Development of a Therapeutic Exercise Robot for Wrist and Forearm Rehabilitation

Physiotherabot©/WF*

Murat ATLIHAN[1], Erhan AKDOĞAN[2], M. Selçuk ARSLAN[3]
Department of Mechatronics Engineering
Yildiz Technical University
Istanbul-Turkey
[1]muratatlihan@hotmail.com, [2]eakdogan@yildiz.edu.tr, [3]msarslan@yildiz.edu.tr

Abstract— **In this study, design steps and system concept of a 3 DOF upper limb rehabilitation robot which is called Physiotherabot/WF are introduced. Functional requirements of design, corresponding design parameters and system concept of the robot were examined in detail. Physiotherabot/WF can perform pronation-supination movement for forearm, abduction-adduction and flexion-extension movements for wrist. It can perform passive, active assisted, isotonic, isometric and isokinetic exercises. In order to control the robot, Hybrid Impedance Control (HIC) method is used. The HIC performance is shown by simulation results.**

Keywords—rehabilitation robot; biomechatronics design; hybrid impedance control;

I. INTRODUCTION

Rehabilitation is a therapeutic process which aims to bring a handicapped person to a better condition medically, psychologically, socially and vocationally, and decrease the permanent disabilities [1]. A limb, which is impaired due to muscle disabilities, work or traffic accidents and chronic diseases, needs rehabilitation to restore its functions permanently or temporarily. Especially, in populous countries, where the number of physiotherapists per patient is not enough (to set an example, in Turkey, physiotherapists are allowed to accept 16 patients in a day [2]), the transportation problems of physiotherapists and patients, the financial problems in the rehabilitation process, the constraints in the existing rehabilitation robots and systems are the main problems of the rehabilitation process. For these reasons, rehabilitation robot researches have increased in last 15 years. The reasons using robots in rehabilitation are given below:

- Robots can make the repetitive movements easily.
- Robots can measure mechanical parameters objectively by using their sensors.
- Robots can apply the desired force to patient precisely [3].

The rehabilitation robots developed for upper limbs are more than lower limbs, since a human uses his upper limbs more than their lower limbs in activities of daily living (ADL).

Krebs *et al.* [4], designed a 3-DOF rehabilitation robot, which is called MIT-MANUS, for shoulder and elbow rehabilitation. It can make planar movements and perform passive, assistive and resistive exercises using impedance control with a task-based interface for motor skill training. It is best known rehabilitation robot in the literature. Lum *et al.* [5], designed a 4-DOF robotic system, which is named MIME, by using a Puma 360 robot. It is for shoulder and elbow rehabilitation, and can perform passive, assistive and resistive exercises bilaterally using force-torque and position control. It can also perform mirror movements. Reinkensmeyer *et al.* [6], designed a 4-DOF robot ARM-Guide (Assisted Rehabilitation and Measurement) for shoulder and elbow rehabilitation, and can perform passive, assistive and resistive exercises using PD position and force control. Toth *et al.* [7] designed a robotic system, which is named REHAROB, by using a 6-DOF industrial robot. It is for shoulder, elbow and forearm rehabilitation, and can perform passive exercises to decrease the spasticity of the limb. Loureiro *et al.* [8] designed a robotic system, which is named Gentle/S, by using a 3-DOF Haptic Master robot. It is for shoulder and elbow rehabilitation, and can perform passive, assistive and resistive exercises using force control. Reiner *et al.* [9] designed an exoskeleton robot, which is named ARMin, for shoulder and elbow rehabilitation. 2-DOF of it works passive whereas 4-DOF of it works active. It can perform passive, assistive exercises using admittance and impedance control. Schmidt *et al.* [10] designed a 2-DOF robot Bi-Manu-Track for wrist and forearm rehabilitation. It can perform passive, assistive and resistive exercises bilaterally using position control. Takahashi *et al.* [11] designed a 3-DOF pneumatic robotic system HWARD for hand and wrist rehabilitation. It can perform assistive and grasping – leaving movements using force control. Sukal *et al.* [12], designed a robotic system, which is named Act 3D, by using a 3-DOF Haptic Master robot. It is for shoulder and elbow rehabilitation, and can perform passive, assistive and resistive exercises using admittance control. Reiner *et al.* [13], designed an exoskeleton robot, which is named PneuWrex, for shoulder and elbow rehabilitation. It has 4-DOF and can perform passive, assistive exercises using force and position control. It is a pneumatically

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system. Deneve *et al.* [14], designed an exoskeleton robot for shoulder and elbow rehabilitation. It has 3-DOF and can perform passive, assistive exercises using PI position, PD force, impedance and force/impedance control. Lewis *et al.* [15], designed a robotic system by using two 3-DOF Haptic Master robots. It is for upper arm, elbow and forearm rehabilitation, and can perform assistive and resistive exercises bilaterally using EMG based admittance control. Colizzi *et al.* [16], designed a exoskeleton robotic system which is named ARAMIS. It has 6-DOF and is for elbow, forearm and wrist rehabilitation. It can perform passive, assistive and resistive exercises using force and position control. It has developed virtual reality features to get visual feedback. Frisoli *et al.* [17], designed a 5-DOF exoskeleton robotic system which is named L-Exos. It is for wrist rehabilitation and can perform grasping, reaching. The positions of the limb are controlled by using Kinect sensors. Wei *et al.* [18], designed a 3-DOF exoskeleton robotic system which is named ULERD. It is for elbow, forearm and wrist rehabilitation, and can perform passive exercise using force and position control. It is controlled remotely by a device which is named is Phantom Premium. It is used for telerehabilitation.

Rehabilitation process has three levels [19]: flexibility and range of motion, strength and muscle endurance, proprioception and coordination. Existing systems are generally designed for the third level of rehabilitation "proprioception, coordination and agility". The common feature of these systems is that they are developed for motor skills training. Their exercise capacity is limited. On the other hand, developed systems usually use position- or force-based impedance control scheme.

The robotic system introduced in this study was designed for using the first level of rehabilitation, which is called "flexibility and range of motion strength and muscle endurance". Design procedure and system concept of a 3 DOF upper limb rehabilitation robot which is called Physiotherabot/WF are introduced. Functional requirements of design, corresponding design parameters and system concept of the robot are examined in detailed.

The most important difference of this system from other systems is that Physiotherabot/WF has been developed for therapeutic exercises. It can perform all therapeutic exercises. The contributions of this work include the development of a Hybrid Impedance Control (HIC) scheme in order to realize the therapeutic exercises. The implementation of therapeutic exercises using HIC scheme has not been reported before in the literature. With this method, position and force can be controlled in a single control scheme with desired mechanical impedance effect. On the other hand, hybrid impedance control is different from classical hybrid force-position control scheme. Desired position and force trajectory can be followed by using the desired impedance thanks to HIC scheme. Therefore, it is very useful for the rehabilitation robot to perform therapeutic exercises. The features of the robotic system Physiotherabot/WF are given below:

- It is used for wrist and forearm rehabilitation.
- It can perform passive, active assistive, isotonic, isokinetic and isometric exercises.
- It has 3-DOF.
- It uses hybrid impedance control scheme.
- It is suitable for using at home and hospitals.
- It has easy to use graphical user interface (GUI).
- It is possible to get and store information of patient and rehabilitation session results.

This paper is organized as follows: Section II presents upper limb rehabilitation theory. Section III explains the design parameters and the concept of the system. The robot manipulator features is presented in Section IV. Section V describes the control method of the system and reports simulation results. Conclusions are given in Section VI.

II. UPPER LIMB REHABILITATION THEORY

The robotic system has been designed for wrist and forearm rehabilitation. The theoretical information about the types of wrist and forearm movements, the definition of the range of motion (ROM) and the types of therapeutic exercises are given in the following subsections.

A. Types of Movements

The robotic system can perform the movements: Pronation(pro)-supination(sup) for forearm, abduction(abd)-adduction(add) and flexion(flx)-extension(ext) for wrist. These movements are illustrated below (Fig. 1).

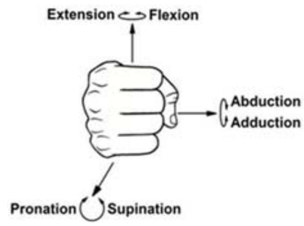

Fig. 1. Types of movements

B. Range of Motion (ROM)

ROM is the overall motion used in a movement and can be specified by linear or angular motion of the body segments [20]. These movements have different limits according to the type of movements. The limits compare the ROM of a healthy person and the designed robotic system (see Table I).

TABLE I. TYPES OF MOVEMENTS AND THEIR LIMITS

Movement	Range of Motion: *Healthy Person* [21]	Range of Motion: *Physiotherabot/WF*
Pronation	70° - 85°	85°
Supination	70° - 85°	85°
Adduction	15° - 20°	30°
Abduction	30° - 40°	45°
Flexion	70° - 90°	80°
Extension	70° - 80°	80°

As seen in Table I, the robotic system is designed so that the ROM limits of a healthy person and the system overlap. Thus, the designed system can perform all the movements in range of motion of a healthy person given in Table I.

C. *Therapeutic Exercises[22]*

Therapeutic exercise is a kind of exercise which aims to remediate or prevent impairments, improve, restore or enhance physical function, prevent or reduce health-related risk factors and optimize overall health status, fitness or sense of well-being. The exercises, which are able to perform by Physiotherabot/WF, are passive, active assistive, isotonic, isometric, and isokinetic.

III. ROBOTIC SYSTEM DESIGN

In this section, functional design requirements of the system and the design parameters which fulfill these requirements are defined. The system concept is also explained.

A. *Functional Design Requirements and Design Parameters*

Functional design requirements and design parameters of the system are given in Table II.

TABLE II. FUNCTIONAL DESIGN REQUIREMENTS AND DESIGN PARAMETERS

Functional Design Requirements	**Design Parameters**
Must perform pronation-supination, abduction-adduction, flexion-extension and provide their ROM limits	3DOF system according to the ROM limits
must perform passive, assistive and resistive exercises	motors, reducers, encoders and force sensor
must measure and and record the force and position data	encoder for measuring position data and force sensor for measuring force data (see Fig. 3)
must be light and transportable system	made of aluminium and designed in a compact structure
must have a easy to use user interface	a graphical user interface GUI for operators and physiotherapists to use the system easily (see Fig. 2)
must be adjustable according to the length of the limb	a slide to adjust the length of the limb
must have software and hardware- based safety to protect the patient if any problems occur	Mechanic- (mechanic limits) software- and electronic-based (with an emergency stop button) safeties (see Fig. 4)

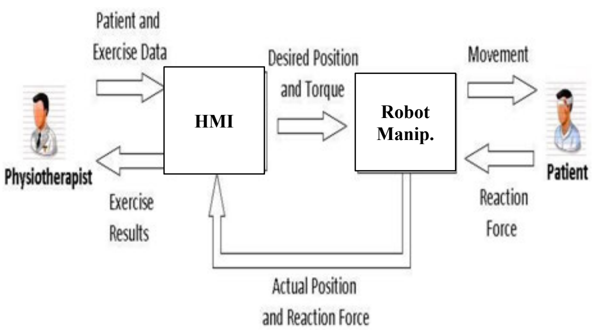

Fig. 2. System concept

Fig. 3. Graphical User Interface

B. *System Concept*

The system includes a physiotherapist, a human-machine interface (HMI), a robot manipulator and a patient (see Fig. 2). The physiotherapist enters the information of patient and exercise using the GUI (see Fig. 3). This information is evaluated by the HMI. The HMI determines the required torque and sends it to the electric motor drivers. The drivers actuate the electric motors so the robot manipulator performs the movement. During the movement of robot, the position and the reaction force are measured by encoders and a force sensor. The measured data is fed back to the HMI.

IV. ROBOT MANIPULATOR

A. *Mechanical Structure of the System*

The mechanical structure of robot manipulator includes four main parts: These are main base, pronation-supination group, adduction-abduction group and flexion-extension group. The manufactured robot manipulator is shown in Fig. 4.

Main base is the fixed part of the system. It makes the system steady while the exercises are being performed. This part includes arm apparatus, pulleys, protection cover, and the bearing of pronation-supination motor.

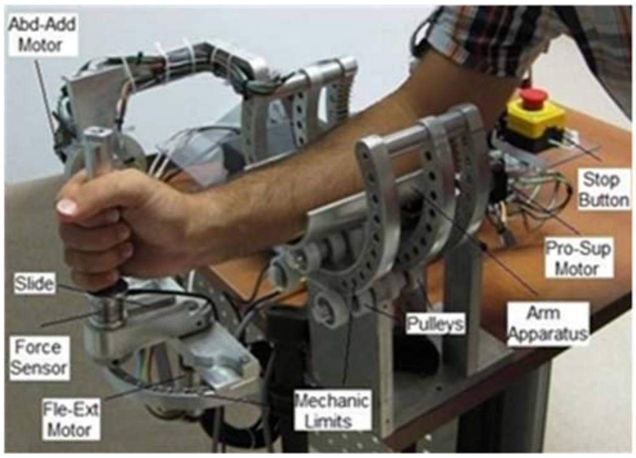

Fig. 4. Robot manipulator

Pronation-supination group is one of the active parts of the system. This part includes the components which provide the system to perform pronation-supination movements. These components include the electric motor, reducer, encoder, a pinion gear between the reducer shaft and the internal gear, and a swing which is mounted to the internal gear.

Adduction-abduction group is another active part of the system. This part includes the components which provide the system to perform adduction-abduction movements. These components include the electric motor, reducer, encoder and links which are mounted to pronation-supination group.

Flexion-extension group is also an active part of the system. This part includes the components which provide the system to perform flexion-extension movements. These components include the electric motor, reducer, encoder, handle, force sensor and links which are mounted with adduction-abduction group.

The 3D views showing the pronation-supination, adduction-abduction and flexion-extension movements of the robot are given below in Fig. 5.

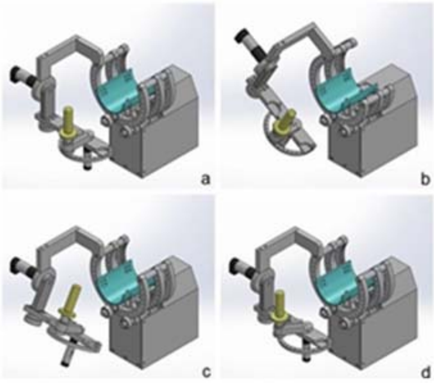

Fig. 5. a) Home position b) pro-sup c) abd-add d) flx-ext.

The dynamic equations of motion of the robotic manipulator can be given as follows:

$$\tau = M(q)\ddot{q} + C(q,\dot{q}) + G(q) - J_e^T F_e \tag{1}$$

where, $\tau \boldsymbol{\tau} \in \mathbf{R}^{3x1}$ is the torque matrix. $\boldsymbol{M(q)} \in \mathbf{R}^{3x3}$, $\boldsymbol{C(q,\dot{q})} \in \mathbf{R}^{3x1}$, and $\boldsymbol{G} \in \mathbf{R}^{3x1}$, are the matrices of inertia, centripetal and Coriolis force and gravitational force respectively. The angular acceleration, velocity and position vectors are, respectively, denoted by $\ddot{\boldsymbol{q}} \in \mathbf{R}^{3x1}$, $\dot{\boldsymbol{q}} \in \mathbf{R}^{3x1}$, $\boldsymbol{q} \in \mathbf{R}^{3x1}$. $\boldsymbol{J_e} \in \mathbf{R}^{3x1}$ is the Jacobian matrix of the end effector, and $\boldsymbol{F_e} \in \mathbf{R}^{3x1}$ is the actual force matrix. The Jacobian matrices of manipulator with respect to each joint are given as below:

$$J_{e1} = \begin{bmatrix} 0 \\ l_2\cos\theta_1 \\ l_2\sin\theta_1 \end{bmatrix}, J_{e2} = \begin{bmatrix} -l_3\cos\theta_2 - l_5\sin\theta_2 \\ 0 \\ l_3\sin\theta_2 - l_5\cos\theta_2 \end{bmatrix}, J_{e3} = \begin{bmatrix} -l_5\sin\theta_3 \\ l_5\cos\theta_3 \\ 0 \end{bmatrix} \tag{2}$$

where, l_i is distance from the rotation axis of each joint to the end effector. The angles of each joint are represented as $q = [\,\theta_1\ \theta_2\ \theta_3\,]^T$. The actual forces for joints can be defined as

$$F_{e1} = \begin{bmatrix} 0 \\ F_{e1_y} \\ 0 \end{bmatrix}, F_{e2} = \begin{bmatrix} F_{e2_x} \\ 0 \\ 0 \end{bmatrix}, F_{e3} = \begin{bmatrix} 0 \\ F_{e3_y} \\ 0 \end{bmatrix} \tag{3}$$

By substituting (2) and (3) into the (1), and after some mathematical manipulations, the equations of motion are obtained:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} m_1 l_1^2 + I_1 & 0 & 0 \\ 0 & m_2 l_2^2 + I_2 & 0 \\ 0 & 0 & m_3 l_3^2 + I_3 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} -m_1 g l_1 \cos\theta_1 \\ m_2 g l_2 \sin\theta_2 \\ 0 \end{bmatrix} - \begin{bmatrix} F_{e1_y} l_2 \cos\theta_1 \\ F_{e2_x}(-l_3\cos\theta_2 - l_5\sin\theta_2) \\ F_{e3_y} l_5 \cos\theta_3 \end{bmatrix} \tag{4}$$

where inertia matrix was calculated according to one degree of freedom movements.

B. Electronic Structure of the System

Electronic structure of the system includes a personal computer, data acquisition (DAQ) card, electric motors, electric motor drivers, force sensor and emergency stop button (see Fig. 6).

Before selection of electric motors (a Maxon EC max 22 and two Maxon EC max 30), the masses of the links and motor torques were calculated. Proper motor and reducers were selected according to desired torques and velocities. Reduction rates of reducers are 103:1 for pro-sup link, 86:1 for flx-ext link and 128:1 for abd-add link. The encoders (an Encoder MR and two Encoder HEDL 5540) have high resolutions to get the position more accurately and are suitable to mount on the

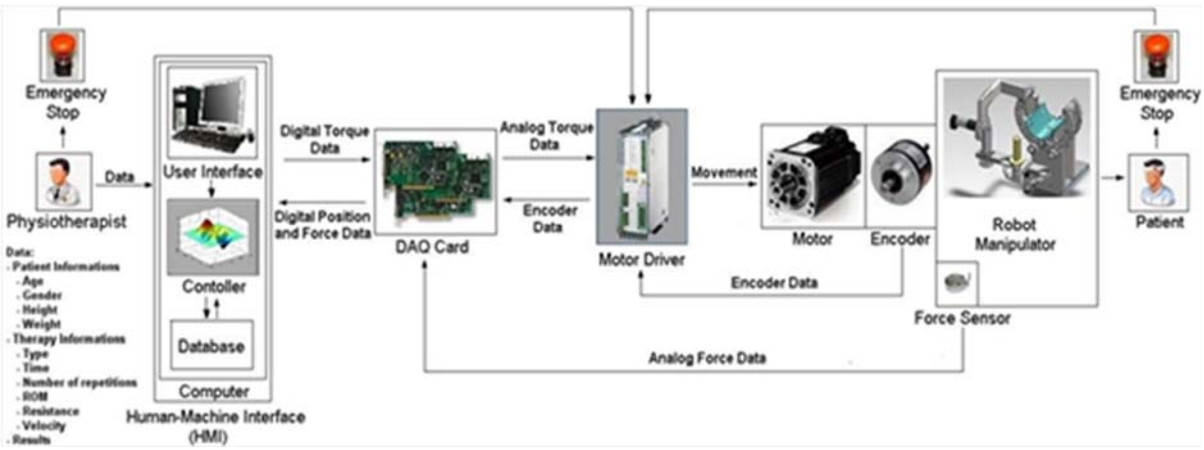

Fig 6. Electronic hardware of the system

electric motors easily. The electric motor drivers (three Maxon EPOS2 50/5 Driver) receive the position feedback by using encoder emulation and can enable torque control by using its own analog inputs. It is planned to apply forces within some ranges to the patient while performing therapeutic exercises. To this regard, the force sensor (ATI Nano25 F/T Sensor) which has the desired force range, high resolution and small size, was selected. The system features are given in Table III.

TABLE III. SYSTEM FEATURES

Feature	Robotic System		
Weight [kg]	11.029		
Dimensions [m]	Width 0.398	Height 0.373	Depth 0.462
Max. Force [N]	Flx-Ext ±30	Abd-Add ±30	Pro-Sup ± 30
Max. Torque [Nm] *(Motor+Reducer)*	Flx-Ext 2.88	Abd-Add 3.46	Pro-Sup 20.747

V. HYBRID IMPEDANCE CONTROL (HIC)

HIC is a control method which allows controlling the force and position in a single scheme [23]. HIC law is generally defined as :

$$M_d(\ddot{x}\text{-}S\ddot{x}_d)+B_d(\dot{x}\text{-}S\dot{x}_d)+K_dS(x\text{-}Sx_d)+(I\text{-}S)F_d=\text{-}F_e \qquad \textbf{(5)}$$

where $\ddot{x}, \dot{x}, x$ are actual acceleration, velocity and position vectors, $\ddot{x}_d, \dot{x}_d, x_d$ are desired acceleration, velocity and position vectors respectively. $\boldsymbol{M_d}$ is desired mass constant matrix, $\boldsymbol{B_d}$ is desired damping constant matrix and $\boldsymbol{K_d}$ is desired stiffness constant matrix. $\boldsymbol{F_d}$ is desired force and $\boldsymbol{F_e}$ is environmental force. ***S*** is a diagonal selection matrix. If the ***S*** is a zero matrix, HIC works in force control mode, and if it is a unit matrix, HIC works in position control mode.

VI. SIMULATION RESULTS

The system has been tested using a simulation model for the modelling of flexion movement of wrist in terms of position control mode and force control mode of HIC. Position control mode of HIC is used for passive exercise whereas force control mode of HIC for active and resistive exercises. In order to simulate the system, mechanical system was modeled using a CAD software. Then, that model was transferred to a simulation program. All kinematic relations and physical properties of the system are provided by this CAD model. Thus, mathematical model of mechanical structure was obtained and the designed HIC scheme was applied to control the system model.

To test the position control mode, impedance parameters were selected as $\boldsymbol{M_d}$=diag [0 0.005 0], $\boldsymbol{B_d}$= diag [0 2 0] and $\boldsymbol{K_d}$= diag [0 10000 0]. A sinusoidal position trajectory was generated and was used as the desired position. After application of the HIC method to the simulation model, the result has shown that robot manipulator follows the desired trajectory accurately. The position error was measured as less than 0.5 degree. The simulation result of position control mode is shown in Fig 7.

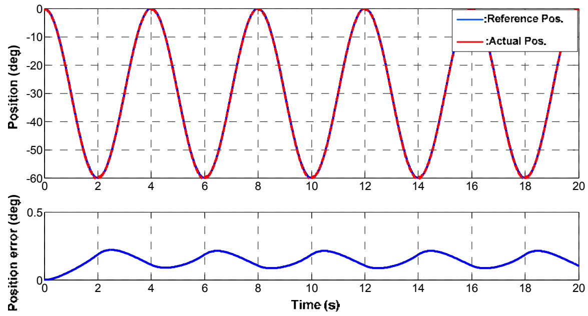

Fig. 7. Position control mode [24]

In testing of the force control mode, impedance parameters were selected as $\boldsymbol{M_d}$=diag [0 0.005 0], $\boldsymbol{B_d}$= diag [0 2 0] and $\boldsymbol{K_d}$= diag [0 10000 0]. A desired force trajectory (5N constant force trajectory) was applied to HIC scheme. On the other hand, to imitate the real wrist force pattern, another trajectory was generated. These trajectory values produce equal, smaller and bigger values compared to desired force trajectory. Application of HIC method in this case study yielded the results shown in Fig 8. As can be seen from this figure, the manipulator moves on the reference force direction, when reference force is bigger than the limb force. Also, the manipulator moves on the limb force direction when the reference force is less than the limb force. From this result it is understood that human wrist generates a force value that is bigger than the applied force generated by manipulator. Hence the user could move the robot manipulator in the direction of flexion. When reference and limb force values are equal (between 3.5 and 8th seconds – between 13,9 and 15th seconds) robot manipulator does not move. It can be noticed that the position does not change when the forces are equal. Simulation results show that hybrid impedance control force control mode works accurately.

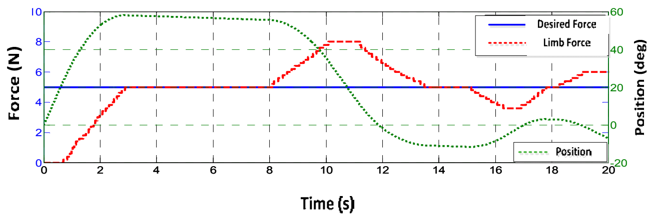

Fig 8. Force control mode [24]

VII. CONCLUSION

A design approach for a 3-DOF upper limb therapeutic exercise robot was presented in this study. The upper limb rehabilitation theory was reviewed based on the context of this work. The design requirements of the system and the parameters, which can fulfill these requirements, were explained. Mechanical and electronic structures of the system were presented. It was also defined how the components of these structures are selected. Hybrid Impedance Control (HIC) was tested for flexion movement. Simulation results showed that the proposed control scheme satisfies the desired exercise performance. As a future work, the control structure of the system will be presented in more detail. Experimental studies will worked with real subjects and patients.

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