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A 3-D Rehabilitation System for Upper Limbs "EMUL", and a 6-DOF Rehabilitation System "Robotherapist", and Other Rehabilitation Systems with High Safety

Junji Furusho & Takehito Kikuchi
Osaka University
Japan

1. Introduction

Movements of upper limbs are indispensable for daily activities. For the aged or disabled persons, it is especially important to exercise for the maintenance or recovery of upper limb function. There are many patients of paralysis caused by stroke. For example, in Japan more than two hundred and fifty thousand people have stroke every year, and many of them are paralyzed. The human brain is capable of an extraordinary degree of plasticity (self-organization), enabling learning, and leaving open the possibility for motor recovery (Janet & Shepherd, 1998). Therefore, neuro-rehabilitation for stroke-patients is effective. Using apparatus that applies robotic technology and virtual reality makes new training methods and exercises in rehabilitation possible (Krebs, Volpe et al., 2000), (Burgar, Lum et al., 2000), (Charles, Krebs et al., 2005).

Force display systems are expected as effective and advantageous interfaces for some scenes, for example computer-assisted-surgery, kinds of rehabilitation methods and so on. In this technology, some kinds of feedback force are generated with mechanical actuators. And such a virtual force is computed in real time by simulating a physical phenomenon of the virtual world in which the operator exists.

Feeding back the quantitative evaluations to the training by a computer can enhance the qualitative effect of training. Therefore, some rehabilitation systems using these technologies for upper limbs have been developed. However, most of them apply training within a two-dimensional horizontal plane. Many movements, however, in daily activities need to move arms in a vertical direction. A system therefore that enables exercise in three-dimensions would seem to be more effective for such training. Although the MIME system (Burgar, Lum et al., 2000) using PUMA-560 by VA and Stanford Univ. can give training in three-dimensions, the PUMA-560 is a robot originally developed for industrial use and may not be sufficiently safe to train the aged and/or disabled.

We have developed innovative rehabilitation supporting robots; "EMUL" and "Robotherapist." The EMUL has performed well in clinical studies, and Robotherapist was exhibited at the Prototype Robot Festival at the 2005 International Exposition held in Aichi Prefecture, Japan.

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"EMUL", short for "Exercise Machine for Upper Limbs", was developed through robotic and virtual reality technology in a 5-year NEDO (New-Energy and Industrial Technology Development Organization of Japanese Government) project (Furusho, Koyanagi, Imada et al., 2005), (Furusho, Koyanagi, Kataoka et al., 2005). It enables new training methods and exercises for use in the field of rehabilitation. The EMUL has 3-DOF (degrees of freedom) for shoulder and elbow training, and this satisfies many of the movements involved in daily activities. Another important feature is safety. In EMUL, ER (electro-rheological) fluid actuators ensure mechanical safety. "Robotherapist" is a 6-DOF rehabilitation robot based on EMUL which has a 3-DOF controllability added at wrist rotations (Furusho, Hu, Kikuchi et al., 2006). In this chapter, we describe mechanism and software of EMUL, Robotherapist and other rehabilitation systems using functional fluids with high safety.

Furusho Laboratory of Osaka University developed 2-D rehabilitation system for upper limbs "NIOH-1" using ER fluid actuators in 1997 (Furusho, Wei, Koga, 1995), (Furusho & Sakaguchi, 1999). EMUL and Robotherapist were developed on the basis of the technology of NIOH. Recently we have developed a upper-limb-rehabilitation system "PLEMO" using ER fluid brakes which could be used in facilities for elderly people and so on (Kikuchi, Furusho et al., 2007), (Kikuchi, Hu et al., 2007).

Furusho Laboratory studied biped locomotion robots during the 1980s and the beginning of 1990s, and realized the human-like biped locomotion with kick action [Furusho & Masubuchi, 1987], [Furusho & Sano 1990]. On the basis of this biped locomotion technology and the technology about functional fluids, we developed the first intelligent prosthetic ankle. Moreover we are developing intelligent ankle-foot orthoses using MR (Magnetorheological) fluid in a 3-year NEDO project. These systems are also introduced in this chapter.

2. 2-D Rehabilitation System "NIOH"

2.1 ER Actuaor

ER fluid is a fluid whose rheological properties can be changed by applying an electrical field (Bossis, 2002). Figure 1 shows the conceptual illustration of an ER fluid actuator. The ER actuator is composed of an ER clutch and its drive mechanism consisting of a motor and a reduction-gear-unit. The rotational speed of the motor is kept constant. The output torque of ER actuator is controlled by the applied electric field (Furusho, 2001), (Furusho & Kikuchi, 2006).

The input torque is transferred to the rotating cylindrical section of the output axis via the particle-type ER fluid filled in the rotating cylinder. Both the input axis cylinders and the output axis cylinder serve as electrodes, and output torque is controlled by the electric field applied between the electrodes. The output cylinder is made of aluminum alloy in order to reduce the moment of inertia of the output axis.

An actuator using ER fluid is effective for human-coexistent mechatronics systems like rehabilitation systems for upper limbs. Figure 2 shows a conceptual illustration of Human-Machine-Coexistent-Mechatronics (HMCM) System using ER Actuators. Merits of ER actuators in applications to HMCM system are as follows:

A: From the Viewpoints of the Characteristics of Operation

(a) Since ER actuators have good back-drivability, the operator can easily operate HMCM system from its end-effector.

(b) When HMCM system is driven by the operator from its end-effector, HMCM system can be moved quickly over the rotational speed of the input cylinder of the ER clutch.

B: From the Viewpoints of Performances in Force Display System:

(a) Quick force response property originated from the low inertia property of ER actuator and the rapid response of ER fluid make the force presentation with high fidelity possible.
(b) Force display systems with large-force presentation ability can be realized safely.

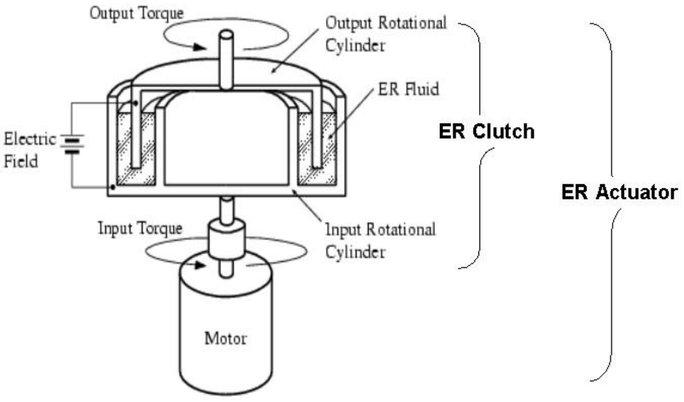

Fig. 1. Conceptual illustration of ER actuator

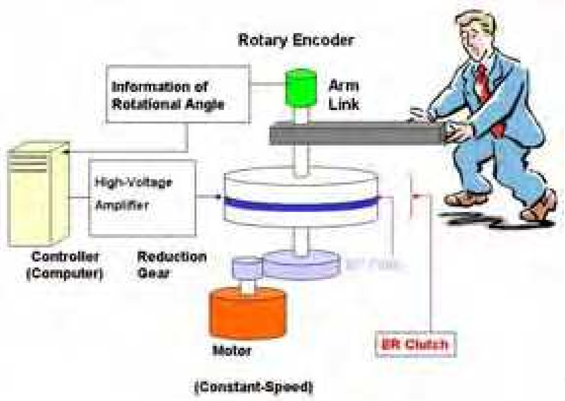

Fig. 2. Conceptual illustration of Human-Machine-Coexistent-Mechatronics (HMCM) Systems using ER actuators.

2.2 Consideration about Safety

A rehabilitation system for upper limbs which has large working area can be regarded as a kind of robots. In such a human-coexistent robot system where an operator must be in contact with or close to the robot, the safety-securing system is necessary in order that an operator can use the robot safely (ISO10218). In industrial robots, an operator cannot access a robot except for teaching in order to avoid hazardous conditions. Figure 3 shows the structure of safety in human-coexistent robots.

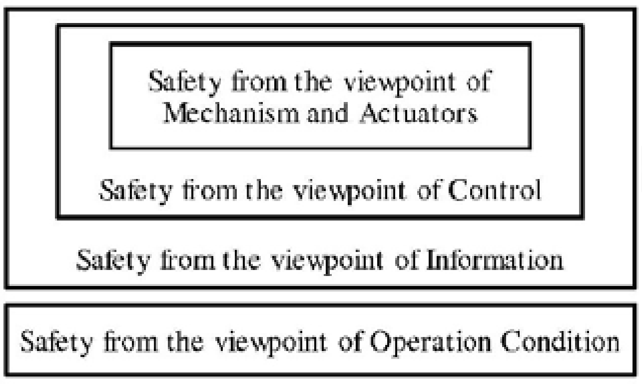

Fig. 3. Structure for securing safety in Human-Coexistent Robots.

ER actuators have the following merits from the viewpoint of safety.

(1) The maximum driving speed of the output shaft of the ER actuator is restricted by the rotational speed of the input shaft of the ER clutch. Therefore, when the rotational speed of the input shaft is set slow, HMCM systems using ER actuators are safe for operators.

(2) The inertia of the output part can be made very small. So, in the case of unexpected accidents, the impact force caused by the inertia of the actuator can be reduced.

Since International Safety Standards for human-coexistent robots have not been established yet, we have no other choice but to use the ISO and domestic standards for machines working close to human beings (see Table 1). The developed rehabilitation system can assure these standards of Table 1 by the usage of ER actuators and the mechanical design as follows:

(1) The items (a) and (b) of Table 1 are satisfied by setting the rotational speed of the input cylinder slow.

(2) The item (c) is satisfied by using a 60-watt motor for the drive of the input rotational cylinder.

(3) Risk Reduction by Design (item (d)) is realized by mechanical limitation of each joint, mechanical gravity-compensation and the usage of ER actuators.

(a) End-effector Speed is less than 0.25 [m/s]	ISO10218: Manipulating industrial robots--Safety
(b) Low Energy Property	ISO14121: Safety of machinery--Principles of risk assessment
(c) Actuator Power is less than 80 [W]	JAPAN, JIS B 8433, 1983: General Code for Safety of Industrial Robots
(d) Risk Reduction by Design	ISO12100: Safety of machinery--Basic concepts general principles for design

Table 1. International and Domestic Safety Standards.

2.3 Rehabilitation and Force Display Systems Using ER Fluids

Furusho Lab. of Osaka University has been developing rehabilitation systems and force display systems using ER fluids since 1993 (Furusho, Wei et al., 1995).

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Figure 4 shows the 2-DOF rehabilitation systems “NIHO-1” using ER actuators (Furusho & Sakaguchi, 1999). The rehabilitation training system was installed in a hospital for testing purpose. 13 patients volunteered to participate in several experiments for evaluation of upper limb’s physical capability and for rehabilitation training. The patients suffered from arm paralysis due to a damaged spinal cord or clogged brain artery. Figure 5 shows the 2-DOF rehabilitation system “NIHO-2” using ER actuators (Ishikawa, 2000).

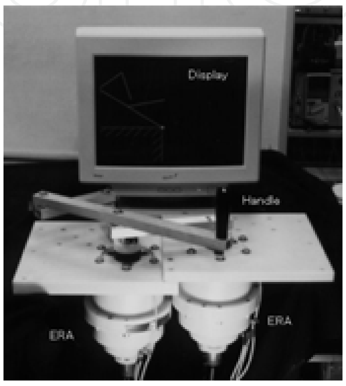

Fig. 4. Rehabilitation system “NIOH-1”.

Fig. 5. Rehabilitation system “NIOH-2”.

3. A 3-D Rehabilitation System for Upper Limbs Developed in a 5-year NEDO Project “EMUL”

3.1 Introduction

The percentage of aged persons in society and their number are increasing, and their physical deterioration has become a social problem in many countries. Early detection of function deterioration and sufficient rehabilitation training are necessary, not only to decrease the numbers of aged who are bedridden or need nursing care, but also to enable the aged to take an active part in society.

This research has been conducted as a part of the NEDO (New Energy and Industrial Technology Development Organization) 5-year Project, “Rehabilitation System for the Upper Limbs and Lower Limbs” since 1999 . Furusho Laboratory of Osaka University and Asahi-kasei Group developed a 3-D rehabilitation system for upper limbs “EMUL”. Hyogo Medical College took part in the project in the final year.

3.2 3-DOF Rehabilitation Training System

We have developed a 3-D rehabilitation system that has a performance suitable for rehabilitation for upper limbs and can display force senses in three-dimensional space (Furusho, Koyanagi, Imada et al., 2005), (Furusho, Koyanagi, Kataoka et al., 2005). Figure 6 shows the whole rehabilitation system. The maximum output torque of the ER actuator is about 3.0 [Nm]. As shown in Fig. 6, a patient can get exercise, sitting on a chair by gripping the handle of the upper limb exercise machine. The major targets in this study are hemiplegic patients who were paralyzed by stroke. The training is thought to include physical therapeutic exercises, such as passive and active exercises, and occupational therapeutic exercise like eating movement.

EMUL has the following specifications.

1) EMUL has 2 DOF for horizontal rotation and 1 DOF for vertical rotation.
2) The length of each link is 0.45 [m] and the height of the whole machine is about 1 [m].
3) All the actuators are set on the base of EMUL.
4) The vertical rotation part adopts a parallel link mechanism. This makes the gravity-effect compensation by counterbalance-weight in all posture possible.
5) The 3rd link is driven by spatial parallel link mechanism instead of belt-pulley and gear transmission system.
6) The motion range is about 0.90[m] (W) * 0.54[m] (D) * 0.50[m] (H).
7) The generative force at the end-effector is about 23 [N] in the horizontal plane and about 60 [N] in the vertical direction.

Fig. 6. Rehabilitation system “EMUL”.

3.3 Software for Training

We show some examples of the training software.

A: Picture-Mask Erasing

As shown in Fig. 7, a semitransparent mask of a picture of 0.40 [m] * 0.40 [m] is erased by a virtual eraser which is operated by a patient. The patient can sense a reaction force from the picture surface through the gripper of 3-D rehabilitation system. For example, when 80 percent of the mask is erased, this picture vanishes and then the next new picture appears 0.05 [m] behind the vanished picture. The pictures are changed one after another until the

6th picture. This software has the effect of improvement about the dexterity and the movable range of limbs.

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Fig. 7. Picure-mask erasing.

B: Virtual Maze & Virtual Hockey

Figure 8 shows a virtual maze of 0.40 [m] * 0.30 [m].When a virtual maze is completed, this maze disappears and then the next new maze appears 0.05 [m] behind the disappeared maze. The mazes are changed one after another until the 6th maze. This software has the effect of improvement about the dexterity and the movable range of limbs.

Figure 9 shows a virtual hockey game with impact-force-sense. Virtual hockey has the training effect about dexterity and agility.

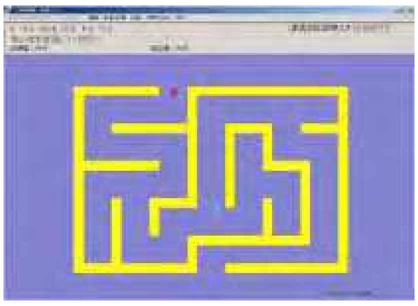

Fig. 8. Virtual maze.

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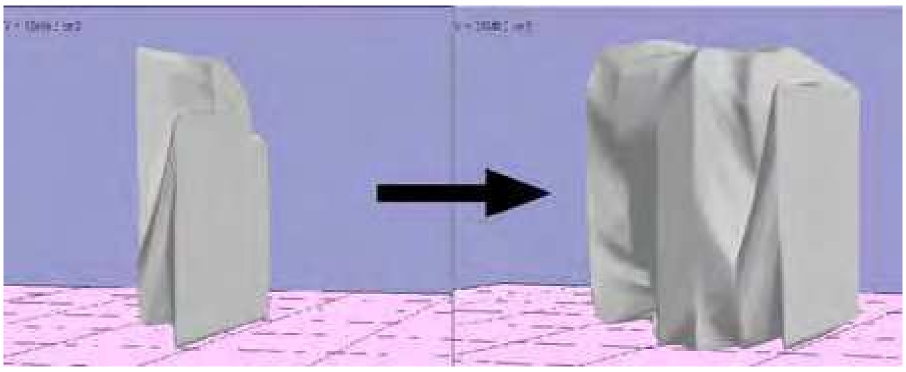
Fig. 9. Virtual hockey.

3.4 Clinical Testing

We conducted clinical testing for six patients. Each patient trained three times a week for six weeks. They all are patients of hemiparesis caused by stroke. The good results were obtained for all patients.

Figure 10 shows the shape of movable range in Picture-Mask-Erasing training of Patient A (67 years old male; 8 months after stroke; Left-side hemiplegia). As seen from this figure, the movable volume is expanded by the training.

Many evaluation methods (Fugl-Meyer Evaluation, Brunnstrom Stage, etc.) have been proposed in rehabilitation (Fugel-Meyer, 1975), (Demeurisse, 1980). The training using the developed system improved Fugl-Meyer Evaluation and Brunnstrom Stage (Furusho, Koyanagi, Imada et al., 2005).



(a) Pre-treatment (b) Post-treatment

Fig. 10. Movable Range in Picture-Mask-Erasing.

At present we have started to evaluate the relationship between some kinds of training using EMUL and cortical activation during operation in joint research with Dr. Ichiro Miyai, Morinomiya Hosipital in in Osaka (Jin, Kikuchi, Haraguchi, Miyai et al., 2007). Figure 11 shows an experimental scene in which a subject operates EMUL and his cortical activation are measured using Near-infrared spectroscopic (NIRS) topography.

Fig. 11. EMUL and NIRS.

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4. 6-DOF Rehabilitation System for Upper Limbs including Wrists "Robotherapist"

4.1 Introduction

We have developed Robotherapist, which is a 6-DOF force display system for upper limbs including wrists (Furusho, Hu, Kikuchi et al., 2006). The system can measure positions and postures of an operator's hand, and generate a large force sense including the wrist torque to the operator. This system enables efficient rehabilitation trainings, which focus on the harmonic movement of the whole upper limb. Robotherapist was exhibited at ``The Prototype Robot Festival at the 2005 International Exposition held in Aichi Prefecture, Japan'' (See Fig. 12).

Fig. 12. Rehabilitation system "Robotherapist".

4.2 Mechanism of Robotherapist

A structure of Robotherapist can be divided into two mechanism groups: one is for positioning of an operating part (3-DOF) and another is for posturing of it (3-DOF). ER actuators drive all of 6-DOF.

A: Mechanism for positioning of an operating part

Figure 13 shows the mechanism for the positioning. As seen from this figure, Robotherapist has 2-DOF for a horizontal rotation and 1-DOF for a vertical movement in arm parts. Actuators for arm motions are set on a base in order to reduce the inertia of the moving parts. Link2 is a parallel link mechanism. A counter-balance weight compensates a gravity-effect of these links in all posture.

B: Mechanism for posturing of an operating part

The mechanism for posturing has 3-DOF; that is, roll, pitch and yaw rotation. Generally, a heavy weight of an end-effecter impairs smooth acceleration of operation. Additionally, such a weight is very risky when the end-effecter collides with the operator. Therefore, the operating part was designed as light as possible. Actuators for the operating part are placed near Link1, and a torque of each actuator is transmitted to it by driving shafts and wire-pulleys systems.

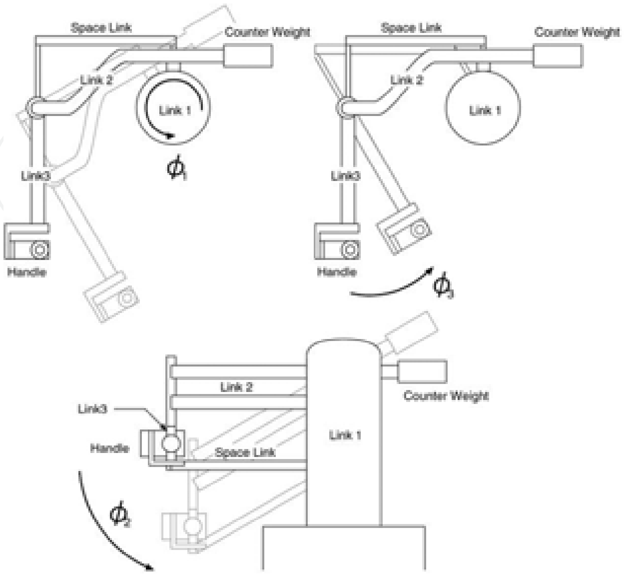

Fig. 13. Configuration of Robotherapist.

4.3 Application Software of Robotherapist

We have also developed application software of Robotherapist for upper limb rehabilitation that includes upper limb's harmonic movements. Important viewpoints for the rehabilitation training software are as follows;

1. Many movements using the shoulder, the elbow, and the wrist harmonically are included.
2. The sense of amusement is needed for long-term training.
3. The recovery degree of upper limbs function can be evaluated properly.

The developed applications are the following four kinds.

A: Water Supply (see Fig. 14)

The operator grasps a handgrip of a watering pod and gives water to the ground. The amount of the water, which comes out of the pod is calculated according as a tilt of the pod, and flower blooms gradually grow up according to the quantity of the given water. The goal of this game is making flower blooms on the whole ground. The system gives the operator a force depending on the tilt and the weight of residual water in the pod. The operator has to cooperate his shoulder, elbow, and wrist, in order to control the position and the tilt of the pod.

B: Window Sweep (see Fig. 15)

At first whole area of the window is masked in white. The operator grasps a wiper and removes the white mask. If the mask is removed, a picture appears in the window. When the wiper is pressed on the window, the reaction force from the window is given to the operator. In order to remove the white mask efficiently, it is necessary to control not only the position but also the posture of the wiper. Therefore, the operator should move his shoulder, elbow, and wrist harmonically.

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Fig. 14. Water supply.

Fig. 15. Window sweep.

C: Squash & Block Break (see Fig. 16 & Fig. 17)

These two games have a same concept. The operator strikes back a ball with a racket, and make the ball hit targets. Breaking all targets is the goal of these games. When the ball hits the racket, a sense of impulse is given to the operator. In Squash, the targets are panels. If the ball hits a panel several times, the panel will disappear and the picture over the panel appears. In Block Break, the targets are spherical blocks. When a block is hit the ball or other blocks, the block vibrates. If the ball hits a block several times, the block will disappear like the case of Squash.

In these games, the operator is required controlling the posture of the racket in order to strike back the ball well. Moreover, it is required to move a whole upper limb quickly, and much amusement nature is included.

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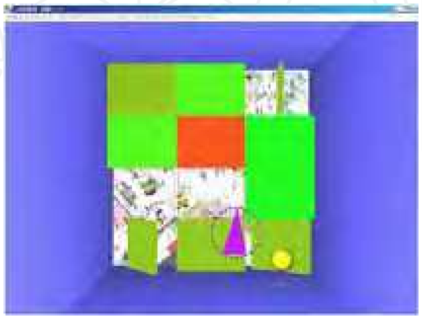

Fig. 16. Squash.

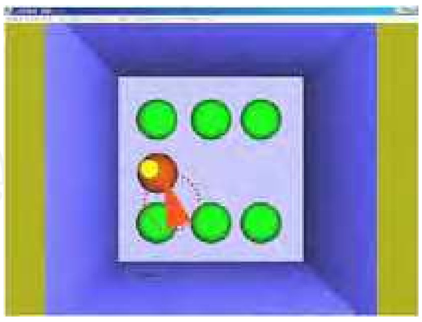

Fig. 17. Block break.

4.4 Application Software of Robotherapist Based on PNF Techniques

Furusho Laboratory of Osaka Univ. and Prof. Kunihiko Oda of Osaka Electro-Communication Univ., Dept. of Physical Therapy are developing the evaluating software developed for the rehabilitation of patients suffered from cerebellum malfunction based on Proprioceptive Neuromuscular Facilitation (PNF) techniques (Furusho, Kikuchi, Oda et al., 2007), (Kikuchi, Furusho, Oda et al., 2007).

A: Rhythmic Stabilization

Figure 18 shows the image of Rhythmic Stabilization, and Figure 19 shows the graphics of Rhythmic Stabilization. As shown in Fig. 18 and Fig. 19, a therapist gives each force from random directions quickly to the hand of a patient. And then the patient is instructed to maintain the position of his/her hand. In Rhythmic Stabilization, therapist want to know whether a patient can maintain the position of his/her hand, and how strong the force is, and which direction he is weak in.

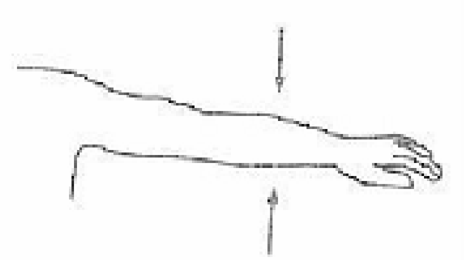

Fig. 18. Image of rhythmic stabilization.

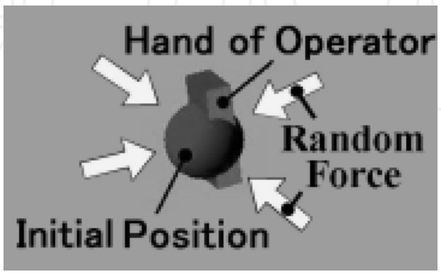

Fig. 19. Display of rhythmic stabilization.

B: Finger Nose Finger (FNF)

As shown in Fig. 20 and Fig. 21, a patient repeats the movement between therapist's finger and his/her nose under the expected orbit. In FNF, therapist would judge recovery degree of patient by his/her movement.

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Fig. 20. Image of FNF.

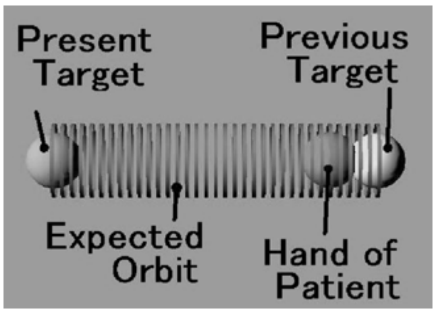

Fig. 21. Display of Finger Nose Finger.

C: Arc Exercise with GUR

In PNF, a therapist gives opposite force to patient in order to guide patient's hand in the desired direction. Then the patient resists the force from the therapist and knows which the desired direction is. We name this technique "Guidance Utilizing Reaction". As shown in Fig. 22, a patient extends his/her arm and moves his/her handle just on the arc orbit. When he moves it along the orbit, there is no force. Otherwise when the handle is away from the given orbit, the patient can sense force to his/her body.

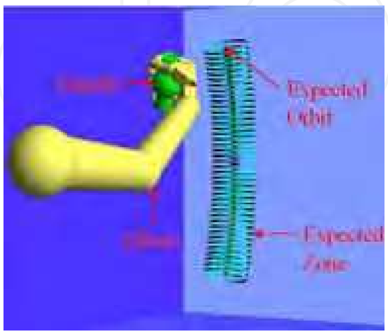

Fig. 22. Display of Guidance Utilizing Reaction.

5. Quasi-3-DOF rehabilitation System “PLEMO”

5.1 Introduction

In general, therapists make the rehabilitation program based on an inspection and a measurement of 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. Recently, Evidence Based Medicine (EBM) is required strongly in the field of rehabilitation. Therefore robot-aided rehabilitation is expected to quantify the effect of rehabilitative activities.

As shown in section 3 and 4 of this chapter, we developed 3-D rehabilitation system for upper limb “EMUL” and 6-DOF rehabilitation system “Robotherapist”, and conducted clinical test. EMUL and Robotherapist adopted to use ER actuators and clutch mechanism for its actuation part. This mechanism makes these systems so safe and back-drivable. However, they have disadvantages in cost, because this system became enlarged to realize the force-feedback in large 3-D space. A system which is more compact and better for maintenance should be required for practical use.

To meet the demands above, we developed new haptic device which has 2-DOF force-feedback function in working plane but its working plane can be adjusted by the inclination of the table. We named this system “Quasi-3-DOF Rehabilitation System for Upper Limbs” or “PLEMO” (shown in Fig. 23) (Kikuchi, Furusho, Jin et al., 2007) (Kikuchi, Hu et al., 2007). PLEMO was developed to realize quantitative evaluation of the rehabilitation training for patients with spasticity after stroke. In this section, we describe the mechanism of PLEMO and its software for upper limb rehabilitation.

Fig. 23. Quasi-3-DOF rehabilitation system “PLEMO”: Horizontal state (left) and slanted state (right).

5.2 ER Brake

Using ER fluid as working fluid, we construct electrically controllable brake (ER brake) with high-performance (good rapidity and repeatability of brake torque) (Kikuchi, Furusho et al., 2003). We use this brake for the force generators of new rehabilitation system (force-feedback system).

Figure 24 show the sectional view and appearance of the brake. As shown in the left drawing of Fig. 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 brake torque with the change of the fluid. Piston mechanism works for the prevention of liquid spill with the expansion of the fluid. We can control the brake torque form 0.1 [Nm] to 4.0 [Nm] with applied electric field from 0.0 [kV/mm] to 3.0 [kV/mm]. Additionally, response time of torque is several milliseconds.

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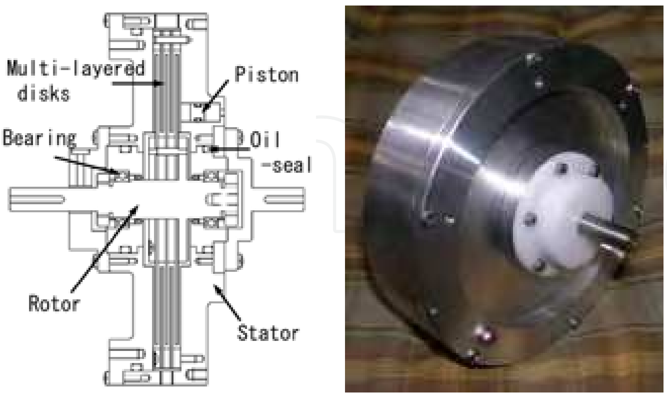

Fig. 24. ER Brake: sectional view (left) and picture (right).

Figure 25 shows a passive force display using ER brakes (IEEE Virtual Reality 2001) in previous research (Furusho, Sakaguchi et al., 2002). In the research, we established control methods with a passive force display system on 2-D space. On the basis of this technology, we developed basic structure and control method of PLEMO.

Fig. 25. Passive force display using ER brakes

5.3 Quasi-3-DOF Rehabilitation System for Upper Limbs, "PLEMO"

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We developed a new haptic device with the two ER brakes shown in Fig. 26. 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". 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 rehabilitation trainings. This system is safe for human because it uses only brakes. Force control unit consist of the two ER brakes and the brake torque generates output-force on a handle through a parallel linkage.

Figure 27 is a structure and signal flow chart of this system. Working area of PLEMO is 0.6 [m] (W) * 0.5 [m] (D). Adjustable angle of the inclination is from -30 to 90 degrees. Plemo-P1 realizes from vertical training to horizontal training by only one system. Total size of the system is 1.0 [m] (W) * 0.6 [m] (D) * 0.7 [m] (H), except for the display. This is similar to the size of general desks. Not to use any actuator contributes to make this system more compact, simple, and reasonable for cost.

Fig. 26. PLEMO.

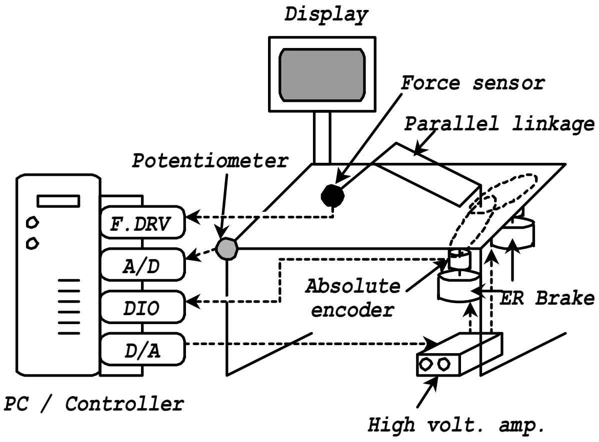

Fig. 27. Structure and signal flow of PLEMO.

5.4 Software of PLEMO

We develop a rehabilitation software shown in Figure 28. This is a tracking test program. An operator grips the handle and moves it to track a target ball. The position of operating handle is displayed as red sphere. The target ball is moving along the target track. White zone in this figure means smooth area without any force-feedback. Blue zone means sticky area; operator feels virtual force like moving his hand in the 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 the output files and we can evaluate accuracy of poison and velocity, range of motion, cognitive faculty and so on. We should make decision of the training protocol and evaluating method depending on the symptom of patient individually.

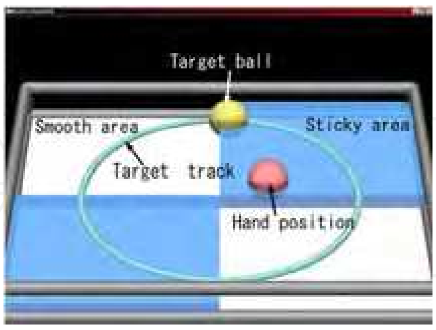

Fig. 28. View of tracking test.

6. Intelligently-Controlled Prosthetic Ankle Joint Using MR Fluid

MR fluid is the non-colloidal solution mixed with ferromagnetic metal particles whose diameter is several millimetres. It is a kind of functional fluid changing viscosity (about several milliseconds in response) of its appearance according to the magnitude of the magnetic field.

All prosthesis users need "foot" part. This part moves so frequently and widely that it needs to be as light as possible. It also must be silent and strong because it is used in daily life. If stiffness or spring characteristics of prosthesises can be changed according to the timing of walking and dorsiflection can be kept adequately, it will be much easier for users to walk and run.

A lot of intelligent prosthetic knees have been developed and are sold on the market. But none of prosthesis that can control the ankle was on the market.

Figure 29 shows an example of a prosthetic "foot" part. It is composed of a prosthetic ankle joint and a foot-ankle unit. Energy of movement stored at the elastic part (rubber) of the prosthetic ankle joint is relieved when kicking, producing driving force. This rubber can also absorb shocks when the heel hits on the ground, and changing the angle smoothly.

After kicking back, a leg leaves from the ground and swings forward during swing phase. Then the rubber goes back to its balanced midpoint, which makes the ankle turns from the dorsal direction instantly (deflecting a tiptoe upward, as shown in Fig. 29 (a)) to the plantar direction (swaging a tiptoe underneath, as shown in Fig. 29 (c)).

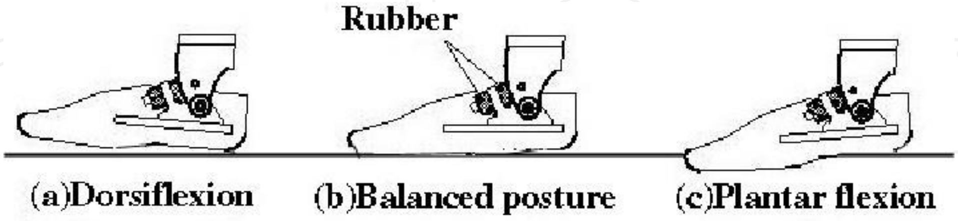

Fig. 29. Prosthetic foot.

Since there is a problem that the tiptoe of the prosthesis tends to collide on the ground (see Fig. 30), users have to walk paying attention to lifting legs in order not to tumble. This is why users walk unnaturally causing to use unnecessary energy. To solve this problem, we suggest setting a linear brake at "foot" part.

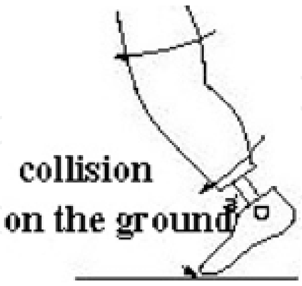

Fig. 30. Walking appearance of prosthetic foot during swing phase.

The MR (Magnetorheological) fluid has been used for the linear brakes. Figure 31 shows a schematic of MR Linear Brake (MRLB). MRLB consists of a piston composed of two rods, a bobbin sandwiched by the rods on both sides, and MR fluid inside a cylinder. When electric current is applied to the coil which rolls the bobbin, magnetic field is generated in loops as follows; Bobbin→MR fluid→Cylinder→MR fluid →Bobbin.

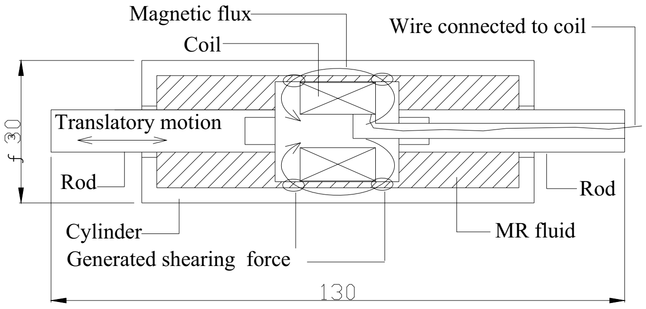

Fig. 31. Construction of MR Linear Brake.

We developed two prototypes of the intelligent prosthetic ankle joint using MR brakes (Furusho, Takesue et al., 2004), (Li, Furusho et al., 2006), (Li, Tokuda, Furusho et al., 2006). Figure 32 shows the 2nd prototypes. Figure 33 and Figure 34 show the series of static images extracted from moving images of the walking experiments. Circles around the ankle in these figures show the test subject's left leg (a swinging leg).

Fig. 32. 2nd prototype.

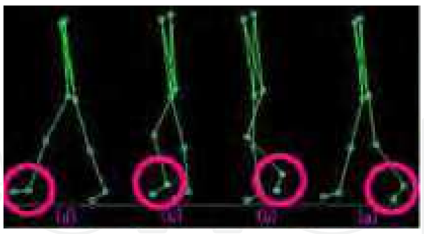

Fig. 33. Walking positions with brake control.

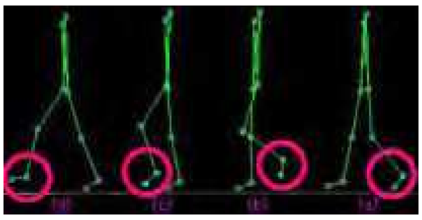

Fig. 34. Walking positions without brake control.

The subject's impressions of experiments with 2nd prototype are as follows: "I felt easier to walk by keeping dorsiflexion. I didn't care the total weight only for some hours, but if I use it in my daily life all day, it will be a load for me ".

7. Intelligent Ankle-Foot Orthosis with Shear-type MR Fluid Brake

Recently, as habits of people has changed, stroke patients tend to increase. There are many cases of the hemiplegia as aftereffects of a stroke. Stroke patient with hemiplegia show difference in the degree by a part and a range of a lesion caused by a disease, however rehabilitation is indispensable to restore functional disorder of lower limbs. We are developing intelligent ankle-foot orthoses using shear-type MR fluid brakes in a 3-year NEDO project (2006~2008)(Furusho, Li et al., 2007), (Furusho, Kikuchi et al., 2007).

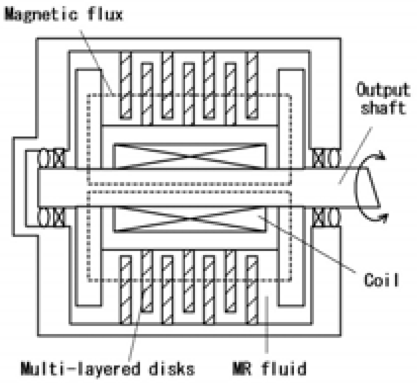

Fig. 35. Structure of MRB.

Figure 35 shows a conceptual illustration of shear-type MR fluid brakes. A coil rolled round a shaft give an MR fluid a magnetic field. Scroll number of coils and spindle diameter are decided by performing magnetic field analysis. As for materials of each part, magnetism materials are used in a magnetic circuit part. In addition, a housing is made of a nonmagnetic body, to avoid the magnetic flux from leaking.

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Fig. 36. Ankle-Foot Orthosis.

Figure 36 shows the second Prototype of intelligent ankle-foot orthosis using the shear-type MR fluid brake. We obtain the maximum torque of 24 [Nm] with the idling torque of 0.1[Nm]. We use four sensors: potentiometer on the ankle, 6-axis force-torque sensor at the center of a foot bottom, a moment of bending sensor and an acceleration sensor on the prop part of an orthosis side.
We divide a walking step into four; into heel reaching the ground, tiptoe reaching the ground, heel leaving ground, tiptoe leaving ground (see Fig. 37). These states are detected by using the above sensors, and then the brake torque is controlled in accordance with each state.

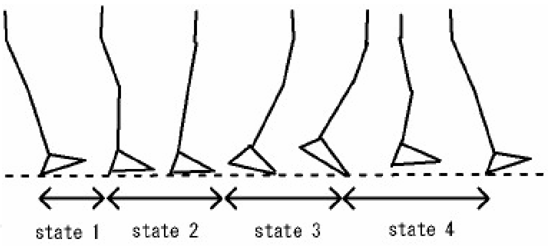

Fig. 37. Walking State.

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8. Conclusion

High safety rehabilitation systems using functional fluid were introduced. Two units of EMUL were made in the 5-year NEDO project, and they were transferred from NEDO to Furusho Laboratory of Osaka University. We continue clinical evaluation of 3-D rehabilitation system and quasi-3-DOF rehabilitation system by using EMUL, Robotherapist and PLEMO.
We have been studying rehabilitation robotics mainly from the standpoint of mechatronics and virtual reality. Now, we started to study it also from the standpoint of physical therapy and motion control of human beings.

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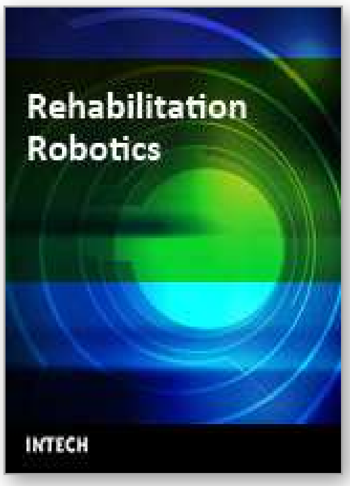

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The coupling of several areas of the medical field with recent advances in robotic systems has seen a paradigm shift in our approach to selected sectors of medical care, especially over the last decade. Rehabilitation medicine is one such area. The development of advanced robotic systems has ushered with it an exponential number of trials and experiments aimed at optimising restoration of quality of life to those who are physically debilitated. Despite these developments, there remains a paucity in the presentation of these advances in the form of a comprehensive tool. This book was written to present the most recent advances in rehabilitation robotics known to date from the perspective of some of the leading experts in the field and presents an interesting array of developments put into 33 comprehensive chapters. The chapters are presented in a way that the reader will get a seamless impression of the current concepts of optimal modes of both experimental and ap- plicable roles of robotic devices.

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Phone: +86-21-62489820
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