Design and Control of an Upper Limb Exoskeleton Robot RehabRoby

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Abstract. In this work, an exoskeleton type robot-assisted rehabilitation system called RehabRoby is developed for rehabilitation purposes. A control architecture, which contains a high-level controller and a low-level controller, is designed for RehabRoby to complete the rehabilitation task in a desired and safe manner. A hybrid system modeling technique is used for high-level controller. An admittance control with inner robust position control loop has been used for the low-level control of RehabRoby. Real-time experiments are performed to evaluate the control architecture of the robot-assisted rehabilitation system RehabRoby.

Keywords: Robot-assisted rehabilitation system, exoskeleton robot, control architecture.

1 Introduction

There are over 650 million people around the world with disabilities. Although it is accepted as 10% of the whole world population, it is 15.7% in Europe, 12% in USA [1] and 12.29% in Turkey [1]. Physical disability, which occurs by birth or acquired during the life span of the person due to the diseases or a trauma to the central nervous system or musculoskeletal system, affects the functionality of people. The physical therapy and rehabilitation programs are applied to the people with disability to increase their joint range, strength, power, flexibility, coordination and agility of the person, and to improve their functional capacity as well as third level of independence [2], [3]. The availability of such training techniques, however, is limited by a number of factors such as the amount of costly therapist's time they involve and the ability of the therapist to provide controlled, quantifiable, and repeatable assistance to complex movement. Consequently, end-effector and exoskeleton robot-assisted rehabilitation that can quantitatively monitor and adapt to patient progress, and ensure consistency during rehabilitation may provide a solution to these problems and has become an active research area [4]-[8].

Exoskeleton type robots resemble the human arm anatomy and each joint of robot can be controlled separately, which reduces control issue complexity. ARMin [4], T-WREX [5], Pneu-WREX [6], L-Exos [6], and Selford Rehabilitation Exoskeleton [8] are well known exoskeleton type robot-assisted rehabilitation systems. Existing

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exoskeleton robot-assisted rehabilitation systems have been developed to provide assistance to patients during the execution of upper-extremity rehabilitation exercises. In this work, an exoskeleton type upper-extremity robot-assisted rehabilitation system, which is called RehabRoby, is developed.

RehabRoby has been designed to implement passive, active-assisted and resistive-assisted therapy modes. RehabRoby has been designed in such a way that it can be easily adjustable for people with different heights and arm lengths. RehabRoby can also be used for both right and left arm rehabilitation. Control of a robot-assisted rehabilitation system in a desired and safe manner is an important issue during the execution of rehabilitation therapies.

Impedance control, position and admittance control have previously been used to control robot-assisted rehabilitation systems. There is a human-robot interaction in the robot-assisted rehabilitation systems, which is an external effect that can cause changes in the dynamics of the robotic systems. The changes in the dynamics of the rehabilitation robotics may result in instability, which indeed may cause unsafe situations for patients during execution of the rehabilitation task. Furthermore, robot-assisted rehabilitation systems, especially exoskeleton types have complex dynamics. Thus, there is a need to design a controller for RehabRoby that compensates changes in the dynamics of the rehabilitation robotics. A controller, which is independent of dynamic model of robot-assisted rehabilitation system, may provide a solution to this problem [9]. Thus, in this work admittance control with inner robust position control loop has been used to control RehabRoby in a desired manner. Note that it is also desirable for a patient to perform the rehabilitation task in a safe manner. A high-level controller, which is a decision making mechanism, has been designed to ensure safety during the execution of the rehabilitation task. The high-level controller presented in this work plays the role of a human supervisor (therapist) who would otherwise monitor the task and assess whether the rehabilitation task needs to be updated.

In this study, control architecture of the robot-assisted rehabilitation system RehabRoby has been evaluated with healthy subjects. Subjects are asked to perform well known rehabilitation tasks elbow flexion with RehabRoby in active-assisted mode and resistive-assisted mode. This assessment may provide us clues on how RehabRoby can be used in upper extremity rehabilitation of stroke patients in different therapy modes.

This paper describes the control architecture of the robot-assisted rehabilitation system RehabRoby in Section 2. An experimental set-up that is used to evaluate RehabRoby system is given in Section 3. Experimental results are presented in Section 4. Discussion of the study and possible directions for future study is given in Section 5.

2 Control Architecture

A control architecture is developed for robot-assisted rehabilitation system RehabRoby to complete the rehabilitation tasks in a desired and safe manner (Fig. 1). Control architecture consists of a robot-assisted rehabilitation system (RehabRoby), low-level and high-level controllers, and a sensory information module. We first describe robot-assisted rehabilitation system RehabRoby, and then present the details of the low-level and high-level controllers that are used to complete the rehabilitation tasks in a desired and safe manner.

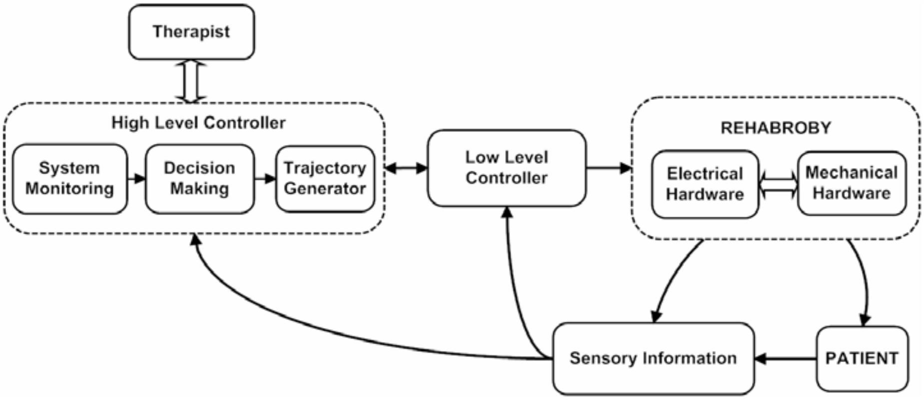

Fig. 1. Control Architecture of the RehabRoby

2.1 RehabRoby

RehabRoby is designed to provide extension, flexion, abduction, adduction, rotation, pronation and supination upper-extremity movements and also combination of these movements that are necessary for activities of daily living (Fig. 2). RehabRoby can provide horizontal abduction/adduction of shoulder rotation (θ_1), shoulder flexion/extension elevation (θ_2), internal and external rotation of shoulder (θ_3), elbow flexion/extension (θ_4), lower arm elbow pronation/supination (θ_5) and wrist flexion/extension (θ_6). RehabRoby has been designed in such a way that it can be easily adjustable for people with different heights and arm lengths. In the design of RehabRoby, anthropometric approaches have been used. The link lengths of RehabRoby are based on the arm lengths of 2100 people in 14 cities in Turkey. RehabRoby can also be used for both right and left arm rehabilitation. Range of motion (ROM), joint torques, velocities and accelerations for RehabRoby have been determined using the measurements of the movements of a healthy subject during two activities of daily living tasks [10], [11].

An arm splint has been designed and attached to RehabRoby (Fig. 2). It has humeral and forearm thermoplastic supports with velcro straps and a single axis free elbow joint. A thermoplastic inner layer covered by soft material (plastazote) is used due to the differences in the size of the subjects' arms. Thus, the total contact between the arm and the splint can be achieved to eliminate loss of movement during the execution of the task. Kistler model press force sensors, which have quite small sizes, are selected to measure contact forces between the subject and RehabRoby. One force sensor has been placed in the inner surface of the thermoplastic molded plate attached dorsally to forearm splint via velcro straps in such a way that the measurement axes of them are perpendicular to each other (Fig. 2). This force sensor is used to measure the applied force during the elbow flexion movement.

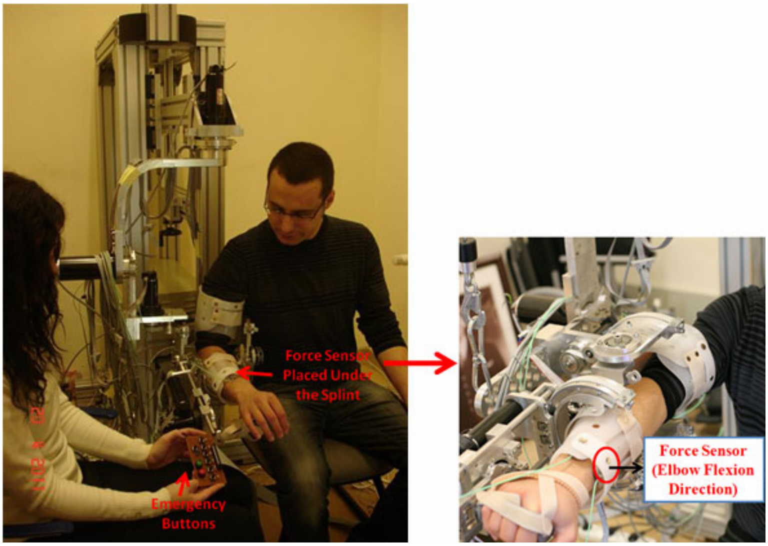

Fig. 2. RehabRoby with Subject

Ensuring safety of the subject is an important issue when designing a robot-assisted rehabilitation system [12]. Thus, in case of emergency situations, the physiotherapist can press an emergency stop button to stop the RehabRoby (Fig. 2). The motor drivers of RehabRoby can be disabled separately or together by pressing the driver enable/disable buttons without disconnecting the energy of the RehabRoby in any case of emergency situations. The power of the system is supported with uninterruptible power supply, thus, there is no power loss and RehabRoby will not collapse at any time. Additionally, rotation angle and angular velocities of each joint of RehabRoby are monitored by the high-level controller which will be described in the next section.

RehabRoby has been interfaced with Matlab Simulink/Realtime Workshop to allow fast and easy system development. Humusoft Mf624 model data acquisition board is selected to provide real time communication between the computer and other electrical hardware. Humusoft Mf624 data acquisition board is compatible with Real Time Windows Target toolbox of MATLAB/Simulink. Digital incremental encoders are coupled with Maxon models of brushed DC motors for joint position measurement. Five of the six encoders have resolutions of 500counts/turn and one of them has a resolution of 1000counts/turn. Encoder data of motors is received through a Humusoft Mf624 with a 500Hz sampling rate. Analog reference current values are converted to digital ones, and then transmitted to the drivers using RS232 serial bus with a baud rate of 115200 using Programmable Interface Controller (PIC) microcontrollers. The current reference values of motors are sent to the microcontroller circuits using the analog outputs of the Humusoft Mf624 card with the same sample rate. Microcontroller circuits are used because four of the six motor drivers of RehabRoby have no analog reference inputs. Analog to digital conversion and serial transmission are completed within 2 milliseconds. A 19'' LCD screen is positioned in front of the subject at a distance of about 1m to display the reference rehabilitation task trajectory and subject's actual movement during the task execution. The force values measured from the force sensors are recorded using the Humusoft Mf624data acquisition card with a sampling rate of 500Hz. The joint torque corresponding to applied forces by the subject is calculated by multiplying the force with the perpendicular distance between the force contact point and the joint axis.

2.2 Low-Level and High-Level Controllers

Low-level controller is responsible to provide necessary motion to RehabRoby so patients can complete the rehabilitation tasks in a desired manner. In this study, admittance control with inner robust position control loop is used as the low-level controller of RehabRoby (Fig. 3).

Admittance control method is a good choice for control applications of the robotic systems which have low back drivability, high inertia and reliable position and force/torque information. Since RehabRoby has complex and uncertain inner dynamics and it is sensitive to external forces during the human-robot interaction, a simple Proportional-Integral-Derivative (PID) or model based position control technique may not be enough to complete the tracking in a desired performance. Thus, a robust position controller has been used in the inner loop of the admittance controller. The effects of the parametric uncertainties in the dynamic model and the external additive disturbances are compensated with an equivalent disturbance estimator in the robust position controller.

Various methods have been previously used to estimate the disturbance in the position control of robotic systems such as adaptive hierarchical fuzzy algorithm [13], model based disturbance attenuation [14]. In this work, we have used discrete Kalman filter based disturbance estimator [15],[16], which is a commonly known and successful technique used to process noisy discrete measurements. Additionally, discrete linear Kalman filter based disturbance estimator estimates the unknown states and parameters in the dynamic model in an accurate manner. To our knowledge admittance control with inner robust position control loop has not been used for control of robot-assisted rehabilitation systems before.

The general structure of the proposed low-level controller for RehabRoby is shown in Fig. 3. The force that is applied by the subject during the execution of the task is measured using the force sensor and this value is then converted to torque using Jacobian matrix. The torque value is then passed through an admittance filter [17], which is used to define characteristics of the motion of the RehabRoby against the applied forces,to generate the reference motion for the robust position controller. The reference motion is then tracked with a robust position control which consists of a linear Kalman filter based disturbance estimator [17].

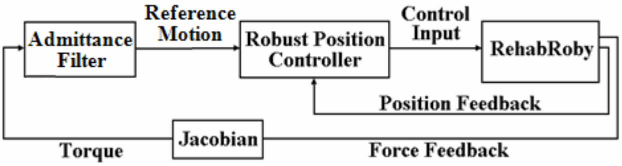

Fig. 3. Block Diagram of Low-level Controller of RehabRoby

High-level controller is the decision making mechanism of RehabRoby. High-level controller decides necessary changes in the low-level controller by analyzing the information that comes from the sensory information module or physiotherapist (system monitoring). The high-level controller presented in this study plays the role of a human supervisor (therapist) who would otherwise monitor the task and assess whether the task needs to be updated. A hybrid system modeling technique is used to design the high-level controller because it is easy to add new rules related to rehabilitation task using the hybrid system modeling technique (Fig. 4).

Initially, states of the high-level controller are defined. When task execution starts, starting and final positions of the joint angles of RehabRoby are initialized in *initialization state*. In this work, three therapy modes, which are passive, active–assisted mode and resistive-assisted mode, have been selected for rehabilitation tasks. *passive state* (*mode=0*), *active state* (*mode=1*) or *admittance controlstate* (*mode=2*) become active based on the therapist's therapy mode selection. In passive mode, the rehabilitation task is performed only in the passive state in which RehabRoby is responsible to help subject to complete the task while subject is passive. The subject's motion is checked periodically in all therapy modes. If the subject's movement, which is measured as (θ) of RehabRoby, is out of limits ($\theta \geq |\varepsilon|$), then *position control state* becomes active. When *position control state* is active, then RehabRoby provides assistance to the subject's motion until subject's movement is in the desired motion range. When the subject's movement is in the range of limits ($\theta < |\varepsilon|$), then the state, which is active before entering the *position control state*, becomes active again. In any state, the safety conditions of the system are checked periodically and if any unsafe situation is occurred (*e=1*), then *emergency stop state* becomes active and the execution of the rehabilitation task is stopped.

3 Experimental Setup

3.1 Task Design

The objective of this study is to investigate use of a robot-assisted rehabilitation system RehabRoby during the execution of rehabilitation tasks. This assessment may provide us clues on how RehabRoby can be used in upper extremity rehabilitation of stroke patients in different therapy modes. Elbow flexion movement (i.e. reaching towards a glass of water on the table) rehabilitation task has been selected in

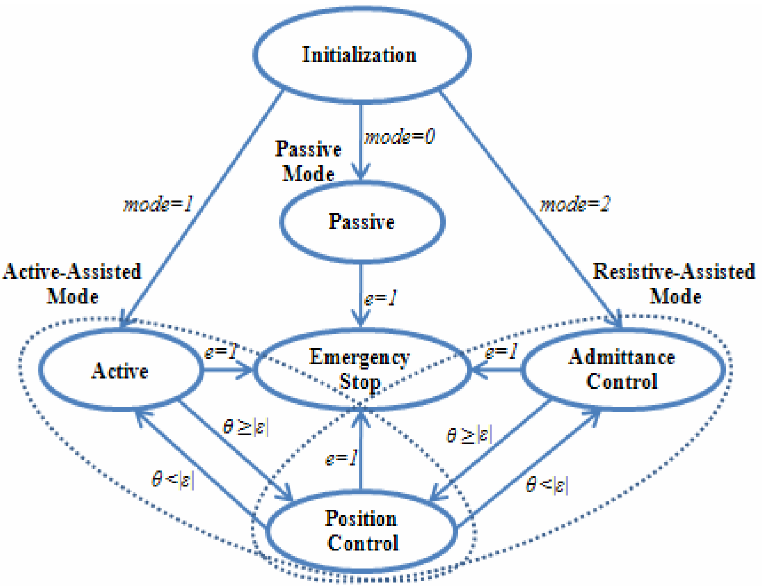

Fig. 4. Control Mechanism for High-Level Controller of RehabRoby

consultation with physiotherapists in Yeditepe University Physical Therapy and Rehabilitation Department. This study has been approved by the Institutional Review Board of Yeditepe University Hospital(IRB #032).

3.2 Experiment Protocol

Subjects were seated in the chair as shown in Fig. 2 and their arms were placed in the splint tightly secured with velcro straps.The height of the RehabRoby was adjusted for each subject to start the task in the same arm configuration. Subject's shoulder was positioned at extension of 90^0, elbow was at neutral position, lower arm was at pronation of 90^0, and the hand and the wrist were free at neutral position as a starting position (Fig. 5a). In elbow flexion movement task (Theta-4 (θ_4)), subjects were asked to flex their elbows to 90^0 in 30 seconds (Fig. 5b and Fig. 5c).

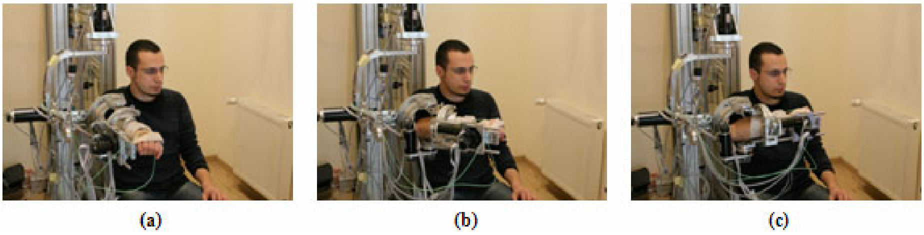
(a) (b) (c)

Fig. 5. Subject with RehabRoby. (a) Initial Position of Elbow Flexion, (b) Middle Position of Elbow Flexion Task, (c) Final Position of Elbow Flexion Task.

It is possible for the subjects to perform the rehabilitation in three different therapy modes. However, we only selected active-assisted and resistive-assisted therapy modes in this work. In active-assisted therapy mode, RehabRoby had been kept passive, subjects were asked to perform the rehabilitation tasks by themselves and RehabRoby provided assistance to the subjects when they can not follow the desired movement. No resistance was applied to the subject's movement in active-assisted mode. In resistive-assisted therapy mode, subjects were asked to perform the rehabilitation tasks with a comfortable resistance applied by RehabRoby using admittance control with inner robust position control loop and RehabRoby provided assistance to the subjects when they can not follow the desired movement. The resistance applied in resistive-assisted mode was quite large compared with the resistance that is caused by the inherent dynamics of RehabRoby. Thus, the resistance of the system during performance of the tasks in active-assisted mode is neglected. The parameters in admittance filter, which provided comfortable resistance, had been determined experimentally. The reference trajectories for the rehabilitation tasks were defined using minimum jerk trajectory method. Desired motion range was determined by setting upper and lower limits to the reference trajectories. The upper and lower limits can be adjusted based on the patient's movement capabilities.

Initially, experiment protocol had been explained to each subject, who participated in the study. Then subjects were asked to practice with RehabRoby to become familiar with the rehabilitation task. Subject performed 5 trials to become familiar with the elbow flexion task and RehabRoby before starting real-time experiments.

3.3 Subjects

Totally 9 subjects (4 female and 5 male) whose ages are in the range of 22 to 26 were participated in the study. None of them have any motor impairment in their arms. Two of the subjects were left handed and the others were right handed.

4 Results

We asked subjects to perform elbow flexion rehabilitation task in active-assisted mode and resistive-assisted mode. Subjects were required to move from 0^0 to 90^0 for the elbow flexion task and they were asked to trace a ball (green ball in Fig. 6) that was shown to them on a computer screen. The actual position of the subject (blue ball), the desired position (green ball) and the desired motion (black line) (Fig. 6) were also shown to the subjects.We have only presented a small portion of elbow flexion task (Theta-4 (θ_4)) in here. Perpendicular lines at equal absolute distance from the desired position (green ball) were drawn to represent the upper and lower limits of the desired motion of elbow flexion rehabilitation task (Fig. 6). In this work, visual feedback was selected to keep the concentrations of the subjects at maximum level during the execution of the task.

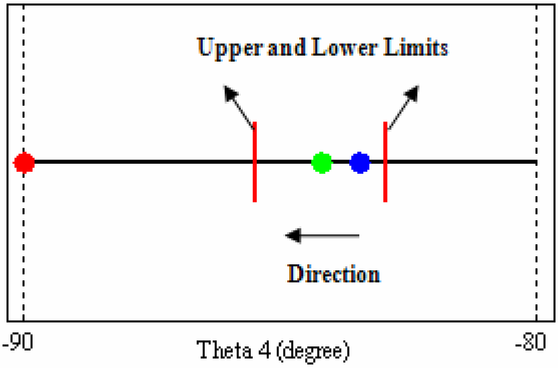

Fig. 6. Visual Feedback Based on Ball Tracking for Elbow Flexion

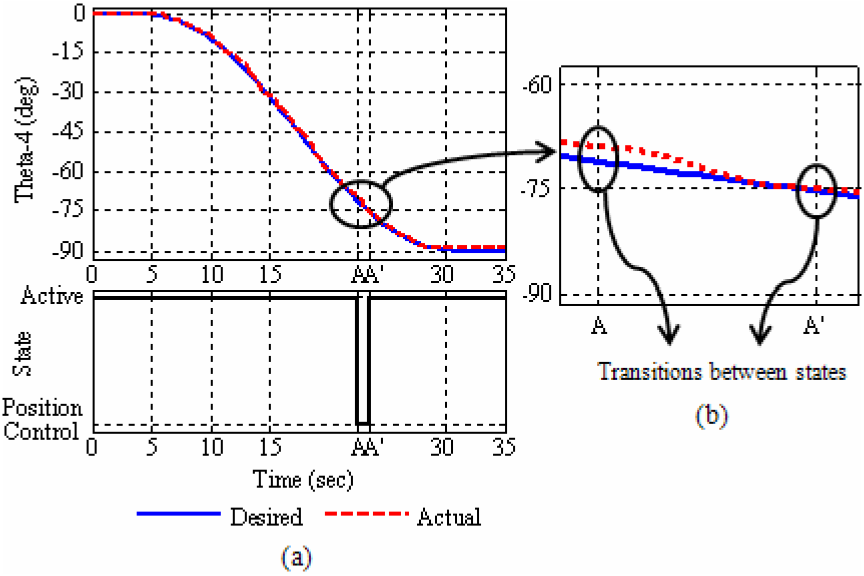

Fig. 7. (a) Motion of Subject 4 During Elbow Flexion Task in Active-Assisted Therapy Mode, (b) A Close Look at the Smoothness of the Transition between Controller States

The subjects were asked to complete the elbow flexion (Theta-4 (θ_4)) in the specified motion ranges using active-assisted and resistive-assisted therapy modes. Allowed maximum deviation from the reference trajectories of each rehabilitation task was selected as 1.5^0. It is possible to increase/decrease the deviation angle depending on the patient's movement capabilities. The subject's movement had been checked in every 2 seconds and if the subject's movement was out of the limits of the desired motion, then RehabRoby became active to provide assistance to the subject to take his/her motion into the desired motion range using the robust position controller with disturbance estimator. Checking time can be changed by the therapist before the therapy starts. The experiments were performed with 9 subjects; however we only presented one of the subjects' data (Fig. 7 and Fig. 8). It could be seen that when the subject was not in the desired motion range, then admittance control with inner robust position control loop became active at A (Fig 7) and the subject came back to the desired motion range at A'. When the subjects were in the desired range, then the RehabRoby became inactive and subject continued execution of the task by his/her effort. Subject needed more number of times of assistance when he/she had performed the elbow flexion task in resistive-assisted therapy mode (Fig. 8). It had also noticed that the transition between the controllers when assistance needed had been smooth (Fig. 7-b). Smooth transitions between the controllers during the execution of the rehabilitation were important to complete the task in a safe manner.

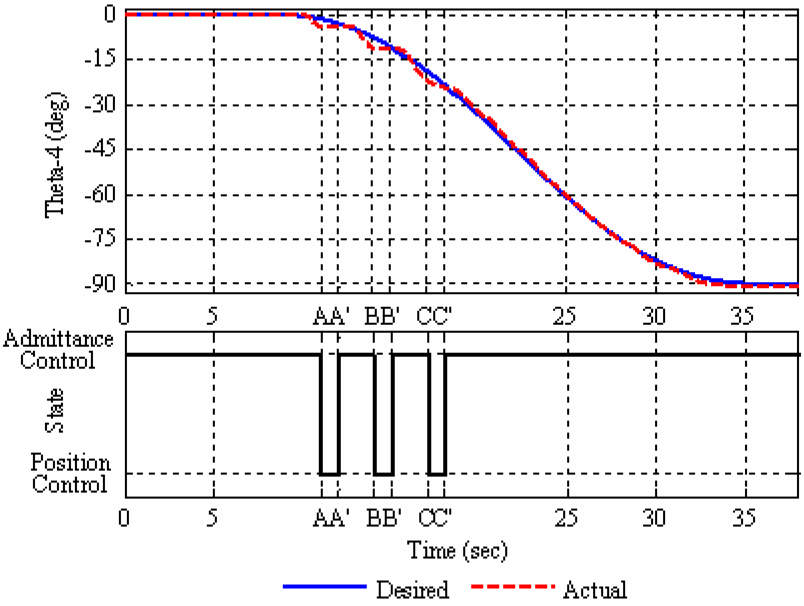

Fig. 8. Motion of Subject 4 During Elbow Flexion Task in Resistive-Assisted Therapy Mode

5 Discussion and Conclusion

We have developed an exoskeleton type upper-extremity robot-assisted rehabilitation system called RehabRoby. RehabRoby can provide passive mode, active-assisted mode and resistive-assisted mode for low-functioning and high-functioning patients. RehabRoby can promote and maintain passive range of motion for low-functioning patient's movements in passive mode. Additionally, RehabRoby can increase strength by providing resistance during the movement of high-functioning patients in resistive-assisted mode. RehabRoby is also adaptable for patients with different gender.

Additionally RehabRoby can be adjusted easily for people with different arm lengths. Furthermore, it can be used for both right and left arm.

A control architecture which consists of a high-level controller and a low-level controller has been developed for RehabRoby. High-level controller is the decision making mechanism that decides necessary changes in the low-level controller according to the sensory information or the therapist's commands. The high-level controller presented in this study plays the role of a human supervisor (therapist) who would otherwise monitor the task and assess whether the task needs to be updated. Admittance control with inner robust position control loop has been used for the low-level controller. Admittance controller has been integrated with a robust position controller which consists of a linear discrete Kalman filter. The evaluation of the proposed robust position controller has shown that discrete linear Kalman filter based disturbance estimator can compensate the effects of the uncertainties in the dynamic model and external disturbances that might happen during human-robot interaction.

As a future work, the robust position controller performance will be improved using adaptive Kalman filter which will adjust the admittance parameters of RehabRoby for each subject. Note also that this is a feasibility study for the proposed robot-assisted rehabilitation system RehabRoby to be used in the future for rehabilitation of stroke patients.

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