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Performance Evaluation of a Novel Master-slave Rehabilitation System

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Abstract - **Despite the benefits of the robotic technologies on rehabilitation, human involvement is still critical. On the aspect of patients, they also need the supervision of the therapist as well as their active guidance and their expertise. Through the master-slave rehabilitation system, the therapist can adjust the training according to the patient's status with their expertise. Therefore, the master-slave rehabilitation system is better than the traditional robotic rehabilitation system in which the training is programmed beforehand. In this paper, a master-slave rehabilitation system including an upper limb exoskeleton rehabilitation device (ULERD) as slave side and a human upper limb-like robot as master side is proposed. Considering that the force feedback that the therapist adjusts the training intensive or training mode (active or passive training) based on is most important during the rehabilitation. Therefore, a novel structure based on the Serial Elastic Actuator (SEA) is applied on a human upper limb-like robot for generating different resistance forces. By detecting the deflection of the elastic element, the interaction force between the human and robot can be calculated. Thanks to the high torque output actuator, the master device can mimic the spasticity of stroke patients by controlling the deflection of the elastic element. Active training can be realized for mild stroke patient with ULERD using an extended impedance control method. Therefore, therapists can perform both active training and passive training according the force feedback with proposed master-slave rehabilitation system.**

Index Terms – Master-slave Rehabilitation System, Serial Elastic Actuator (SEA), Human upper limb-like robot, Upper Limb Exoskeleton Rehabilitation Device (ULERD)

I. INTRODUCTION

According to the statistics, approximately 795,000 people suffer from a new or recurrent stroke every year [1]. Rehabilitation can recove the patient's physical, sensory capabilities. Rehabilitation can also support the patient to compensate for deficits that cannot be treated medically. Rehabilitation robots can be separated into two categories, including the end-effector type and the exoskeleton type. End-effector based devices are simpler to adjust to accommodate different patients. However, they cannot perform human arm rehabilitation in joint respectively [2]. The ARMin robot is one of the typical exoskeleton devices. It can support the entire arm for rehabilitation with patient-cooperative control strategy during activities of daily living (ADL) training tasks [3]. An upper limb exoskeleton rehabilitation device has been developed aiming at the home-rehabilitation with light weight and compact structure [8].

Those systems can provide the exercises for patients that assist them in daily life activities. However, the trajectories that the patient must follow are programmed beforehand. This will induce some drawbacks. On the one hand, patients need the supervision of the therapist as well as their active guidance and their expertise. One the other hand, the rehabilitation intensive and training mode should be adjusted according to the expertise and the status of patients for obtaining better rehabilitation effect. Some research groups are dedicated to the master-slave rehabilitation system which can involve the expertise in rehabilitation. In [4], a two DoFs master-slave robot arm system was proposed with haptic feedback feeling. The master robot arm is on a smaller scale than the slave arm for reducing the energy consumption. Instead of actuators, brakes were used for implementing the force feedback. Different from it, we aimed at developing a human upper limb-like robot as master device with good operability and high torque output for mimicking the spasticity of patients.

In order to perform the rehabilitation training well, the relationship between the human upper limb-like robot and the human upper limb should dynamically change. In 1985, Hogan proposed the impedance control which attempts to implement a dynamic relation between manipulator variable [5]. In rehabilitation robotic, impedance control has been successfully implemented at MIT-MANUS. The other method is admittance control which can minimize the friction and the effects of inertia by suitable controller, measuring the force by a load cell. In mechanical systems, particularly in the field of haptic, admittance is a dynamic mapping from force to motion. The input of admittance is force and the output is velocity or position. However, a load cell induces instabilities and high cost [6]. For the human-robot interaction actuator, it should meet two requirements. One is that actuator should have perfectly backdrivable. The other is that the output torque or force is proportional to the control input.

To overcome these disadvantages, the Series Elastic Actuator (SEA) was designed by adding a spring between an actuator and a human joint [7]. The spring also plays the role of an energy buffer as well as a force sensor. The force is generated from the differential position or the deflection of the spring, which is controlled by a position controller. This implies that the Series Elastic Actuator (SEA) can change the force control problem to position control problem. In this paper, a human upper limb-like robot which can generate different resistance forces during the human-robot interaction based on the SEA principle is introduced. This robot can be applied as the master device operated by the therapist during the master-slave rehabilitation.

This paper is organized as follows. Some benefits of master-slave rehabilitation and requirements for human-robot interaction are introduced first in section I. An upper limb exoskeleton rehabilitation device and a human upper limb-like robot which constitute the master-slave rehabilitation system will be introduced in section II, including the structure and the principle of resistance generating. The controller design is introduced in section III. Some experiments are carried out for evaluating the performance and feasibility of the proposed robotic system in section IV. The last section presents some conclusions.

II. SYSTEM INTRODUCTION OF THE MASTER-SLAVE REHABILITATION

A. Introduce the Upper Limb Exoskeleton Rehabilitation Device (ULERD) as a slave device

The motivation for the ULERD design was to provide passive and active training for patients with motor dysfunction (Fig.1). This device can provide assistance to the patient's impaired upper limb including the elbow extension/flexion, forearm pronation/supination, and wrist flexion/extension actions. By detecting the motion of forearm with MTx sensor, this device can also provide reasonable resistance force for obtaining better effects [8].

Fig.1 A person is wearing the ULERD

Therefore, this device has three active DoFs in elbow and wrist joint. Another four passive DoFs were added to the elbow and wrist joints to correct any misalignment between the human and device joints. The mass of the device was decreased as light as possible. The total mass is 1.3kg. For the safety, a helical capstan shaft is designed apart from the motor shaft when overload, and force between the forearm and device is detected by a load cell avoiding danger. An exoskeleton device with these features is suitable for home-rehabilitation. In previous researches, multi-strategries have been realized with the ULERD, including the master-slave rehabilitation and self-rehabilitation. In [9][10], a haptic device (Phantom Omni) and the ULERD constitute the master-slave rehabilitation system for performing the training with a Human Mechine Interface (HMI). And the ULERD was applied on the imparied side and a haptic device (Phantom Premium) was used as a manipulator on the intact side [11]. The joint space symmetry in which the motions are mirrored and the joints of each limb follow the same angles was considered.

B. Introduce the human upper limb-like robot

Both of two kinds of haptic devices (Phantom Omni and Phantom Premium) used in pervious researches can be manipulated by the therapist for rehabilitation with force feedback. However, the motor impedance (mechanical impedance) as shown in (1) which represents a measure of how much the motor resists motion when adding an extra force

$$Z(w) = \frac{f(w)}{v(w)} \quad (1)$$

where *Z(w)* represents the motor impedance, f(w) means the resistive force, and *v(w)* represents the velocity is not enough for mimicking a stroke patient. In the other word, these devices cannot provide enough torque for reflecting the stroke patient's status, even if the spasticity. In some literatures, the *f(w)* is extended to the following terms: [12]

$$f(w) = f_f(w) + f_d(w) + f_i(w) + f_b(w) + \Delta f(w) \quad (2)$$

where f_f represents the Coulomb friction force which will increase the motor impedance in the low frequency range. f_d represents the linear damping force and increases the motor impedance over the entire frequency range, f_i increases the impedance in the high frequency range, f_b is the bias value of the force output, and the $\Delta f(w)$ represents forces due to other factors.

One of the principal barriers to achieving high impedance accuracy and precision are the dynamic of the device itself. Commercial haptic devices like Phantom Premium and Phantom Omni can provide good performance on the force feedback with perfect backdrivability. It will become increasingly difficult with large actuators, drive mechanisms, and linkages which will lead to more inertia and friction as the demand for force production continues to rise. For the stroke patient, especially the severe patient, the spasticity causes large force production. In order to mimic the human's upper limb well, even the spasticity, large output torque actuator is necessary.

Considering about these requirements, a stepping motor producted by the Oriental motor in Japan was first selected in this paper. This motor can output 16N*m maximum torque after adding a high reduction gear. However, a high reduction gear with 1:120 ratio makes the device non-backdrivable. The drivetrain of this robot was designed considering the operability and feasibility. The cable-pulley transmission method which is widely applied on haptic device can bear enough torque. However, in order to transmit force in two directions, the cable winds around a grooved pulley and main pulley must be designed in “8” mode. Therefore, the motor must be designed near to the elbow joint which decrease the operability. The design showed in Fig.2 is chosen by adding a clutch directly for connecting the shaft of the motor and the device after considering the condition of the device. Two linkage bars and a long bar are fixed with the axis with two modules which are fasten to the axis. This device is compact, and does not hamper the operation of therapists.

On the other hand, high reduction gear induces more inertia and friction even if the harmonic reduction gear is applied. To overcome these disadvantages, the serial elastic actuator was designed by adding an elastic element between the motor and its output. Serial elastic actuator (SEA) has a spring placed in the actuator output. By measuring the deflection of the spring, the actuator gives an accurate measurement for closed-loop actuator force control. In this paper, two linkage bars with good stiffness were applied instead of the spring as the elastic element.

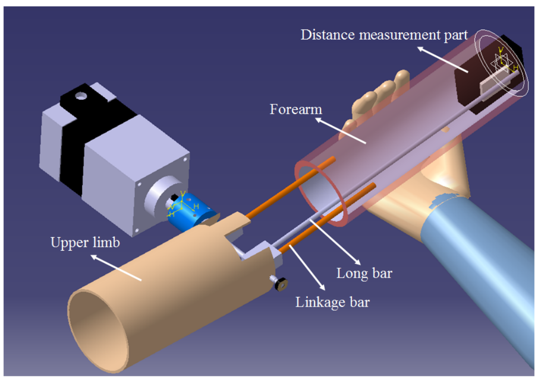

Fig.2 The human upper limb-like robot designed with CATIA

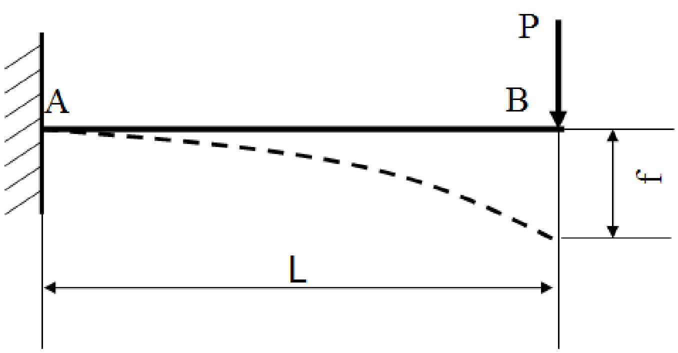

Fig.3 The deflection of the linkage bar related to the exerted force

Fig.3 shows the deflection of the linkage bar related to the exerted force. The flexible curve equation can be written as (3). When calculating the deflection on the extreme point, (4) is applied, in which y represents the deflection of the linkage bar, P represents the exerted force, L is the length of the linkage bar, E and J represent the elastic modulus and the moment of inertia respectively. Since the elastic element used in proposed robot is a steel bar with good stiffness, the moment of inertia can be written as (5). At last, the relationship between the deflection and the length of the elastic bar can be obtained as (6). Here the P approximately equates to 100N, d equates to 0.005m, and E equates to 200GPa. In order to decrease the error, the deformation at the extreme point was enlarged by a long bar which is fixed on the shaft. The long bar keeps straight and it provides a reference position when detecting the deflection of the long bar. Considering the condition of the robot, the length of the elastic bar was chosen as 80mm at last.

$$y(x) = \frac{1}{EJ}\left(-PL\frac{x^2}{2} + \frac{1}{6}Px^3\right) \tag{3}$$

$$y = -\frac{PL^3}{3EJ} \tag{4}$$

$$J = \frac{\pi d^4}{64} \tag{5}$$

$$y = -\frac{64PL^3}{3E\pi d^4} \tag{6}$$

During the human-robot interaction, the actuator should not resist the human motion and generate only the desired force. Therefore, the measurement accuracy of the deflection of the elastic bar is important. The slide rheostat with low friction and the distance measurement sensor (SHARP 2Y0A21) were considered first. Through several experiments, results revealed that the friction of the slide rheostat will influence the measurement accuracy, and the noise of the distance measurement sensor also brings some disadvantages when performing the control even if some filter processing methods are applied. In order to avoid these disadvantages, the structure showed in Fig4 was decided. The structure mainly contains two parts, which are the optical sensor and the distance adjustment frame. By regulating the distance adjustment frame, the friction between the extreme part and the optical sensor part can be adjusted. During the measurement, the origin displacement of the long bar seems as the reference, since the long bar always keeps straight. Therefore, by controlling the deflection of the elastic bar, different resistance forces can be generated. The relationship between the deflection and the output resistance force can be written as (7), where F represents the resistance and the k is the coefficient.

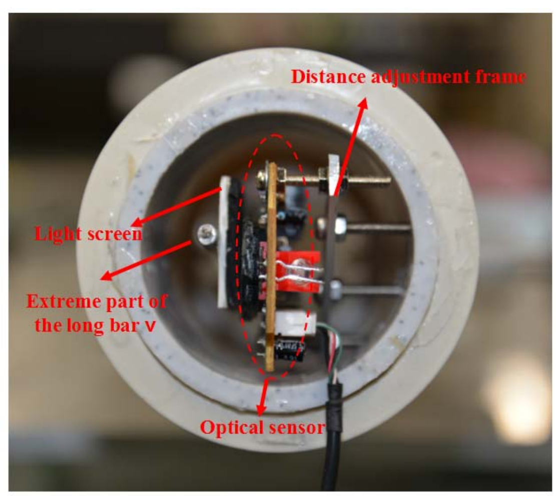

Fig.4 The deflection of the linkage bar related to the exerted force

$$F = -k\frac{64PL^3}{3E\pi d^4} \quad (7)$$

III. CONTROLLER DESIGN

The control system of the human upper limb-like robot mainly contains two parts, including the upper-computer and low-computer. Upper computer (Windows 7 Professional system with 3.00Hz AMD Processor and 4.00GB RAM) is used for recording the sensor's data, including the optical sensor, force sensor and MTx sensor. Especially, the position data y of the optical sensor is sampled with the Window API by the upper-computer and send to the DSP2812 controller. As the Fig.5 shows, the difference between the desired deflection y_1 and the deflection feedback y recorded with the optical sensor will be sent to the DSP2812 controller. Different resistance forces were realized by setting different thresholds. The resistance generating algorithm can be written from (9) to (11), where the H is a threshold, f_{PWM} represents the frequency used for controlling the speed of stepping motor, and k is a coefficient. During the training, the H can be changed according the status of stroke patients. However, limiting with the precision of sensors, the structure of the device and the performance of the steeping motor, the range of H can only be set within a specified range. As the section II described, several methods were applied for improving the accuracy in our research. First of all, the optical sensor was used for detecting the deflection of the elastic bar for its low noise and high accuracy. The measurement accuracy was also be improved by adding a long bar from the shaft to the extreme part of the robot. Since the long bar keeps straight during the extension and flexion, the long bar can not only provide a reference position, but also enlarge the tiny deflection to an easily measured deflection.

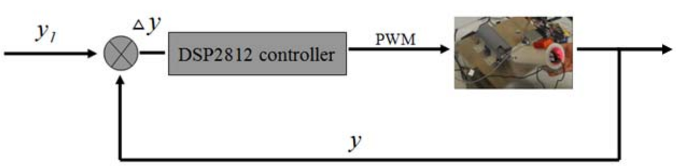

Fig.5 Control diagram for the human upper limb-like robot

$$\Delta y = y_1 - y \quad (8)$$

$$\begin{cases} \Delta y < -H, \ \Delta y \cdot k = f_{PWM} & (9) \\ -H \le \Delta y \le H, \ f_{PWM} = 0 & (10) \\ |\Delta y| > H, \ \Delta y \cdot k = f_{PWM} & (11) \end{cases}$$

IV. EXPERIMENT AND RESULTS

In order to verify the performance and feasibility of designed robot, several experiments were carried out. The MTx sensor was used for detecting the deflection of the robot's forearm part. In this paper, only the pitch angle was used and recorded with a 100Hz sampling rate through the USB2.0. A strain gauge inside force sensor was used for detecting the resistance force (interaction force), and recorded with a 500Hz sampling rate through the AD module.

The experiment setup shows in Fig.6. Three thresholds were set in this experiment, including the low resistance, medium resistance, and large resistance. In order to compare the relationship of the forearm deflection and the resistance force, the recorded data were interpolated into the same time length. In Fig.7, the result reveals the relationship between the forearm deflection and the low resistance force. In (12), θ_{pitch} represents the angle detected with the MTx sensor. As (12) shows, the θ_{pitch} includes three parts, which are the $\theta_{elastic}$, $\theta_{forearm}$ and θ_{others}. $\theta_{elastic}$ represents the deflection angle of the elastic bar, which connects the upper limb part and the forearm part. $\theta_{forearm}$ represents the rotation angle of the steeping motor, and the θ_{others} represents the deflection caused by the plastic deformation. From the result Fig.7, it can be known that after exerting a small force, the forearm starts to bend until it reach to the threshold set beforehand. After the deflection detected at the extreme part larger than the threshold, the forearm part starts to rotate following the stepping motor until the exerted force removed. Another two experiments were also carried out for verifying the feasibility and performance with different threshold. The results showed in Fig.8 and Fig.9 represent the relationship between the deflection of the forearm and the medium resistance force or high resistance force respectively. Experiment results show that the stability of the proposed system was improved by increasing the threshold value. However, it will induce unstable when a small threshold was chosen. The main reasons are caused by the measurement accuracy of optical sensor and the plastic deformation of the robot. Therefore, the equilibrium position will always change which will influence the control. This can be improved by changing a more advanced sensor or detecting the equilibrium position and then renew it.

$$\theta_{pitch} = \theta_{elastic} + \theta_{forearm} + \theta_{others} \quad (12)$$

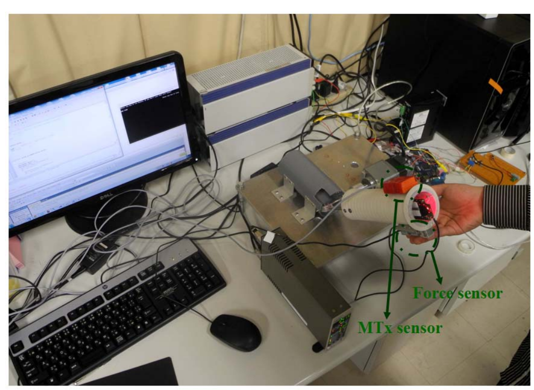

Fig.6 Experimental setup for verifying the resistance force generating

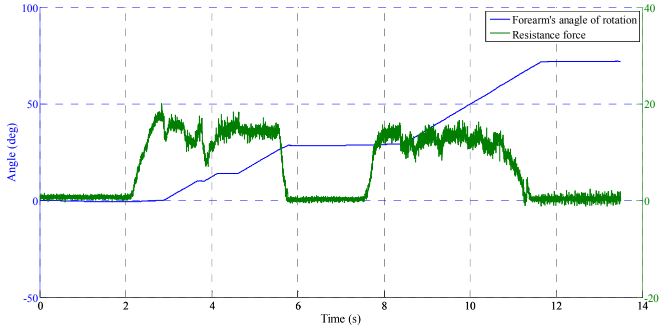

Fig.7 Relationship between the forearm deflection and the resistance force (low resistance)

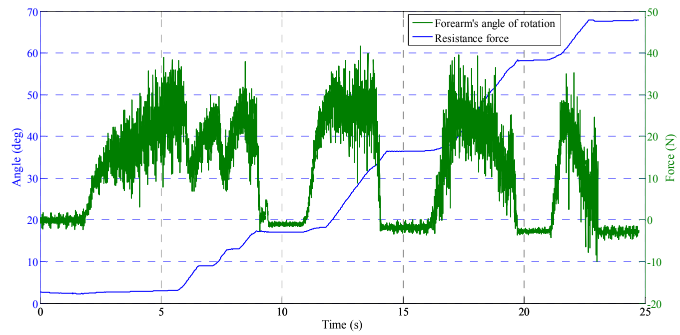

Fig.8 Relationship between the forearm deflection and the resistance force (medium force)

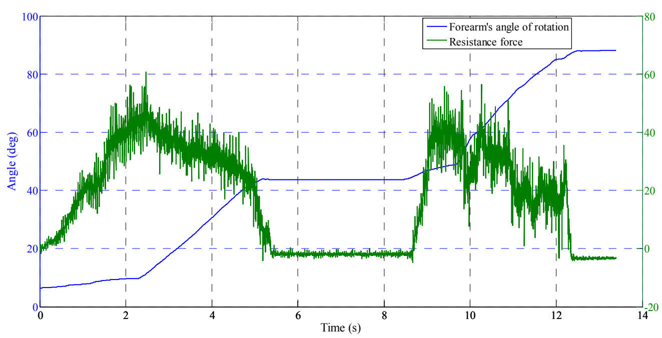

Fig.9 Relationship between the forearm deflection and the resistance force (large resistance)

V. CONCLUSIONS

By using the master-slave rehabilitation system, therapists can adjust the training intensity and training mode (passive or active) according to the expertise. Human involvement can also make the rehabilitation more safety, avoiding dangers. In this paper, a master-slave rehabilitation system which has a ULERD and human upper limb-like robot is introduced. The ULERD is worn by the therapist providing the assistance force, and controlled by the therapist as master side. It is important to detect and reflect the force feedback from the slave part to the therapists. For actually reflecting the force information, a human upper limb-like robot is designed and manufactured. Especially, with a novel structure based on the SEA principle, this robot can output different resistance forces (motor impedance) for mimicking the limb of stroke patients. The principle of the proposed structure is analyzed for choosing a suitable structure, including the length of the elastic bar and the deflection measurement section at the extreme point of the long bar. At last, the controller is designed for the proposed system with the velocity control by controlling the deflection of the elastic bar. Several experiments were carried out for evaluating the performance and feasibility of the proposed system. Experiments indicated that the robot can generate difference resistance forces, despite some error occurred. The error can be reduced by applying a better measurement sensor and some advanced control algorithms.

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