Quasi-3-DOF Rehabilitation System for Upper Limbs: Its Force-Feedback Mechanism and Software for Rehabilitation

Takehito Kikuchi, Hu Xinghao, Kazuki Fukushima, Kunihiko Oda, Junji Furusho and Akio Inoue

Abstract— Rehabilitation robots are effective to evaluate quantitatively rehabilitative therapies. Some kinds of haptic devices have been developed by many researchers and evaluated its efficiency with clinical tests for example upper limb training for patients with spasticity after stroke. Almost all the devices for upper limb rehabilitation have only 2-DOF for its active motion (except for wrists). But the upper limb of human works in 3-D space even except for the wrist; therefore designing a rehabilitation system for 3-D training is important. We developed new haptic devices which have 2-DOF force-feedback function on a worktable but the inclination of the worktable can be adjusted. We named this system "Quasi-3-DOF Rehabilitation System for Upper Limbs" or "PLEMO". In this paper, we describe the mechanism of PLEMO and its software for the upper limb rehabilitation.

I. Introduction

In general, therapists make rehabilitation programs based on an inspection and a measurement of each patient. However, it is difficult to adopt the appropriate rehabilitation programs for all patients, because the evaluation method is based on experiences of each therapist. Nowadays, Evidence Based Medicine (EBM) is required strongly in the field of rehabilitation [1]. Therefore robot-aided rehabilitation is expected to quantify the effect of rehabilitative activities.

Many reports said that rehabilitation robots are effective to evaluate quantitatively rehabilitative therapies (e.g. physical therapy, PNF, etc). Krebs et al. [2] developed MIT-MANUS, which has two degree 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 such training. Actually, in the sanding-training (woodworking as sanding long boards shown in Fig.1) [3], which is one of the clinical training in the occupational therapy, the inclination of the sanding board can be adjusted. The patient tries to push the sander higher and higher which provide some stretch to the extensors. Because the range of motion or muscles used in the training are different depending on the inclination, the therapist can gradually change the inclination as the patient improves.

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Fig. 1. Sanding on a inclined plane [3]

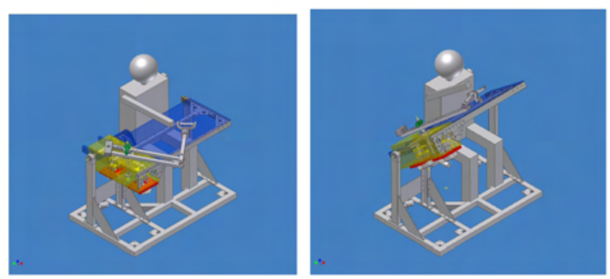


Fig. 2. Quasi-3-DOF rehabilitation system "PLEMO": Horizontal state (left) and inclined state (right)

Although the MIME system [4] using PUMA-560 by VA and Stanford Univ. can execute 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" [5] and conducted clinical test with several kinds of video game [6], [7]. "EMUL" adopted to use ER actuators [8] and clutch mechanism for 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 the 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 working plane can be adjusted the inclination. We named this system "Quasi-3-DOF Rehabilitation System for Upper Limbs" or "PLEMO" (shown in Fig.2). PLEMO was developed to realize quantitative evaluation of the rehabilitation training for patients with spasticity after stroke or elderly persons. In this paper, we describe the mechanism of PLEMO and its software for upper limb rehabilitation.

II. ER BRAKE

ER fluid is a fluid whose rheological properties can be changed by applying an electrical field [9]. To use this fluid as working fluid, we can construct electrically controllable brake (ER brake) with high-performance (good rapidity and repeatability of brake torque) [10], [11]. We use this brake for the force generators of a new rehabilitation system (force-feedback system) in this paper.

Figure 3 shows a basic structure of the cylindrical-type ER brake. It consists of fixed cylinders and rotating cylinders with the ER fluid between them. The 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 in the ER fluid between them, and then the viscosity of the fluid increases. This increase of viscosity generates the braking torque and reduces the rotational speed.

Figures 4 show the sectional view and appearance of the brake. As shown in the left drawing of Figs.4, this brake consists of multi-layered disks. ER fluid is filled between the rotor-disks and stator-disks. As a result, six layers of ER fluid generate the brake torque with change of the fluid. Piston mechanism works for the prevention of liquid spill with the expansion of the fluid.

Table 1 shows specifications of the 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. As shown in left figure in Figs.5, the time constant of response is 2~3 [ms], [11]. In this figure, a solid line is the torque response of the ER brake, and a dashed line is inputs of electric fields to the brake. Due to this rapidity, a haptic device using this ER brakes can realize a high frequency response (e.g. an impact force of virtual hockey).

Right figure in Figs.5 shows the brake torque of the ER brake depending on the electric field applied to it. This characteristic has good repeatability and we can formulate this relation as follows;

$$T = 0.39E^{2} + 0.12E + 0.10 . \qquad (1)$$

'T' represents the brake torque [Nm] and 'E' represents the electric field [kV/mm]. The resolution of force depends on other components described as the next section.

III. QUASI-3-DOF REHABILITATION SYSTEM FOR UPPER LIMBS, "PLEMO-P1"

We developed a new haptic device with two ER brakes shown in Fig. 6. This is a passive-type force display which can output several kinds of virtual force, for example resistance, viscosity, vibration etc.

This machine has two active degrees of freedom (DOF) in a working plane and one passive DOF of the inclination of the working plane. We named this system "Quasi-3-DOF Rehabilitation System for Upper Limb" or "PLEMO-P1". "PLEMO" is a combination of "pleasant" and "motivation". This word includes our hope that this system gives patents a pleasant experience of recovery and motivation for

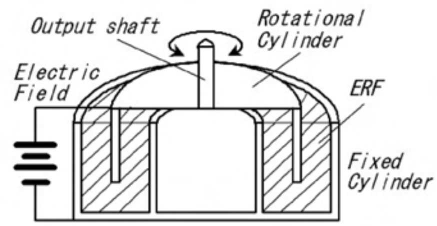
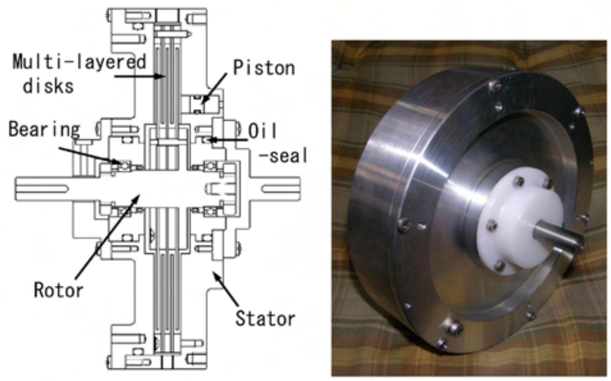


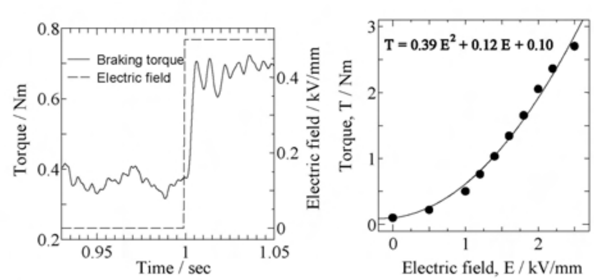
Fig. 3. Basic structure of ER Brake



Figs. 4. ER Brake: Sectional view (left) and picture (right)

TABLE I
SPECIFICATIONS OF ER BRAKE

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



Figs. 5. Basic characteristics of the ER brake:
Step response (left) [11] and braking torque vs. electric field (right)

rehabilitation trainings. "P1" means first prototype with passive mechanism. This system is safe for human because it does not use any actuator.

Force control unit consists of the two ER brakes and the brake torque generates output-force on a handle by a parallel linkage. Figure 7 shows parallel linkage of this system. As shown in this figure, T1 or brake torque of brake1 generates force F1 and similarly torque T2 generates force F2. If the movement of the handle is vertical direction like this figure and this system generates force F1 and F2, the user feel resistance against his movement direction. If these forces are constant, users feel constant resistance. In other case, if these forces are proportion with velocity of the movement, the users feel viscous force. Necessary torques T1 and T2 are calculated from required forces F1 and F2 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.

Figure 8 is a structure and signal flow chart 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), which 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 by 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-effecter is $1.4*10^{-2}$[N] for each DOF.
3. Working area is 600[mm] (W) * 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]

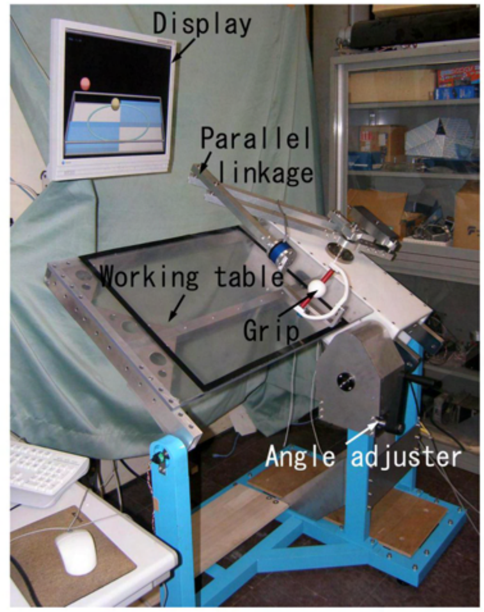


Fig. 6. PLEMO-P1

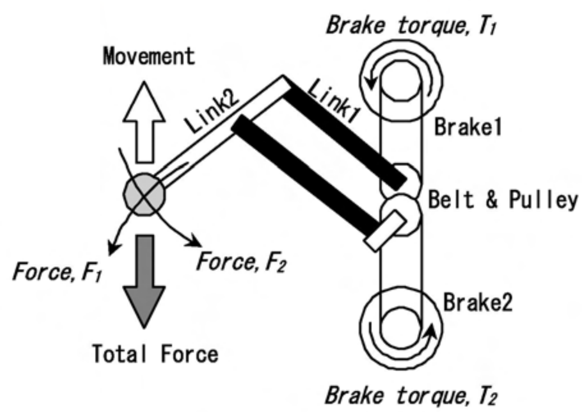


Fig. 7. Parallel linkage of PLEMO-P1

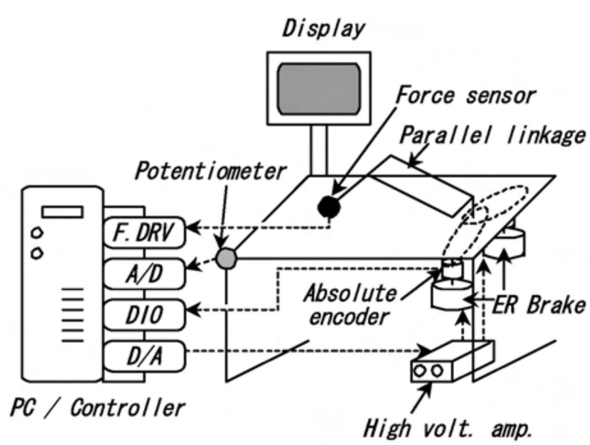


Fig. 8. Structure and signal flow of PLEMO-P1

(W) * 600 [mm] (D) * 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.

IV. Software of PLEMO-P1

We developed rehabilitation software shown in figure 9. This is a tracking test program. An operator grips the handle and moves it in order to track 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 viscous fluid. It is easy to change kinds of the virtual forces and its area.

Data of position, velocity and operating force are saved in output files and we can estimate accuracy of poison and velocity, range of motion, cognitive faculty and so on. We should make decision of the training protocols and evaluating method depending on the symptom of the patient individually.

We conducted pre-tests by healthy persons (24 years old). And figure 10 shows an experimental result of the position data. A circle in thick line represents the target trajectory and thin line represents operating track.

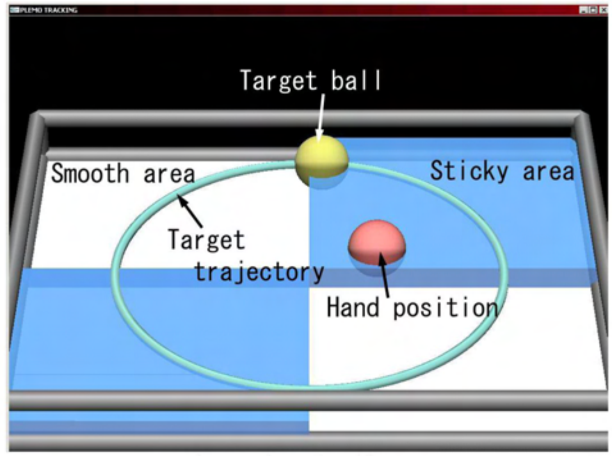


Fig. 9. View of tracking test

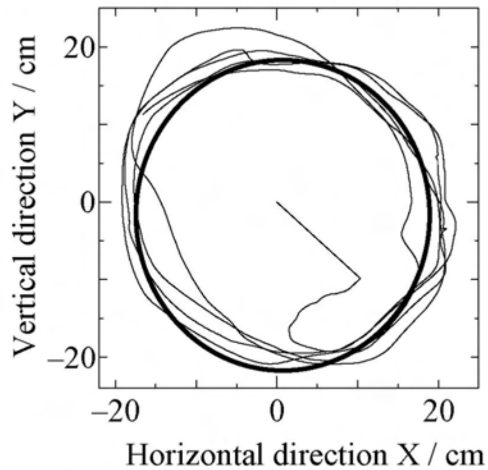


Fig. 10. Experimental result of tracking test

V. Conclusion

In this paper, we present the development of "Quasi-3DOF Rehabilitation System for Upper Limb" named "PLEMO-P1" and its software. PLEMO-P1 has two controllable DOF on a working plane and one passive DOF to adjust 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 dose not have any actuators and it cannot move automatically.

At the last of this paper, we achieved a pre-test by healthy person. However, test for patients is not carried out. We should carry out it at the next stage.

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