

# Chapter 13

## A Human–Machine Interface Design to Control an Intelligent Rehabilitation Robot System

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### ABSTRACT

*The demand for rehabilitation increases daily as a result of diseases, occupational and traffic accidents and population growth. In the present time, some important problems occur regarding the rehabilitation period: the transportation of patients, the acquisition and storage of treatment data and the need to support the physiotherapists with intelligent devices. In order to overcome these challenges, the authors hereby propose a human machine interface to control an intelligent rehabilitation robot system designed for the lower limbs. The human machine interface has a structure that is created with a rule-based intelligent controlling structure, combined with conventional controller and an easy-to-use graphical user interface. By means of this interface, the rehabilitation sessions can be stored and members of the rehabilitation team can reach to this stored data via internet. Additionally, the patient can receive treatment in his house. One physiotherapist is able to treat several patients at a time by utilizing this system. The system's capacity has been elaborated through the test results.*

### INTRODUCTION

The growing world population and the increasing number of problems people have with their

limbs have intensified the need for rehabilitation particularly for lower limbs. Reestablishing and improving the limb functionality and strength are major issues. Furthermore, it is most important to help patients to return to society, to reintegrate them into social life and thus to improve the patients'

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quality of life. Injuries in extremities like arms and legs are caused mainly due to old age, work and traffic accidents. The role of the rehabilitation process is to restore functionality of previously damaged limbs. Throughout the therapy, physical exercises for extremities like arms and legs have a key role in the recovery of the patient. Therapeutic exercises consist of active or passive physical movements of the patient, carried out through the physiotherapist (PT), or of movements carried out by the patient with the assistance of the physiotherapist, depending on the condition of the patient. Among them, the performing of resistive exercises is particularly difficult and exhausting for physiotherapists. For rehabilitation either the patient has to go to a healthcare center, or the physiotherapist has to come to the patient. Considering the often time-consuming process of rehabilitation, this is difficult and cost-intensive for both patient and physiotherapist, and demands a high amount of patience of all parties involved. Furthermore, a physiotherapist can only fully attend one patient at a time. Another important issue is to record the treatment period of the patient and to provide the members of the rehabilitation team-physiotherapist, occupational therapist etc- with fast and easy access to these records. By means of this access, the rehabilitation period can proceed well and a database can be formed for patients with similar conditions. The progress of a patient can be therefore monitored and compared to other patients. To achieve this aim and therefore to increase the efficiency of the rehabilitation process, the following issues have to be solved:

- The patient's condition should be monitored and recorded throughout the treatment period. The monitoring information should be saved on the database of the medical center and must be easily accessible.
- Computerized mechanisms, capable of performing therapeutic exercises, are needed to support physiotherapists

- Intelligent human-machine and human-computer interfaces are needed to enable the physiotherapists to control these mechanisms.
- To overcome the problem of transporting patients to the medical center, internet-based rehabilitation methods should be developed for remote operation and treatment.

## **BACKGROUND**

Over the last decade, the number of studies about robots in rehabilitation has increased. Studies carried out in near past have proved that rehabilitation robots have many advantages compared to classic therapy methods (Lum et al., 2002). In addition, robotic therapy provides better possibilities to acquire and store information such as the therapy response of the patient (Richardson, Brown, & Plummer, 2000). A number of studies – as part of the general studies made about rehabilitation robots – in which particularly conventional control techniques stand out, have hitherto been carried out. Lum and others (1995 & 1997) introduced an assisted rehabilitation system for arms. Krebs and others (1998 & 2003) have developed and have clinically evaluated a robot-aided neuro rehabilitation system called MIT-MANUS. This device provides multiple-degree of freedom exercises of upper extremities for stroke patients. Rao, Agrawal and Scholz (1999) introduced another system using a Puma 240 robot for active and passive rehabilitation of upper extremities. Richardson and others developed a 3 DOF (degree of freedom) pneumatic device for rehabilitation of upper extremities using PD control and impedance control methodologies (Richardson et al., 1999, 2000, & 2003). Reinkensmeyer and others (2000) developed a 3 DOF system called ARM Guide (Assisted Rehabilitation and Measurement Guide) for rehabilitation of upper extremities. Another system with 3 DOF, called GENTLE/s,

is developed in England for the rehabilitation of upper extremities, controlled by the admittance control method (Loueiro et al., 2003). The robots and methods developed in these studies generally realize specific tasks or assist the patient throughout rehabilitation.

However, some researchers have applied more intelligent techniques as well. Lee and others developed a robotic system for rehabilitation of upper limbs of paralyzed patients using an expert system (Lee, Agah, & Bekey, 1990). Utilizing two industrial robots, the REHAROB project serves for the rehabilitation of upper extremities. A knowledge base is formed by the sensing force and position during manually conducted rehabilitation sessions. Industrial robots then repeat the same procedure using this knowledge base (REHAROB Project, 2000). Okada et al. (2000) employed impedance control methodologies in a 2 DOF robotic system for lower limbs rehabilitation. Position and force information are received and recorded for the robotic system to reproduce the corresponding motion. The REHAROB Project and Okada's robotic mechanism both deal with the reproduction of the physiotherapist's exercise motions.

These studies for rehabilitation robots generally have a limited exercise capacity and stand out on account of their control techniques. Furthermore, they have a limited capability with regard to having soft computing techniques, an internet-based study environment, data storage and the ease of a user-friendly graphical user interface (GUI).

In this study, a human-machine interface (HMI) is developed for the control of a three degrees of freedom robot manipulator (RM) designed for the rehabilitation of the lower limbs. With the developed HMI, the rehabilitation robot system can perform all active and passive exercises as well as learn specific exercise motions and perform them without the physiotherapist. With this feature, the system differentiates itself from the current rehabilitation robot systems. The HMI

possesses a rule-based intelligent control structure merged with conventional control techniques and a practical GUI. Moreover, the entire treatment period of the patient can be stored in the database. At the same time the HMI has a flexible software structure that makes the system suitable for remote online operation. The preliminary experimental results of this study have been published Akdoğan E., Taçgın E., Adlı M.A. (2009).

## **REHABILITATION ROBOT SYSTEM**

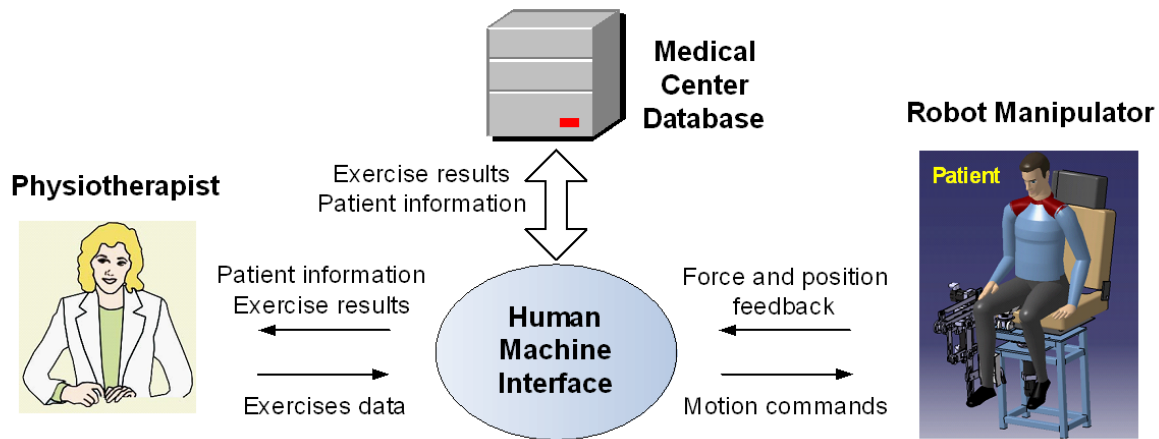
The following exercises are performed by therapeutic devices or physiotherapists during hip and knee rehabilitation:

- Moving the patient's limb passively (passive exercise)
- Assisting the motion of the patient's limb (active assistive exercise)
- Resisting the motion of the patient's limb (resistive exercise)
- Opening the patient's limb with force despite reaction from the patient (stretching)

The exercises that are given above are procedures that can also be described and modeled as position and force control. The position and force relations and sequences are clear and have no complex uncertainties. With the developed HMI, the rehabilitation robot system (see Figure 1) is able to work as a therapeutic exercise device. It can generate and apply necessary position and force sequences to the patient's limb. The rehabilitation robot system is able to model the physiotherapists' movements and experiences and is therefore enabled to behave like a physiotherapist.

Because of the reasons mentioned above, the developed system has the required features for the rehabilitation of the lower limbs. It can perform six different types of exercises which results in six working modes. These exercise types are of the following kinds:

Figure 1. Rehabilitation robot system



- passive
- isotonic
- isometric
- isokinetic
- active assistive
- manual

The passive, isotonic, isometric and isokinetic exercises can be done with the assistance of the physiotherapist, using some tools such as constant weight, spring or devices such as CPM (continuous passive motion). All these exercises are resistive except for the passive ones. However, the active assistive and manual exercises are done manually only by physiotherapist. A method called *robototherapy* has been developed to model the manual exercises. Robototherapy operates in two modes: teaching mode and therapy mode. The physiotherapist performs the necessary exercise motion on the patient with the robot manipulator. In the therapy mode, the system applies the therapy to the patient with the RM using the data that was obtained during the teaching mode (the position and force data applied by physiotherapist, their limit values and therapy time).

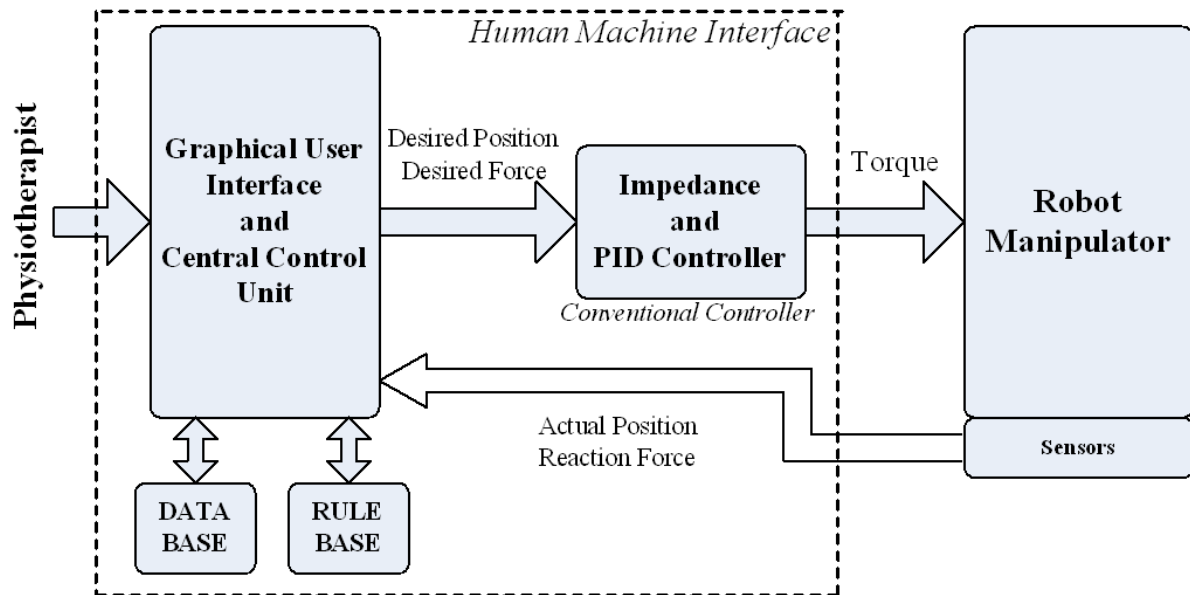
For this mode, two different sub modes have been developed: direct therapy and reactive therapy. Direct therapy imitates the physiothera-

pist completely. The reactive mode models the physiotherapists' stretching motions. Namely, the patient's limb is stretched with force to certain limits in accordance with the patient's muscular condition. These limits are determined in the teaching mode. The detailed explanations of the exercise modes are given in the next section.

The system consists of three basic components. These are the physiotherapist, the human-machine-interface and the robot manipulator.

The physiotherapist has the role of preparing and adjusting the system for the patient. He decides the necessary exercises and teaches the exercise movements to the RM. The physiotherapist inputs the patient's information using the graphical user interface of the HMI. The information needed for input is age, height, weight, and foot size of the patient. For active and passive exercise modes such as passive, isometric, isotonic and isokinetic, the physiotherapist inputs the information on the type of the exercise and the information for that specific exercise (number of repetitions, exercise duration, range of motion, angles and velocity). In the robototherapy mode, he selects the teaching mode for the manual exercises. The patient then performs the necessary exercise movements with the help of the robot manipulator. Next, the physiotherapist selects the therapy mode from

Figure 2. The structure of the HMI



the GUI and the robot manipulator performs the exercise movements with the patient without the physiotherapist.

The robot manipulator’s design is suitable for both left and right knees and hips. The mechanism can be adjusted for different body and limb lengths. The manipulator can perform flexion – extension motion for knee rehabilitation and flexion – extension as well as abduction-adduction motion for hip rehabilitation. It has position and force sensors to acquire feedback from the patient. For deeper information refer to (Akdoğan, Taçgın, & Adlı 2009). The robot manipulator is controlled by closed-loop control algorithms based on PID or impedance control depending on the exercise. For PID control, control parameters are proportional, integral and derivative coefficients. For impedance control, the control parameters are inertia ( $M_d$  [kg]), stiffness ( $K_d$  [N/deg]) and damping coefficients ( $D_d$  [Ns/deg]).

The HMI has the key role for the rehabilitation robot system. All communication is performed amongst the system’s elements through the HMI. Selecting the proper conventional technique and

determining the control parameters are realized by the HMI in accordance with the exercise type. In the next section, a detailed explanation of HMI will be given.

## HUMAN-MACHINE INTERFACE IMPLEMENTATION

The human-machine interface has been developed using MATLAB/Simulink and the graphical user interface toolbox. The Real Time Windows Target Toolbox is used for realtime control and signal processing. The HMI was developed in a way that allows an internet-based use. It consists of the central control unit, a conventional controller (impedance and PID controller), a data base, a rule base and the GUI (see Figure 2).

As the appropriate control technique must be selected, a database has been realized to store the control parameter values for the upcoming exercise. The communication between all HMI units is provided by a central control unit. The functions of these units are given in Table 1 according to

exercise modes. Additionally, the central control unit performs the following tasks for all exercise modes: the selection of the appropriate control algorithm, transferring the patients' parameters on the database to the algorithm, sending the data from the sensors to the rule base and the database, and finally sending the data from the database and the rule base to the controller. The database also stores the data about the patients (individual information such as name, gender and birth date and physical parameters such as length, height, limb length) and the exercise results for all conducted exercises. In this system, exercise results of the patient are evaluated in terms of the mechanical parameters' (joint angle, torque, velocity) index. This index has two different evaluation versions – a patient index and an error index. The patient index reflects patient performance only, while the error index shows the differences between patient performance and commands from the system. In the patient index, three scores are computed or measured: the instant values over time, the time average value for each trial and the overall average value for all trials. For the instant values over time, mechanical parameters are calculated or measured and stored on the database. At the same time, these parameters are shown on the display to the therapist or patient during the rehabilitation session. With the time average value for each trial, the patient and therapist can understand the evaluation results after each session. Using the overall average value for all trials, the patient and the therapist can check changes in the index depending on the day, and compare values before and after training. The aim of the error index is to evaluate the patient's performance. The index consists of the success rate and the mean value of error in tasks. The success rate is computed from the rate of patient motion, while task commands and the mean error come from differences between the patient's motion and the system/therapist commands. For future work, EMG parameters index will be added to the database as well. The usage of the HMI units in

accordance with exercise modes are given in the following part of this section.

The exercise motions require to control position and force. In this regard, suitable control techniques have been selected and integrated into the HMI's structure according to the exercise types. Impedance control is used for the exercises that require force control. PID control is used for the exercises that require position control. Some exercise types involve a combined use of both position and force control which is realized by switching between both controller modes. Table 2 shows an overview about which controller is used for which exercise mode.

Impedance control aims at controlling position and force by adjusting the mechanical impedance of the end-effector to external forces generated by contact with the manipulator's environment. Mechanical impedance is roughly an extended concept of the stiffness of a mechanism against a force applied to it. It is accepted to be the most appropriate control technique for physiotherapy and is used in many rehabilitation robot applications (Culmer et al., 2005, Krebs et al., 1998, & 2003, Tanaka, Tsuji, & Kaneko, 2000). The robot manipulator can apply resistance to the treated limb at the required level of smoothness and stiffness by changing the impedance control parameters. In addition, the physiotherapist can have the patient perform the exercise motions with a high level of ease and with no degree of vibration.

## **HUMAN-MACHINE INTERFACE EXERCISE MODES**

In this section, the algorithms regarding the exercise modes will be explained in detail.

*A) Passive Exercise Mode:* This type of exercise is specifically applied to patients with little or no muscle contraction (e.g. paralyzed patients). The limb of the patient is moved around the range of motion without resistance. The therapist inputs the angles of the ROM, the number of repetitions

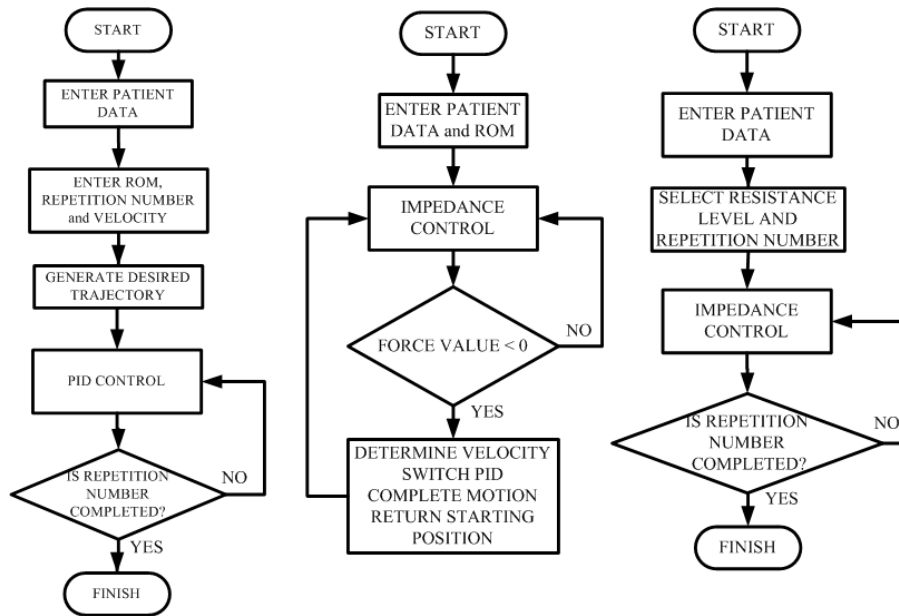
*Table 1. HMI functions*

<b>Exercise Mode</b>	<b>Central Control Unit</b>	<b>Data Base</b>	<b>Rule Base</b>
<b>Passive</b>	- According to extension and flexion angles, repetition number and velocity, determination of motion trajectory and sending this information to data base - Transfer of trajectories to PID controller throughout the exercise.	Storage of exercise trajectory	Not used
<b>Active assistive</b>	- According to information that come from force sensor, transferring of opposite force data to rule base.	Storage of minimum impedance parameter values	If there is an opposite force on the force sensor, running of PID controller
<b>Isotonic</b>	- According to selected resistance level, receiving of proper impedance parameter values from data base - Calculation the number of repetitions using position data and sending it to the rule base.	Not used	- Therapy is stopped when repetition numbers completed - Proper impedance values are determined according to resistance level
<b>Isometric</b>	Sending of weight, duration and limb length values that have been received from data base to the controller	Storage of patient’s limb length	Determination of impedance parameter values according to resistance level
<b>Isokinetic</b>	Sending of velocity data to the controller	Not used	Not used
<b>Teaching</b>	Detection of limit values of teaching mode and sending them to data base	Storage of position-force data and maximum values of them	Not used
<b>Direct therapy</b>	Sending of teaching position-force data that have been received from data base to the controller	Recall teaching mode position and force data	Not used
<b>Reactive Therapy</b>	-Updating of rule base using maximum position and force data in data base -Sending of these data to conventional controller - Using maximum position data and patient’s weight, finding and sending of proper desired position and force data in data base to conventional controller - Sending of actual position and force data to rule base in order to control patient reaction and safety	Storing of maximum position and force data during the teaching mode, teaching time and desired position and force data that will be applied to patient	- Determining of data file according to patients limb weight and maximum position value. - In the case of exceeding of limit values, switching on PID controller according to real time data that come from central controller unit

*Table 2. Exercise modes and control techniques*

<b>Exercise Mode</b>	<b>Control Method</b>
Passive	PID Position Control
Active assistive	PID Position Control + Impedance Control
Isometric	Impedance Control +Torque Control
Isotonic	Impedance Control
Isokinetic	Impedance Control
Robototherapy	Impedance Control + PID Position Control

Figure 3. Flow charts of exercise modes (from left to right): Passive, Active Assistive, Isotonic



and the movement velocity through the GUI. The passive exercises basically require position control. Therefore, the robot manipulator makes its moves using the PID position control method for the passive exercises in this system. The desired trajectory of the exercise is generated by the HMI according to the ROM and velocity input by the GUI. The trajectory data is saved on the database. The HMI runs the PID algorithm using the desired trajectory when the exercise starts. The flow chart of this process is shown in Figure 3.

*B) Active Assistive Exercise Mode:* The active-assistive exercise is a type of exercise performed by physiotherapist and patient together. In this type of exercise, the patient moves his limb to the extent he is capable of. The patient is helped to move the limb to the required extent by the robot manipulator, which now replaces the physiotherapist, from the position that the patient is unable to move the limb any further. It is applied to patients with a muscle degree of 2 and 3 (The degree of muscles are evaluated with a scale that has six levels. This test is done by physiotherapist as manual. For deeper information refer to (Sarı,

Tüzün, & Akgün, 2002). The GUI input parameters are the range of motion values.

The patient's limb weight is eliminated by the system via a compensation of the gravity effects using impedance control, while always remaining within the patients' range of motion. This way the patient is enabled to move his limb to this level easily despite his muscle weaknesses. In the selection of the impedance control parameters, issues such as enabling the patient to move his limb at the lowest possible level of resistance and eliminating any possibility of causing vibration in the mechanism during the motion have been considered. These parameter values were determined experimentally and are stored in the database. With the evaluation of the force sensor signals it is determined when the patient cannot move his limb any further during the exercise. This force value arising in the opposite direction of the movement is detected by the HMI, which in turn activates the PID position control algorithm for the completion of the motion. Then, the patient's limb is moved to the limit of the range of motion with constant velocity and

then brought back to the starting position also at constant velocity. For the flow diagram of this mode refer to Figure 3.

*C) Isotonic Exercise Mode:* It is used for patients with a muscle degree of four and has the purpose of strengthening remaining muscles. A constant resistant force is applied to the patient throughout the entire duration of the movement. The robot manipulator is controlled using impedance control with parameters optimized to the resistance level to be applied. For the isotonic exercise, four different resistance levels have been determined: *low, medium, high, and very high*. When the physiotherapist selects the resistance level in the user interface, the appropriate impedance parameter values are selected respectively from the rule base. There is a total of eight rules for this mode in the rule base. The knee controller has one DOF and performs flexion-extension. The rules for the knee controller are:

- **Rule1**<If Resistance Level is**Low**then  $M_d=4, K_d=20, D_d=0$ >
- **Rule2**<If Resistance Level is**Medium**then  $M_d=5, K_d=60, D_d=0$ >
- **Rule3**<If Resistance Level is**High**then  $M_d=8, K_d=40, D_d=0$ >
- **Rule4**<If Resistance Level is**Very High**then  $M_d=10, K_d=100, D_d=1$ >

The hip controller is a 2 DOF system and performs flexion-extension as well as abduction-adduction simultaneously. The rules for the hip controller are:

- **Rule1**<If Resistance Level is**Low**then  $M_{dx}=10, K_{dx}=5000, D_{dx}=5000, M_{dz}=10, K_{dz}=5000, D_{dz}=100000$ >
- **Rule2**<If Resistance Level is**Medium**then  $M_{dx}=10, K_{dx}=5000, D_{dx}=5000, M_{dz}=500, K_{dz}=50000, D_{dz}=5000$ >
- **Rule3**<If Resistance Level is**High**then  $M_{dx}=10, K_{dx}=5000, D_{dx}=5000, M_{dz}=500, K_{dz}=50000, D_{dz}=100000$ >

- **Rule4**<If Resistance Level is**Very High**then  $M_{dx}=10, K_{dx}=5000, D_{dx}=5000, M_{dz}=1000, K_{dz}=100000, D_{dz}=5000$ >

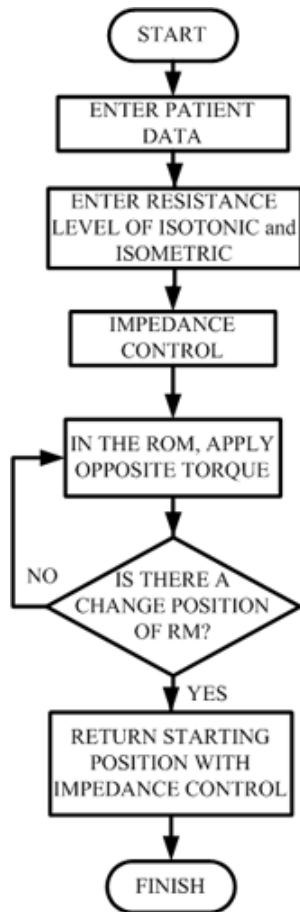
The x and z subscripts in the hip-controller rules represent the axes where motion occurs. The isotonic exercise modes' flow diagram is shown in Figure 3.

*D) Isometric Exercise Mode:* It is applied to patients with a muscle degree of four in order to strengthen them just as in the isotonic exercise. The exercise is realized with the application of constant resistance to the patient again staying within the range of motion. Isometric and isotonic exercise can be applied to the patient in a single exercise mode. The patient can perform isotonic and isometric exercises on the robot manipulator, which is one of the novelties of this system. A device that can perform this type of exercise has not been found in the literature. The GUI parameters are the resistance level of the isotonic and isometric exercise, the number of repetitions and the duration of the isometric resistance.

The patient moves his limb with a counter resistance force according to the resistance level that has been selected. The application of this counter resistance occurs as follows: the central control unit receives the impedance parameter values which have been determined according to the selected resistance level and sends them to the conventional controller. So the patient performs the isotonic exercise during the movement. The torque value that corresponds to the opposite torque input by the robot manipulator in the position of the limb is applied to the patient for the duration of the determined time. If the patient fails to maintain his position against the applied resistance, the HMI detects the situation with data from the sensor values, and switches to impedance control, consequently enabling the patient to easily convey his limb to the beginning position. This mode' flow diagram is shown in Figure 4.

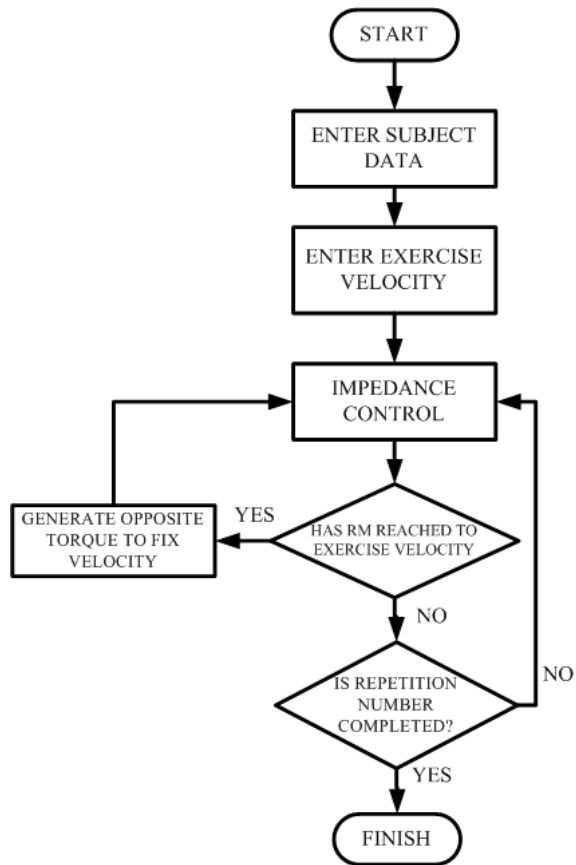
*E) Isokinetic Exercise Mode:* The aim of this type of exercise is to facilitate the exercise by

Figure 4. Flow chart of isometric mode



countering the maximum resistance and by keeping the movement velocity of the patient’s limb at a stable level (Sarı, Tüzün, & Akgün, 2002). For this exercise, the therapist inputs the movement velocity through the user interface. The flow diagram of this mode is shown in Figure 5. When the exercise is started, the impedance control starts operating and the patient moves his limb. The movement velocity of the limb is continuously inspected by the HMI. If the movement velocity reaches the velocity value determined by the physiotherapist, an equal level of counter resistance is generated for the limb movement by calculating the force value detected by the HMI via force sensors. Doing so, the force generated in the reverse direction of the limb helps to main-

Figure 5. Flow chart of isokinetic mode

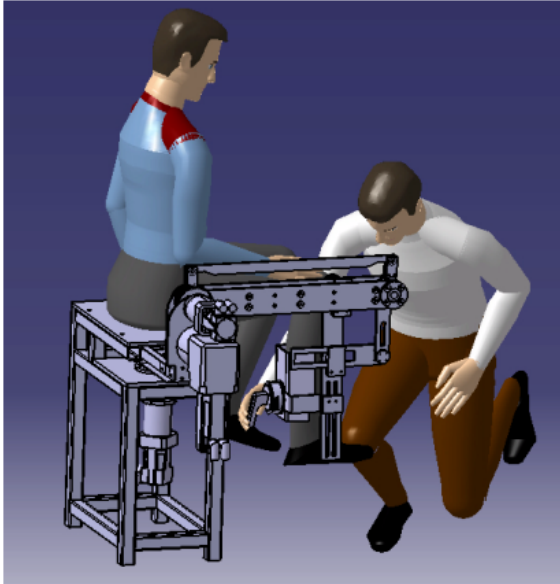


tain the movement velocity at the same level, even if the patient tries to accelerate the limb movement.

*F) Robototherapy:* This mode allows to model the physiotherapist’s manual exercises in a very intuitive way. It is the most important novelty of the developed system. Robototherapy has two modes of operation, teaching mode and therapy mode. For the therapy mode, two different sub modes - free manual exercise movements and stretching exercises - have been developed in order to model the physiotherapist’s movement.

In the *Teaching mode*, the physiotherapist assists the patient manually to perform the required motion with the patient on the robot manipulator as seen in Figure 6. In this mode, resistive effects of the mechanics of the robot manipulator are

Figure 6. Robototherapy teaching mode (Akdoğan, Taçgin, & Adli 2009)



compensated by impedance control to an extent, that the limb of the patient can be moved freely. Force and position values as well as limits the time history are recorded to the data base by the HMI while the therapist is conducting the exercise with the patient. This information is later on used to reproduce the behavior of the physiotherapist by the robot manipulator.

In the case of the patient’s reaction to the physiotherapist’s movement, the saved force and position values also include the patient’s reaction since the physiotherapist has eliminated this reaction during the exercise. Because of this, the saved limit values of position and force will be the limit values of the exercise in the therapy mode and the system will not apply an effect to the patient above the values in question. This situation provides the required safety for the patient which is of crucial importance in rehabilitation. The teaching mode block diagram is shown in Figure 7. The flow diagram of teaching mode is shown in Figure 8.

In the *therapy mode* the robot manipulator reproduces the therapy independent of the phys-

Figure 7. Teaching mode block diagram

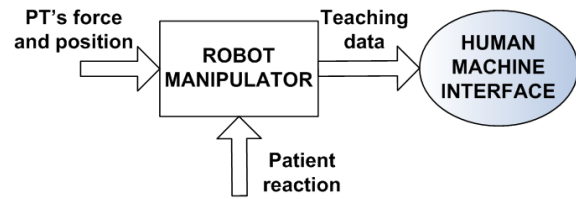
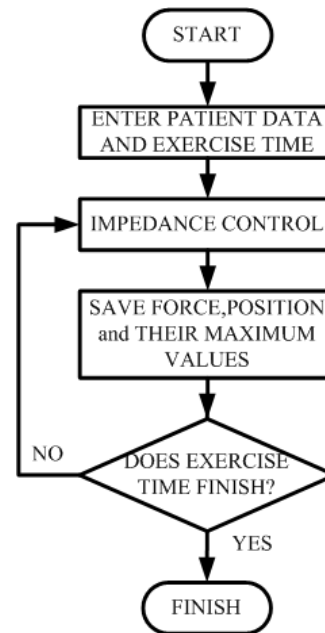


Figure 8. Flow chart of teaching mode

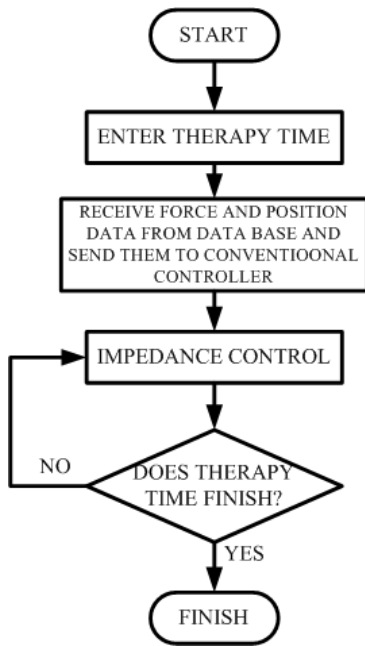


iotherapist using the information recorded during the teaching mode session. The Therapist is no longer required to be present at this point anymore. Therapy mode has two sub modes itself, direct therapy and reactive therapy.

In *direct therapy* mode, the robot manipulator simply repeats the previously recorded motion of the therapist. The recorded teaching data is retrieved by the central control unit and is used as the desired input data of the impedance controller. The robot manipulator performs the exercise according to this data. The flow diagram of this mode is shown in Figure 9.

*Reactive therapy* is used for patients whose limb cannot be opened due to muscle contraction.

Figure 9. Flow chart of direct therapy mode

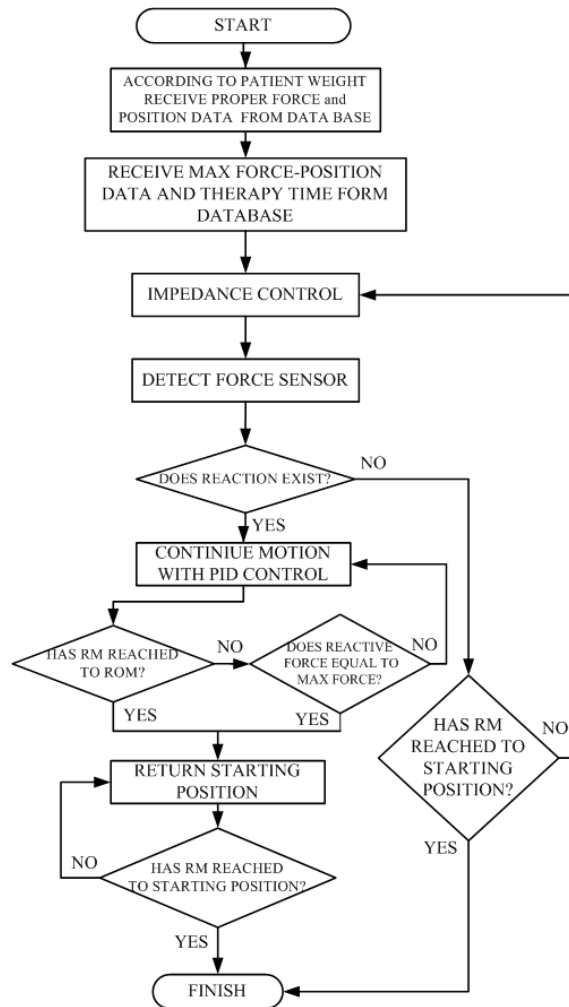


The traditional situation would be that the physiotherapist forces the limb to open. This is called *stretching*. This exercise mode aims to model these stretching exercises. The therapist eliminates the patient’s reaction to a certain extent by applying force. The level of this force is in proportion with the therapist’s personal experience. How the reactive therapy is applied in the system is systematically explained in the following.

The physiotherapist selects and starts *reactive therapy* mode via the GUI. The central control unit realizes the necessary process in order to determine the limit values of the exercise mode. In other words, the *physiotherapist’s experience* is transferred to the system. These are the limit values to be considered and the robot manipulator won’t exceed these limits. If the patient’s reaction approaches these limit values, the HMI stops the robot manipulator. The flow diagram of this mode is shown in Figure 10.

At this point, the database already contains the force and position values previously gathered for each range of motion from six healthy subjects

Figure 10. Flow chart of reactive therapy mode



with their mass ranging from 67 to 86 kilos (at every 10 degrees on a scale of 75 degrees). The physical specifications of subjects are given in Table 3. The amount of the data from the subjects recorded on the database can be increased due to the flexible structure of the HMI.

While filing the data from the healthy subjects, folders were formed according to the nick name of each subject (such as A, B, C...) and the files in these folders were also named accordingly, such as “1, 2, 3...”. The file names with respect to the ROM interval are given in Table 4. Then, the folder name that consists of the proper subject

*Table 3. Subjects’ physical specifications*

Subject	Weight [kg]	Height [cm]	Foot Length [cm]	Leg length [cm]	Age
A	67	174	27	92	21
B	74	175	27	95	22
C	75	175	25	105	23
D	80	174	27	95	21
E	81	175	28	93	21
F	86	175	24	105	24

*Table 4. File names according to range of motion intervals*

File Name	Range of Motion Interval
1	$0 \leq \text{ROM} < 15$
2	$15 \leq \text{ROM} < 25$
3	$25 \leq \text{ROM} < 35$
4	$35 \leq \text{ROM} < 45$
5	$45 \leq \text{ROM} < 55$
6	$55 \leq \text{ROM} < 65$
7	$65 \leq \text{ROM} < 75$
8	$75 \leq \text{ROM} < 85$
9	$85 \leq \text{ROM} < 95$
10	$-30 \leq \text{ROM} < 0$

data files and the file name selected in line with the data regarding the maximum stretching position in the teaching mode are determined in the rule base according to the patient’s weight. The determined data are received from the database by the HMI and sent to the RM. There are 70 rules in the rule base and the sample rules are given as follows:

*<Rule: if BW is bigger than 75 kg. or equal and less than 80 kg. and MXP bigger than 15 degree or equal and less than 25 degree, then Folder is C File is 2>*

...

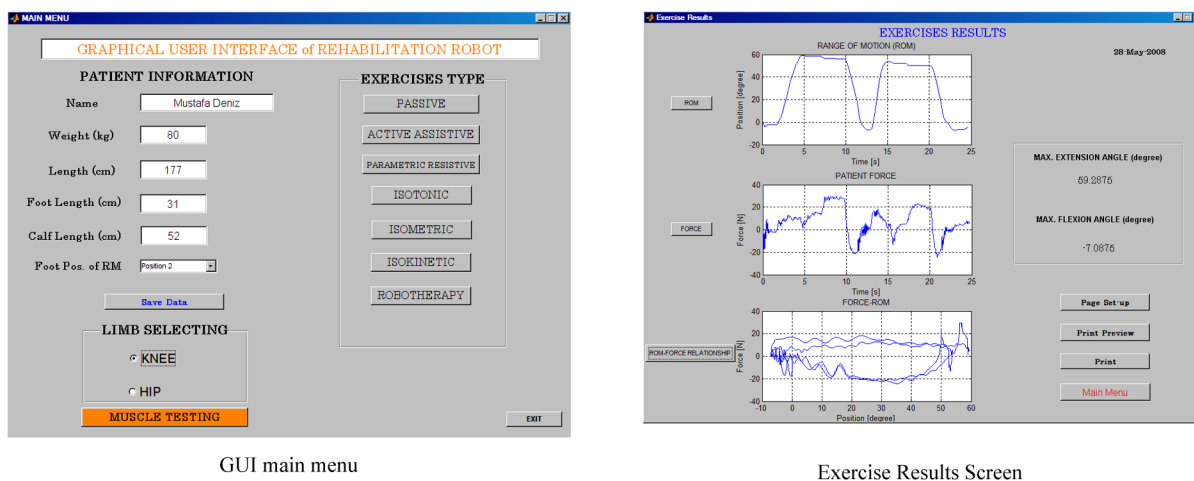
*<Rule: if BW is bigger than 81 kg. or equal and less than 86 kg. and MXP bigger than 65 degree or equal and less than 75 degree, then Folder is E File is 7>*

The therapy continues with this data unless the patient shows a reaction of some kind. In the event the patient reacts, the HMI activates the PID control and the robot manipulator conveys the patient’s limb to the range of motion limit that was determined in the teaching mode and then brings it back to the starting position. The HMI detects the patient’s reaction continuously in real-time with the system wide used sampling time of 1 ms.

## GRAPHICAL USER INTERFACE

The graphical user interface of the HMI enables the user to communicate with the HMI. The main menu, as shown in the first screen of Figure 11, is used to input the patient’s data. This data is used in order to calculate several mechanical parameters. The body limb, which is to be exercised, and the exercise type are selected from the main menu as well. Results from carried out exercises can be accessed from the main menu and are visualized graphically. The graphics display the patients’ range of motion numerically and the patient’s limb trajectory during the exercises session together with the corresponding forces (the last screen of Figure 11). These results are stored in the database and can be printed out optionally.

Figure 11. GUI main menu and exercise results screen



GUI main menu

Exercise Results Screen

## EXPERIMENTAL RESULTS

In the following some experimental results of the robotherapy modes including both direct and reactive therapy are shown. For experimental of the other modes of operation results refer to (Akdoğan, 2007).

Figure 12 illustrates a sample teaching mode sequence, and the corresponding “direct therapy mode” for knees. In this figure, from the top, teaching position ( $p_{teach}$ ), therapy position ( $p_{ther}$ ) and position error ( $p_{teach} - p_{ther}$ ) between teaching and therapy position are shown. As seen from this figure, the robot manipulator can perfectly repeat the motion of the physiotherapist the way it was learned during the teaching mode.

In Figure 13, the teaching mode sequence and the direct therapy mode results on the hip flexion-extension movement are given. The graph titled “Link 1” shows the position data on Link 1 (hip link), the graph titled “Link 2” shows the position data on Link 2 (knee link). The dashed line shows the position of the links during the teaching mode while and the solid line shows the position of the links during the therapy mode.

The teaching mode sequence and direct therapy mode results for the abduction-adduction

movement are shown in Figure 14. The abduction-adduction movement is realized by the actuator that moves the hip about the vertical  $z$ -axis of the robot manipulator. In Figure 14, from the top, teaching position, therapy position and position error between teaching and therapy position are shown. Both Figure 13 and Figure 14 show a successful performance of the hip movement previously taught by the physiotherapist.

Figure 15 illustrates a sample “reactive therapy mode” for the knee of a test person with a weight of 80 kg up to a limit position of 75°. As seen in this figure, when the position is above 10°, the reaction force becomes negative indicating that the patient is resisting against motion. It may be caused by reflexes or disabilities. The subject applies just above 20N reaction force for the position of 75°, and then the rest of the motion is completed by means of the robot manipulator by forcing the patient’s knee within possible limits. The reactive therapy mode for the hip movements will be realized in the following studies.

Figure 12. An example of direct therapy for knee flexion-extension movement (Akdoğan, Taçgin, & Adli 2009)

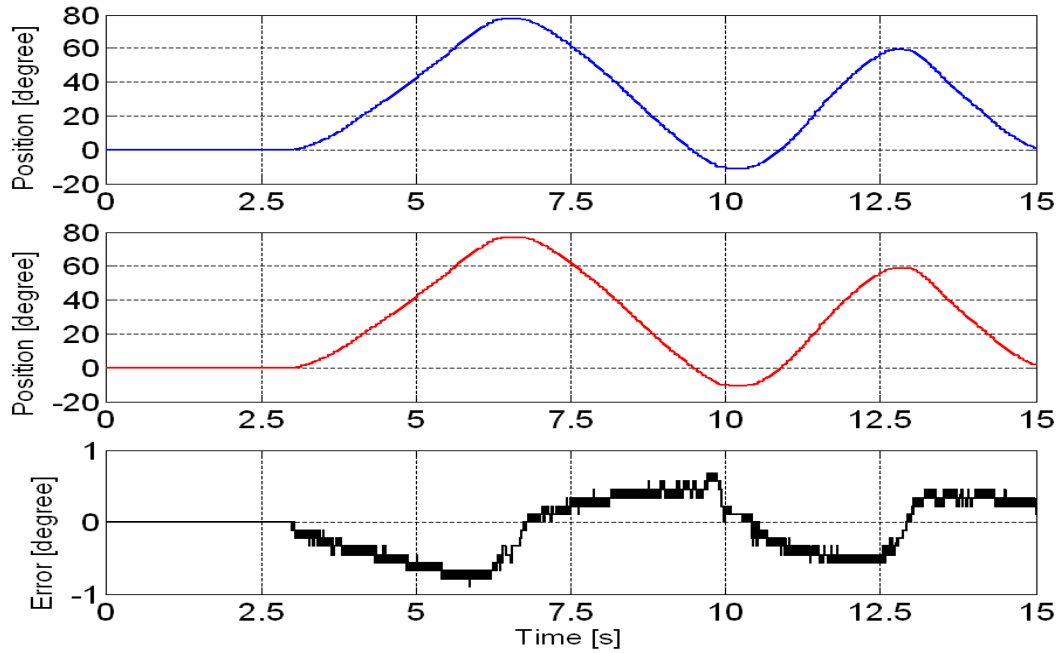


Figure 13. An example of direct therapy for hip flexion-extension movement

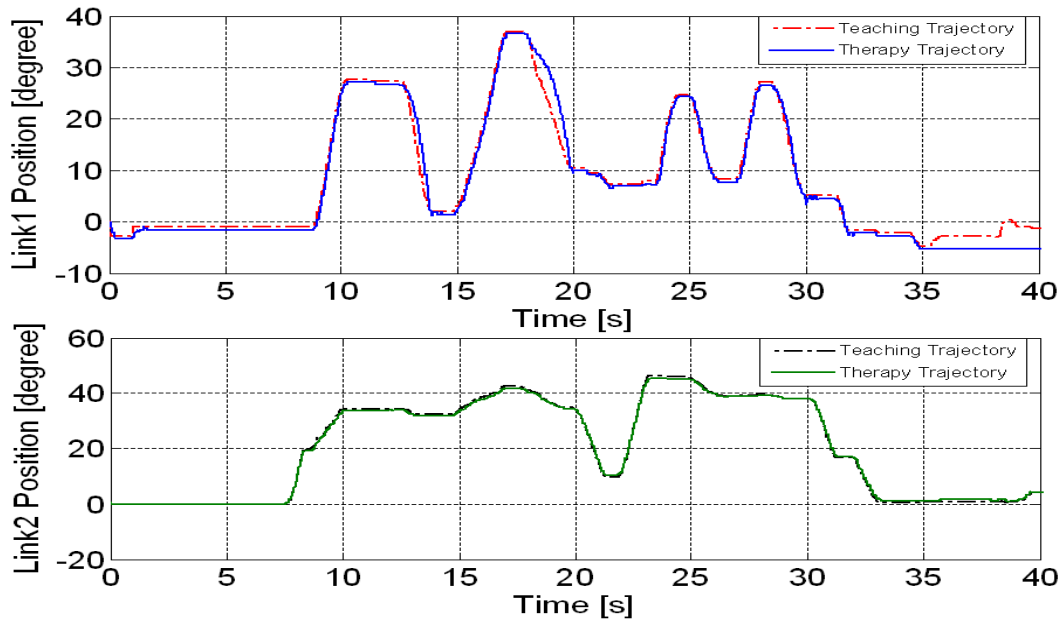


Figure 14. An example of direct therapy for hip abduction-adduction movement

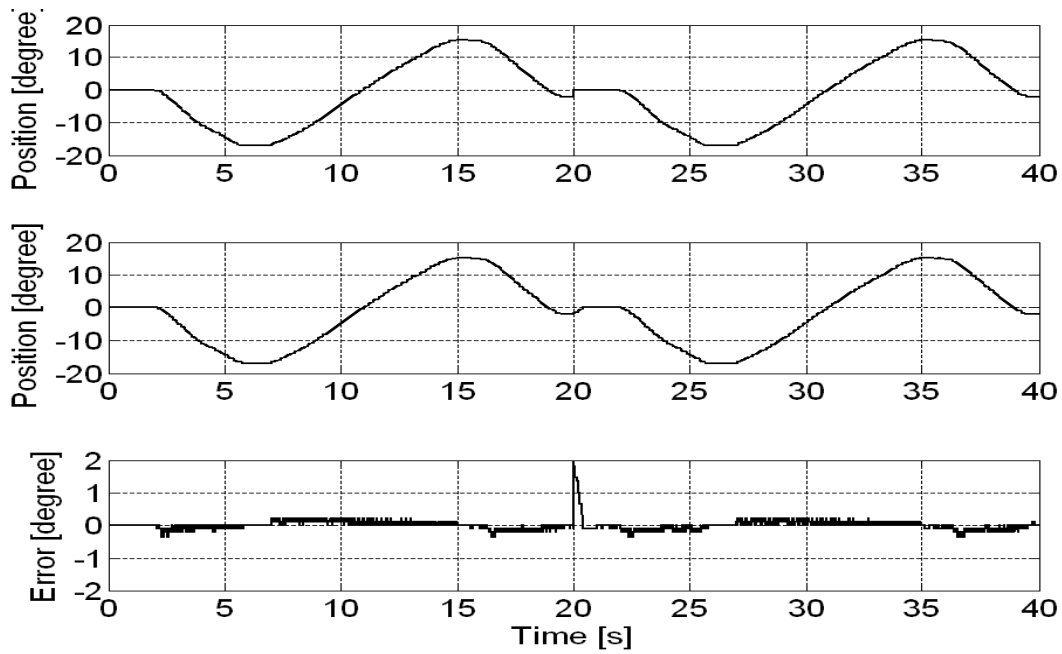
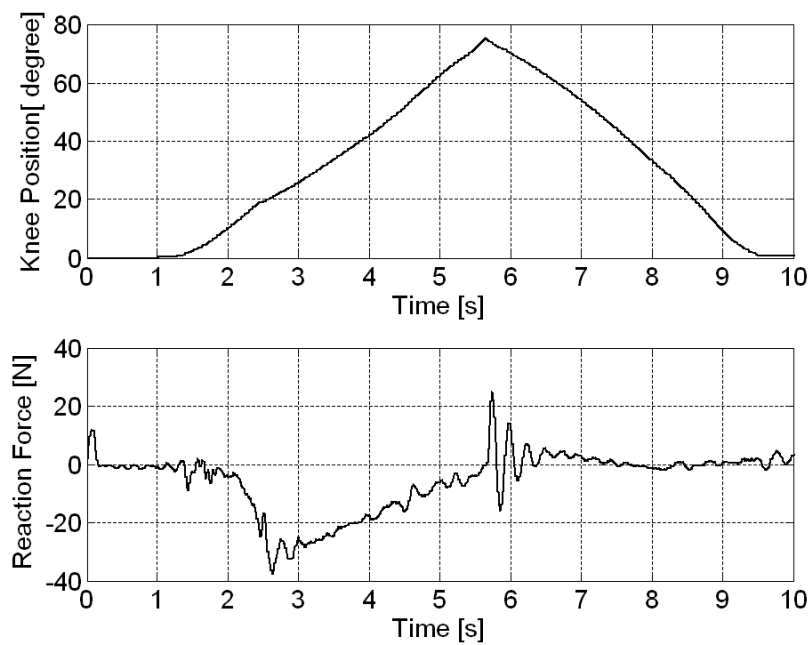


Figure 15. Knee position and reaction force in reactive therapy (Akdoğan, Taçgin, & Adli 2009)



## CONCLUSION AND FUTURE WORK

In this study, a human-machine interface (HMI) was proposed to control a developed robot manipulator (RM) that has three-degrees of freedom for the rehabilitation of the lower limbs. The HMI has a structure created with a rule-based intelligent controller structure, combined with conventional control algorithms of the type impedance and PID control. It also has an easy-to-use, user friendly GUI. With the developed HMI, the progress and the current state of a patient's rehabilitation can be stored on the database. Furthermore, its flexible structure is suitable for internet-based use. With the use of this system, some common problems such as the transportation of patients, storage of data and availability of data of the progress of patients' rehabilitation, and the lacking support of physiotherapists with intelligent devices can be diminished.

The developed HMI can not diagnose the status of patients. If it is able to realize muscle testing like a physiotherapist before the rehabilitation session, it will be able to design a treatment period in order to help physiotherapists. On the other hand, human body signals such as EMG signals reflect the real status of patients. Because of this, evaluating of EMG signals will provide important benefits. EMG pattern recognition though is a highly complex process. Especially the neural networks theory, which is one of the soft computing techniques, appears to be suitable for the interpretation of EMG signal patterns. For future work, we are planning to study on these two aspects using effective soft computing techniques.

## ACKNOWLEDGMENT

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## **KEY TERMS AND DEFINITIONS**

**Data Base:** A collection of information which is organized using a computer program to be accessible, manageable and updatable.

**Human–Machine Interface:** Platforms which provide a connecting interface between a machine, ie a robot manipulator, and a user.

**Impedance Control:** A control method in order to control position and force by adjusting the mechanical impedance of the end-effector to external forces generated by contact with the manipulator’s environment.

**Intelligent Control:** Control technique which adopts itself or its parameters to changing control situations to runtime.

**Internet-Based Rehabilitation:** A novel rehabilitation concept that allows patients to be rehabilitated at their homes.

**Rehabilitation Robot:** Robotic devices in order to support daily activities of the people

who have not sufficient motion capability and rehabilitate the patients who need motor recovery.

**Soft Computing:** A computing method which aim is to model human behavior for special purposes where it is not easy or impossible to realize a mathematical model such as traffic control, weather estimation and so on.

## APPENDIX: RULES OF HMI

< **Rule 1:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 0 degree or equal and less than 15 degree, then **Folder** is **A File** is 1>

< **Rule 2:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 15 degree or equal and less than 25 degree, then **Folder** is **A File** is 2>

< **Rule 3:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 25 degree or equal and less than 35 degree, then **Folder** is **A File** is 3>

< **Rule 4:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 35 degree or equal and less than 45 degree, then **Folder** is **A File** is 4>

< **Rule 5:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 45 degree or equal and less than 55 degree, then **Folder** is **A File** is 5>

< **Rule 6:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 55 degree or equal and less than 65 degree, then **Folder** is **A File** is 6>

< **Rule 7:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 65 degree or equal and less than 75 degree, then **Folder** is **A File** is 7>

< **Rule 8:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 75 degree or equal and less than 85 degree, then **Folder** is **A File** is 8>

< **Rule 9:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than 85 degree or equal and less than 95 degree, then **Folder** is **A File** is 9>

< **Rule 10:** if *BW* is bigger than 67 kg. or equal and less than 70 kg. and *MXP* bigger than -30 degree or equal and less than 0 degree, then **Folder** is **A File** is 10>

< **Rule 11:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MXP* bigger than 0 degree or equal and less than 15 degree, then **Folder** is **B File** is 1>

< **Rule 12:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MXP* bigger than 15 degree or equal and less than 25 degree, then **Folder** is **B File** is 2>

< **Rule 13:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MXP* bigger than 25 degree or equal and less than 35 degree, then **Folder** is **B File** is 3>

< **Rule 14:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MXP* bigger than 35 degree or equal and less than 45 degree, then **Folder** is **B File** is 4>

## **A Human–Machine Interface Design to Control an Intelligent Rehabilitation Robot System**

**< Rule 15:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MPX* bigger than 45 degree or equal and less than 55 degree, then **Folder is B File is 5**>

**< Rule 16:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MPX* bigger than 55 degree or equal and less than 65 degree, then **Folder is B File is 6**>

**< Rule 17:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MPX* bigger than 65 degree or equal and less than 75 degree, then **Folder is B File is 7**>

**< Rule 18:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MPX* bigger than 75 degree or equal and less than 85 degree, then **Folder is B File is 8**>

**< Rule 19:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MPX* bigger than 85 degree or equal and less than 95 degree, then **Folder is B File is 9**>

**< Rule 20:** if *BW* is bigger than 70 kg. or equal and less than 74 kg. and *MPX* bigger than -30 degree or equal and less than 0 degree, then **Folder is B File is 10**>

**< Rule 21:** if *BW* is equal to 74 kg. and *MPX* bigger than 0 degree or equal and less than 15 degree, then **Folder is B File is 1**>

**< Rule 22:** if *BW* is equal to 74 kg. and *MPX* bigger than 15 degree or equal and less than 25 degree, then **Folder is B File is 2**>

**< Rule 23:** if *BW* is equal to 74 kg. and *MPX* bigger than 25 degree or equal and less than 35 degree, then **Folder is B File is 3**>

**< Rule 24:** if *BW* is equal to 74 kg. and *MPX* bigger than 35 degree or equal and less than 45 degree, then **Folder is B File is 4**>

**< Rule 25:** if *BW* is equal to 74 kg. and *MPX* bigger than 45 degree or equal and less than 55 degree, then **Folder is B File is 5**>

**< Rule 26:** if *BW* is equal to 74 kg. and *MPX* bigger than 55 degree or equal and less than 65 degree, then **Folder is B File is 6**>

**< Rule 27:** if *BW* is equal to 74 kg. and *MPX* bigger than 65 degree or equal and less than 75 degree, then **Folder is B File is 7**>

**< Rule 28:** if *BW* is equal to 74 kg. and *MPX* bigger than 75 degree or equal and less than 85 degree, then **Folder is B File is 8**>

**< Rule 29:** if *BW* is equal to 74 kg. and *MPX* bigger than 85 degree or equal and less than 95 degree, then **Folder is B File is 9**>

< **Rule 30:** if **BW** is equal to 74 kg. and **MXP** bigger than -30 degree or equal and less than 0 degree, then **Folder** is **B File** is 10>

< **Rule 31:** if **BW** is equal to 75 kg. and **MXP** bigger than 0 degree or equal and less than 15 degree, then **Folder** is **C File** is 1>

< **Rule 32:** if **BW** is equal to 75 kg. and **MXP** bigger than 15 degree or equal and less than 25 degree, then **Folder** is **C File** is 2>

< **Rule 33:** if **BW** is equal to 75 kg. and **MXP** bigger than 25 degree or equal and less than 35 degree, then **Folder** is **C File** is 3>

< **Rule 34:** if **BW** is equal to 75 kg. and **MXP** bigger than 35 degree or equal and less than 45 degree, then **Folder** is **C File** is 4>

< **Rule 35:** if **BW** is equal to 75 kg. and **MXP** bigger than 45 degree or equal and less than 55 degree, then **Folder** is **C File** is 5>

< **Rule 36:** if **BW** is equal to 75 kg. and **MXP** bigger than 55 degree or equal and less than 65 degree, then **Folder** is **C File** is 6>

< **Rule 37:** if **BW** is equal to 75 kg. and **MXP** bigger than 65 degree or equal and less than 75 degree, then **Folder** is **C File** is 7>

< **Rule 38:** if **BW** is equal to 75 kg. and **MXP** bigger than 75 degree or equal and less than 85 degree, then **Folder** is **C File** is 8>

< **Rule 39:** if **BW** is equal to 75 kg. and **MXP** bigger than 85 degree or equal and less than 95 degree, then **Folder** is **C File** is 9>

< **Rule 40:** if **BW** is equal to 75 kg. and **MXP** bigger than -30 degree or equal and less than 0 degree, then **Folder** is **C File** is 10>

< **Rule 41:** if **BW** is bigger than 76 kg. or equal and less than 80 kg. and **MXP** bigger than 0 degree or equal and less than 15 degree, then **Folder** is **D File** is 1>

< **Rule 42:** if **BW** is bigger than 76 kg. or equal and less than 80 kg. and **MXP** bigger than 15 degree or equal and less than 25 degree, then **Folder** is **D File** is 2>

< **Rule 43:** if **BW** is bigger than 76 kg. or equal and less than 80 kg. and **MXP** bigger than 25 degree or equal and less than 35 degree, then **Folder** is **D File** is 3>

< **Rule 44:** if **BW** is bigger than 76 kg. or equal and less than 80 kg. and **MXP** bigger than 35 degree or equal and less than 45 degree, then **Folder** is **D File** is 4>

## **A Human–Machine Interface Design to Control an Intelligent Rehabilitation Robot System**

**< Rule 45:** if *BW* is bigger than 76 kg. or equal and less than 80 kg. and *MXP* bigger than 45 degree or equal and less than 55 degree, then **Folder** is *D* **File** is 5>

**< Rule 46:** if *BW* is bigger than 76 kg. or equal and less than 80 kg. and *MXP* bigger than 55 degree or equal and less than 65 degree, then **Folder** is *D* **File** is 6>

**< Rule 47:** if *BW* is bigger than 76 kg. or equal and less than 80 kg. and *MXP* bigger than 65 degree or equal and less than 75 degree, then **Folder** is *D* **File** is 7>

**< Rule 48:** if *BW* is bigger than 76 kg. or equal and less than 80 kg. and *MXP* bigger than 75 degree or equal and less than 85 degree, then **Folder** is *D* **File** is 8>

**< Rule 49:** if *BW* is bigger than 76 kg. or equal and less than 80 kg. and *MXP* bigger than 85 degree or equal and less than 95 degree, then **Folder** is *D* **File** is 9>

**< Rule 50:** if *BW* is bigger than 76 kg. or equal and less than 80 kg. and *MXP* bigger than -30 degree or equal and less than 0 degree, then **Folder** is *D* **File** is 10>

**< Rule 51:** if *BW* is equal to 81 kg. and *MXP* bigger than 0 degree or equal and less than 15 degree, then **Folder** is *E* **File** is 1>

**< Rule 52:** if *BW* is equal to 81 kg. and *MXP* bigger than 15 degree or equal and less than 25 degree, then **Folder** is *E* **File** is 2>

**< Rule 53:** if *BW* is equal to 81 kg. and *MXP* bigger than 25 degree or equal and less than 35 degree, then **Folder** is *E* **File** is 3>

**< Rule 54:** if *BW* is equal to 81 kg. and *MXP* bigger than 35 degree or equal and less than 45 degree, then **Folder** is *E* **File** is 4>

**< Rule 55:** if *BW* is equal to 81 kg. and *MXP* bigger than 45 degree or equal and less than 55 degree, then **Folder** is *E* **File** is 5>

**< Rule 56:** if *BW* is equal to 81 kg. and *MXP* bigger than 55 degree or equal and less than 65 degree, then **Folder** is *E* **File** is 6>

**< Rule 57:** if *BW* is equal to 81 kg. and *MXP* bigger than 65 degree or equal and less than 75 degree, then **Folder** is *E* **File** is 7>

**< Rule 58:** if *BW* is equal to 81 kg. and *MXP* bigger than 75 degree or equal and less than 85 degree, then **Folder** is *E* **File** is 8>

**< Rule 59:** if *BW* is equal to 81 kg. and *MXP* bigger than 85 degree or equal and less than 95 degree, then **Folder** is *E* **File** is 9>

< **Rule 60:** if **BW** is equal to 81 kg. and **MXP** bigger than -30 degree or equal and less than 0 degree, then **Folder** is **E File** is 10>

< **Rule 61:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 0 degree or equal and less than 15 degree, then **Folder** is **F File** is 1>

< **Rule 62:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 15 degree or equal and less than 25 degree, then **Folder** is **F File** is 2>

< **Rule 63:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 25 degree or equal and less than 35 degree, then **Folder** is **F File** is 3>

< **Rule 64:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 35 degree or equal and less than 45 degree, then **Folder** is **F File** is 4>

< **Rule 65:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 45 degree or equal and less than 55 degree, then **Folder** is **F File** is 5>

< **Rule 66:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 55 degree or equal and less than 65 degree, then **Folder** is **F File** is 6>

< **Rule 67:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 65 degree or equal and less than 75 degree, then **Folder** is **F File** is 7>

< **Rule 68:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 75 degree or equal and less than 85 degree, then **Folder** is **F File** is 8>

< **Rule 69:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than 85 degree or equal and less than 95 degree, then **Folder** is **F File** is 9>

< **Rule 70:** if **BW** is bigger than 81 kg. or equal and less than 86 kg. and **MXP** bigger than -30 degree or equal and less than 0 degree, then **Folder** is **F File** is 10>