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Arm Exoskeleton Rehabilitation Robot with Assistive System for Patient after Stroke

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Abstract: Exercise dosage is proven to be an important factor in the physical treatment. Robot assistive approach can improve the rehabilitation quality and evaluate patient's recovery quantitatively. This paper presents kinematic structure, assistive control system, and integrated F/T sensor for an upper limb rehabilitation robot. By using the human arm dynamic, there are three rehabilitation modes presented in this paper: active mode, assistive mode, and passive mode. In assistive mode, we have two strategies to implement it. One is to amplify interactive torque, and the other is to apply assist-as-needed concept. The goal of this mode is to assist patients to finish motion tasks. The rehabilitation robot under investigation has 7 degree of freedom (DOF) actuated by DC motors, which are programmed to drive the robot arm in the 3D space. To validate our control design, some realistic experiments are conducted and its satisfactory performance is demonstrated. This work is approved clinical testing by the Department of Health, Executive Yuan, R.O.C. So far, we are demonstrating the effect of our controller.

Keywords: Rehabilitation robotics, human arm dynamics, assistive control, upper extremity, exoskeleton.

1. INTRODUCTION

Recent researches have shown that there are approximately 0.79 million people incur new or recurrent stroke every year in the United States [1]. Contracture and motor impairment are the major symptom of the stroke, which will affect the upper limb's normal activity. Several studies show that repetitive motor functional motion will be a new therapeutic treatment for stroke patients and patient's recovery degree is positively influenced by intensive training [2]. In traditional physical therapy, therapists helping patients to rehabilitate are one on one based. However, it will be labor-intensive, and the duration of training actually depends on the therapists' energy, instead of patients. Besides, it will be difficult to measure and evaluate the patient's performance quantitatively. In contrast with traditional therapy, robot assistance will increase the therapy duration and measure the outcome objectively. It is possible for therapists to rehabilitate two or more patients simultaneously. It will reduce the staff costs. Therefore, robot assistance for rehabilitation is important.

There are several types of rehabilitation robot that have been developed. By the sort of mechanical structure, there are two types of robots: end-effector based and exoskeleton based. End-effector robot is that patient and robot are only one point connected. The benefit of this type is that the robot is simpler and easier to adapt to different arm. However, it will be difficult to determine the arm posture of patient and to analyze the interaction forces from which joint of patients only through one connected point. The MIT Manus[3], the Mirror Image Motion Enabler[4], and the GENTLE/s[5], belong to end-effector type.

Fig. 1. National Taiwan University Hospital-ARM (NTUH-ARM)

The exoskeleton type of robots resemble the human anatomy. Robot joints are matched to the human joints, so human arm will be attached to the robot arm over one point. The advantage of these types of robot is that it can measure the individual joint angle of the human arm more precisely. The pre-determined robot arm posture can be used to control the individual joint of the human arm. It is essential to control each joint separately. It will reduce the effect of synergy pattern, help patients to improve their coordination of upper limb movement. Furthermore, the interactive force exerted from certain joints of the human can be easily analyzed. Besides, compared to the end-effector robot, the exoskeleton robot has larger range of motion (ROM), enabling more movements to be included in the rehabilitation exercise.

So far, the existing prototypes in the field, ARMin I, II and III[6-8], the MGA Exoskeleton[9], the IntelliArm[10], the L-Exos[11], the NTUH-ARM[12], and so on are classified into exoskeleton type.

For the early version of the exoskeleton robot, it only uses about 3 degree of freedom (DOF) to represent the shoulder motion (e.g. flexion/extension, abduction/adduction, and internal/external rotation). However, the center of glenohumeral joint (CGH) will raise in different levels according to the humerus elevation, which is because of shoulder girdle movement [13]. Misalignment between human and robot will cause the patient to feel uncomfortable and decrease the effect of the recovery. Therefore, kinematic structure of human's shoulder joint must be taken into account. Recent rehabilitation robots have taken this point into consideration; however, they still have some problems in approximating the shoulder joint[14]. To achieve the assistive mode, there are two strategies used for implementation. One is to amplify the human torque, such as [15, 16], whereas the other is to adopt the assist-as-needed notion like [17, 18]. The purpose of this mode is to assist patients to finish motion tasks.

This paper will revisit the National Taiwan University Hospital-ARM (NTUH-ARM) (Fig. 1), a 7 DOF exoskeleton type robot, which can control shoulder and elbow separately, and simultaneously. Shoulder girdle movement is also taken into account. It can easily align the shoulder joint. By using the human arm dynamic, we can transfer the pure human torque sensing from subject to the desire angle. The rehabilitation robot can be operated in active mode, assistive mode, and passive mode by choosing assistive gain.

2. DESIGN

2.1 Kinematics Design

The goals of the design NTUH-ARM is to imitate the human anatomy and to generate correct trajectory of each joint to rehabilitate patients suffering from stroke. The NTUH-ARM totally has 7 DOF, where the first six DOFs, including one prismatic joint and five rotational joints, are to actuate the shoulder joint, and one DOF is to actuate the elbow joint (Fig. 2). Fig. 3 shows the kinematic structure of the NTUH-ARM along with the Denavit-Hartenberg (D-H) link frame assignments. The D-H parameters for the kinematics of the robot arm are given in TABLE 1. The length of upper arm (26~34cm) and forearm (24~30cm) could be adjusted passively to accommodate most of patient subjects [12].

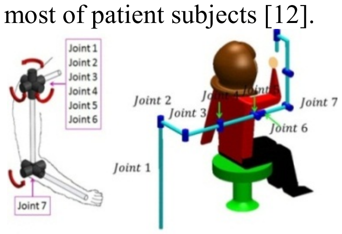

Fig. 2. The association of the motions between the human upper limb and NTUH-ARM.

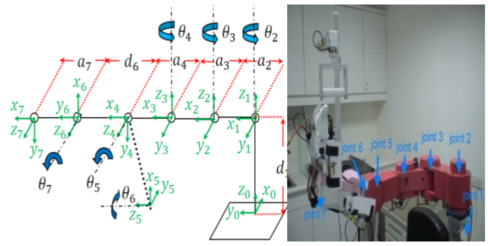

Fig. 3. Simplified kinematic configuration of the NTUH-ARM.

TABLE 1.
DENAVIT–HARTENBURG PARAMETERS OF NTUH-ARM

Axis	θ_i	d_i	a_i	α_i	Home
1	0	d_1	0	0	$\pi/2$
2	θ_2	0	a_2	0	0
3	θ_3	0	a_3	0	0
4	θ_4	0	a_4	$-\pi/2$	0
5	θ_5	0	0	$-\pi/2$	$-\pi/2$
6	θ_6	d_6	0	$\pi/2$	0
7	θ_7	0	a_7	0	$\pi/2$

The glenohumeral joint movement includes shoulder flexion/extension, horizontal adduction/abduction, internal/external rotation, shoulder girdle elevation/depression, and protraction/retraction. The elbow joint includes flexion/extension. The kinematic design of the NTUH-ARM is to provide lager range of motion to training patients for activities of daily living (ADL).

There are two sensitive 6-DOF force/torque sensors mounted at the upper arm and front of the wrist gripper to measure the interaction force/torque feedback from patients (Fig. 4). At each joint, a pair of potentiometer and encoder to measure the joint position. With these two kinds of position sensor, the robot could analyze and record the position of each joint for any configuration of human upper arm. The potentiometer could also be used to set the initial position of the robot.

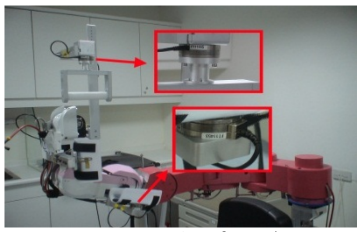

Fig. 4. There are two 6-DOF force/torque sensors. The one is equipped on the orthosis of the upper arm, and the other is mounted on the wrist gripper.

2.2 Modeling

Fig. 5 shows an interface of the trajectory for the therapist to generate or edit the personal arm trajectory for patients. The top slide is for time, and the other four are used to edit the four human joint angles. By these, the therapist can set each joint angle so as to reach certain degree goals at some pre-specified times. According to each patient's control ability, the therapist can adjust different movement and speed. Besides, the therapist can move multiple joints simultaneously. The lower right graph shows the trajectory designed by the therapist. Such trajectory will be saved in the database, so the therapist can use it next time repeatedly. If over the speed limit, the window will show error of that joint and the invalid trajectory will not be enforced. By this interface, the therapist can edit the trajectory easily.

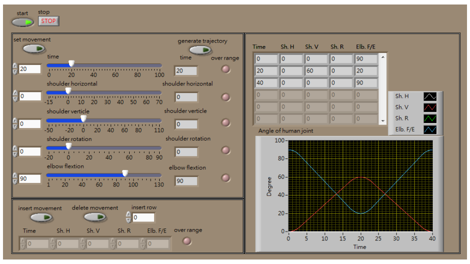

Fig. 5. An interface for generating and editing the trajectory, where the lower right graph shows the defined trajectory, of which white wave is the shoulder horizontal trajectory, red wave is the shoulder flexion/extension trajectory, green wave is for the shoulder internal/external rotation, and blue wave is for the elbow flexion/extension.

3. CONTROL SYSTEM

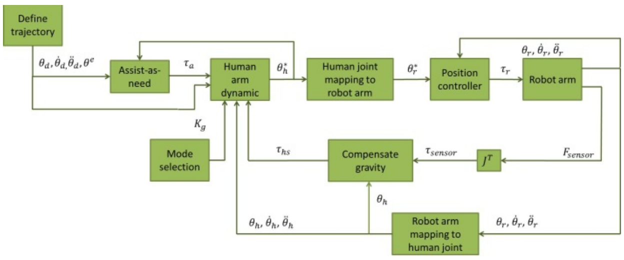

Fig. 6. Control block

Fig. 6 shows the control diagram of overall system. There are three rehabilitation modes for therapists, which consist of active mode, passive mode, and assistive mode.

The kinematic model of human upper extremity can use D-H notation to represent in Fig. 7. In human arm model the joint 1, 2, and 3 represent shoulder joint. These three joint intersect at one point. The joint 4 indicates the motion of elbow flexion/extension. Lengths L_u and L_f are the lengths of the upper arm and the forearm, respectively. The D-H parameters are shown in Table 2.

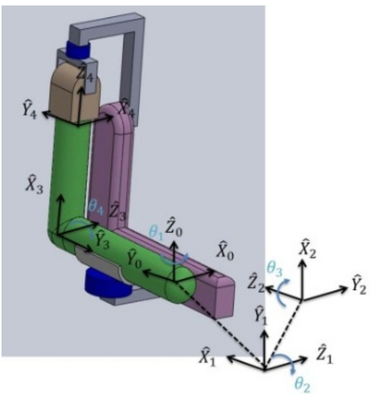

Fig. 7. Kinematic model of the human upper extremity.

Table 2.
DENAVIT–HARTENBURG PARAMETERS OF HUMAN ARM

Axis	θ_i	d_i	a_i	α_i	Home
1	θ_1	0	0	$\pi/2$	$\pi/2$
2	θ_2	0	0	$\pi/2$	$\pi/2$
3	θ_3	L_u	0	$-\pi/2$	0
4	θ_4	0	L_f	$-\pi/2$	$-\pi/2$

3.1 Robot Arm Mapping to Human Joint

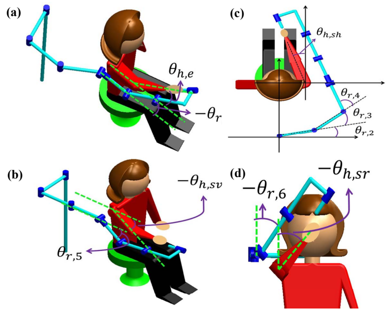

Fig. 8. Corresponding relationship between the robot arm and the human arm. (a) elbow flexion/extension; (b) shoulder flexion/extension; (c) shoulder horizontal adduction/abduction; and (d) shoulder internal/external rotation.

We use some structure condition to map the robot joint angle to the human joint angle, the relationship between robot and human as show in the Fig. 8. The elbow flexion/extension$\theta_{h,e}$, shoulder flexion/extension $\theta_{h,sv}$, shoulder horizontal adduction/abduction $\theta_{h,sh}$, and shoulder internal/external rotation $\theta_{h,sr}$ are shown from the Fig. 8 (a)~(d) respectively. Human joint angles can be obtained by following:

$$\begin{aligned} \theta_{h,e} &= -\theta_{r,7} \\ \theta_{h,sv} &= -\theta_{r,5} \\ \theta_{h,sh} &= \theta_{r,2} + \theta_{r,3} + \theta_{r,4} - \frac{\pi}{2} \\ \theta_{h,sr} &= \theta_{r,6} \end{aligned} \tag{1}$$

The $\theta_{r,i}$ means the robot joint angle, i means which joint. Use (1) we can map the robot angle to corresponding angle of human arm joint.

3.2 Analyze the Joint Torque from Measure Sensor

In the configuration of the NTUH-ARM, the force/torque sensors are mounted on the upper arm and the gripper, respectively. First, we use force-moment transformation to transfer these two sensor measure torques into same frame, shown in Fig. 9. After combining these two force and moment vector, we use the Jacobian transport to map measured Caresian force into human joint torques. The following show detail that we used:

$$\begin{bmatrix} {}^{2}f_{2,su} \\ {}^{2}n_{2,su} \end{bmatrix} = \begin{bmatrix} {}^{2}_{su}R & 0 \\ {}^{2}P_{su,org} \times {}^{2}_{su}R & {}^{2}_{su}R \end{bmatrix} \begin{bmatrix} {}^{su}f_{su} \\ {}^{su}n_{su} \end{bmatrix} \tag{2}$$

Eq. (2) is the force-moment transformation, where ${}^{su}f_{su}$ and ${}^{su}n_{su}$ are 3×1 force and moment vector measured from the upper arm F/T sensor described in frame $\{su\}$. ${}^{2}_{su}R$ is a rotation matrix describing the orientation of frame $\{su\}$ relative to frame $\{2\}$. ${}^{2}P_{su,org}$ is a 3×1 vector that locates the origin of frame $\{su\}$ relative to frame $\{2\}$. ${}^{2}f_{2,su}$ and ${}^{2}n_{2,su}$ are the 3×1 force and moment vector measured from the upper arm F/T sensor described in frame $\{2\}$.

Then, we transfer these forces and moments from frame $\{2\}$ into frame $\{4\}$ as shown below:

$$\begin{bmatrix} {}^{4}f_{4,su} \\ {}^{4}n_{4,su} \end{bmatrix} = \begin{bmatrix} {}^{4}_{2}R & 0 \\ {}^{4}P_{2,org} \times {}^{4}_{2}R & {}^{4}_{2}R \end{bmatrix} \begin{bmatrix} {}^{2}f_{2,su} \\ {}^{2}n_{2,su} \end{bmatrix} \tag{3}$$

where ${}^{4}_{2}R$ is a rotation matrix describing the orientation of frame $\{2\}$ relative to frame $\{4\}$. ${}^{4}P_{2,org}$ is a 3×1 vector that locates the origin of frame $\{2\}$ relative to frame $\{4\}$. ${}^{4}f_{4,su}$ and ${}^{4}n_{4,su}$ are the 3×1 force and moment vector measured from upper arm described in frame $\{4\}$.

Use the similar method, we also can obtain the force/torque measurement in frame $\{4\}$ from gripper F/T sensor frame $\{sg\}$. Combine the upper arm and gripper sensor data in frame $\{4\}$ as follows:

$$\begin{bmatrix} {}^{4}f_{4,total} \\ {}^{4}n_{4,total} \end{bmatrix} = \begin{bmatrix} {}^{4}f_{4,su} \\ {}^{4}n_{4,su} \end{bmatrix} + \begin{bmatrix} {}^{4}f_{4,sg} \\ {}^{4}n_{4,sg} \end{bmatrix} \tag{4}$$

where ${}^{4}f_{4,total}$ and ${}^{4}n_{4,total}$ are the total force and moment vector measured from upper arm and gripper described in frame $\{4\}$.

Next, we use Jacobian transpose to map the Cartesian forces ${}^{4}f_{4,total}$ and moments ${}^{4}n_{4,total}$ on the wrist into the equivalent human joint torques, *i.e.*,

$$\tau_{h,sensor} = {}^{4}J^{T}_{4,h} \begin{bmatrix} {}^{4}f_{4,total} \\ {}^{4}n_{4,total} \end{bmatrix} \tag{5}$$

where the ${}^{4}J^{T}_{4,h}$ is the Jacobian transpose of the human upper extremity described in frame $\{4\}$.

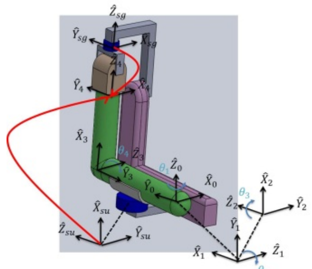

Fig. 9. Measured force/torque from each sensor transfer to the wrist frame (frame$\{4\}$).

3.3 Model of Human Arm Dynamic

Assume human upper extremity is the manipulator, applying the Newton-Euler equation, similarly we can derive the human arm dynamic model in the form:

$$\tau_{hm} = M_h(\theta_h)\ddot{\theta}_h + V_h(\theta_h, \dot{\theta}_h) + G_h(\theta_h) + F_h(\theta_h, \dot{\theta}_h) \tag{6}$$

where θ_h, $\dot{\theta}_h$, and $\ddot{\theta}_h$ are vector of human joint angles, angular velocities and angular accelerations. τ_{hm} is vector of motion torques generated from the subject. $M_h(\theta_h)$ is the inertia matrix, $V_h(\theta_h, \dot{\theta}_h)$is centrifugal and Coriolis terms, $G_h(\theta_h)$ is gravity term, and $F_h(\theta_h, \dot{\theta}_h)$ is friction term of the upper limb. The dynamics are calculated based on some existing human database in the literatures. For example, each segment of the human upper limb is modeled as a conical frustums with homogeneous mass [21], and the center of mass of each segment is taken from the literature [22]. Assume the human arm and robot arm are compact closely; therefore, during the motion, the velocity between human arm and robot arm are almost zero.

We can get the following equation:

$$\tau_{hm} = J^T F_{hm} = J^T F_{sensor} \tag{7}$$

where F_{hm} is human arm Cartesian force from human to robot, F_{sensor} is Cartesian force sensing from human.It can be measured by force/torque sensor. Combine the Eqs. (6), (7), and replace the interaction torque by the measured sensor torque $\tau_{h,sensor}$, we can obtain the dynamic equation as following:

$$J^T F_{sensor} = M_h(\theta_h)\ddot{\theta}_h + V_h(\theta_h, \dot{\theta}_h) + G_h(\theta_h) + F_h(\theta_h, \dot{\theta}_h) \tag{8}$$

To simulate the motion of human arm, we make use of Eq. (8) to simulate by solving the dynamic equation for acceleration:

$$\ddot{\theta}_h = M_h^{-1}(\theta_h)[J^T F_{sensor} - G_h(\theta_h) - V_h(\theta_h, \dot{\theta}_h) - F_h(\theta_h, \dot{\theta}_h)] \tag{9}$$

In order to achieve the assistive mode, we combine the $\tau_{h,sensor}$ and $G_h(\theta_h)$ to compensate the gravity influence on sensor Eq. (9) can be modified as follows:

$$\ddot{\theta}_h^* = M_h^{-1}(\theta_h)[K_g \tau_{hs} - V_h(\theta_h, \dot{\theta}_h) - F_h(\theta_h, \dot{\theta}_h)] \tag{10}$$

where $\ddot{\theta}_h^*$ are the desired angular accelerations of the upper limb, K_g is the diagonal gain matrix for torque adjusting, τ_{hs} is the measured sensor torque remove the gravity influence. This type of assistive mode is to amplify the human torque.

3.4 Assistive as needed

Assisting by amplifying human torque has been illustrated previously. In this part, we will introduce the assist-as-needed concept. The torque generate from the ith joint trajectory is shown as follows (i=1~4):

$$\tau_{ai}(t) = 2m_{aii}(\dot{\theta}_{di}(t) - \dot{\theta}_{hi}^*(t)) + m_{aii}\ddot{\theta}_{di}(t) + m_{aii}(\theta_{di}(t) - \theta_{hi}^*(t)) \tag{11}$$

where θ_{di}, $\dot{\theta}_{di}$, and $\ddot{\theta}_{di}$ are the vector of ith define trajectory joint angle, angular velocity and angular acceleration. τ_{ai} is the assist-as-needed torque of ith joint. $\theta_{hi}^*(t)$, and $\dot{\theta}_{hi}^*(t)$ are the desired angle and angular velocity of the ith joint. m_{aii} is a positive constant. By using the assist-as-needed torque, we can simulate the trajectory torque to assist the subject to the correct trajectory. Combine Eq. (11) into Eq. (10), we modify the ideal motion model with assist torque to achieve assist-as-needed goal, shows as follows:

$$\ddot{\theta}_h^* = K_s M_a^{-1}\tau_a + (I - K_s)M_h^{-1}(\theta_h)[K_g \tau_{hs} - V_h(\theta_h, \dot{\theta}_h) - F_h(\theta_h, \dot{\theta}_h)] \tag{12}$$

$$M_a = \begin{bmatrix} m_{a11} & 0 & 0 & 0 \\ 0 & m_{a22} & 0 & 0 \\ 0 & 0 & m_{a33} & 0 \\ 0 & 0 & 0 & m_{a44} \end{bmatrix} \tag{13}$$

$$K_S = \begin{bmatrix} k_{s1} & 0 & 0 & 0 \\ 0 & k_{s2} & 0 & 0 \\ 0 & 0 & k_{s3} & 0 \\ 0 & 0 & 0 & k_{s4} \end{bmatrix} \tag{14}$$

$$k_{si} = \begin{cases} 1 & \dot{\theta}_{hi}(t)(\theta_{di}(t) - \theta_{hi}(t)) > 0 \\ 0 & otherwise \end{cases} \tag{15}$$

where M_a is a diagonal positive definite matrix. K_s is a diagonal matrix for switching the τ_a.

With this assistance condition, the robot will support the patients to move in the predefined trajectory only if the patients move slower than the desired trajectory; otherwise, patients have to move by themselves. In other words, the robot will assist the patients only as they need. According to Eq. (12), we can operate in active mode assistive, and passive mode by adjusting K_g and K_s. Table 3 shows the condition of the rehabilitation mode.

Table 3. Rehabilitation mode

Rehabilitation mode	Active	Assistive	Passive
Coefficient	$K_g = I$, $K_s = 0$	Element of $K_g > 1$, $K_s = 0$ or $K_g = I$, $K_s = I$	$K_g = 0$, $K_s = I$

3.5 Human Joints Map to Robot Arm

Using the Fig. 7 and Table 2, we can derive forward kinematics easily. After obtaining the position of human joints, we can use the inverse kinematics of robot show in our previous work [12] to derive the robot joint angle.

4. SAFETY

Safety is the most important issue for the design of a rehabilitation robot; similarly, NTUH-ARM is designed based on it. On the software side, several surveillance routines are included, such as those monitoring positions, velocities, current of the motors, and positions of the potentiometers as well as several watchdog systems. For example, we will compare the angle of potentiometer with the angle of encoder during operation. If the difference is larger than some given degree, it means that some of line is snapped and the system will be stop immediately. In addition, two stop buttons are designed: one is hand-button, which is for the patient or physiotherapist whereas, the other one is emergency button, as shown in Fig. 10.

The hand-button is designed to prevent the robot from imposing harm to the patient during the training. The patient can immediately stop the training exercise when they feel painful. The emergency button is used for emergency cases which are unexpected.

Fig. 10. Two stop buttons in NTHU-ARM system. The left one is emergency button, and the right one is hand-button.

5. EXPERIMENTAL RESULT

To validate our design, some realistic experiments are demonstrated in this section. Before the experiment, we have to measure the weight of the upper arm for gravity compensation. The following experiments are executed by health subject and the LabVIEW 8.6 is used for programming.

Fig. 11 shows the passive mode of the elbow flexion/extension and shoulder internal/external rotation, the trajectory is edited show in 2.2. The white line is the predefined trajectory and the red line is the measures angle. As you can see the trajectory almost overlap with each other, the root mean square error of the elbow and shoulder are 1.04°and0.3°, respectively.

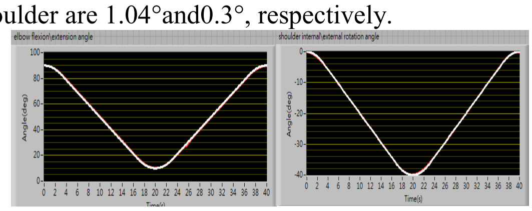

Fig. 11. Passive mode of the elbow flexion/extension (left) and shoulder internal/external rotation (right).

The experiment is to do elbow flexion/extension in active mode and assistive mode. In both modes, the subject tries to do a task of extending the elbow from 90 degrees to 10 degrees back and forth in about twelve seconds, and the K_s equal 0. The element of K_g corresponding to elbow flexion/extension is made equal to 1 and 2, respectively. From Fig. 12, we can see that the subject needs to exert the largest work to do the task in the active mode. By comparison, the assistive mode requires almost half of the work of the active mode.

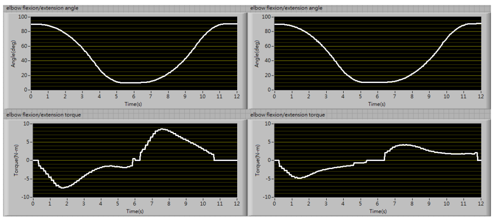

Fig. 12. This figure shows the result of elbow flexion/extension task in active mode (left) and in assistive mode (right). The top plot indicates the angle of the elbow flexion/extension, the lower plot indicates the pure torques of the motion of the elbow flexion/extension generated from the subject.

If subject does not have sufficient torque to finish the motion, in the assist-as-needed paradigm mode, the assistive controller will generate needed torque to help patient to target, as show in Fig. 13. The top plot indicates the angle of elbow flexion/extension, the red curve is the desired trajectory, the white curve is the measured trajectory. The lower plot indicates the torque of elbow flexion/extension, the red curve is the assistive torque from robot arm, the white curve is the torque generated by subject. In (a) and (c) parts, the measured angle of the human joint slower than the desired angle, so robot will generate an assistive torque to support the subject. In (b) and (d) parts, the measured angle of the human joint faster than the desired angle, so robot will have no assistive torque to support the subject.

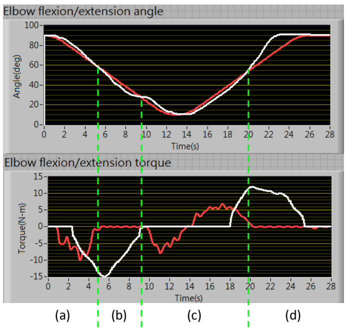

Fig. 13. The result of the assistive mode by assist-as-needed notion in elbow flexion/extension.

6. CONCLUSIONS AND FUTURE WORK

This paper introduces an integration of the human arm dynamics into control of an upper limb robotic arm to implement a promising therapeutic exercise. Taking the human arm dynamics, it can physically simulate the volitional movements of subject. By analyzing the torques purely generated from the subject from the 6-DOF force/torque sensors, the torque generated from every joint can be obtained. Besides, the robot has lager range of motion for rehabilitation. Due to being the first prototype of NTUH-ARM, some limitations inevitably exist at the present stage. In the future for developing the next robot prototype of NTUH-ARM, the robotic weight should be further reduced.

ACKNOWLEDGMENT

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