Passive-type Rehabilitation System for Upper Limbs Which Can Display the Exact Resistance Force in the Orientation Opposite to Hand Motion

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Abstract—**In these days, there are many patients with ataxia, which is paralysis caused by a brain stroke or asynergia. Early detection of functional deterioration and sufficient rehabilitative training are necessary for these patients. Rehabilitation support systems for upper limbs using force display devices are expected to quantify the effects of rehabilitative training and enhance the motivation of patients. The application of passive-type force display devices unactuated by motors is especially desirable for its high safety. There are, however, some orientations and positions for which it is difficult to display force in an unactuated force display systems using only passive elements. To solve this problem, a method for the improvement of controllability using larger number of brakes than the degree of freedom of system had been suggested. This method made it possible to display more various force power and orientations than could be done with previous systems. However, the system with the larger number of brakes often become huge system. In this study, we have developed a rehabilitation system for the upper limbs which use only the same number of brakes as the degree of freedom but can display the resistance force in the orientation opposite to operator's motion in any orientations and link posture: "Neo-PLEMO".**

I. Introduction

In Japan, there are currently 1.37 million patients with brain strokes, and most of them have motor function disorders as after effects. As the country's population grows older, the number of brain stroke patients and hence the number of people who have motor function disorders will increase. It is an important social issue to provide them with adequate rehabilitation environments. In particular, since the large correlation between the recovery of upper limb function and Activities of Daily Living (ADL) has been pointed out and since recent neurorehabilitation has indicated that the plasticity of the brain could recover motor functions even in patients with chronic disorders, it is expected that the method and continuation of rehabilitation of the upper limbs will become more important than previous time.

In addition, in the field of rehabilitation, Evidence- Based Medicine (EBM) has been strongly demanded [1]. Rehabilitation equipment using robotics technologies and virtual reality technologies can make the quantitative evaluation of rehabilitation training easier. The equipment also enables a variety of types of training by improving training methods, unlike ordinary training done by doctors or therapists. This variety would contribute to the enhancement of patient motivation.

The force display devices used in these systems can be classified into two types: self-actuated devices with force generators including actuators such as motors, and unactuated devices with passive components such as brakes and dampers.

Self-actuated force display devices can provide various trainings by controlling the actuator. Some rehabilitation system with self-actuated force display devices have been developed. Krebs et al. have developed planar upper-limb rehabilitation support system "MIT-MANUS" driven by motors and a number of clinical tests were performed [2]. Ball et al. have developed planar upper-limb rehabilitation support system "MEDARM" [3]. MEDRAM has several unique features as their exoskeleton and cable-driven actuation mechanism. These self-actuated systems, however, when unexpected motion due to run-away of software or electronic circuits, could cause harmful risk to operators. The complexity and high price of these systems are also a problem.

In contrast, unactuated force display devices provide force sensing by generating the resistance force against the operator's input. Although the variety of training may be limited compared to the self-actuated type, it can ensure mechanical safety and provide a large force rather easily. It can also be used to develop compact and low-cost systems. Furusho et al. have developed such upper-limb rehabilitation support systems as the PLEMO-Series [4] (Conceptual illustration of training with PLEMO is shown in Fig.1).

Unactuated force display systems cannot, however, generate force by themselves and need an original control method to display a virtual object. There are also some handle positions or motion orientations with which it is difficult to provide a force sense. To solve these problems, Davis and Book reported that using larger number of brakes than the degree of freedom of system could improve the operability of unactuated devices [5], so we developed a force display system with larger number of ER (Electrorheological) fluid brakes [6] than the degree of freedom , and examined its force display performance to confirm that the introduction of the larger number of ER fluid brakes could lead to superior force display performance [7][8].

However, the system with the larger number of brakes has the problem that it often become huge system. In this paper, we

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introduce new system which can display the resistance force opposite to operator's motion in the arbitrary orientations and link posture. This system use only two (the same number of brakes as the degree of freedom) ER fluid brakes for force generation, so become compact. Moreover, We conduct a force display experiment to show the effectiveness of the system. We then introduce training software in order to improve coordination of movement using Neo-PLEMO.

II. Introduction of Unactuated Force Display System in Rehabilitation Training for Upper Limbs

A. Unactuated Force Display System

With the self-actuated type system, accidents may occur due to system errors and improper use. Unactuated systems are, in contrast, safe because handles or arms are always passive. Even if control systems or digital circuits malfunction, no harmful force is applied to the user.

We have been developing force display systems that use brakes. These systems are the PLEMO-Series (PLEMO-P-Prototype, PLEMO-P1, PLEMO-P2, PLEMO-P3, PLEMO-P4, PLEMO-Y). The system that we first developed is the 2-D force display device PLEMO-P-Prototype (Virtual Reality Society of Japan Paper Award Winner) [4] . Based on this system, we developed quasi- 3D rehabilitation support systems, PLEMO-P1 and PLEMO-P2 (joint research with Hyogo College of Medicine). And we conducted practical application, developed PLEMO-P3 and PLEMO-P4. On PLEMO-P3 and PLEMO-P4, several tests with hemiplegic subjects were performed to evaluate the effectiveness of these systems [9]. PLEMO-Y was developed toward a practical use with support from the project of Ministry of Economy, Trade and Industry in 2011. Now, we are improving PLEMO-Y to place this system on the market in fiscal 2013.

We consider to construct the rehabilitation program by using unactuated display system such as PLEMO-Series. In order to use unactuated systems, users must be able to move their arms by themselves. Unactuated rehabilitation support systems for upper limbs therefore target patients in Brunnstrom Recovery Stage [10] (BRS) III or higher (III-VI). The BRS emphasizes synergy movement that develops during recovery from hemiplegia.

B. Training by Using Unactuated Force Display System

Training in the treatment of motor disorders due to neurological diseases is different from ordinary training in physical skills, such as sports training. Because, in motor-disorder training, undamaged nerve control circuits are facilitated to learn (compensate) the lost skills instead of the damaged nerve circuits. For physical disorders, physical therapy is conducted mostly for the recovery of basic activities.

It is reported that the motor function disorder of hemiplegia patients due to brain stroke includes coordination disorder and muscle performance disorder [11]. Here, coordination means physical motion that is smoothly made for its purpose with no wasted motion. There is a report stating that coordination consists of three basic elements: spacing to adjust orientation, timing to adjust time, and grading to adjust force[5]. We need to design a rehabilitation program for training to help patients recover from disorders in action coordination and muscle performance.

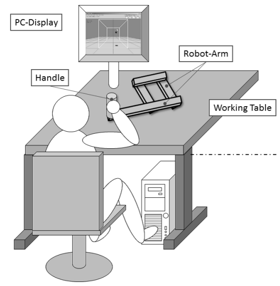

Fig. 1. Training Scenery with PLEMO

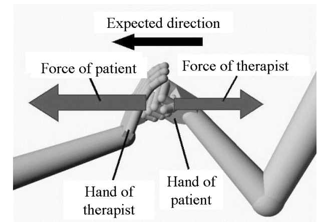

Fig. 2. Guidance Utilizing Reaction Training

We use an essentially safe unactuated force display system to realize rehabilitation training that takes account of the above-mentioned three elements of coordination, i.e., spacing, timing and grading. An example is the training giving resistance force to an operator's hands. In terms of spacing, timing and grading, the following training can be considered:

i) For improvement of the spacing function, resistance force in orientation opposite to the operator's motion accurately guides the operator into the required motion trajectory. This method uses the fact that the patient tries to move following resistance force. For patients at a low recovery level who cannot easily follow guidance by using resistance force, a strong blocking guidance is used for correcting motion by using brakes against unwanted motion for guiding motion orientation.

ii) For improvement of the timing function, the patient makes a reciprocating motion between two targets in rhythm at a fixed time interval. Sensing a light force, patients who are not able to move easily would find an orientation to move in and adjust their motion.

iii) For the improvement of the grading function, the patient moves at a fixed speed along a trajectory with changing resistance force. To keep the speed constant, the patient has to adjust force against changing resistance force.

In Proprioceptive Neuromuscular Facilitation (PNF) which is one of physical therapy techniques, a therapist gives weak opposite force to patient in order to guide patient's hand in the desired orientation (Fig.2). Then the patient resists the force from the therapist and knows which the desired orientation is. Here, the guidance force must be given weakly enough to sense the desired orientation not to prevent the motion. On the other hand, if operator's hand moves in the wrong orientation, no force or strong blocking force is applied.

In this case, unactuated rehabilitation system must be able to produce the force at least in the orientation oppsite to patient's hand movement. Unactuated systems, however, generally have a problem in that they cannot produce resistance force with some handle positions or motion orientations. We will describe this problem and solution in the next section.

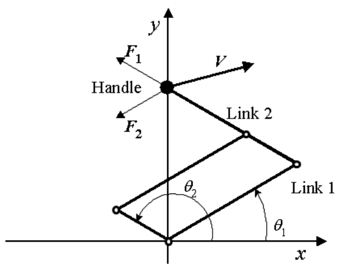

Fig. 3. Two-link parallel linkage system

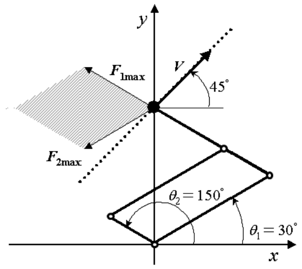

Fig. 4. Example of bad posture and orientation of handle movement for force display

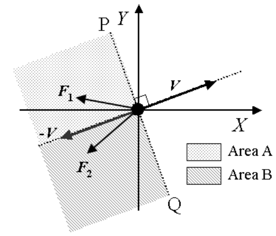

Fig. 5. A posture enabled to display force

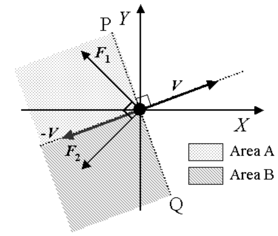

Fig. 6. Situation where two brakes cross at right angle

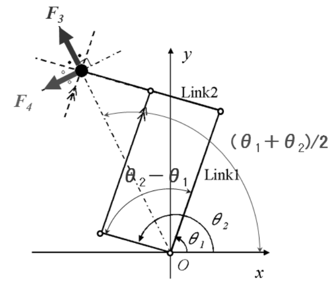

Fig. 7. Two additional brakes: F_3, F_4

III. Improvement of the Mechanical Characteristics of the Unactuated Force Display System

A. Problem of Unactuated Force Display System

As will be necessary for the following discussion, let us clearly define "direction" and "orientation." *Orientation* is a vector from a start point to an end point and is illustrated by an arrow. *Direction* is a straight line that lies on the orientation vector and is used with no concern about orientation. Namely, orientation and its opposite orientation have the same direction. Direction is illustrated by a straight line.

The unactuated force display system can only provide resistance force against the operator's input force. We here consider a two-dimensional system, the parallel linkage mechanism, shown in Fig. 3. For simplicity, we suppose that links 1 and 2 have the same length and we employ an absolute coordinate system, i.e., xy-coordinates with the origin at one end of link 1. Brake 1 acts for angle θ_1 of link 1 and brake 2 for angle θ_2 of link 2, where angles are defined as positive in the counterclockwise direction. When motion vector V of the handle is given as illustrated in Fig. 3, the resistance force vector at the handle produced by brake 1 (hereafter called the brake force vector) is F_1 and that by brake 2 is F_2. F_1 and F_2 are parallel to links 2 and 1 respectively. The orientation of F_1 and F_2 changes depending on the orientation of V.

We consider moving of the handle to a 45° orientation with link position (θ_1 = 30° and θ_2 = 150°) as shown in Fig. 4. Let the maximum brake force vector produced by brake 1 be F_{1max} and that by brake 2 be F_{2max}. Resistance force can only be produced within the area between them (shaded area in Fig. 4). The unactuated system therefore cannot provide resistance force in the orientation opposite to the orientation of V when having a certain handle motion (V) or a certain link orientation.

From the viewpoint of rehabilitation in the physical therapy mentioned in the previous section, it is important to produce force accurately in the orientation opposite to the patient's motion. In other words, it is necessary to circumvent a situation in which the system cannot provide force in the orientation opposite (-V) to the patient's motion. We solve this problem in the next subsection.

B. Solution with Introduction of Another Brakes

Using Fig. 5, we consider what brake force vectors are necessary to produce force in the orientation of -V. A (X,Y) coordinate system with its origin on the handle is shown in Fig. 5. The straight line passing through points P and Q in Fig. 5 is a line perpendicular to motion vector V of the handle. Force on the half plane on the V vector side of the straight line cannot express brake force and force on the other half plane has to be used. We divide this other half plane by the line along the V vector into two areas: Areas A and B.

If brake force vectors lie in each of Areas A and B as shown in Fig. 5, they can be combined to make force in the orientation of -V. Therefore, if the two brake force vectors F_1 and F_2 are perpendicular to each other as in Fig. 6, one of them is always in Area A and the other is in Area B and the system can always produce force in the orientation of -V.

In order to satisfy this situation, we introduce another two brake force; F_3 (that bisects angle $\theta_2 - \theta_1$) and F_4 (that bisects angle $180° - (\theta_2 - \theta_1)$) (see Fig.7). As seen in Fig. 7, if rotation angle $\theta_2 - \theta_1$ is constrained, the motion in the F_3 direction is constrained, so if we apply brake torque to rotation angle $\theta_2 - \theta_1$, we can produce force in the F_3 direction. In the same way in Fig. 7, if the rotation angle $\theta_1 + \theta_2$ is constrained, the motion in the F_4 direction is constrained and so, if we apply brake torque to rotation angle $\theta_1 + \theta_2$, we can produce force in the direction.

As shown in Fig. 8(a), for example, a brake (Brake 3) is placed on the origin with one link being connected to the brake axis and the other link to the brake itself. This can be used as a clutch. This can then apply brake torque to relative angle $\theta_2 - \theta_1$ of the two links, producing F_3. Also, for example, we may place a linear guide as illustrated in Fig. 8(b) and constrain rotation of the linear guide axis by using the brake (Brake 4) placed on the origin. This allows us to constrain central angle

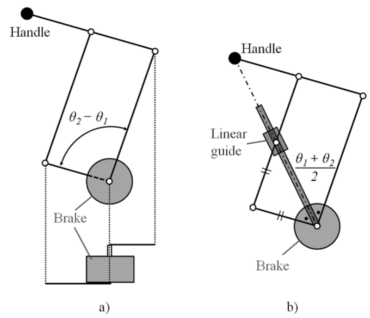

Fig. 8. Example of brake setting

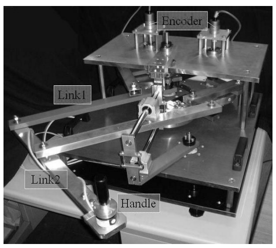

Fig. 9. Overview of 2-D Unactuated Force Display System with the Larger Number of Brakes "Redundant-PLEMO"

Fig. 10. Overview of quasi-3-D Unactuated Force Display System with Two Brakes "Neo-PLEMO"

Fig. 11. Quasi-3D mechanism of Neo-PLEMO

$(\theta_1 + \theta_2)/2$ of the two links, i.e., $\theta_1 + \theta_2$, producing F_4. We can thus consider various mechanisms that produce F_3 and F_4.

If using the above all four brakes (Brake 1-4), the system can display not only force in the orientation of -V but also force in the orientations inclined at the constant angle from -V. We developed Redundant-PLEMO with four brakes (see in Fig.9) [8]. System using larger number of brakes than the degree of freedom , however, become enlarged, so we will use only the same number of brakes as the degree of freedom, i.e., brake 3 and brake 4. Because F_3 and F_4 are always perpendicular to each other, the system can always produce force in the orientation of -V.

IV. Quasi-3D Unactuated Rehabilitation System for Upper Limbs "Neo-PLEMO"

A. Outline of Mechanism of Neo-PLEMO

Neo-PLEMO, the quasi-three-dimensional rehabilitation support system for upper limbs, is shown in Fig. 10. Quasi-three-dimensional system has two degrees of freedom but its work plane can be tilted (see in Fig.11). Worm gear was adapted to incline the work table. Worm gear has self-lock mechanism and high reduction ratio.

Fig.12 shows the core structure of Neo-PLEMO. A parallel link structure is employed and links 1 and 2 have the same length of 550 mm. ER fluid brake 3 is mounted to work as a clutch on the relative angle ($\theta_3 = \theta_2 - \theta_1$) between link 1 and link 2. ER fluid brake 4 works against the central angle ($\theta_4 = (\theta_1 + \theta_2)/2$) through the sub-link and linear guide.

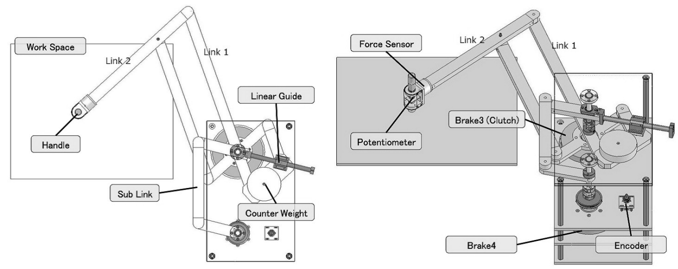

Fig. 12. Mechanism of Neo-PLEMO (CAD)

A handle is attached to the end of the parallel link mechanism. Working space of Neo-PLEMO is 600 wide mm, 500 deep mm. Origin of working space is set to (X,Y)=(-550 mm,150 mm). The user controls the handle while watching the PC display.

We set the graphic coordinate system (X_G,Y_G) with its origin on the origin position of working space. Two incremental encoders were used to measure angles of both link 1 and link 2. A 6 axial force sensor was attached to the handle. The sensor was used to measure multi-axis wheel force. Brake control and graphic display were performed on a single PC. ART-Linux allowed us to do real time control.

With the parallel link mechanism, which has little abrasion and is close to a direct drive mechanism, and highly-responsive ER fluid brakes, the system has superior force display performance. The system is also compact and inexpensive without brake 1 and brake 2.

B. ER Fluid Brake

Neo-PLEMO uses ER fluid brakes [6] to produce force. The ER fluid brake consists of electrodes and ER (electrorheological) fluid encapsulated between them. ER fluid is a functional fluid whose apparent viscosity is changed by applying an electric field. The shear stress of ER fluid, almost independent of shear velocity, can be accurately controlled by the applied electric field. The response speed is very high, about several milliseconds.

ER fluid brakes (see Fig.13) used for the unactuated rehabilitation support system for upper limbs, PLEMO-P1, has a problem in that sufficient torque is available only under a high electric voltage, so Furusho's group, in collaboration with ER tec Co., Ltd., developed a new ER fluid brake with superior characteristics. Fig. 14 shows the newly-designed ER fluid brake. The diameter is 188 mm and the height, including the rotational axis, is 85.9 mm. As shown in Fig. 14, application of an electric field between the fixed cylinder and the rotational cylinder generates brake torque. Polystyrene sulfonate particles and fluorine oil solvent are used for ER fluid. For this ER fluid brake, we adopted a multi-layered cylinder structure so that the gap between the electrodes, which had been 1 mm, became 0.5 mm. We also succeeded in suppressing the base viscosity of the

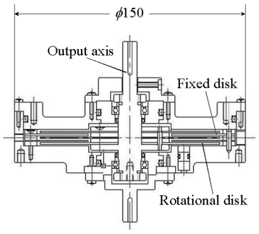

Fig. 13. Structure of previous ER fluid brake of PLEMO-P1

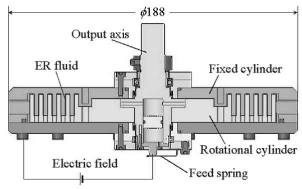

Fig. 14. Structure of novel ER fluid brake of Neo-PLEMO

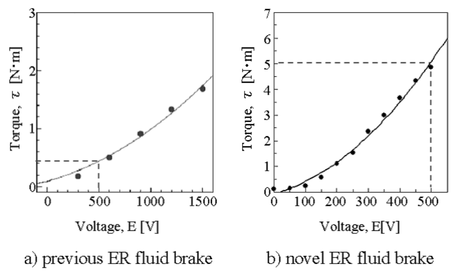

Fig. 15. Characteristics of previous and novel ER fluid brakes

fluid, while keeping its high torque under the applied electric field, by lowering the concentration of ER fluid. Characteristics test results of the ER fluid brake used in the PLEMO-P1 are shown in Fig. 15(a) and those of the ER fluid brake used in the present study are shown in Fig. 15(b).

As seen from Fig. 19(b), the newly-developed ER fluid brake produces a large torque with a low voltage applied. PLEMO-P1 with brake characteristics shown in Fig. 19(a) uses a belt pulley system to increase brake torque, while the present system does not need speed reduction and can provide superior force sensing.

Also as seen from Fig.13, the brake of PLEMO-P1 has a multi-layered disk structure and change in the disk shape changes the gap between electrodes, which results in unstable brake torque. In contrast, the brake used in the present system in Fig.14 has a multi-layered cylinder structure, which is machined from a single piece of material, and the inter-electrode gap does not change much, resulting in stable brake torque.

The new ER fluid brake can produce sufficient torque with a voltage 1 kV or lower and has advantages in safety, cost and operability in comparison with the previous type. Since the brake still uses high voltage, however, it is necessary to ensure not only mechanical safety but also electrical safety. For electrical safety, we grounded the high-voltage power supply and every ER fluid brake. An isolation circuit is also installed between the high-voltage power supply and the control PC to protect the PC from counter electric current from the power supply in case of runaway.

C. Control System of Brakes

Our system employs the following control method in order to provide the force in the orientation of -V. First, we consider a case in which handle motion velocity and two brake forces are oriented as indicated in Fig.16. Among brake forces, the

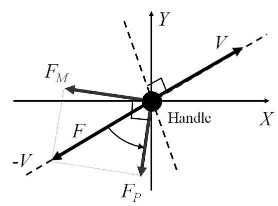

Fig. 16. Brake torque control system

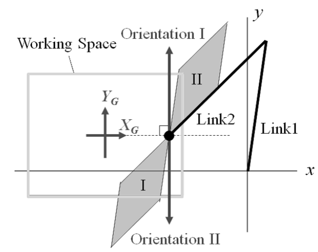

Fig. 17. Orientations of the handle for Basic Property Test

one that is located at a positive angle from -V is called F_P and the one that is located at a negative angle is called F_M. (Which F_3, or F_4 they correspond to changes depending on the situation.) The angle between F_P and -V is β [rad]. If we choose the force to have the following magnitude, we could produce resistance force F against arbitrary handle motion force:

$$|F_P| = |F|\cos\beta, |F_M| = |F|\sin\beta \qquad (1)$$

We can obtain the magnitude of brake force ($|F_3|$, $|F_4|$) from Eq.(1). Even when V changes, we just need to adjust brake forces according to Eq.(1). We do not have to make a rapid change of voltage to brakes, but just make continuous change in voltage load.

V. Basic Property Test

We will verify that Neo-PLEMO always can display the force in the orientation of -V. With the link posture shown in Fig. 17, if the handle is operated toward y orientation (Orientation I shown in Fig.17), the conventional unactuated system can display only forces within the area I, but cannot display the force in the orientation of -V. As well as the case of Orientation I, when operating the handle toward $-y$ orientation (Orientation II), the conventional unactuated system can display only forces within the area II, but cannot display the force in the orientation of -V.

Figs. 18 and 19 show the test results when moving the handle toward Orientation I and II in Neo-PLEMO. The horizontal axis means graphic handle position Y_G (graphic coordinate system whose origin is set to the center of work plane). Dashed line means angle of desired brake force in the orientation opposite to the handle motion. Straight line means angle of actual brake force measured by the force sensor. Shaded area means the area where Neo-PLEMO can display the brake force.

As can be seen from Fig.18, the measured force angle is close to -90° i.e., the force is oriented to Orientation I. As seen from Fig.19, the measured force angle is close to 90°, i.e. the force is oriented to Orientation II.

VI. Training Software for Coordination

A training program was created to improve coordination of movement introduced in the section II-A. The developed training program aims to improve spacing, timing, and grading of patients.

Reaching software used for spacing is shown in Fig.20. The patient uses the upper limb to move the handle to the

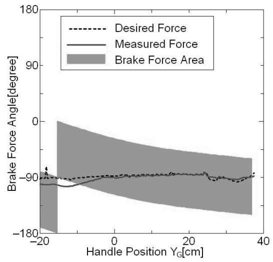

Fig. 18. Experimental data of force display toward the direction I

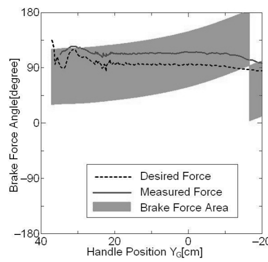

Fig. 19. Experimental data of force display toward the direction II

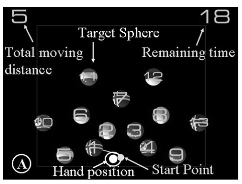

Fig. 20. Reaching software for Spacing Training

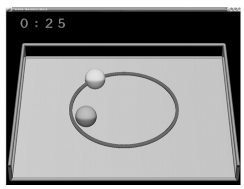

Fig. 21. Tracking software for Timing Training

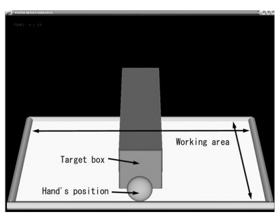

Fig. 22. Virtual sanding software for Grading Training

target (reaching), then the user must return to initial position (pulling). Resistance is used to guide the user to the target position.

Trail-following software was used for timing (Fig.21). The user moves the handle to move the position of the ball on the screen. The screen shows a target rotating around a circle at constant speed. The user must follow the target. Resistance is also used here to guide the user.

Virtual Sanding Board software was used for grading (Fig.22). The user must push the rectangular solid into the screen. Virtual friction is generated by controlling the electric field. Brake force magnitude $|F|$ [N] of the sinusoid is defined by the following equation:

$$|F| = 10.0\{0.5 + 0.5\sin(2\pi ft)\} \quad (2)$$

where f is the vibration frequency [Hz]. The user feels as if he is pushing a box on top of a Sanding Board. The user must locate and push the front plane of the box, or force feedback is not applied.

VII. Conclusion

In this research, we have studied the following about rehabilitation support systems that used only brakes:

I) We have developed Neo-PLEMO, a rehabilitation support system for upper limbs that uses only two brakes, which can display the force in the orientation opposite to patient's motion in any situation for the exact direction guidance training. We have employed a parallel link mechanism causing little abrasion, i.e., a mechanism similar to a direct drive mechanism, and have used highly responsive ER fluid brakes. With these, the system shows superior force display performance.

II) We have made a force display test of the present system. By calculating the magnitude of each brake force and controlling brake, we have shown Neo-PLEMO can produce the resistance force in the orientation opposite to the handle motion.

III) We have developed three training programs in order to improve coordination of movement. Each developed training program aims to improve spacing, timing, and grading of patients.

References

[1] Miyai, I., Yagura, H., Oda, et al., "Premotor Cortex is Involved in Restoration of Gait in Stroke", Annals of Neurology, Vol.52, No.2, pp.188-194, 2002.

[2] Krebs, H.I., et al., " A paradigm shift for rehabilitation robotics", Engineering in Medicine and Biology Magazine, IEEE, Vol.27, No.4, pp. 61-70, 2008.

[3] Ball, S.J., Brown, I.E. and Scott, S.H., "A planar 3DOF robot exoskeleton for rehabilitation and assessment", Proceedings of the 29th Annual International Conference of the EMBS, pp.4024-4027, 2007.

[4] Furusho, J., Kikuchi, T. and Haraguchi M., "Development of Rehabilitation Systems for Upper Limbs: EMUL,Robotherapist, and PLEMO," Assistive Technology Research Series, IOS Press, Vol.28, pp. 84-92, 2011.

[5] Davis, H. and Book, W., "Torque Control of a Redundantly Actuated Passive Type Force Manipulator", Proc. of the American Control Conference, pp.959-963, 1997.

[6] Furusho, J., Sakaguchi, M., Takesue, N. and Koyanagi, K., "Development of ER brake and its application to passive type force display", Journal of Intelligent Material Systems and Structures, Vol.13, No.7/8, pp.425-429, 2002.

[7] Furusho, J., Jin, Y., Oda, K., et al., "A Performance Evaluation Method of a Passive Type Force Display and Rehabilitation System with Redundant Brakes", Proc. of the 2009 IEEE 11th international conference on Rehabilitation Robotics, pp.950-955, 2009.

[8] Haraguchi, M., Kobayashi, H., Inoue, A. and Furusho, J., "A Development of 2-D Force Display System with Redundant Low-voltage Driving ER Fluid Brakes (in Japanese)", Journal of the Society of Rheology, Japan, Vol.38, No.2, pp.99-105, 2010.

[9] Ozawa, T., Furusho, J., Kikuchi, T.,Fukushima, K., Tanida, S. and Fujikawa, T., "Development of Rehabilitation System for Upper Limbs: PLEMO-P3 System for Hemiplegic Subject (Motor Function Test for Assessment and Training, and Research for Development of Practical Type)", Journal of Robotics and Mechatronics, Vol.25, No.1, 2012.

[10] Brunnstrom, S., "Movement therapy in hemiplegia; A neurophysiological approach", Medical Dept., Harper & Row,; First Edition edition, 1970.

[11] Mochizuki, H., "Impairments and Their Assessment in Stroke Patients", The Journal of Physical Therapy Science, Vol.22, No.1, pp.33-38, 2007.

[12] Fukui, T., Inoue, K. and Tsunehisa, K., "Development of the Apparatus for Hand Coordination's Evaluation - Simultaneous Evaluation of Spacing, Timing, and Grading Functions", Kawasaki Medical Welfare Journal, Vol.11, No.1, pp.205-209, 2001.

[13] Bossis, G. ed., Proc. of the 10th International Conference on Electrorheological Fluids and Magnetorhealogical Fluid Suspensions, World Scientific, 2007.

[14] Reed, M.R. and Book, W. J., "Modeling and Control of an Improved Dissipative Passive Haptic Display", Proceedings of the 2004 IEEE International Conference on Robotics & Automation, pp.311-318, 2004.