we can formulate this relation as follows in this case;

$$T = 0.39 E^2 + 0.12 E + 0.10 \quad (1)$$

where, "T" represents the brake torque [Nm] and "E" represents the electric field [kV/mm].

Fig. 6. Basic characteristics of the ER brake: Step response (left) (Kikuchi et al., 2003) and braking torque vs. electric field (right)

4. Basic structure and property of PLEMO-P1

We developed a new haptic device with two ER brakes shown in Fig. 7. This is a passive-type force display which can perform several kinds of virtual force, for example resistance, viscosity, vibration etc.

This machine has two controllable DOF in a working plane (working table) and one adjustable DOF for the inclined angle of the working plane. We named this system "Quasi-3-DOF Rehabilitation System," or "PLEMO-P1". "PLEMO" is a combination of "PLEasant" and "MOtivation". This name came from our hope that this system gives patients a pleasant experience of recovery and motivation for rehabilitation trainings. "P1" means first prototype with passive force feedback mechanism. This system is safe for human because it does not use any actuator.

Fig. 7. PLEMO-P1

Two ER brakes are included in a force control unit and the brake torque generates output-force on a handle through a parallel linkage. Figure 8 shows parallel linkage of this system. In this figure, T_1 or brake torque of brake1 generates force F_1 and similarly torque T_2 generates force F_2 . If the movement of the handle is vertical direction like this figure and then this system generates force F_1 and F_2 , the user feel resistance against his movement direction. If these forces are constant, users feel constant resistance. In other case, if these forces are proportional to velocity of the movement, the users feel viscous force. Necessary torques T_1 and T_2 are calculated from required forces F_1 and F_2 based on the inverse kinematics. Lengths of the link 1 and the link 2 are 450mm. This value is designed on the basis of the manipulability-analysis.

Fig. 8. Parallel linkage of PLEMO-P1

Figure 9 is a structure and a signal flow of this system. Absolute encoders (FA Coder, TS566N320, Tamagawa Seiki Inc., Japan, resolution: 17bits) measure the rotational angle of brakes. We can calculate the position and the velocity of the handle depending on each angle of brakes. Digital Input/ Output (DIO) board (PCI-2154C, Interface Inc., Japan) loads this information to a controller (personal computer). Operating handle includes a force sensor (IFS-70M35A, Nitta Inc., Japan), and operating force is measured by this sensor. A potentiometer (CP-2F, Midori Precision Inc., Japan) measures the inclination of the worktable and the angle is loaded by Analog/Digital converter (A/D) board (PCI-3165, Interface Inc., Japan, resolution: 16bits). The brake torque of the ER brake is controlled by applied voltage from high voltage amplifiers (HEOP-3P10-LS, Matsusada Precision Inc., Japan). Digital/Analog converter (D/A) board (PCI-3338, Interface Inc., Japan, resolution: 12bits) outputs the reference signal to the amplifiers.

A controller of PLEMO-P1 is a personal computer (DOS/V), and an operating system (OS) is Vine Linux 2.6 and ART-Linux (kernel 2.4.20), that is real-time OS made in Japan. Open-GL and Glut3.7 are used for the graphic library. Graphic process and control process are executed by one PC. Multi-process programming is used to realize it. The control process is repeated every 3 ms exactly.

Depending on the above specifications of the components, specifications of the PLEMO system are as follows;

1. Resolution of the angle is 4.8×10^{-5} rad and resolution of the displacement is 0.02 mm for each DOF.
2. Resolution of the braking torque is 6.5×10^{-3} Nm and resolution of the force at the end-effector is 1.4×10^{-2} N for each DOF.
3. Working area is 600 mm (W) $\times$ 500 mm (D).
4. Adjustable angle of the inclination is from -30 to 90 degree.

PLEMO-P1 realizes from vertical training to horizontal training by only one system. Total size of the system is 1000 mm (W) $\times$ 600 mm (D) $\times$ 700 mm (H), except for the display. This is similar to the size of an office desk. This passive system is more compact, simple, and reasonable for the cost than conventional actuator-type systems.

Fig. 9. Structure and signal flow of PLEMO-P1

5. SOFTWARE OF PLEMO-P1

We developed several kinds of rehabilitation and virtual haptic software as shown in figure 10, 12~14. Figure 10 shows a view of tracking test program. An operator grips the handle and moves it with tracking a target trajectory and a target ball. A position of the operating handle is displayed as a red sphere. The target ball is moving along the target trajectory. White zones in this figure mean smooth area without any force-feedback. Blue zones mean sticky area; operator feels virtual force like moving his hand in a viscous fluid. It is easy to change kinds of the virtual forces and its location.

Fig. 10. Tracking test of PLEMO-P1

We also developed evaluation tools as shown in Fig. 11. Data of position, velocity and operating force are saved in a host computer, and test results can be shown graphically and automatically whenever you want to see. We can assess the motion abilities of the patients with accuracy of position and velocity, range of motion, cognitive faculty and so on. In the Fig.11, position data of tracking test (circular trajectory) is shown as an example.

Fig. 11. Evaluation tools of PLEMO-P1

Figure 12 shows a view of virtual hockey game. We develop this software as an amusement use. Users operate the handle and manipulate the racket. When the racket hits the puck, impulse force is generated on the handle and the users feel like impact from a real puck thanks to the quick response of the ER brake.

Fig. 12. Virtual hockey of PLEMO-P1

Figure 13 shows a view of window cleaning. At first, a semitransparent mask covers the all area of a picture. The goal is to erase this mask with an eraser that can be manipulated with the handle of PLEMO. When the eraser erases the mask, ER brakes generates preset resistance. For example, when 80 percent of the mask is erased, this picture vanishes and then the next new picture appears. The pictures are changed one after another. This software is effective to improve dexterity of reaching and movable range of motion.

Fig. 13. Window cleaning of PLEMO-P1

We suggested application software “Virtual Sanding” for reaching trainings shown in Fig.14. This software was developed on the basis of conventional sanding training in the occupational therapy. In “real sanding”, the patient is instructed to actively push up the sander higher and higher which provide resistance against the extensors. This resistance activates patient’s intention to move their own arm. Actually, in physical therapy and occupational therapy, reaching training is done without pulling patient’s hand in the correct direction, but with giving resistance against correct direction. The inclination of the sanding board is adjusted depending on the recovery level of the patients. So therapists gradually change the inclination depending on recovery level of their motor functions.

On the other hand, in the “Virtual Sanding”, patients are instructed to actively push the rectangle with extending their arm toward front direction like a real sanding. The position of the hand is feed backed visually, so patients can check physical relationship between the object (a rectangle box) and their own hand (a sphere). In the only case that the patients push the box to the proper direction (straight front), the box move to the front and resistive force was generated on the end-effector. Moreover, if the system detects their abnormal movements, the system stops presenting the force. Following the hand position, velocity and operating force, this system can judge the patient’s movements. Objective of this training is to help the patients recognize a correct movement and to restructure their motion control function which they lost following stroke (Post stroke patients basically lose independent control of individual joints and coordination among the joints. Especially, it is difficult for them to control movements toward extension). The width of the box can be adjusted depending on the recovery level of the patients.

Fig. 14. Virtual Sanding of PLEMO-P1

Figure 15 shows an experimental result of the Virtual Sanding. An “Allowable area” means the width of the box. The solid line is a trajectory of the hand and white circles represent hand’s position under the proper training. As shown in this figure, the hand departed from the allowable area at the point A. Once the operator departed from this area, he recognized disappearance of the resistive force (point B), modified his trajectory to the allowable area and restarted the proper reaching (point C).

Fig. 15. Experimental result of virtual sanding

6. PLEMO-P2 & its clinical tests

6.1 PLEMO-P2

In order to conduct clinical tests in a hospital, we improved the torque generation unit and appearance of the PLEMO-P1. By utilizing a double-output ER brake (Kikuchi et al., 2008)[18], basic structure of the brake unit was simplified. We named the newly developed machine PLEMO-P2. Figure 16 shows appearance of the PLEMO-P2. Quasi-3DOF structure mentioned above was also utilized to the PLEMO-P2. Table angle can be adjusted by linear actuators with Up-Down switches in front of users.

Fig. 16. PLEMO-P2 and post-stroke patient

6.2 Clinical tests

PLEMO-P2 is now under clinical tests in Hyogo College of Medicine. Until now, 8 chronic stroke patients with Brunnstrom stage 4~5 have examined clinical tests. All tests were safely executed. Experimental results will be reported from research team of the Hyogo College of Medicine soon.

Figure 17~19 show views of training software used in the clinical tests with PLEMO-P2. Figure 17 shows a view of wall pushing. 7 target walls are located in specific position on the plane, and operator is required to push each wall toward proper direction. If the operator pushes a wall with proper direction, proper force and proper time, the wall disappears. The operator can learn proper reaching motion with this training.

Fig. 17. Wall pushing of PLEMO-P2

Figure 18 shows a view of tracking test of PLEMO-P2. Basic function of this program is same as the tracking test of the PLEMO-P1. In the clinical tests, PLEMO-P2 did not perform resistance force; all of area was under free force.

Figure 19 shows a view of Whack-a-mole game of PLEMO-P2. This game was utilized to get patients relaxed between formal tests.

Fig. 18. Tracking test of PLEMO-P2

Fig. 19. Whack-a-mole of PLEMO-P2

6.3 Problems

In the clinical tests conducted in the hospital, we realized several problems. In the previous PLEMO system, we could not detect symptoms of abnormal movement of patients, for example synergy patterns of hemiplegic patients, because of a lack of sensors.

Fig. 20. Abnormal palmar flexion of wrist

Furthermore, in reaching tests with the previous system, we realized unfavorable movements of stroke patients as follows;

1. Excessive reaction force against the table,
2. Excessive gripping force,
3. Abnormal flexion of the wrist (Fig.20).

The synergy movements of hemiplegic patients must have caused such symptoms. In other words, if we can measure such information, we have a chance to detect their synergy movements and give patients a warning for their abnormality. It becomes great help for their effective recovery.

7. Future works

Figure 21 shows mechanisms of our former and current handle. The former handle mechanism is shown in Fig. 21(A): it is gimbal mechanism with no sensors. On the other hand, the current handle (Sensor grip device) consists of three kinds of sensors (shown in Fig. 21(B), (D)): four grip force sensors for grasping; a potentiometer for yaw rotation of patient's wrist; one axis force sensor for detecting the reaction force against the table.

We are now trying to detect abnormal movements or forces during patients' reaching with the sensor grip devices (Fig.22). In the future, the results will be reported.

Fig. 21. Sensor grip device to detect abnormal movement

Fig. 22. PLEMO with sensor grip device

8. Conclusion

In this chapter, we presented the development of "Quasi-3DOF Rehabilitation System for Upper Limb"; PLEMO-P1 & PLEMO-P2 and its software. PLEMO-P1 has two controllable DOF on a working plane and one adjustable DOF for the inclination of the working plane. Using the ER brake, PLEMO-P1 has a good performance for its force feedback and guarantees the safety for humane by prevention of the attack from external force because PLEMO-P1 is passive haptic device; it does not have any actuators and it cannot move automatically. PLEMO-P2 was developed based on the PLEMO-P1 for clinical tests. PLEMO-P2 and PLEMO-P1 with sensor grip device were now under clinical tests. The results will be reported soon.

9. Acknowledgments

This work was financially supported by a JAPAN Grant-in-Aid for Scientific Research. We thank Dr. Akio Inoue, who is the president of ER tec Co. Ltd. and contributed to the developments of all ER fluid devices.

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Rehabilitation Engineering

Edited by Tan Yen Kheng

ISBN 978-953-307-023-0

Hard cover, 288 pages

Publisher InTech

Published online 01, December, 2009

Published in print edition December, 2009

Population ageing has major consequences and implications in all areas of our daily life as well as other important aspects, such as economic growth, savings, investment and consumption, labour markets, pensions, property and care from one generation to another. Additionally, health and related care, family composition and life-style, housing and migration are also affected. Given the rapid increase in the aging of the population and the further increase that is expected in the coming years, an important problem that has to be faced is the corresponding increase in chronic illness, disabilities, and loss of functional independence endemic to the elderly (WHO 2008). For this reason, novel methods of rehabilitation and care management are urgently needed. This book covers many rehabilitation support systems and robots developed for upper limbs, lower limbs as well as visually impaired condition. Other than upper limbs, the lower limb research works are also discussed like motorized foot rest for electric powered wheelchair and standing assistance device.

How to reference

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Takehito Kikuchi and Junji Furusho (2009). Quasi-3 DOF Rehabilitation System for Upper Limbs, *Rehabilitation Engineering*, Tan Yen Kheng (Ed.), ISBN: 978-953-307-023-0, InTech, Available from: <http://www.intechopen.com/books/rehabilitation-engineering/quasi-3-dof-rehabilitation-system-for-upper-limbs-plemo->

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