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"Hybrid-PLEMO", Rehabilitation system for upper limbs with Active / Passive Force Feedback mode

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1. Introduction

The aging society and physical deterioration of the aged people have become a serious problem in many countries. Moreover, there are many patients of ataxia: paralysis caused by brain stroke, or asynergia. Early detection of the functional deterioration and sufficient rehabilitative trainings are necessary for such patients.

In general, therapists make rehabilitative programs based on inspections and measurements for each patient. However, it is difficult to adopt appropriate rehabilitation 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, the rehabilitation systems using robotics technologies or virtual reality technologies are expected to quantify the effect of rehabilitative trainings. Furthermore, robot system can enhance motivation of patients by creating new and unique training methods that have not existed yet.

Until now, some kinds of rehabilitation systems for upper limbs have been reported and developed (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). Almost all rehabilitation robots have utilized electric motors or other actuators. Such actuator-based (active type) systems have great advantages in rehabilitative activities, for example, those systems can perform assistive forces, spring-like reactions and so on. But from a view point of safety, we have room to consider utilizations of brake-based (passive type) rehabilitation systems.

Munir S., et al. (Munir S., et al., 1999) have developed passive haptic devices. In their system, conventional powder brakes were used as haptic generators. Grossly speaking, the response time of the powder brake is more than 50ms and it causes lack in quality of force feedbacks. To solve this problem, we have developed several types of haptic devices for upper limbs rehabilitation with ER fluid (Electrorheological fluid) brakes (Kikuchi T., et al., 2007). Thanks to the quick response of the ER fluids, these systems presented high quality haptics.

However, the effects and roles of active / passive force feedback for rehabilitative trainings have not been clarified yet. In this study, we have developed an active / passive switchable rehabilitation system for upper limbs (Hybrid-PLEMO), and planed to address its

effectiveness. In this chapter, we will explain a basic structure, properties and results of functional tests on the Hybrid-PLEMO.

2. Reaching function of brain-injured patient and its rehabilitation

Motor palsy is a decrease in physical capabilities of a voluntary movement. It appears clinically as a muscular weakness. Motor palsy is recognized as abnormal posture, movements, and abnormal motion patterns in the rehabilitation medicine a scapular girdle, a shoulder joint, an elbow joint, a wrist joint, and fingers cannot be moved separately. For severely impaired stroke survivors, such abnormal coordination is characterized with enforced co-activations between shoulder adductors and elbow extensors (extensor synergy) as well as between shoulder abductors and elbow flexors (flexor synergy) (Brunnstrom S., 1970). These synergy patterns gradually decrease depending on recovery of paresis with adequate rehabilitative trainings.

Upper extremity is mainly used for operations of objects; reaching, grasping and releasing. A normal reaching action takes great amount of efforts to adequately adjust a combination of motions of a shoulder, an elbow, a wrist joint and fingers. In many cases, the normal reaching is a very difficult task for the patients with ataxia because of their synergy movements.

In the rehabilitation to the paretic upper extremities, an improvement of the reaching function is one of the most important objectives. It is thought that stroke patients with the synergy pattern can improve their performances of upper extremities by acquiring the movement free from synergy patterns (Brunnstrom S., 1970). It is reported that, 30 to 66 percent of stroke patients do not use their upper extremity functions in daily life (Johanna H., et al., 1999). Two factors are related to this fact. Firstly, a lot of stroke patients tend to do almost all of ADL (Activities of Daily Living) with compensations of a normal side limb and they rarely use a paretic side limb, which is called "learned-non-use" (Wolf SL, Et al., 1989). Secondly, once their brains are damaged, excitements of the non-damaged side increase (Liepert J., et al., 2000) and it results in excessive weakening of the function of the damaged side.

Plautz et al. (Plautz EJ., et al., 2000) studied on the brain recovery using a squirrel monkey and its damaged-brain model. In their research, it is clarified that re-composition of a cerebral cortex is promoted by not only using the hand but also by advanced operation training with a motor learning. This indicates that re-composition of cerebral cortex can be facilitated by an advanced accurate operation task such as drawing tracks accurately. Moreover this can bring about good effects to improvements of stroke patient's upper extremity functions.

3. Development history

In our previous researches, clutch-type actuators with functional fluids have been adopted for torque control of rehabilitation systems. A conceptual diagram of ER fluid clutch actuator (ER actuator) is shown in Figure 1. Basic concept for safety with this clutch-type actuator was reported (Furusho J. & Kikuchi T., 2007). Then its applications for "EMUL" system, 3-D rehabilitation system for upper limbs (Furusho J., et al., 2005), and "Robotherapist", 6-DOF rehabilitation system for upper limbs (Furusho J., et al., 2006) were also reported. These actuator-based (active type) machines have great advantages of

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variation, accuracy and other performance of haptic forces. However, due to the usage of many actuators, these systems have disadvantages of cost, space and usability.
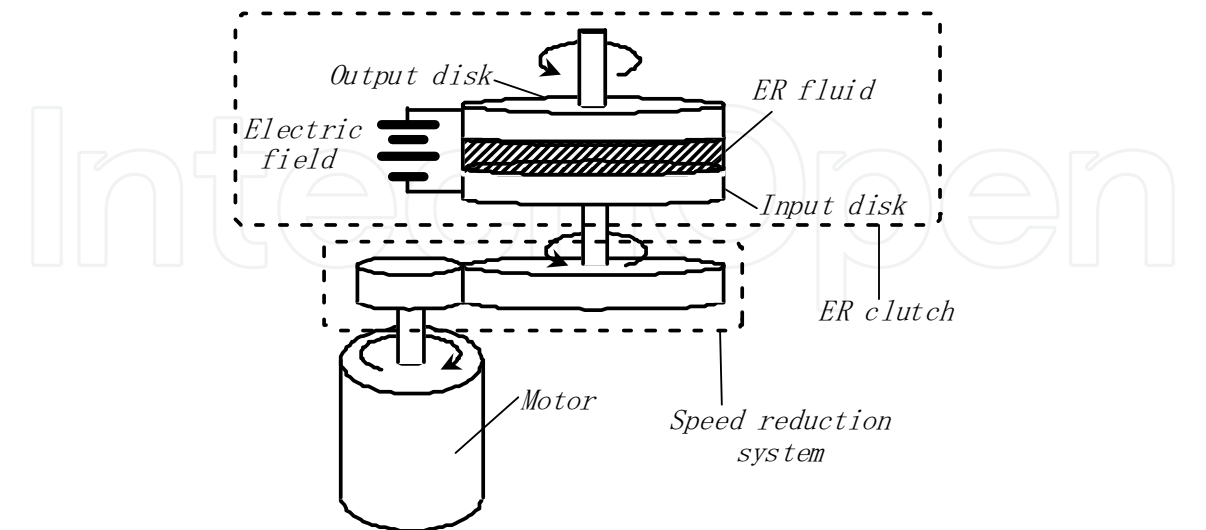

Fig. 1. ER-clutch-type actuation system for safety

In late years, we developed PLEMO systems with another concept for safety (Kikuchi T., et al., 2007). We have developed the PLEMO systems with demand of downsizing, low-cost, good usability and more advanced safety. The PLEMO systems have only 2-DOF force feedback function on a working plane for downsizing and cost-cutting, but the working plane can be adjusted its inclined angle. We named this system "Quasi-3-DOF Rehabilitation System for Upper Limbs" (Figure 2). For another feature of PLEMOs, its haptic control is conducted by only brakes with ER fluid (ER brake). These systems are safer than any other rehabilitation systems with actuators. The features of active / passive force feedback are compared in Table 1. As shown in this table, active type (actuator-based) machines have a great advantage on applicability for users. On the other hand, passive type (brake-based) machines have merits of safety, cost and size. The PLEMO systems are now under the clinical tests (Ozawa T., et al., 2009) (Figure 3).
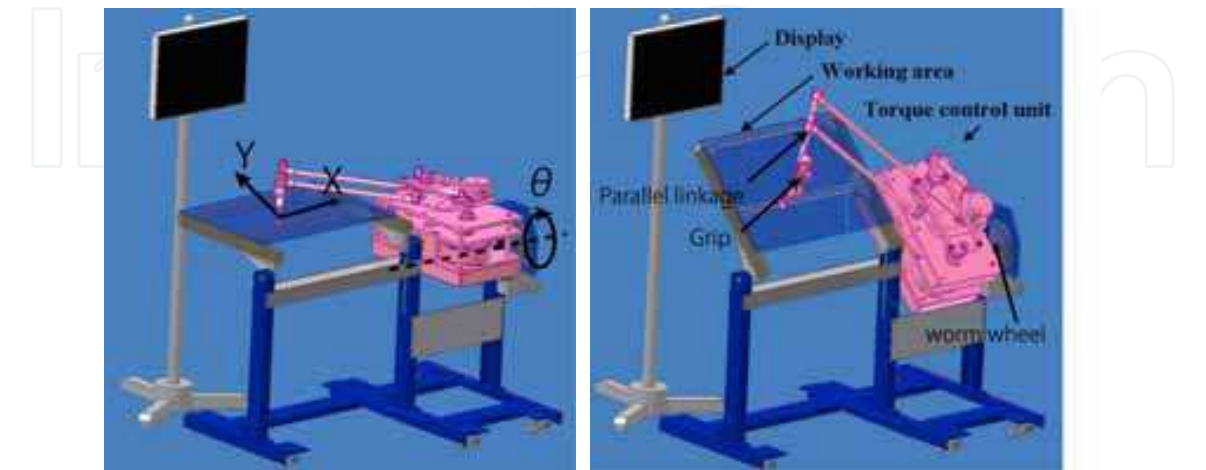

Fig. 2. Quasi-3-DOF mechanism; Horizontal state (left) and slanted state (right)

Feedback mode	Active force feedback	Passive force feedback
Force feedback	Actuator	Brake
Subject	Every subjects	Patient who can move his arm voluntarily
Safeness	Less safer than passive force feedback	Safe in mechanism
Cost	Expensive	Less expensive than active force feedback

Table 1. Comparison between active / passive force feedbacks in rehabilitation system

Fig. 3. PLEMO system in clinical tests

Table 1 shows comparisons in only engineering factors. However, it has not been cleared how active / passive forces effect to the upper limbs function in rehabilitation. We need a haptic device that provides active / passive haptic forces on the same environment to discuss this question. Then, we decided to develop the active / passive switchable haptic device for upper limbs rehabilitation; Hybrid-PLEMO (Kikuchi T., et al., 2008), mentioned in following sections.

4. Core technology

4.1 ER Fluid
ER fluid is one of the functional fluids of which rheological properties can be changed by applying electrical fields (Winslow W.M., 1949). In this paper, a particle-dispersed-type ER fluid is used. The characteristics of the fluid are shown in Figure 4. As shown in this figure, its shear stress depends on the application of electric field from 0.0kV/mm to 2.0kV/mm and does not depend on shear rate. The time constant of the viscosity change is several millseconds, and the response is stable and repeatable. Thanks to these characteristics, we can build up clutch / brake devices utilizing the ER fluid.
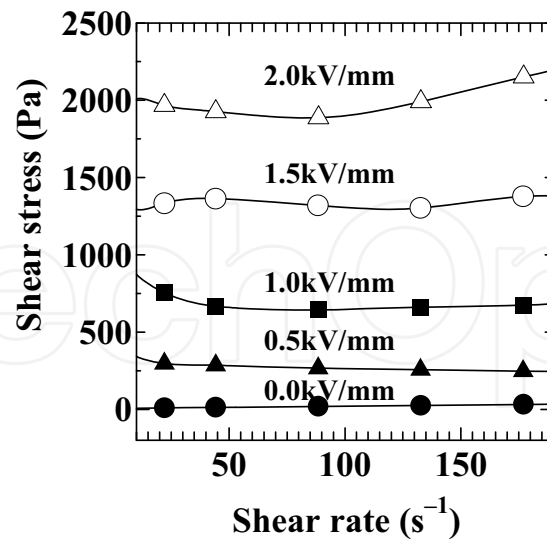
Fig. 4. Flow curve of ER fluid (Particle-dispersed type)

4.2 Basic structure of ER Actuator & brake

Figure 5 shows a basic structure of a cylindrical-type ER brake. It consists of a fixed cylinder and a rotating cylinder with the ER fluid between them. These cylinders also play the role of a pair of electrodes. The rotating cylinder is fixed on 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.
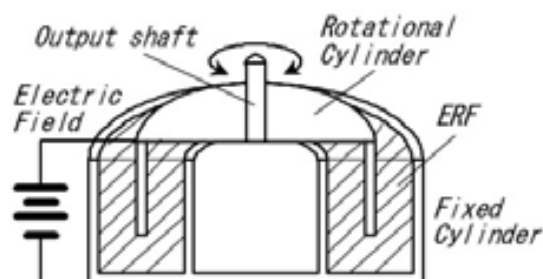
Fig. 5. Basic structure of ER Brake

With the same configuration and rotation of the fixed-side of the ER brake, we can compose ER actuator (see Figure 1) (Furusho J. & Sakaguchi M., 1999). In the configuration of the ER actuator, a conventional motor generates driving torque from input part of the ER clutch. Additionally, output torque of the ER actuator is controlled with the ER clutch separated from motor rotation. By restricting the rotational speed of the motor, we can easily keep safe state. This system has good controllability of torque, low inertia and high safety, which is suitable for human-machine coexisting systems, for example haptic displays or rehabilitation systems.

4.3 Double-Output ER Fluid Clutch / Brake device

Figure 6 shows an appearance and a cross section of the double-output and multilayered-disk-type ER fluid clutch/brake device developed in this study. This device has two groups of multilayered disks (input disks / output disks) in its package. Stator disks (input disks) are fixed on the casing for each group. However, when the casing is rotated by an electric motor, these disks are rotated simultaneously and the device works as a clutch. When the casing is locked, input disks are also locked and the device works as a brake. Two groups of output disks are connected to the inner shaft and the outer shaft, respectively. The particle type ER fluid is filled between each disk and we can control 2 output torques independently.
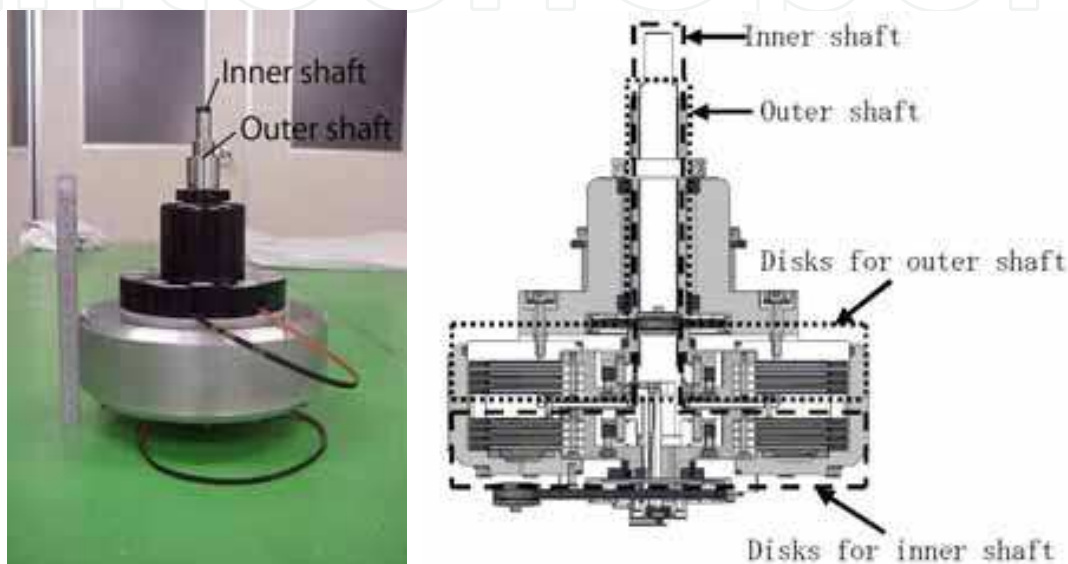

Fig. 6. Double-output ER fluid clutch / brake (left: Appearance, right: Sectional view)

Specification of the device is shown in table 2. Figure 7 shows output torque of this device. We can control transmission (or braking) torque by application of the electric field between rotor / stator disks accurately and rapidly.
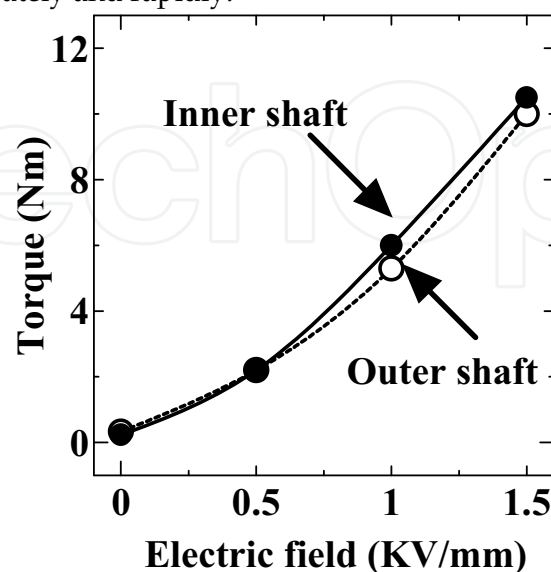

Fig. 7. Output torque of double-output ER fluid clutch

Total diameter	192 mm
Total heigth (include output shaft)	225 mm
Num. of disks (for inner / outer parts each)	4 (ER fluid layer: 8)
Diameter of disk	155 mm
Thickness of disk	1 mm
Disk gap	1 mm

Table 2. Specification of double-output ER fluid clutch

5. Basic structure and property of Hybrid-PLEMO

5.1 Concept

The PLEMO has 2 controllable DOFs on a working plane and 1 passive DOF of the inclined angle of the working plane as shown in Figure 2. We defined this working space as a "Quasi-3-DOF Working Space". An operator grasps a handle on the end-effecter of its arm, watches visual information on a display and plays application software as rehabilitative trainings and evaluation tests.

In a previous report (Kikuchi T., et al., 2007), we used only ER brakes for its torque control. Therefore, its haptic control was passive. In a new type of haptic device developed in this research, we use ER actuators for its haptic control with the quasi-3-DOF mechanism mentioned above. At the same time, we adopt a switchable mechanism between active / passive modes by releasing / fixing rotation of input parts of the clutches. We named this new haptic devices "Hybrid-PLEMO". Figure 8 shows the Hybrid-PLEMO, and table 3 shows specifications of it.
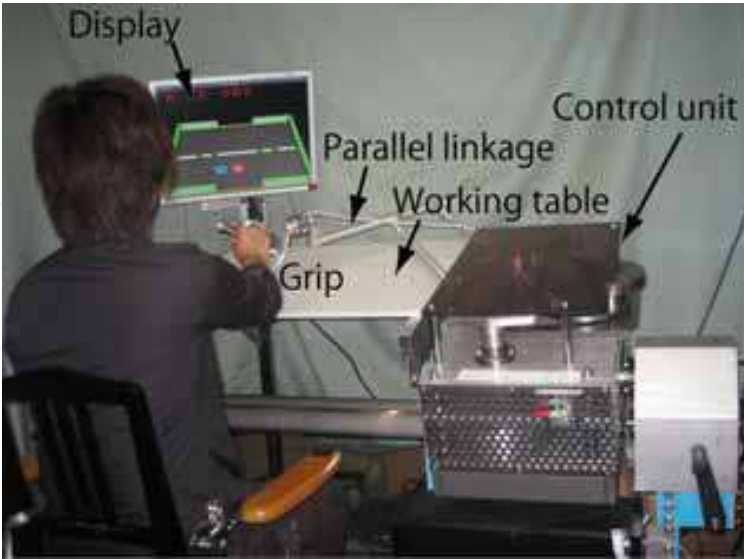

Fig. 8. Hybrid-PLEMO

Size	W0.6m x D0.5m x H1.0m
Motion region	W0.6m x D0.5m Adjustable angle of the inclination is -30~90deg
Maximum force	4kfg at end-effector
Num. of double-output ER clutch	2
Power of motor	40W

Table 3. Specification of Hybrid-PLEMO

5.2 Force control mechanism

Haptic force on the end-effector of the Hybrid PLEMO is controlled by a torque control unit with ER actuators mentioned above. In Figure 1, the motor is rotated by simply constant voltage (without feedback control) in order to assure high safety of the clutch-type actuator. Therefore, the rotation direction of the ER actuator is basically one way. We need two actuators for CW (clockwise) direction and CCW (counterclockwise) direction for one controllable DOF.

To realize two controllable DOFs of the Hybrid-PLEMO, we utilized two sets of double-output ER fluid clutch/brake devices described above. The one is rotated in CW direction. The other is rotated in CCW direction. Driving parts of the ER actuators are shown in Figure 9. As shown in this figure, both CW and CCW direction are generated by gears and one way rotation of a DC servo-motor. Each CW and CCW rotation is transmitted by belt-pulley system to the "ER Device1" and the "ER Device2". Additionally, when the motor is locked by a disk brake built in this system, each clutch works as a brake.
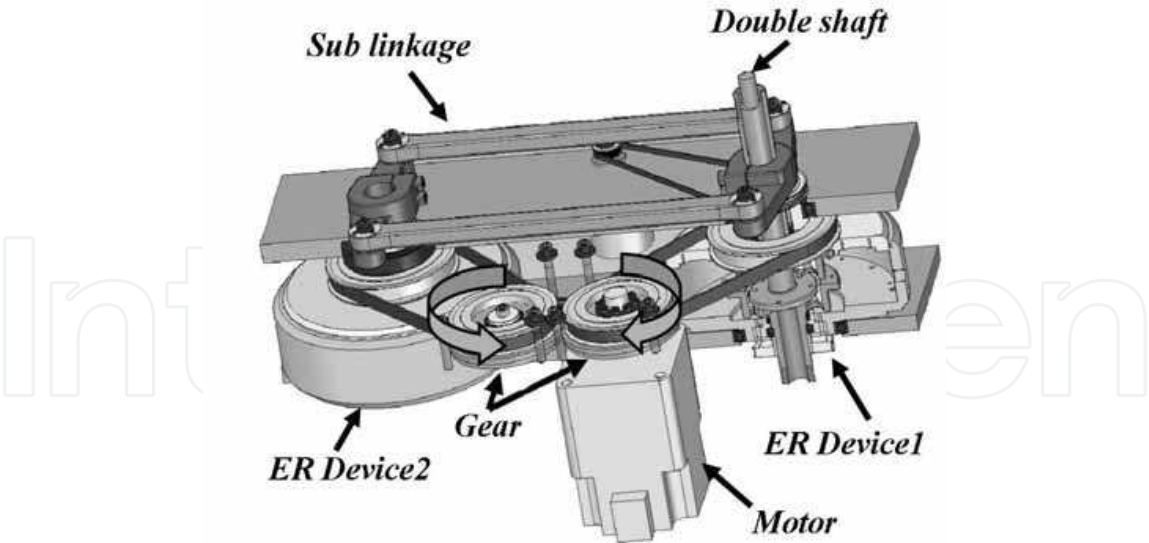

Fig. 9. Driving parts of ER actuators

A parallel linkage mechanism of the Hybrid-PLEMO is shown in Figure 10. the "ER Device1" and the "ER Device2" have a pair of two controllable shafts, which are a pair of an outer shaft and an inner shaft. Two outer shafts with opposite rotations are connected with the "Sub Link1". In same manner, two inner shafts are connected with the "Sub Link2". By

using sub-links, we can realize two controllable DOFs for haptic control. These two DOFs are converted to orthogonal two directions of the end-effector by using main parallel linkage which consists of the "Link1" and the "Link2".
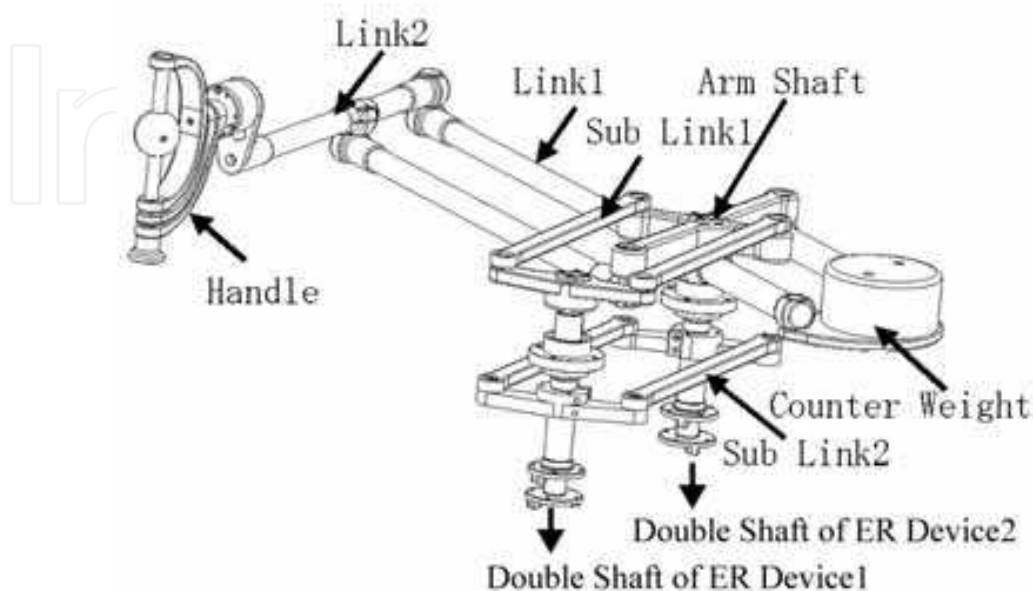

Fig. 10. Parallel linkage system for Hybrid PLEMO

5.3 Control system

Figure 11 shows the control system for the Hybrid-PLEMO. Absolute encoders (FA Coder, TS566N320, Tamagawa Seiki Inc., Japan, resolution: 17bits) measure the rotational angle of ER actuators or brakes. We can calculate the position and the velocity of the handle depending on each angle. A Digital / Input/ Output (DIO) board (PCI-2154C, Interface Inc., Japan) loads this information to a controller (personal computer). The handle includes a force sensor (OPFT-220N, Minebea Co. Ltd., 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 an Analog/Digital (A/D) converter board (PCI-3165, Interface Inc., Japan, resolution: 16bits). The brake torque of the ER brake is controlled by applied voltage from high voltage amplifiers (High voltage amplifier, MAX-ELECTRONICS, Co. Ltd., Japan). A Digital/Analog (D/A) converter board (PCI-3338, Interface Inc., Japan, resolution: 12bits) outputs the reference signal to the amplifiers.

A controller is a personal computer (DOS/V), and an operating system (OS) is Vine Linux 3.2 and ART-Linux (kernel 2.4.31) as a real-time OS. Open-GL and Glut3.7 are used for the graphic libraries. A graphic process and a control process are executed by one PC. Multi-process programming is used to realize it. The control process is repeated every 1 ms exactly.
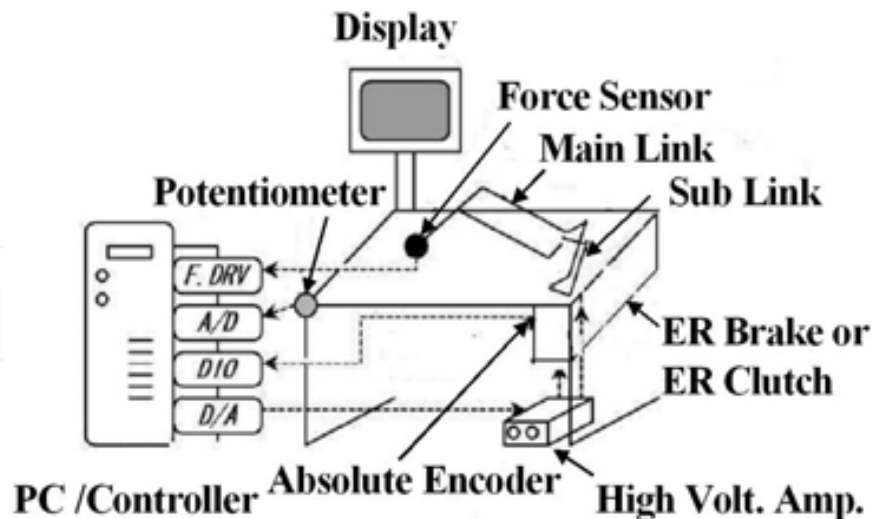
Fig. 11. Control System for Hybrid PLEMO

5.4 Experimental result for constant resistive force

To evaluate the performance of the haptic force of the Hybrid-PLEMO, constant resistive forces with active / passive haptic controls were measured. Figure 12 shows experimental results. A solid line represents force with the active haptic control, and a dashed line represents force with the passive haptic control. In these experiments, an operator manipulated a handle forward from an initial position. Initially, resistive forces were zero, but when the hand entered a friction area, resistive forces of constant 5N were instantly presented. As shown in this figure, haptic forces with both active/passive haptic methods were accurately controlled.
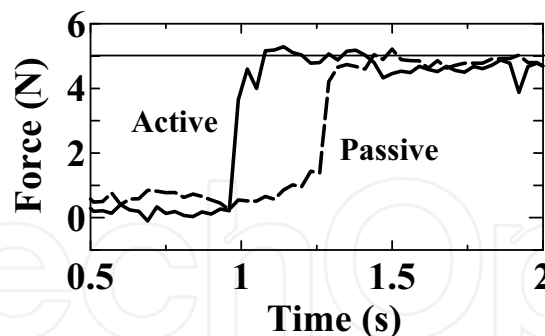

Fig. 12. Constant resistive force by passive / active mode

6. Reaching with active / passive force guidance

6.1 Motivation

Reaching motion is one of the most important tasks for rehabilitative trainings. In physical therapy (Voss D.E., et al., 1985) or occupational therapy (Trombly C.A., 1983), the reaching training is done without pulling patient's hand in a correct direction, but with giving resistance against the correct direction. This resistance force activates patient's intention to move their own arm by themselves.

In this section, we suggest two types of reaching programs with the Hybrid PLEMO system. These two programs are based on the reaching training with force guidance or resistance mentioned above. However, the methods of force feedback are different each other. The one utilizes active force feedback mode, and the other utilizes passive mode.

6.2 Method

For lab-level tests, examinees were healthy students (22~30 years old) in this section. Figure 13 shows a view displayed during this test. Initially, an examinee sets a handle position (red circle) on the starting position by manipulating the handle of the system. After that, subjects move their arm toward "Y" direction shown in Figure 13 along a target trajectory. However, a correct trajectory is not displayed in order to evaluate simply the effect of force information. Subjects have to find the correct trajectory from 5 choices (numbered from "0" to "4") based on only force information of the Hybrid-PLEMO. The aim of this program is to operate the handle, search target trajectories with only force information and trace it.

Fig. 13. View of the reaching program

Methods of force display in the active / passive modes are shown in Figure 14. In these figures, broken lines show the target trajectories. In active mode, the PLEMO system generates outgoing-vector forces of 5N from the target trajectory. On the other hand, in passive mode, the system generates a distribution of resistant forces (0N or 3N or 5N). The nearer to the target the hand position is, the stronger the resistance is. The start position was same (X = 0cm) in every experiments. The target trajectory was changed in a random manner.
In this experiments, "X" position of each trajectory (Num.0~ Num.4) is set as follows; X = -20 cm (Num.0), -10 cm (Num.1), 0 cm (Num.2), 10 cm (Num.3), 20 cm (Num.4).
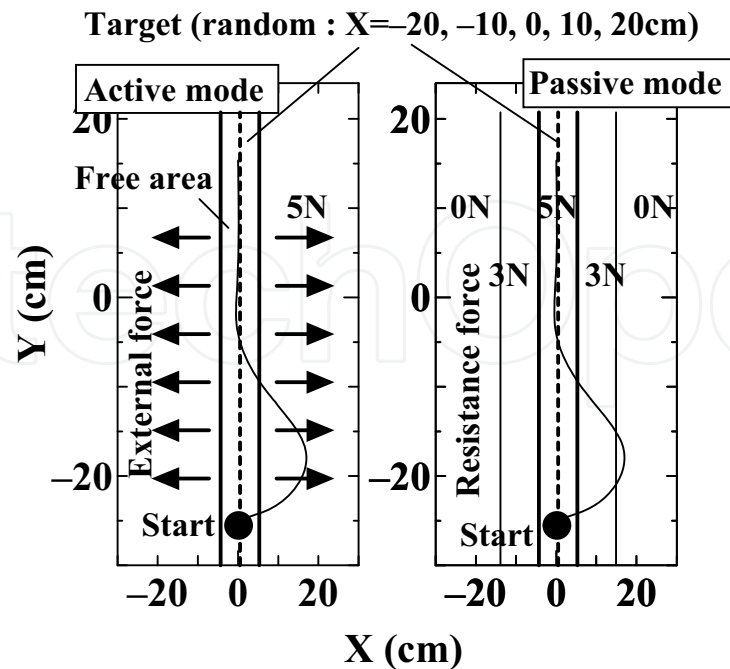
Fig. 14. Force feedback method for reaching program (Left: active mode, right: passive mode)

6.3 Result

The target trajectories were decided in the random manner. Figure 15 shows a set of experimental results for the same target position (Num.3; X = 10cm) with active/passive mode each. Broken lines show the target trajectories, and black dots show the starting positions of the handle. As shown in the left side of Figure 15, the operator can recognize the target position smoothly with active-type force guidance. On the other hand, as shown in the right side of Figure 15, it took more time to recognize the target position with passive-type force guidance than active mode.
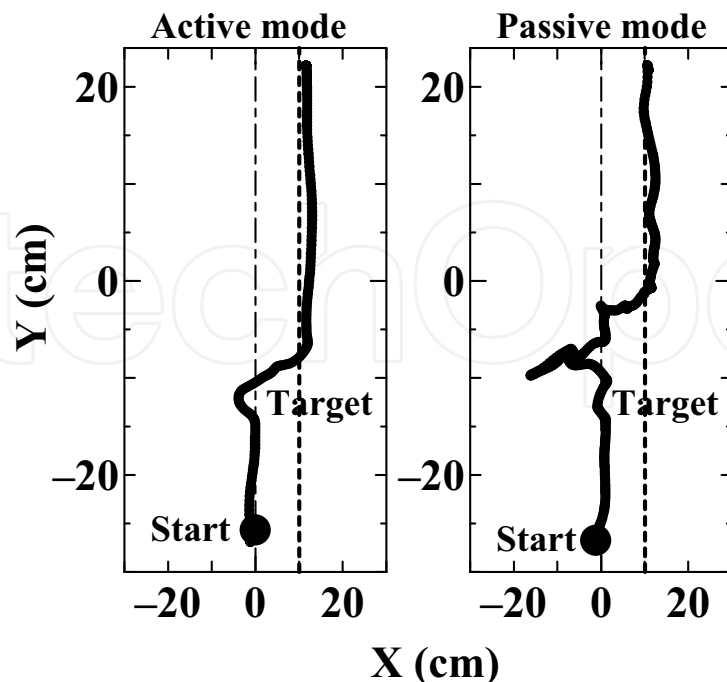
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Fig. 15. Experimental Results (Left: active mode, right: passive mode)

6.4 Discussion

In order to evaluate the delay for searching target trajectories, we categorized a reaching path by two phases; a "search-phase" and a "reach-phase" shown in Figure 16. In this section, we defined the "search-phase" as a period from the beginning to the condition which meets both of following two equations,

$$\dot{Y} \equiv Vy > 10 \, [cm \, / \, s], \tag{1}$$

and,

$$\left| \dot{X} \right| \equiv \left| Vx \right| < 10 \, [cm \, / \, s]. \tag{2}$$

Therefore, above two equations mean conditions for the beginning of the "reach-phase". Equation (1) was defined to detect subject's intention for reaching. Equation (2) was defined to detect subject's intention for end of searching.

Experiments were conducted by 50 times each for the active / passive modes. We picked out 10 data whose target number was "1" from each data of the active / passive modes as shown in Table 4. The time of the "search-phase" in the active mode was longer than that in the passive mode.

The reason of this delay is thought that, in the passive mode, the operator needs more time to understand the distribution of force field with his own motion, and recognize correct direction toward the target.
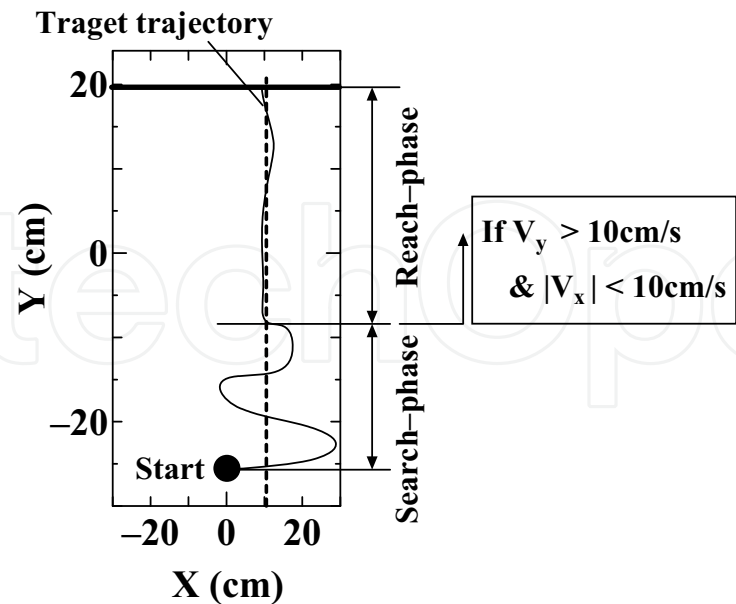
Fig. 16. Experimental Results (Left: active mode, right: passive mode)

	Search-Phase[s]	Reach-Phase[s]	Total time [s]
Active 1	2.059	0.562	2.621
Active 2	1.709	0.680	2.389
Active 3	1.639	0.789	2.428
Active 4	1.699	0.776	2.475
Active 5	1.429	0.952	2.381
Active 6	1.457	0.906	2.363
Active 7	1.309	0.988	2.297
Active 8	1.229	0.827	2.056
Active 9	1.269	0.757	2.026
Active 10	1.139	0.874	2.013
Ave.	**1.491**	**0.811**	**2.305**
SD	**0.282**	**0.128**	**0.207**
Passive 1	1.739	1.537	3.276
Passive 2	2.479	1.509	3.988
Passive 3	2.379	1.018	3.397
Passive 4	2.089	1.284	3.373
Passive 5	1.739	1.480	3.219
Passive 6	2.018	1.322	3.340
Passive 7	1.839	0.994	2.833
Passive 8	2.079	1.131	3.210
Passive 9	2.119	1.229	3.348
Passive 10	1.329	2.278	3.607
Ave.	**1.981**	**1.378**	**3.359**
SD	**0.335**	**0.370**	**0.295**

Table 4. Duration of "search-phase" and "reach-phase" in active / passive force feedback mode

7. Conclusion & Future works

This chapter described the development and evaluation of the "Hybrid-PLEMO", which is one of the rehabilitation systems for upper limbs with the quasi-3-DOF mechanism and the switchable mechanism between the active/passive modes. In the last part of this chapter, we compared the effect of the active / passive forces on the reaching tests for a healthy person. The duration of "search-phase" in the "passive mode" was longer than that in the "active mode".

In the future works, we will clarify the effects and roles of the active / passive force feedback in rehabilitative trainings with this system. It will be possible to measure the effect of rehabilitation with EEG or NIRS for the same subjects under the same environments by using this system.

8. Acknowledgments

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Recent Advances in Biomedical Engineering

Edited by Ganesh R Naik

The field of biomedical engineering has expanded markedly in the past ten years. This growth is supported by advances in biological science, which have created new opportunities for development of tools for diagnosis and therapy for human disease. The discipline focuses both on development of new biomaterials, analytical methodologies and on the application of concepts drawn from engineering, computing, mathematics, chemical and physical sciences to advance biomedical knowledge while improving the effectiveness and delivery of clinical medicine. Biomedical engineering now encompasses a range of fields of specialization including bioinstrumentation, bioimaging, biomechanics, biomaterials, and biomolecular engineering. Biomedical engineering covers recent advances in the growing field of biomedical technology, instrumentation, and administration. Contributions focus on theoretical and practical problems associated with the development of medical technology; the introduction of new engineering methods into public health; hospitals and patient care; the improvement of diagnosis and therapy; and biomedical information storage and retrieval. The book is directed at engineering students in their final year of undergraduate studies or in their graduate studies. Most undergraduate students majoring in biomedical engineering are faced with a decision, early in their program of study, regarding the field in which they would like to specialize. Each chosen specialty has a specific set of course requirements and is supplemented by wise selection of elective and supporting coursework. Also, many young students of biomedical engineering use independent research projects as a source of inspiration and preparation but have difficulty identifying research areas that are right for them. Therefore, a second goal of this book is to link knowledge of basic science and engineering to fields of specialization and current research. The editor would like to thank the authors, who have committed so much effort to the publication of this work.

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