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Paper:

2-D Force Display System with Redundant ER Fluid Brake Aimed at Rehabilitation Support System for Upper Limbs

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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 systems are expected to quantify the effects of rehabilitative training and enhance the motivation of patients. The application of a passive-type force display system is especially desirable for its high safety. There are, however, some directions and positions for which it is difficult to display force in a passive-type force display system using only passive elements. To solve this problem, a method for the improvement of controllability using redundant brakes had been suggested. This method made it possible to display more various force power and directions than could be done with previous systems. In this study, we have developed a redundant-brake rehabilitation system for the upper limbs: Redundant-PLEMO-1.

Keywords: ER fluid, rehabilitation, upper limbs, redundancy, passive force display

1. Introduction

In Japan, there are currently 1.37 million patients with brain strokes [1], 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 [2] 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 [3]. Rehabilitation equipment [4–6] 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.

In this situation, various rehabilitation support systems for upper limbs have been developed [7–13]. The force display devices used in these systems can be classified into two types: active-type devices [7–10] with force generators including actuators such as motors and passive-type devices [11–13] with passive components such as brakes.

Active-type force display devices can provide various force senses by controlling the actuator. Unexpected motion due to run-away of software or electronic circuits could, however, cause harmful risk to operators. The complexity and high price of these systems are also a problem.

In contrast, passive-type 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 active 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. has developed such upper-limb rehabilitation support systems as the PLEMO-P series (P-Prototype, P1, P2, P3) [14–17].

Passive-type force display systems cannot, however, generate force in a passive manner 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 the use of a redundant number of brakes could improve the operability of passive-type devices [12], so we developed a force display system with a redundant number of ER fluid brakes and examined its force display performance to confirm that the introduction of a redundant number of ER fluid brakes could lead to superior force display performance [18].

In the present study, based on the knowledge obtained in these research efforts, we developed Redundant-PLEMO-1, a rehabilitation support system for upper limbs using a redundant number of ER fluid brakes. In this article, we describe the functions required for upper-limb rehabilitation support systems, the properties of passive-type force display systems, and an outline and evaluation of Redundant-PLEMO-1 developed based on this knowledge. We then conduct a force display experiment to show the effectiveness of the system.

2. Introduction of Passive-Type Force Display System in Rehabilitation Training for Upper Limbs

2.1. Setting Index for Upper-Limb Rehabilitation Training

Training in the treatment of motor disorders due to neurological diseases is different from ordinary training in physical skills because, in motor-disorder training, an undamaged nerve control circuit is facilitated to learn an unusual method of physical control. For physical disorders, physical therapy is conducted mostly for the recovery of basic activities.

It is reported [19] that the motor function disorder of hemiplegia patients due to brain stroke includes coordination disorder and muscle performance disorder. 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 direction, timing to adjust time, and grading to adjust force [20]. We need to design a rehabilitation program for training to help patients recover from disorders in action coordination and muscle performance.

2.2. Training by Using Passive-Type Force Display System

In this section, we use an essentially safe passive-type 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:

a) 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 trainee tries to move following resistance force. For patients at a low recovery level who cannot easily follow guidance by using resistance force, a blocking guidance is used for correcting motion by using brakes against unwanted motion for guiding motion orientation.

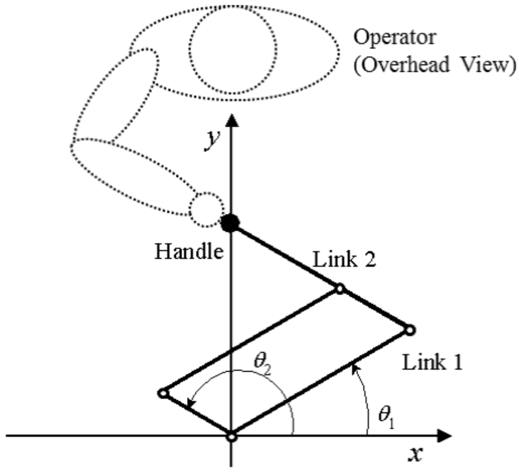

Fig. 1. Two-link parallel linkage system.

b) For improvement of the timing function, the trainee 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.

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

Passive-type systems, however, 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.

3. Improvement of the Mechanical Characteristics of the Passive-Type Force Display System Using Redundant Brakes

3.1. Problem of Passive-Type 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 passive-type 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. 1**. 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 $\boldsymbol{V}$ of the handle is given as

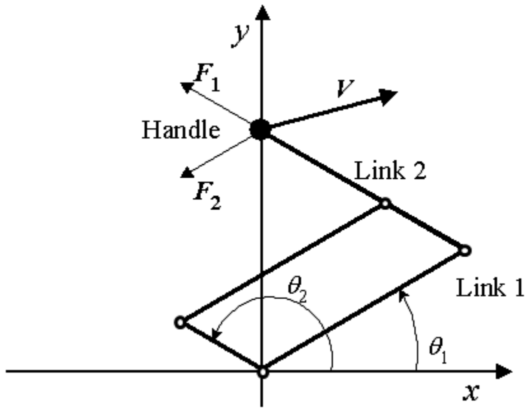

Fig. 2. Force direction of the linkage system.

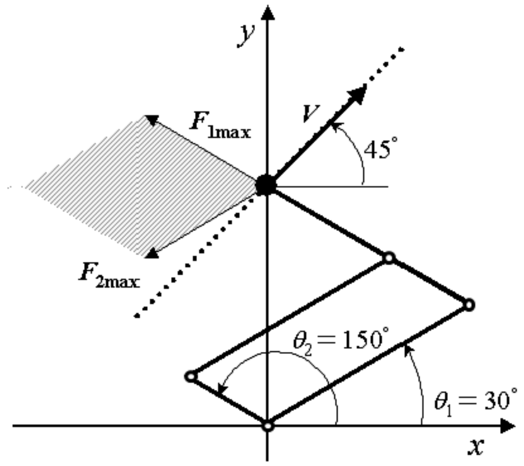

Fig. 3. Example of poor posture and orientation of handle movement for force display.

illustrated in **Fig. 2**, the resistance force vector at the handle produced by brake 1 (hereafter called the brake force vector) is $\boldsymbol{F_1}$ and that by brake 2 is $\boldsymbol{F_2}$. $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are parallel to links 2 and 1 respectively. The orientation of $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ changes depending on the orientation of $\boldsymbol{V}$.

We consider moving of the handle to a 45° orientation with link position ($\theta_1 = 30°$ and $\theta_2 = 150°$) as shown in **Fig. 3**. Let the maximum brake force vector produced by brake 1 be $\boldsymbol{F}_{1\max}$ and that by brake 2 be $\boldsymbol{F}_{2\max}$. Resistance force can only be produced within the area between them (shaded area in **Fig. 3**). The passive-type system therefore cannot provide resistance force in the orientation opposite to the orientation of $\boldsymbol{V}$ when having a certain handle motion ($\boldsymbol{V}$) 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 trainee's motion. In other words, it is necessary to circumvent a situation in which the system cannot provide force in the orientation opposite ($-\boldsymbol{V}$) to the trainee's motion. We solve this problem by introducing a redundant number of brakes, which is more than the number of degrees of freedom.

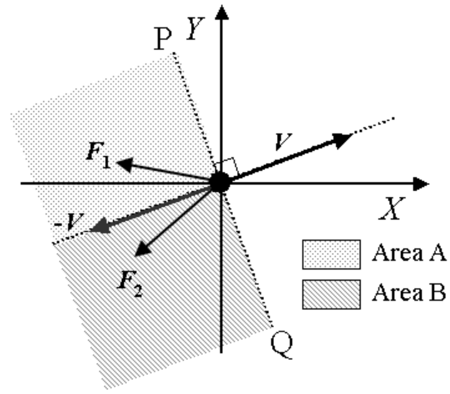

Fig. 4. Posture enabled to display force.

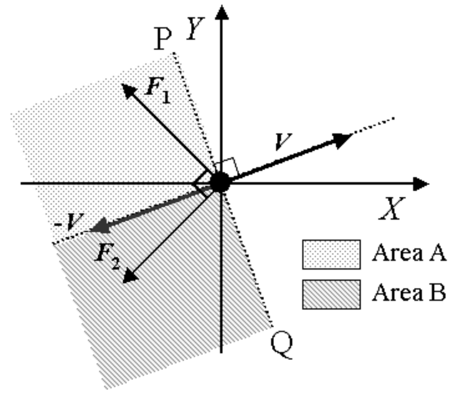

Fig. 5. Situation in which two brakes cross at right angles.

3.2. Solution with Introduction of Redundant Brakes

Using **Fig. 4**, we consider what brake force vectors are necessary to produce force in the orientation of $-\boldsymbol{V}$. A (X,Y) coordinate system with its origin on the handle is shown in **Fig. 4**. The straight line passing through points P and Q in **Fig. 4** is a line perpendicular to motion vector $\boldsymbol{V}$ of the handle. Force on the half plane on the $\boldsymbol{V}$ 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 $\boldsymbol{V}$ vector into two areas: Areas A and B.

If brake force vectors lie in each of Areas A and B as shown in **Fig. 4**, they can be combined to make force in the orientation of $-\boldsymbol{V}$.

If the two brake force vectors $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are perpendicular to each other as in **Fig. 5**, 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 $-\boldsymbol{V}$. If, however, the two brake force vectors $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are not perpendicular to each other as in **Fig. 6**, both of them may be in Area A in some cases where the system cannot produce force in the orientation of $-\boldsymbol{V}$, but if we add an appropriate brake force, e.g., $\boldsymbol{F_R}$ in **Fig. 6**, Areas A and B both have at least one brake force and the system can always produce brake force in the orientation of $-\boldsymbol{V}$. We write the acute angle between $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ as ϕ_a and the obtuse

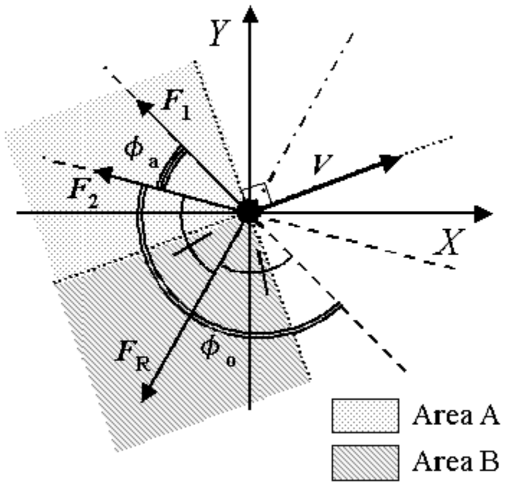

Fig. 6. Merit of adding additional brake force.

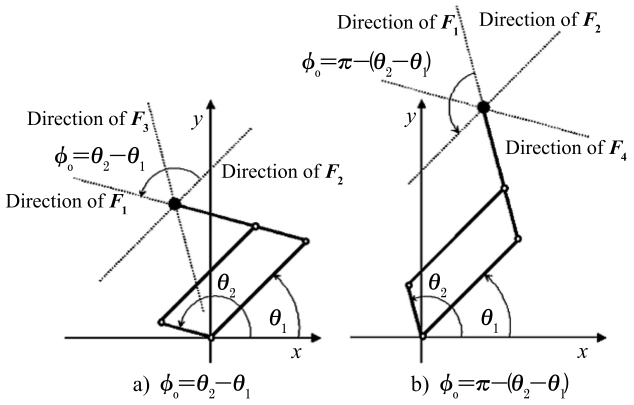

Fig. 7. Direction of force.

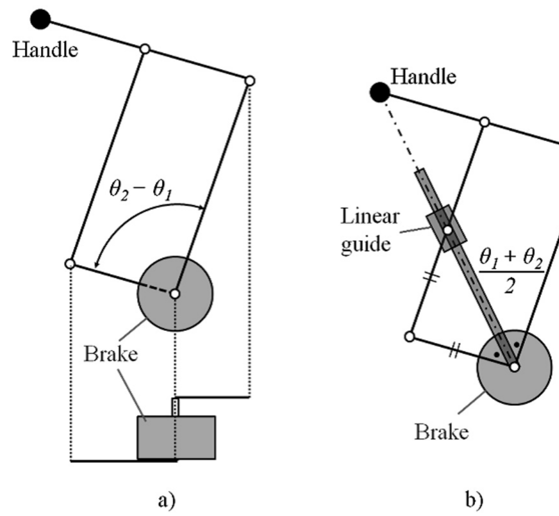

Fig. 8. Example of brake setting.

angle between them as ϕ_o. $\boldsymbol{F_R}$ in **Fig. 6** is chosen in the direction of the bisector of obtuse angle ϕ_o (indicated by the double-line arc in the figure) between $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$. If chosen in this manner, $\boldsymbol{F_R}$ always stays in Area B irrespective of the magnitude of ϕ_o.

3.3. Relation Between Redundancy and Link Posture

Next, we consider the relation between redundancy and link posture. With the link posture in **Fig. 7(a)**, for example, angle $\theta_2 - \theta_1$ is obtuse, so we have $\phi_o = \theta_2 - \theta_1$. If we add $\boldsymbol{F_R} = \boldsymbol{F_3}$ that bisects angle ϕ_o, we could always produce force in the orientation opposite to handle motion orientation by combining the three forces $\boldsymbol{F_1}$, $\boldsymbol{F_2}$, and $\boldsymbol{F_3}$. With the link posture in **Fig. 7(b)**, however, angle $\theta_2 - \theta_1$ is acute ($\phi_a = \theta_2 - \theta_1$) and its complementary angle is obtuse, so we have $\phi_o = \pi - (\theta_2 - \theta_1)$ and need to add brake force $\boldsymbol{F_R} = \boldsymbol{F_4}$ that bisects angle ϕ_o.

As shown above, the necessary redundant brake changes depending on the link posture, and if we have four brake forces, we could always produce force in the orientation of $-\boldsymbol{V}$ for any link posture. Since the angle between $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ depends on the link posture, the following brakes are necessary to produce a force in the orientation of $-\boldsymbol{V}$ if handle operation is limited in a certain range:

a) Brakes 1, 2, and 4 when $0 < \theta_2 - \theta_1 < \pi/2$ (**Fig. 7(b)**).

b) Brakes 1 and 2 when $\theta_2 - \theta_1 = \pi/2$ (**Fig. 5**).

c) Brakes 1, 2, and 3 when $\pi/2 < \theta_2 - \theta_1 < pi$ (**Fig. 7(a)**).

The number of additional redundant brakes should be made as small as possible to make the system compact, and it is necessary to examine additional brakes taking account of the necessary force display performance and handle operation range. This issue will be discussed in the next section.

3.4. Brake Mechanism Producing $\boldsymbol{F_3}$ and $\boldsymbol{F_4}$

As seen in **Fig. 7(a)**, if rotation angle $\theta_2 - \theta_1$ is constrained, the motion in the $\boldsymbol{F_3}$ direction is constrained, so if we apply brake torque to rotation angle $\theta_2 - \theta_1$, we can produce force in the $\boldsymbol{F_3}$ direction. In the same way in **Fig. 7(b)**, if the rotation angle $\theta_1 + \theta_2$ is constrained, the motion in the $\boldsymbol{F_4}$ 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 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. 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 placed on the origin. This allows us to constrain central angle $(\theta_1 + \theta_2)/2$ of the two links, i.e., $\theta_1 + \theta_2$, producing $\boldsymbol{F_4}$. We can thus consider various mechanisms that produce $\boldsymbol{F_3}$ and $\boldsymbol{F_4}$.

4. Selection of Redundant Brakes Necessary for Upper-Limb Rehabilitation System

4.1. Problems of Existing Systems

P-TER [12] developed by Davis et al. is a passive-type force display system with two degrees of freedom on the plane having the redundant number of brakes. It uses four electromagnetic brakes to provide force sensing for the system. The brake for rotation angle $\theta_2 - \theta_1$ (brake 3) is introduced between link 1 and link 2 as a clutch. The brake for rotation angle $\theta_1 + \theta_2$ (brake 4) reverses the rotation of link 2 by using three bevel gears, so the brake works as a clutch between this rotation and rotation angle θ_1. Since P-TER uses electromagnetic brakes, however, it has problems such as poor controllability and poor force display performance. It also has a problem of back rush due to bevel gears.

Furusho et al. have developed a highly-controllable system [17, 18, 21] with high-response-speed ER fluid brakes [15]. In their system, brake 3 is used as a clutch between links 1 and 2 as in the system of Davis et al., and brake 4 is made with a belt pulley. Since the brake is attached to the system through the belt pulley, it has little back rush but large abrasion.

4.2. Relation Between Rehabilitation Performance and Redundant Brakes

The system described in Section 4.1 has a complex structure and the cost could be high, so we try to simplify the system from the viewpoint of upper-limb rehabilitation. **Fig. 9** shows areas categorized by a), b) and c) of Section 3.3 where force can always be produced in the orientation of $-\boldsymbol{V}$.

In general, for patients with central paralysis caused, e.g., by a brain stroke, flexion of the elbow joint is rather easy but extension tends to be difficult [22]. They therefore cannot extend the entire arm in many cases, which means that motion in the distal area from the operator, i.e., area with a small y-coordinate, in **Fig. 9** is difficult. To improve force sense display performance in such areas, introduction of the redundant brake 3 would be effective.

In order to clarify this, we consider reach training [23] in **Fig. 10**. Reach training is training moving the trainee's hand to a target to improve the spacing function. **Fig. 10** uses the same coordinates as **Fig. 9** and the upper side of the figure shows the position where the operator is standing. The black circle in **Fig. 10** indicates start point $(0.0, 0.82)$ of the reach motion and white circles are targets. In training, the operator moves the handle from the start point to each target along the trajectory as shown in **Fig. 10**. For this training, we want to produce a resistance force in the orientation opposite to motion by using a passive-type force display system.

Although it is ideal for the operator to move just along the trajectory, even a healthy person might deviate from the straight line. It is therefore necessary to produce force in such a way that the operator's motion is adjusted when it deviates from the line. As shown in **Fig. 11**, for example, it is necessary to produce not only resistance force in the orientation opposite along the ideal trajectory but also force in the orientation opposite to move back to the trajectory. Namely, not only the resistance force of $-\boldsymbol{V}$ but also that slightly angled from $-\boldsymbol{V}$ are necessary.

We made calculations to see if force could be produced in the orientation of $-\boldsymbol{V}$ (**Fig. 12(a)**) and in the orienta-

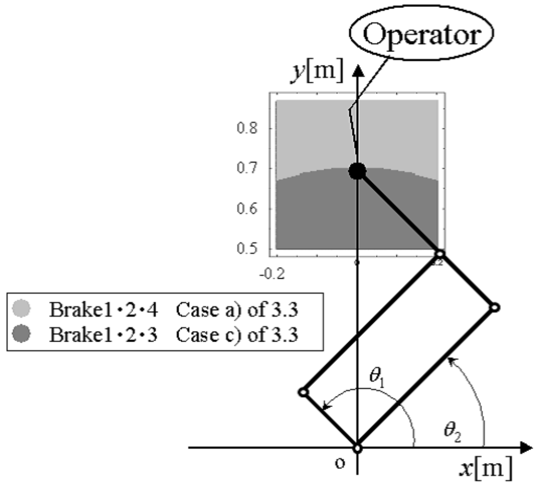

Fig. 9. Area enabled for displaying inverse resistance force.

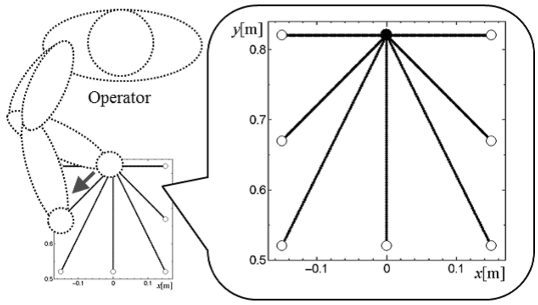

Fig. 10. Trajectory of reach training.

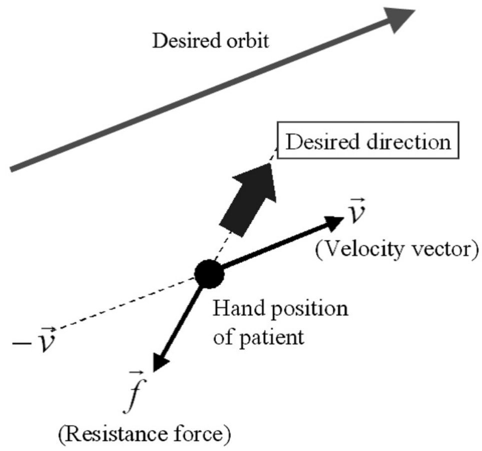

Fig. 11. Guidance to desired orbit.

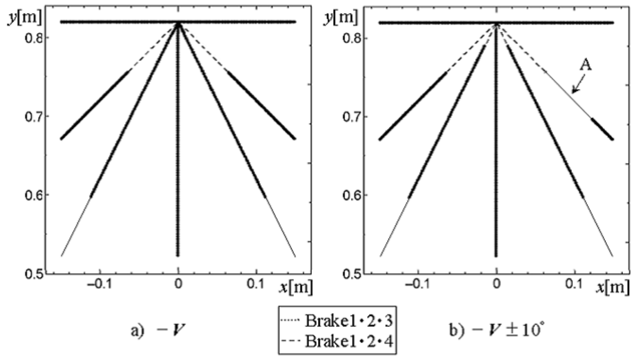

Fig. 12. Area enabled for displaying reach training force.

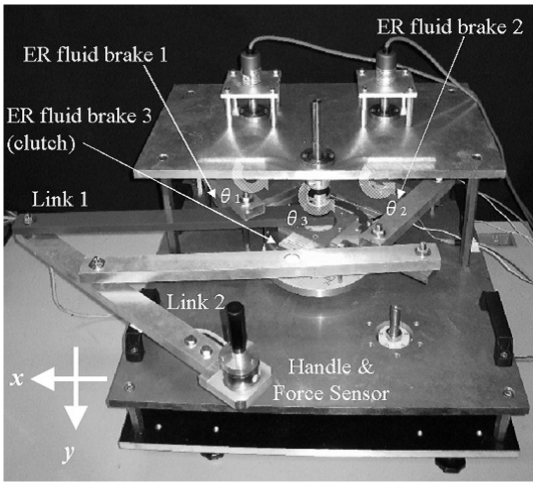

Fig. 13. Rehabilitation system for upper limbs with redundant ER fluid brake: Redundant-PLEMO-1.

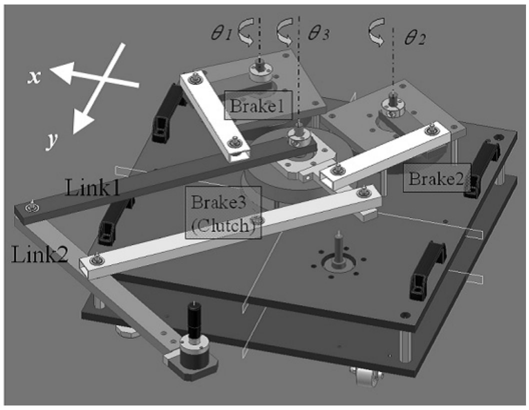

Fig. 14. Brake system of Redundant-PLEMO-1.

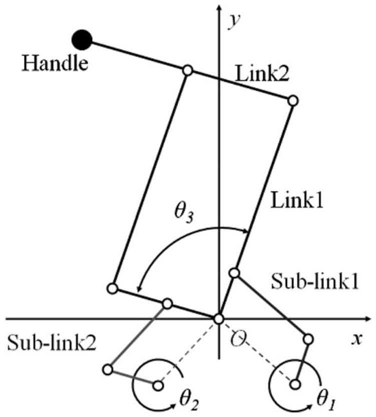

Fig. 15. Coordinate system of brake.

tion angled by $\pm 10^\circ$ from $-\boldsymbol{V}$ (**Fig. 12(b)**) on the reach trajectory. Results are shown in **Fig. 12**. The thick solid line shows the area where wanted force is available without redundant brakes. The thin solid line shows the area where wanted force is available using redundant brake 3 and the dashed line shows the area where wanted forces are available using redundant brake 4. The performance improvement effect of brake 3 and that of brake 4 are independent of each other and the thin solid line and the dashed line do not overlap.

As clearly seen in **Fig. 12(a)**, wanted force cannot be produced in the area close to the operator if brake 3 is used or in the area far from the operator if brake 4 is used. Also from **Fig. 12(b)**, if brake 4 is used, wanted force cannot be produced even in the middle of the second trajectory from the right (indicated by "A" in **Fig. 12(b)**).

Since, as stated in the first half of this section, it is more desirable to produce wanted force in the area distal to the operator, it would be sufficient if only redundant brake 3 is introduced. Since brake 3 can be easily realized by mounting a clutch, it can greatly simplify the mechanism but brake 4 cannot, which is an advantage of brake 3. The two systems presented as examples in Section 4.1 have a complex structure and are relatively large since they have a rotation angle reverse mechanism to mount brake 4. We therefore decided to develop a system that has redundant brake 3 only.

5. Outline of Mechanism of Redundant-PLEMO-1

5.1. Redundant-PLEMO-1

Redundant-PLEMO-1, the two-dimensional rehabilitation support system for upper limbs, is shown in **Fig. 13**. A parallel link structure is employed and links 1 and 2 have the same length of 500 mm.

Figure 14 shows the core structure of Redundant-PLEMO-1. **Fig. 15** shows the core structure in the coordinate system. ER fluid brakes 1 and 2 are attached respectively to link 1 (with angle θ_1) and link 2 (with angle θ_2) through the parallel link mechanism (sublinks 1 and 2, respectively). ER fluid brake 3 (ER fluid clutch) is mounted to work as a clutch on the relative angle ($\theta_3 = \theta_2 - \theta_1$) between link 1 and link 2. 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 4.

In the coordinate system of **Fig. 2**, the link angle vector is $\boldsymbol{\theta} = [\theta_1, \theta_2]^T$, and the handle position vector $\boldsymbol{r} = [x, y]^T$. The relation between $\delta \boldsymbol{r}$ and $\delta \boldsymbol{\theta}$ is given by

$$\delta \boldsymbol{r} = J \delta \boldsymbol{\theta} \quad \ldots \ldots \ldots \ldots \ldots \quad (1)$$

where J is a Jacobian matrix,

$$J = \begin{bmatrix} -L\sin\theta_1 & -L\sin\theta_2 \\ L\cos\theta_1 & L\cos\theta_2 \end{bmatrix}. \quad \ldots \ldots \quad (2)$$

Here, L presents the link length (= 500 mm).

The relation between brake torque vector $\boldsymbol{\tau} = [\tau_1, \tau_2]^T$ and handle force vector $\boldsymbol{F} = [F_x, F_y]^T$ is given by

$$\boldsymbol{\tau} = J^T \boldsymbol{F}. \quad \ldots \ldots \ldots \ldots \ldots \quad (3)$$

Handle force is therefore given by

$$\boldsymbol{F} = (J^T)^{-1} \boldsymbol{\tau}. \quad \ldots \ldots \ldots \ldots \quad (4)$$

$\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ can be obtained from Eq. (4). $\boldsymbol{F_3}$ can be obtained in a similar manner. $\boldsymbol{F_1}$, $\boldsymbol{F_2}$ and $\boldsymbol{F_3}$ are then given by the following:

$$\boldsymbol{F_1} = \frac{\tau_1}{L\sin(\theta_2 - \theta_1)} \begin{bmatrix} \cos\theta_2 \\ \sin\theta_2 \end{bmatrix} \quad \ldots \ldots \quad (5)$$

$$\boldsymbol{F_2} = \frac{-\tau_2}{L\sin(\theta_2 - \theta_1)} \begin{bmatrix} \cos\theta_1 \\ \sin\theta_1 \end{bmatrix} \quad \ldots \ldots \quad (6)$$

$$\boldsymbol{F_3} = \frac{-\tau_3}{L\sin\left(\dfrac{\theta 2 - \theta 1}{2}\right)} \begin{bmatrix} \cos\left(\dfrac{\theta 1 + \theta 2}{2}\right) \\ \sin\left(\dfrac{\theta 1 + \theta 2}{2}\right) \end{bmatrix}. \quad (7)$$

Here, τ_3 is the torque generated by brake 3.

5.2. ER Fluid Brake

Redundant-PLEMO-1 uses ER fluid brakes [15] to produce force. The ER fluid brake consists of electrodes and ER (electrorheological) fluid encapsulated between them. ER fluid [24–27] 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.

Although the ER fluid response speed is several milliseconds, the response speed of the ER fluid brake would not be on the same level. To check brake response speed, we attach an actuator (speed control motor that rotates at a low speed) to the ER fluid brake and measured torque, which is shown in **Fig. 16**. The figure presents the step response characteristic of torque with the electric field applied to the brake changed from 0.9 kV/mm to 1.0 kV/mm. The rise time in which output torque increases to 63% value is about 5 msec irrespective of the strength of the electric field. This high speed response can be obtained if the inertia moment is made sufficiently small.

ER fluid brakes (see **Fig. 17**) used for the passive-type rehabilitation support system for upper limbs with no redundant brake, PLEMO-P1 [16, 17], 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. 18** 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. 18**, 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,

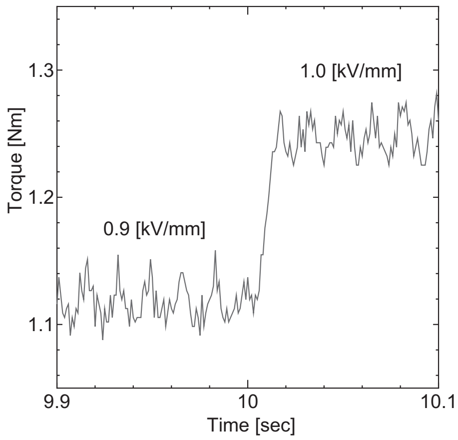

Fig. 16. Output against step input.

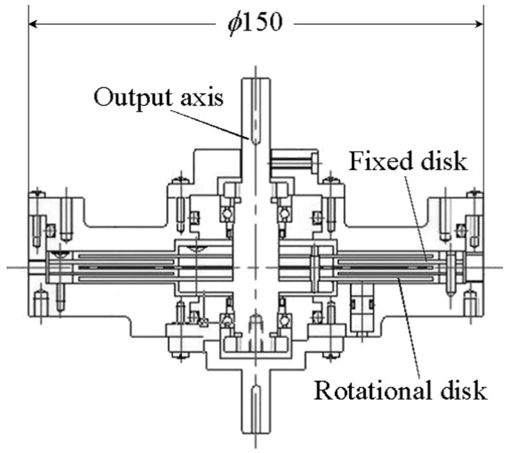

Fig. 17. Structure of previous ER fluid brake of PLEMO-P1.

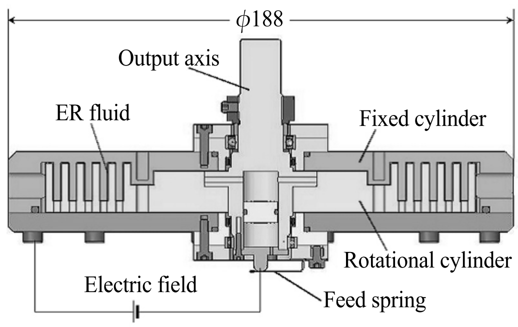

Fig. 18. Structure of novel ER fluid brake.

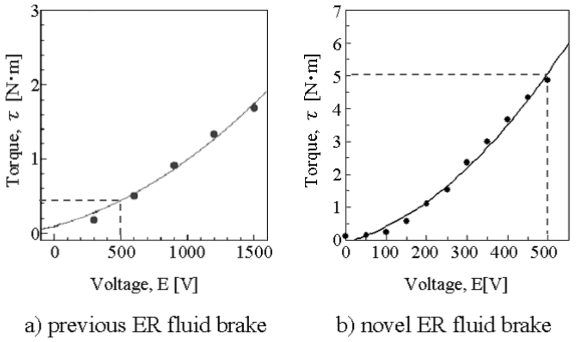

Fig. 19. Characteristics of ER fluid brake.

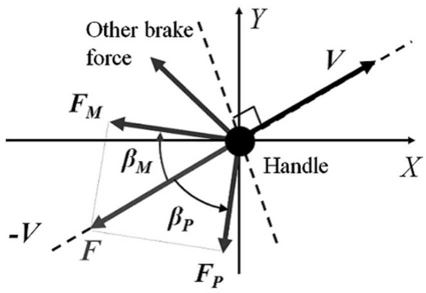

Fig. 20. Brake torque control system.

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 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. 19(a)** and those of the ER fluid brake used in the present study are shown in **Fig. 19(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. 17**, 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. 18** has a multi-layered cylinder structure, which is machined from a single piece of material, and the interelectrode 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.

5.3. Switching Control of Redundant Brakes

Systems that have redundant brakes need to switch brakes. Our system employs the following control method.

First, we consider a case in which handle motion velocity and three brake forces are oriented as indicated in **Fig. 20**. Among brake forces that are closest to the orientation opposite $-\boldsymbol{V}$ to the handle motion velocity, the one that is located at a positive angle from $-\boldsymbol{V}$ is called $\boldsymbol{F_P}$ and the one that is located at a negative angle is called $\boldsymbol{F_M}$. (Which $\boldsymbol{F_1}$, $\boldsymbol{F_2}$, or $\boldsymbol{F_3}$ they correspond to changes depending on the situation.) The angle between $\boldsymbol{F_P}$ and $-\boldsymbol{V}$ is β_P [rad] and the angle between $\boldsymbol{F_M}$ and $-\boldsymbol{V}$ is β_M [rad]. If we choose the force to have the following magnitude, we could produce resistance force $\boldsymbol{F}$ against arbitrary handle motion force:

$$|\boldsymbol{F_P}| = |\boldsymbol{F}|\frac{\sin\beta_M}{\sin(\beta_M+\beta_P)}, |\boldsymbol{F_M}| = |\boldsymbol{F}|\frac{\sin\beta_P}{\sin(\beta_M+\beta_P)}. \quad (8)$$

We can obtain the magnitude of brake force ($|F_1|$, $|F_2|$, $|F_3|$) from Eq. (8) and magnitude of torque necessary for brakes (τ_1, τ_2, τ_3) from Eqs. (5)–(7). Also from the characteristics of the ER fluid in **Fig. 19**, we can calculate the applied voltage necessary for brakes. With this applied voltage, we can produce wanted resistance force $\boldsymbol{F}$.

Even when $\boldsymbol{V}$ changes and necessary brakes are switched, we just need to adjust brake forces according to Eq. (8). We do not have to make a rapid change of voltage to brakes, but just make continuous change in voltage load.

6. Examination of Force Production of Redundant-PLEMO-1 (Simulation)

In this system, the range in which resistance force can be produced changes as the orientation of handle velocity vector $\boldsymbol{V}$ changes. Passive-type force display systems would be superior if various kinds of resistance force were available for a certain $\boldsymbol{V}$.

To evaluate the system performance, we define angle α from the orientation of $-\boldsymbol{V}$ as shown in **Fig. 21**. The area between maximum angle α_1 and minimum angle α_2 is the range in which resistance force can be produced. We present angles α_1 and α_2 on a line along velocity vector $\boldsymbol{V}$ as shown in **Fig. 22**. The thick solid line between maximum angle α_1 and minimum angle α_2 represents the range in which resistance force can be produced. The solid-line circle shows that resistance force is in the orientation of $-\boldsymbol{V}$. Namely, if the thick solid line crosses the solid circle as in **Fig. 22**, resistance force in the orientation opposite to motion can be produced. Dashed-line circles correspond to angles $\alpha = \pm\pi/2$ respectively, which present the limits of the range in which the passive-type

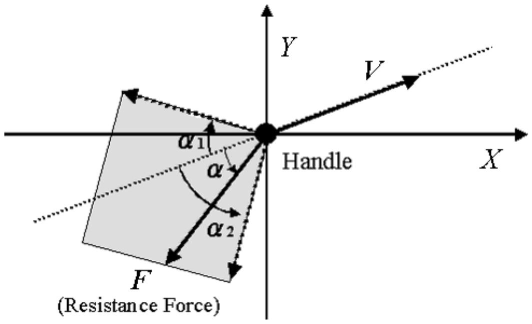

Fig. 21. Definition of angles α_1, α_2.

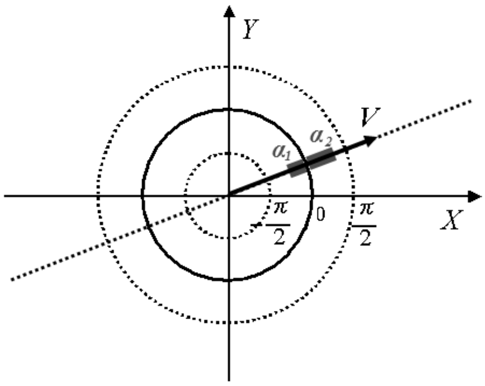

Fig. 22. Angle graph of α_1, α_2.

force display system can produce resistance force.

Furusho et al. used this expression method to evaluate the range in which resistance force can be produced in a passive-type force display system [22]. This evaluation method only shows the range of force, however, not the magnitude, although not only the angle of force but also the magnitude are important for providing force sensing.

For Redundant-PLEMO-1, we therefore calculated the angle range in which resistance force can be produced for a given force magnitude. Results are shown in **Figs. 23–26**. **Figs. 23** and **24** show the angle range in which resistance force of 15 N or higher can be produced and **Figs. 25** and **26** show the angle range in which resistance force of 30 N or higher can be produced. The target magnitude of the resistance force, 15 N and 30 N, was selected according to the clinical knowledge of the physical therapist, one of our collaborators. **Figs. 23** and **25** show the result for brakes 1 and 2 only, and **Figs. 24** and **26** show results for brakes 1 and 2 and redundant brake 3.

The figures present calculation results for five handle positions: $(-0.2, 0.483)$, $(0.2, 0.483)$, $(0, 0.683)$, $(-0.2, 0.883)$, and $(0.2, 0.883)$. Here, we assume an operation range of 400W $\times$ 400D, which we consider sufficiently large for a trainee who moves only the upper limbs and fixes the body trunk (shoulders). The maximum brake torque of each brake is set to 10 N·m.

As seen by comparing **Figs. 23** and **24**, the addition of brake 3 (ER fluid clutch) enlarges the angle range, including the orientation of $-\boldsymbol{V}$, where resistance force can be produced, in the area distal to the operator.

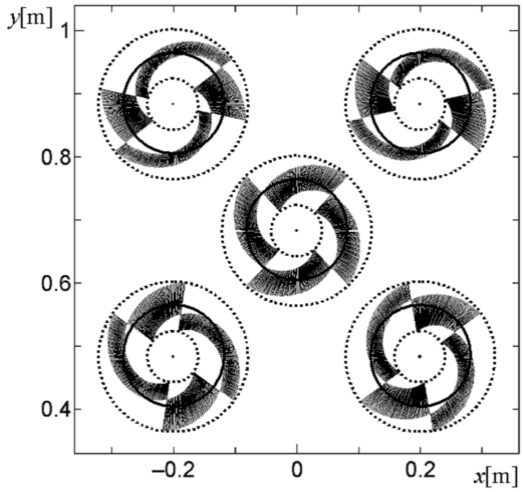

Fig. 23. Angle graph with 15 N and no redundant brake.

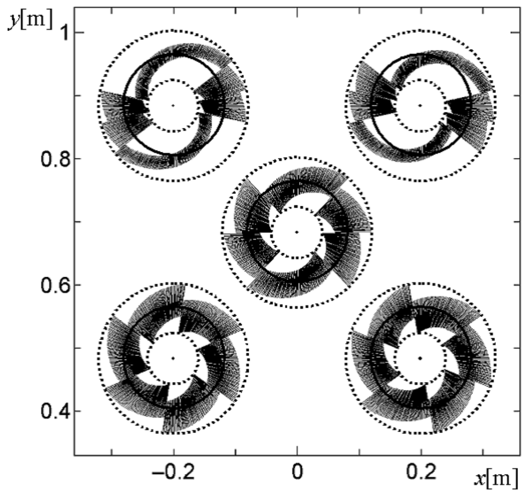

Fig. 24. Angle graph with 15 N and redundant brake.

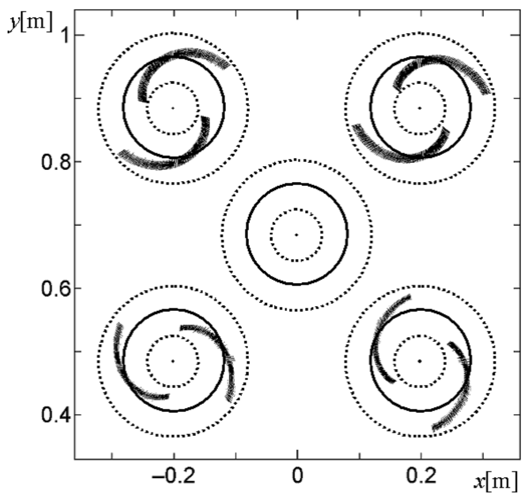

Fig. 25. Angle graph with 30 N and no redundant brake.

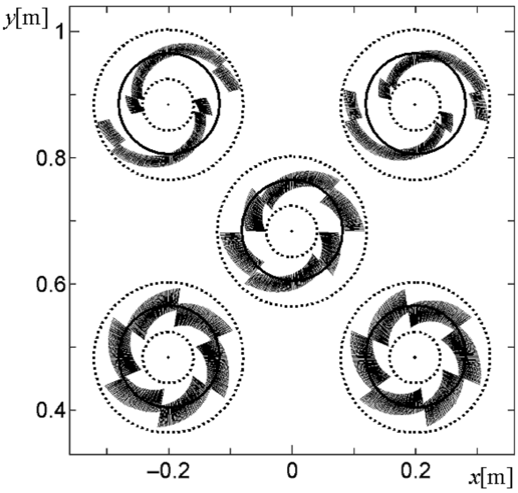

Fig. 26. Angle graph with 30 N and redundant brake.

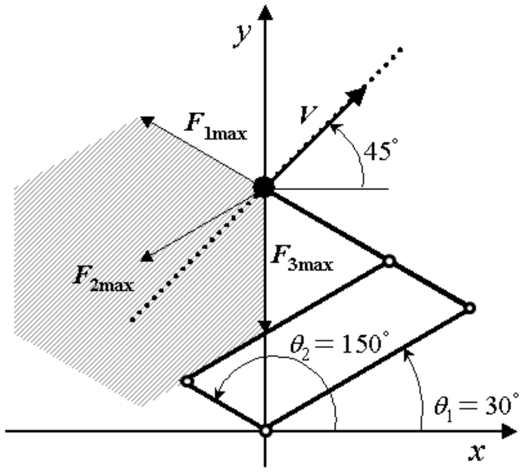

Fig. 27. Example of effect of additional brake.

As seen by comparing **Figs. 25** and **26**, where wanted resistance force is made larger than 30 N, the addition of brake 3 (in **Fig. 26**) enables the system to provide, in the distal area, 30 N force in the angle range including the orientation of $-\boldsymbol{V}$. In **Fig. 25** with no brake 3, however, there are many handle positions or motion orientations with which 30 N force cannot be provided.

We also see by comparing **Figs. 23–26** that, as wanted resistance force increases, the angle range in which force can be produced becomes smaller. From these results, we see that force display performance in terms of orientation and magnitude of resistance force largely improves with the introduction of redundant brakes.

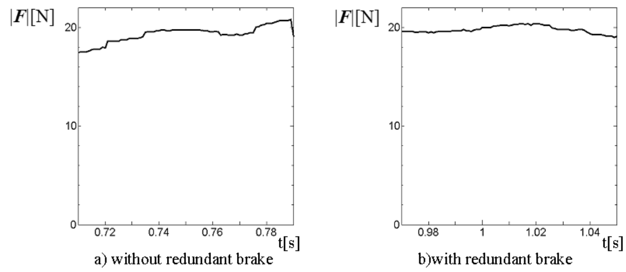

Fig. 28. Results of experiment; magnitude of force.

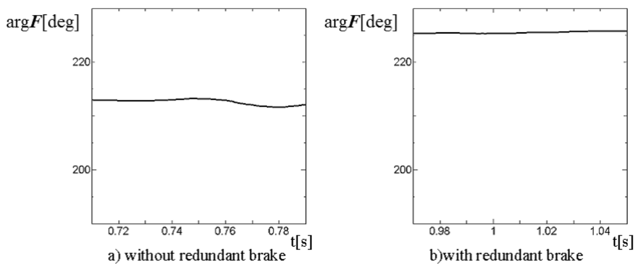

Fig. 29. Results of experiment; orientation of force.

7. Basic Property Test

To check the effect of adding redundant brakes, we made a basic property test of the system. With the link posture and handle motion orientation as illustrated in **Fig. 27**, resistance force $\boldsymbol{F}$ of orientation $-\boldsymbol{V}$ and magnitude 20 N is to be provided.

1) Control method without using redundant brake 3

In an ordinary passive-type force display system without redundant brake 3 (which corresponds to the case of **Fig. 27** without using brake 3, namely to the case of **Fig. 3**), force in the orientation of $-\boldsymbol{V}$ cannot be provided. So we try to provide force in the orientation of $\boldsymbol{F}_2$, which is closest to the orientation of $-\boldsymbol{V}$. Since we know the necessary torque value from Eq. (6), we can calculate the voltage to apply from **Fig. 19**.

2) Control method using redundant brake 3

In the present system, wanted force in the orientation of $-\boldsymbol{V}$ can be provided in the area indicated by the shaded area in **Fig. 27** by using redundant brake 3 (ER fluid clutch). There are three combinations of brakes that provide wanted resistance force: brakes 1 and 3, brakes 2 and 3, and brakes 1, 2 and 3. Here, we select the combination of brakes 2 and 3 that produces brake forces $\boldsymbol{F}_2$ and $\boldsymbol{F}_3$, the force closest to $-\boldsymbol{V}$. We control the handle as mentioned in Section 5.3 and move it in the 45° orientation as shown in **Fig. 27**.

Test results are shown in **Figs. 28** and **29**. We see from **Fig. 28** that either case can produce resistance force of the target magnitude. From **Fig. 29**, we also find that the system without the redundant brake can produce resistance force only in the orientation of $\boldsymbol{F}_2$, as shown in **Fig. 29(a)**, but the system with brake 3 can produce force in the orientation of $-\boldsymbol{V}$ (225°) as in **Fig. 29(b)**.

8. Conclusions

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

1) We have examined the function required for upper-limb rehabilitation and have designed a rehabilitation support system for upper limbs with a redundant number of brakes that satisfied the functional requirement. Systems with fewer redundant brakes would be advantageous for practical realization in terms of size and cost. We therefore have studied how redundant brakes should be introduced.

2) We have developed a new ER fluid brake that could be driven by a relatively low voltage compared to previous brakes. It could also produce stable torque since the gap between electrodes was kept constant. The new brake can produce a brake torque of several times larger magnitude than the previous one of the same size.

3) We have developed Redundant-PLEMO-1, a rehabilitation support system for upper limbs that uses a redundant number of brakes. 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.

4) We have proposed a method of evaluating passive-type force display systems and have analyzed the system's performance.

5) We have made a force display test of the present system. By selecting appropriate brakes and controlling brake force, we have shown that wanted magnitude and orientation of resistance force could be provided.

Use of the training program created for this system in actual clinical situations and acquisition of clinical data to check the effectiveness of the system are left for future work.

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