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Development of Quasi-3DOF Upper Limb Rehabilitation System Using ER brake: PLEMO-P1

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Abstract. In recent years, many researchers have studied the potential of using robotics technology to assist and quantify the motor functions for neuron-rehabilitation. Some kinds of haptic devices have been developed and evaluated its efficiency with clinical tests, for example, upper limb training for patients with spasticity after stroke. However, almost all the devices are active-type (motor-driven) haptic devices and they basically require high-cost safety system compared to passive-type (brake-based) devices. In this study, we developed a new practical haptic device ‘PLEMO-P1’; this system adopted ER brakes as its force generators. In this paper, the mechanism of PLEMO-P1 and its software for a reaching rehabilitation are described.

1. Introduction

The increasing numbers of the aged people and their physical deteriorations have become one of the most serious problems in many countries. Many stroke patients suffer from disabilities which restrict Activities of Daily Living (ADL), e.g., reaching actions. Therefore, sufficient rehabilitative training is necessary for such patients.

In general, therapists make rehabilitation programs based on their inspections and measurements of each patient. However, it is difficult to adopt appropriate rehabilitative programs for all patients, because the evaluation method is based on experiences of each therapist. Nowadays, Evidence Based Medicine (EBM) is required strongly in the field of rehabilitation. Therefore, rehabilitation systems that utilize robotics technologies are expected for; 1) quantification of the effect of the rehabilitative training; 2) enhancement of the motivation for patients with creating new training methods (many patients are giving up rehabilitative training because of its boredom); 3) improvement of the efficiency of physical therapist’s works.

Krebs H.I., et al. [1] have developed active (motor-driven) haptic device (MIT-MANUS) and conducted many clinical tests for upper limbs rehabilitation. However, the motor-driven robots basically require high-cost safety system compared to passive (brake-based) devices. Book W.J., et al. [2] have developed passive haptic devices. In their system, conventional powder brakes were used as haptic generators. Generally, the response time of the powder brake is more than 100ms and it causes lack in quality of force feedback.
To solve these problems, we have developed passive haptic devices using ER Fluid Brakes (ER Brake) [3]. Due to the rapid response of the ER Brake (2~3ms), our haptic device presented good performance as a force display. In this study, we improved this system (ER brake-based system) as a practical rehabilitation system for upper limbs. To meet demands for the rehabilitative training in 3-D space, we developed a new haptic device "Quasi-3-DOF Rehabilitation System for Upper Limbs" or "PLEMO-P1" (shown in Fig.1). PLEMO-P1 has 2-DOF force-feedback function in its working plane but the working plane can be adjusted its inclination. In this paper, the mechanism of PLEMO-P1 and its software are described.

Table 1. Specifications of ER brake

| Specification       | Value                           |
|---------------------|---------------------------------|
| Total weight        | 2.3kg                           |
| Diameter            | 150mm                           |
| Height              | 40mm                            |
| Maximum brake torque| 4.0Nm (for 3.0kV/mm)            |
| Idling torque       | 0.1Nm                           |
| Num. of rotor disks | 3                               |
| Disk gap            | 1mm                             |
| Time constant of response | 2-3 ms                   |

2. Rehabilitation System "PLEMO-P1"

PLEMO-P1 is a stand-alone robot and one of the passive haptic devices: it can present several kinds of virtual force, for example resistance, viscosity force, vibration etc. This machine has two controllable degrees of freedom (DOF) in a working plane and an uncontrollable DOF for the angle-adjustment of the working plane. Two ER brakes are installed as the torque generators.

Under the training, an operator grasps a handle of PLEMO-P1, watches a display in front of him/her and plays several kinds of application software as rehabilitation trainings or evaluation tests. This system can measure the position of the hand and its manipulating forces with rotary encoders installed on link joints and a force sensor built in its grip, respectively. In this section, we describe both the ER brake and the mechanism of PLEMO-P1.

2.1. ER brake

ER fluid is one of functional fluids, whose rheological properties can be changed by applying an electrical field [4]. To use this fluid as working fluid, we can construct an electrically controllable brake with the ER fluid, which has high-performance (good rapidity and repeatability of brake torque) [5]. We use this brake for the force generators of a new rehabilitation system (force-feedback system) in this paper. Figures 2 show the developed ER brake for PLEMO-P1. This brake consists of multi-layered disks. ER fluid is filled between the rotor-disks and stator-disks. As a result, six layers of ER fluid generate the brake torque. Piston mechanism prevents the fluid from leaking with its expansion. Table 1 shows specifications of the brake. We can control the brake torque from 0.1Nm to 4.0Nm with the electric field from 0.0kV/mm to 3.0kV/mm, respectively.
As shown in the left figure of Figs.3, the time constant of response is 2~3ms [4]. Due to this rapidity of the response, a haptic device using this ER brake can realize a high frequency response (e.g. an impact force of virtual hockey).

The right figure of Figs.3 shows the brake torque of the ER brake depending on the electric field applied to it. This characteristic has good repeatability and we can formulate this relation as follows:

\[ T = 0.39E^2 + 0.12E + 0.10 \]  

(1)

‘T’ represents the brake torque [Nm] and ‘E’ represents the electric field [kV/mm].

2.2. Mechanism of Force Control

Force control unit consists of two ER brakes and the brake torques control external force on a handle built on the front edge of the parallel linkage shown in Fig.4. As shown in this figure, T1 or brake torque of brake1 generates force F1 and similarly torque T2 generates force F2. If the movement of the handle is vertical direction like this figure and this system generates force F1 and F2, the user feel resistance against his movement direction. If these forces are constant, users feel constant resistance. In other case, if these forces are proportion with the velocity of the movement, the users feel viscous force. Necessary torques T1 and T2 are calculated based on the inverse kinematics. Lengths of the link 1 and the link 2 are 450mm. This value is designed on the basis of the manipulability-analysis.

3. Software of PLEMO-P1

We suggest application software “Virtual Sanding Training” for reaching trainings shown in Figs.5 (A, B, C). This software is developed on the basis of conventional sanding training in the occupational therapy (shown in the picture D of Figs.5 [5]). In the sanding-training, the patient is instructed to actively push the sander higher and higher which provide some resistance against the extensors. This resistance activates patient’s intention to move their own arm. Actually, in physical therapy and occupational therapy, reaching training is done without pulling patient’s hand in the correct direction, but with giving resistance against correct direction. The
inclination of the sanding board is adjusted depending on the recovery level of the patients. So therapists gradually change the inclination as the patient improves.

In the “Virtual Sanding Training”, patients are instructed to actively push the rectangle with extending their arm toward front direction like a sanding-training (shown in Fig.5 (A-B)). The position of the hand is feed backed visually, so patients can check physical relationship between the object (a rectangle box) and their own hand (a sphere). In the only case that the patients push the box to the proper direction (straight front), the box move to the front and resistive force was generated on the end-effector. Moreover, if the system detects their abnormal movements, the system stops presenting the force. Following the hand-position, velocity and operating force, this system can judge the patient’s movements. Objective of this training is to help the patients recognize a correct movement and to restructure their motion control function which they lost following stroke (Post stroke patients basically lose independent control of individual joints and coordination among the joints. Especially, it is difficult for them to control movements toward extension). The width of the box can be adjusted depending on the recovery level of the patients.

Figure 6 shows an experimental result of the Virtual Sanding Training. An “Allowable area” means the width of the box. The solid line is a trajectory of the hand and white circles represent hand’s position under the proper training. As shown in this figure, the hand departed from the allowable area (box width) at the point A. Once the operator departed from the allowable area, he cognized disappearance of the resistive force (point B), modified his trajectory to the allowable area and restarted the proper reaching (point C).

4. Conclusion
In this paper, we described the development of “Quasi-3DOF Rehabilitation System for Upper Limb” or “PLEMO-P1” and its software. PLEMO-P1 has two controllable DOF on a working plane and one uncontrollable DOF to adjust the inclination of the working plane. Using ER brakes as a torque generator, PLEMO-P1 has a good responsibility for its force feedback and guarantees the safety for humane because PLEMO-P1 is a passive haptic device; it dose not have any actuators and it cannot move automatically.

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