A 4-DOF Upper Limb Exoskeleton for Stroke Rehabilitation: Kinematics Mechanics and Control

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***Abstract*—A 4-DOF power-assist exoskeleton for stroke rehabilitation is developed in this research work. Its configuration consists of three degrees of freedom, two of them are adjustable to suit patient arm, at the shoulder joint and one degree of freedom at the elbow joint. The mechanical system is designed based on low friction, no backlash, low inertia, large dynamic range, and backdrivable. Kinematics, link-configuration, and control strategies are detailed here. Two control strategies: assistive-resistive mode, based on impedance force control, for a patient who has some difficulty in moving his hand or physically weak persons. An impedance model, based on the concept of virtual wall, has been purposed in the torque control scheme. The resistive mode for a patient who want to improve his hand motion or after finishing the assistive-resistive operation training program. Each jointed of the exoskeleton arm is actuated by brushless DC servomotor. To simplify torque measurement, each joint torques in the feedback loop are obtained by measuring the input current of the motor drivers multiply by the motors torque constant. Otherwise, sophisticate procedure needed, if we measure current in the armature coil. Both operation modes have been tested with patients, the feedback from patients and medical doctors are very positive.**

***Index Terms*—exoskeleton arm, stroke rehabilitation, force control, backdrivability**

I. Introduction

The application of robotic can improve muscular strength and movement in patients with neurological or orthopedic lesions. Several studies prove that arm therapy has positive effects on the rehabilitation progress of stroke patients [1]-[5]. The exoskeleton robot, serve as an assistive device, is an external structural mechanism with joints and links corresponding to human body. Safety is the main issue for design. Every joint must have mechanical end stops to guarantee that no joint can exceed the anatomical range of motion of the human limbs. The detail of mobility study of the purposed configulation had done by the authors and can be consulted in [6]. The controller have to control force so that no force exceed the desired force. To achieve good performances of dynamic systems, the robot must have low friction, no backlash, low inertia, large dynamic range of force controlability, robustness, high bandwidth, high efficiency and good backdrivability.

II. Kinematics of the 4-DOF Upper Limb Exoskeleton for the Stroke Rehabilitation Robot

In this research, we develop a 4-DOF upper limb exoskeleton robot mainly for physical therapy of stroke patients, therefore, the robot must be able to move the shoulder joint (3-DOF) and the elbow joint (1-DOF) as show in Fig. 1. and its Denavit-Hartenberg parameter as show in Table I.

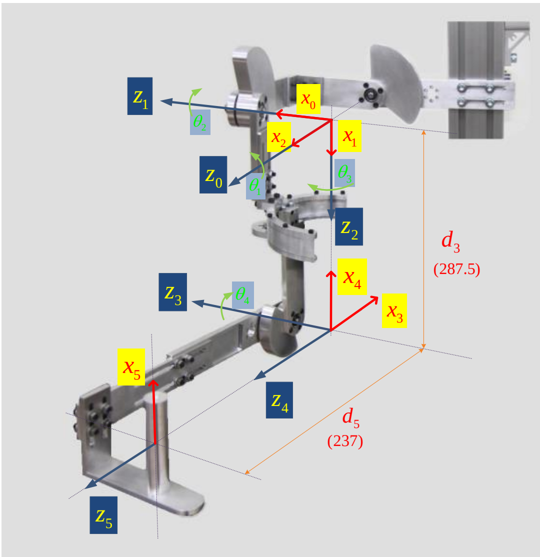

Figure 1. 4-DOF rehabilitation robot and its Denavit-Hartenberg parameter.

The robot coordinate frames were chosen based on Denavit-Hartenberg notation. The link offset d_3 and d_5 can be adjusted to suit the patient arm. Each the joint variables, θ_i , can be obtained from an encoder attached to each joints. The position of the end-effector for the defined reference coordinate frame {0} at the shoulder joint can be shown in Eq. (1) as following:

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$$P_{end\,effector} = \begin{bmatrix} X_{EE} \\ Y_{EE} \\ Z_{EE} \end{bmatrix} = \begin{bmatrix} d_5(s_4(s_1s_3 + c_1c_2c_3) - c_1c_4s_2) + d_3c_1c_2 \\ -d_5(s_4(c_1s_3 - c_2c_3s_1) + c_4s_1s_2) + d_3s_1s_2 \\ d_5(c_2c_4 + c_3s_2s_4) - d_3c_2 \end{bmatrix} \quad (1)$$

TABLE I. THE DENAVIT-HARTENBERG PARAMETER OF 4-DOF REHABILITATION ROBOT

i (Link)	θ_i Rot(z)	d_i Tran(z)	α_i Rot(x)	a_i tran(x)
1	θ_1	0	$\pi/2$	0
2	θ_2	0	$\pi/2$	0
3	θ_3	d_3	$\pi/2$	0
4	θ_4	0	$\pi/2$	0
EE	0	d_5	0	0

III. MECHANISM DESING OF THE 4-DOF EXOSKELETION REHABILITATION ROBOT

Backdrivable is a main property for mechanism design. For good backdrivability, the inertia of motor times the square of the transmission ratio must be kept lower than link structure inertia as Eq. (2).

$$I_{link} > n^2 I_{motor} \quad (2)$$

Even through the control strategies purposed here have passivity property, for more safety, we designed the mechanical stopper at the joint which guarantee that the joint cannot excess the limit of human range as show in Fig. 2. We used the cable drive with pulley system to amplify torque as shown in Fig. 3. The compliance in the cable will act like a spring series between actuator and load, this will increase safety in the feedback control mode as explained in [7].

Without any counterbalance, the actuators of the first 2-DOF of the robot need to generate high torques to move a patient upper limb against gravity. To reduce this large motor load, we design counterweight system to compensate the gravity load as show in Fig. 3. The moment arm or the distance d, $(Moment = T * d)$, as shown in Fig. 4.can be obtained from Eq. (3)., where $\overline{OA}$ and $\overline{OB}$ is the distance from rotate axis to cable support.

The first 2-DOF of the robot arm, shoulder joints adduction/abduction flexion/extension, are actuated by Maxon EC 90 Flat-type, Brushless DC Servomotor, which connected to the cable-pulley system with 1:12.5 transmission ratio. The interior/exterior rotation of the upper arm joint is actuated by Maxon RE35 DC servomotor, a direct current, and connected to the cable-pulley drive with 1:15 transmission ratio. And the last joint, the elbow joint, is actuated by the Maxon EC 90 with 1:7 transmission ratio of cable-pulley system.

$$d = \frac{\overline{OA}\,\overline{OB}\sin\theta}{\sqrt{\overline{OA}^2 + \overline{OB}^2 - 2\overline{OA}\,\overline{OB}\cos\theta}} \quad (3)$$

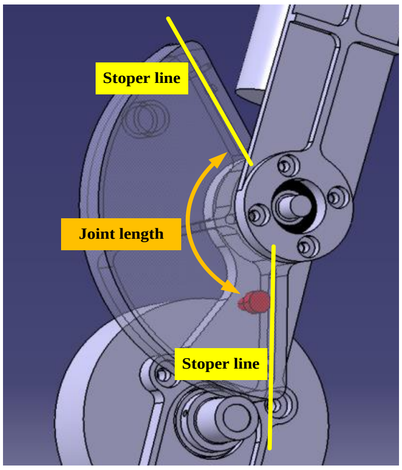

Figure 2. The mechanical stoper at the joint of robot.

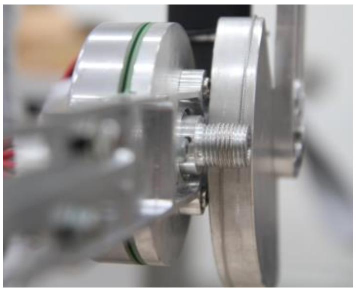

Figure 3. The cable drive transmission.

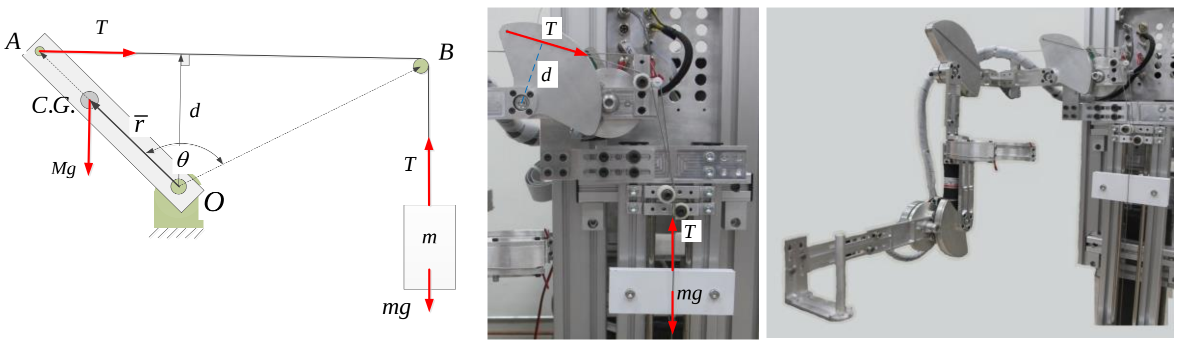

Figure 4. The designed counterweight of 4DOF rehabilitation robot.

IV. Control Strategy of Each Joints

The control strategy proposed in this paper has two modes of operation: the assistive-resistive and the resistive. The assistive-resistive operation is suitable for a patient who has some difficulty in moving his hand or physically weak persons. The exoskeleton will help the patient by guiding his hand along a defined path. With this help, the patient will gain more confident during the training. It is believed that it will increase the efficiency of the training program compare to the manual training program. The other mode is the resistive mode of operation. This mode is suitable for a patient who want to improve his hand motion or after finishing the assistive-resistive operation training program. The two control strategies have been implemented on each joints of our exoskeletion robot to improved patient cooperativeness with variable trajectories. The robot system is also include features which a trajectory can be defined prior to the training program as well as the trajectory can be selected from the list of prespecified trajectories.

A. Assitive-Resitive Mode of Operation

As mention previously, this mode of operation, the robot arm will help a patient to follow along a prescribed path either assist or resist. Due to the load (joint) is coupled to the drive using cable with some compliance. We assume that this compliance is very small value and can be neglected in the control loop. But for real implementation, this compliace will act as safety component in the control scheme. More details concerning about the safety can be consulted in [7]. Fig. 5 is the block diagram of our control strategy. It is an impedance control cascased with torque control. The inner loop is a velocity control is closed with a filtered differentation of the encoder signal in contrast with using Hall-based velocity sensor as discussed in [7]. This will induce some time delay in the velocity control loop about half of the sampling time. From our experiment, the effect of this time delay has not shown any significant problem within our design bandwidth.

The torque controller is designed to generate the torque in the cable track by assuming that the compliance of the cable is very small and can be neglected. This assumption can be used due to magnitude of controlled torque is not that high. For the impedance *P*, we puposed a virtual wall control strategy based on the concept studied in [8] and [9] as following:

$$T_{L,d} = \text{sgn}\left|\theta_d - \theta_L\right| \; K_p e^{\left|\theta_d - \theta_L\right| K_f} - 1 \tag{4}$$

where K_p and K_f are gains that can be adjusted so that the desired torque of the torque control loop will generate torque in the exoskeleton arm that suitable for a training. Normally, the value of gain K_p is much smaller than the gain K_f. The torque feedback, T_L ,in the feedback loop is obtained by measuring the input current of the power supply or motor driver of the brushless DC servo motor multiply by torque constant, K_a, of the motor.

B. Resistive Mode of Operation

When a patient has through the assistive training mode or any patient who want to futher improve his hand motion, the resistive mode of operation will be applied. Fig. 6 shows the block diagram of this control mode. The torque command of each joint, $T_{L,d}$, can be specified in the program. We use integral control to generate the desired angular velocity. We can adjusted the amplitude of the resistived torque of the exoskeleton by adjusting the gain G_i. The inner loop is a PI motion control loop. The joint torques in the feedback loop are obtained by current measurement of the motor driver.

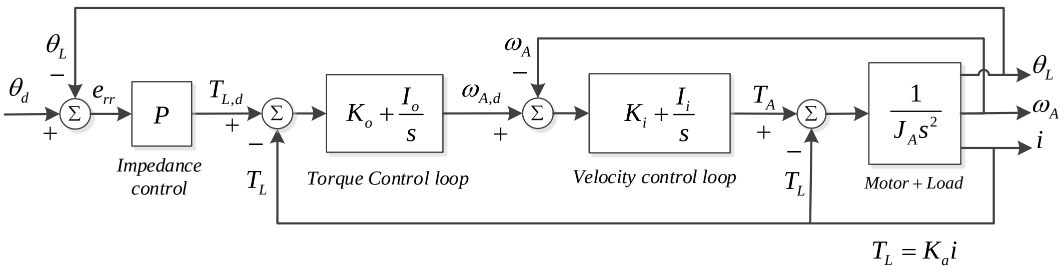

Figure 5. Block diagram of the assistive-resistive control strategy.

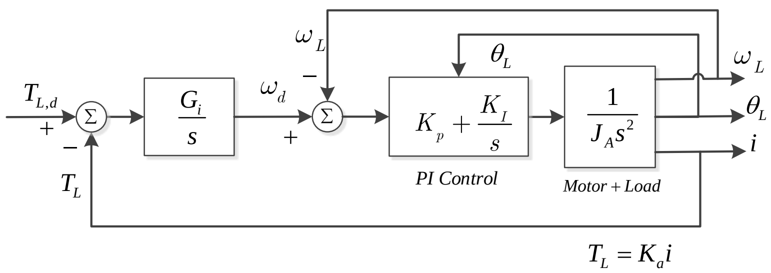

Figure 6. Block diagram of the resistive control strategy.

V. Results

The exoskeleton arm system is equiped with a 55-inch 3D monitor to improve the visualization. Patients can observe in real-time their performance through this 3D monitor. Both operation modes have been tested with patients, the feedback from patients and medical doctors are very positive. The results of the rehabilitation will be reported in the future paper.

VI. Summary

This paper is to purpose a development of a 4-DOF exoskeleton arm with the control strategy. There are two modes of operation: the assistive-resitive mode of operation and resistive mode of operation. The assistive-resitive mode of operation is suitable for patients who have difficulty in control of their arms motion. While the resistive mode of operation can be applied to patients who want to improved arms motion control after successfull of assistive-resistive training program. The exoskeleton system is aimed to improve patients cooperativeness with variable trajectories

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