



The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherobot

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ABSTRACT

This study explains the design and control of three degrees of freedom therapeutic exercise robot (Physiotherobot) for the lower limbs of a patient who needs rehabilitation after a spinal cord injury (SCI), stroke, muscle disorder, or a surgical operation. In order to control this robot, a “Human–Machine Interface” with a rule-based control structure was developed. The robot manipulator (RM) can perform all active and passive exercises as well as learn specific exercise motions and perform them without the physiotherapist (PT) through the Human–Machine Interface. Furthermore, if a patient reacts against the robot manipulator during the exercise, the robot manipulator can change the position according to feedback data. Thus, the robot manipulator can serve as both therapeutic exercise equipment and as a physiotherapist in terms of motion capability. Experiments carried out on healthy subjects have demonstrated that the RM can perform the necessary exercise movements as well as imitate the manual exercises performed by the PT.

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1. Introduction

Rehabilitation aims to bring back the patient's physical, sensory, and mental capabilities that were lost due to injury, illness, and disease, and to support the patient to compensate for deficits that cannot be treated medically [1]. After the spinal cord injury (SCI), stroke, muscle disorder, and surgical operation such as knee arthroplasty, patients need rehabilitation to recover their movement capability (mobilization) [2–7]. The number of those who need rehabilitation is steadily increasing every day. Parallel to this, equipment and techniques used in the field of rehabilitation are becoming more advanced and sophisticated. There are two basic elements in the total rehabilitation program: therapeutic modalities and therapeutic exercise. While the goal of therapeutic modalities is to treat and resolve the effects of pain, spasm and edema, the ultimate goal of therapeutic exercise is to return the injured patient to pain-free and fully functional activity. Specific parameters must be addressed sequentially to an effective exercise program during the therapeutic exercise. In order to have the patients safely resume fully normal activity, each of these parameters must be restored to at least pre-injury levels. In their proper sequence these parameters are [8]:

- flexibility and range of motion
- strength and muscle endurance
- proprioception, coordination and agility.

They are sequentially related to each other. A previous one is the precondition of the next. As can be seen from these parameters, a rehabilitation program starts with a passive range of motion and continues with assistive exercises followed by resistive exercises.

To restore the flexibility and range of motion passive range of motion exercises are applied to the patient, for the strength and muscle endurance resistive exercises are performed by patient, and for the proprioception, coordination and agility, strength exercises are applied to the patient by the physiotherapist [6,9]. In general, a person with movement disabilities due to arm or leg problems needs to undergo periods of therapeutic exercise sessions spread over a long period of time. The sessions comprise a series of repeated and routine physical movements with the assistance and under the observation of a physiotherapist. Transporting the patient to the medical center or calling a PT to where the patient is located are factors that further increase the cost of this process. The process of strengthening muscles to their normal values is costly and requires time and patience. In order to solve these problems in rehabilitation, the number of studies about the usage of robots in rehabilitation has increased, especially in the last 10 years. Some important reasons for the utilization of robots in rehabilitation can be listed as follows [10]: Robots easily fulfill

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the requirements of cyclic movements in rehabilitation; robots have better control over introduced forces; they can accurately reproduce required forces in repetitive exercises; and robots can be more precise regarding required therapy conditions.

Devices called “Continuous Passive Motion” (CPM) are widely used in many medical centers for therapy and rehabilitation purposes. The CPM concept was first introduced in the 1970s [11]. During the rehabilitation process, patients sometimes move their extremities suddenly due to reflexes. Conventional machines such as CPMs do not respond in these kinds of situations and are hence not suitable for physical therapy. If a reflex causes a patient’s leg to move while the machine is operating, an improper load results and can damage the patient’s muscle or tendon tissue [12]. Because of this, there is a need for an intelligent device which can accomplish the rehabilitation of extremities based on the patient’s complaints and real-time feedback during rehabilitation processes.

Rehabilitation robots can be classified into three groups [13]:

- i. To assist disabled people in special need with their daily life activities.
- ii. To support mobility.
- iii. To assist therapists performing repetitive exercises with their patients (therapeutic exercise robot).

There have been attempts to develop robotic systems for the motor rehabilitation of leg and arm extremities. These robotic systems can be considered in terms of therapeutic exercise types, movement capability (mechanical specifications) and control methods.

1.1. Rehabilitation robot systems for upper limbs

Lee and others developed a robotic system for the rehabilitation of upper limbs of paralyzed patients using an expert system [14]. This system combines the needed skills of therapists with a sensor-integrated orthosis and a real-time graphics system to ensure proper interaction and cooperation with the patient in order to achieve the goals of therapy. It can achieve passive exercises, motor-learning training and tone reduction. Lum and others developed a prototype device called MIME (Mirror Image Motion Enabler) that implements passive and active assistive movements for upper extremities [15,16]. This system uses a commercial robot and a position sensing device. Another system developed for rehabilitation of upper extremities is a robot manipulator with 5-DOF (degrees of freedom) called MULOS [17]. It is used as an assistive device and to perform passive and resistive exercises. Krebs and others developed and have been clinically evaluating a robot-aided neurorhabilitation system called MIT-MANUS [18,19]. This device provides multiple degrees of freedom exercises of upper extremities for stroke patients. This study showed the effect of robot-aided rehabilitation. Rao and others introduced another system using a Puma 240 robot for passive and active rehabilitation of upper extremities [20]. In the passive mode, the robot moves the subject’s arm through specified paths. In the active mode, a subject guides the robot along a predefined path, overcoming specified joint stiffness. Richardson and others developed a 3-DOF pneumatic device for the rehabilitation of upper extremities using PD control and impedance control methodologies [21,22]. Another study for the rehabilitation of upper extremities is the REHAROB project, which uses two industrial robots [23]. A database is formed with the necessary force and position produced by the sensors placed on the patients during the rehabilitation process. Industrial robots then repeat the same procedure using this database. Reinkensmeyer and others developed a 3-DOF system called ARM Guide (Assisted Rehabilitation and Measurement Guide) for the rehabilitation of upper extremities [24]. The ARM Guide can

diagnose and treat arm movement impairment following stroke and other brain injuries. As a diagnostic tool, it provides a basis for the evaluation of several key motor impairments, including abnormal tone, incoordination, and weakness. As a therapeutic tool, the device provides a means to implement and evaluate active assistive therapy for the arm. A 3-DOF system, called GENTLE/s, was developed for the rehabilitation of upper extremities using a haptic device and the virtual reality technique, controlled by the admittance control method [25]. Tsagarakis and Caldwell developed a 7-DOF assistive exoskeletal robot manipulator for upper arm physiotherapy and training [26].

1.2. Rehabilitation robot systems for lower limbs

The therapeutic exercise robots for lower extremities are divided in two groups: leg, ankle, foot robots and walking (gait) robots [27].

LOKOMAT [28], Gait Trainer [29] and Autoambulator [30] are commercial gait rehabilitation devices and are available on the market. On the other hand some prototypes for gait rehabilitation have been developed by researchers, such as ALEX [31], Haptic Walker [32] PAM and POGO devices of University of California, Irvine [33] and LOPES exoskeleton of Universiteit Twente [34].

Lower limb exoskeletal robots were developed to assist people who have some handicap in their lower extremities [35–37]. The robotic systems for therapeutic exercises for lower limbs were developed to perform some repetitive, resistive, and assistive exercises which are performed by the PT or equipment. Okada et al. employed an impedance control methodology in a 2-DOF robotic system, where the position and force data are received and recorded for the robotic system to imitate the corresponding motion [2]. Homma et al. developed a 2-DOF system around the patient’s bed [38]. They only tested it for passive exercises. Bradley et al. developed a 2-DOF autonomous system called NeXOS [3] that is able to perform active assistive, passive and resistive exercises using pre-training visual position information. It can be used for knee and hip extension–flexion movements. Moughamir et al. devised a training system called Multi-Iso [39]. This system is also able to perform assistive, resistive and passive exercises like NeXOS. This 1-DOF system is used for knee limb and extension–flexion movements. Multi-Iso uses classical force, position and speed control methods developed with fuzzy control techniques. Motion Maker is a commercial lower limb rehabilitation device developed by Swortech SA. It consists of a couch and two orthoses enabling a controlled movement of the hip, knee, and ankle joints. It can perform flexion/extension movement for lower limbs. Its control algorithm includes a model based feed-forward and a conventional regulator [40,41].

Many of the developed therapeutic robotic systems are designed for only assistive or only passive and resistive exercises. Furthermore, few studies aim to model the PT’s manual exercise and directly convey the PT’s rehabilitation capability to the patient [2,23].

The main goal of the developed system in this study – the Physiotherobot – is to perform all active and resistive therapeutic exercises in addition to manual exercises of the PT for the lower limbs of a patient who needs rehabilitation after an SCI, stroke, muscle disorder, or a surgical operation. In terms of exercise capability, Multi-Iso and NeXOS are the closest systems to the Physiotherobot. However, they cannot completely model PT’ manual exercises. What distinguishes Physiotherobot from these systems is that it has 3-DOF and can perform flexion–extension movement of the knee and hip, and the abduction–adduction movement of the hip.

Robots developed for rehabilitation purpose generally employ two control methods: hybrid control and impedance control.

Bernhardt et al. [42] applied hybrid control to the LOKOMAT and Ju et al. applied hybrid force–position control method to the upper limb rehabilitation robot mechanism [43]. It is, however, commonly accepted that the impedance control method is more convenient for the development of rehabilitation systems [18]. This leads to it being extensively used in controlling rehabilitation devices [2,18,19,21,22,44]. Intelligent techniques are much less common compared to the former two methods [12,14,23,37]. In this study, an intelligent controlling scheme combined with an impedance controller was developed in order to manage the robotic system. On the other hand, in previous research studies, different control paradigms were developed and used by researchers, as well. For example, Banala et al. developed a force-field controller which was used to assist or resist the motion of the leg as needed, by applying force-field on the foot [31]. Wicke et al. developed patient-cooperative path control strategy which was utilized for gait training that allows patients to influence the timing of their leg movements, along physiologically meaningful path [56]. The path control algorithm used allows patients to move actively along the spatial path of a defined walking pattern. Their approach was motivated by the work of Cai et al. [58]. However, to focus more on the leg postures rather than on end-effector position, they designed a torque field tunnel in joint space rather than a force field in Cartesian space.

The main research questions for this study are:

- Can a Human–Machine Interface to control a rehabilitation robot mechanism which behaves not only as a therapeutic exercise device but also as a physiotherapist be developed?
- Can a low-cost versatile robot mechanism which is able to perform lower limbs therapeutic exercises for the rehabilitation of both legs and that can be adjusted for different limb sizes be realized?

The original features of the developed system which were designed with taken into account these research questions are as follows:

- It is able to perform active, passive and active assistive exercises as well as model the PT's exercise movements.
- It is a 3-DOF robot manipulator. Thanks to this feature, it can perform the flexion–extension movement for the knee and hip and the abduction–adduction movement for the hip.
- It can be used for rehabilitation of two legs.
- It uses special force sensors suitable for rehabilitation in order to measure the reacting force of the patient.
- It has a rule-based intelligent controlling scheme that was combined with an impedance controller. This control scheme uses a Human–Machine Interface (HMI). Furthermore, its flexible structure allows for a web-based and user-friendly graphical user interface (GUI).
- Safety is ensured using both software and hardware.

The preliminary experimental results of this prototype have been published [45,46]. The aim of this paper is to explain the design process and control method of the developed system. In order to demonstrate the developed system's features, tests were carried out with healthy subjects. Testing the system with real patients in a medical center is being planned and these results will be introduced in studies to follow. This paper is organized as follows: Section 2 explains theory of lower limb rehabilitation, Section 3 contains a description of the system; Section 4 describes the control technique of the robot manipulator for knee and hip movement; Section 5 explains the performance of exercise types and gives the experimental results of these exercise types, showing that the robot manipulator can perform active and passive

exercises and imitate the PT's manual exercises successfully; finally, Section 6 concludes the paper.

2. Theory of lower limb rehabilitation

In order to decide the most suitable exercise type for the patient, the muscle tone [47] must be determined first. The muscle tone is evaluated according to a scale which ranges from 0 to 5. This scale is given in Table 1 with description and the corresponding proper exercise type. The therapeutic exercise to be applied is determined according to muscle tone of the patient. This process is performed by a PT.

2.1. Movements of lower limbs exercises

In hip and knee rehabilitation exercises, there are three movements. These are abduction–adduction, flexion–extension and rotation. The RM developed in this study is able to perform abduction–adduction, flexion–extension movements.

2.2. Therapeutic exercise types

Passive or range of motion (ROM): These exercises are performed for the patient by another person (nurse or therapist) or by an exercises device (robotic device or CPM). They are usually applied to patients who do not have muscle strength.

Active assistive: As the patient develops the ability to produce some active movement, active exercises begin. Assistance can be provided manually by a therapist, by counterbalancing with weights or by gravity. These exercises are helpful in increasing the strength of the patient.

Isotonic: Isotonic exercises refer to moving the resistance through a range of motion.

Isometric: It refers to contraction against a fixed resistance. No change in the joint angle occurs.

Isokinetic: The aim of this type of exercise is to facilitate the exercise by countering the maximum resistance and by keeping the movement speed of the patient's limb at a stable level.

Manual exercise: It refers to all active and passive exercises which are performed by a PT manually.

3. System description

The PT operates the system, which comprises a Human–Machine Interface (HMI) and a robot manipulator (Fig. 1). Using the graphical user interface (GUI), the PT enters information (input) about the patient (weight, height, limb length, etc.) into the system and selects the suitable type of exercise.

The information needed to control the RM (position, joint torques, impedance parameters) is computed by the HMI and submitted to the robot manipulator. The patient's reactions during the exercise are sensed by the force sensors and evaluated by the

Table 1
Muscle tone scale [47].

Score	Description	Exercise type
(0)	No palpable or observable muscle contraction	Passive
(1)	Palpable or observable contraction, but no motion	Passive
(2)	Moves without gravity loading over the full ROM	Active assistive
(3)	Moves against gravity less over the full ROM	Active
(4)	Moves against gravity and moderate resistance over the full ROM	Active +resistive
(5)	Moves against gravity and maximal resistance over the full ROM	Active +resistive

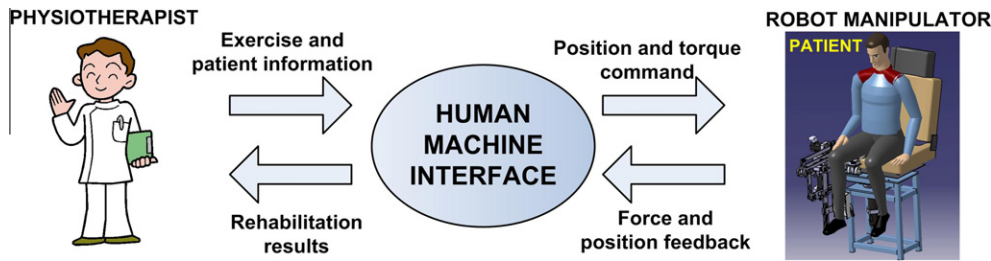


Fig. 1. System concept.

HMI. Thus, if necessary, the robot manipulator can change the position or the applied force.

3.1. Robot manipulator and hardware configuration

3.1.1. Robot manipulator

3.1.1.1. Design requirements. The design requirements of the RM were determined in accordance with the lower limb rehabilitation theory. In order to meet these requirements, the design of the appropriate mechanism and the hardware to control this mechanism were developed. The design requirements were set as follows:

- Main exercise movements are flexion–extension and abduction–adduction for lower limbs. That is why, the RM must be able to perform flexion–extension movement for the knee and flexion–extension and abduction–adduction movements for the hip that are necessary for the rehabilitation of lower limbs in the range of necessary gaps.
- The RM can be used for wide range of patient in terms of physical characteristics. That is why, the actuators of the RM must be able to generate torques for the rehabilitation of patients with various mass (up to 100 kg) and its mechanism should be adjusted according to patient limb size.
- The motor that will move the knee link must not contribute any payload, therefore it should be placed at a location such that it will not cause any gravitational load.
- Since the RM is to be used in medical applications, the RM's moving parts must be light.
- Since usually PT handles the patient leg at two different points during the rehabilitation process, the RM must be able to measure voluntary and involuntary reacting forces at these particular locations of the patient's leg (hip and knee).

- Measuring, monitoring and recording the interaction forces and limb position are very important in rehabilitation. Therefore, the RM must be able to provide the real time position and force data during and after the rehabilitation session.
- Safety is a very important aspect for medical applications. Therefore, safety must be ensured by both software and hardware in the system.
- In order to perform therapeutic exercises for lower limbs rehabilitation, the developed system must have the suitable hardware to control the position and force of the RM.

These are the most important requirements for the lower limb rehabilitation. If additional specifications are set, the number of requirements and the design parameters is to be modified accordingly.

The designed and manufactured mechanism meeting these requirements is shown in Fig. 2. This mechanism's hardware features are explained below.

3.1.1.2. Mechanism specifications.

- It has three degrees of freedom.
- It is able to perform:
 - flexion–extension for the knee where only Link 1 works (Fig. 3a),
 - flexion–extension for the hip where Link 1 and Link 2 work together (Fig. 3b),
 - abduction–adduction for the hip where only Link 0 works around the z-axis (Fig. 3c).
- All the motors were placed on the base and are immobile so that the effect of motors' weight on the dynamics of the RM is eliminated (see Fig. 2).
- A parallelogram structure was used for Link 2 that allows placing the actuator that moves the knee link at the base.

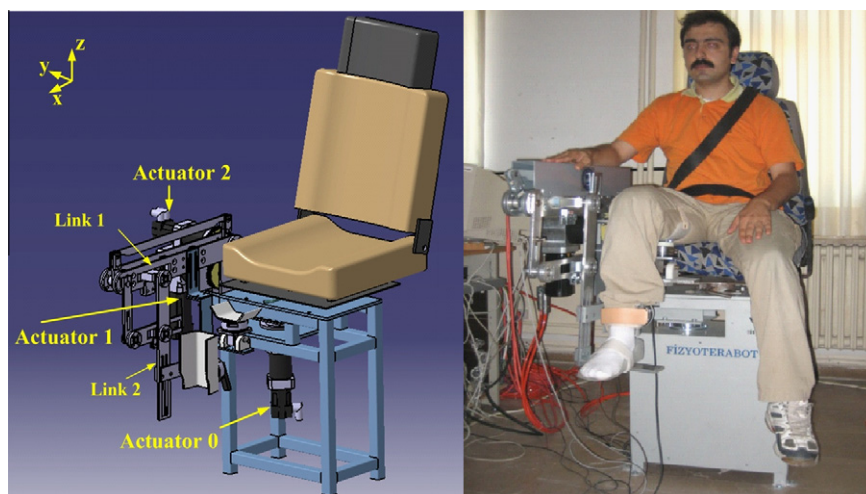


Fig. 2. The architecture of the robot manipulator.

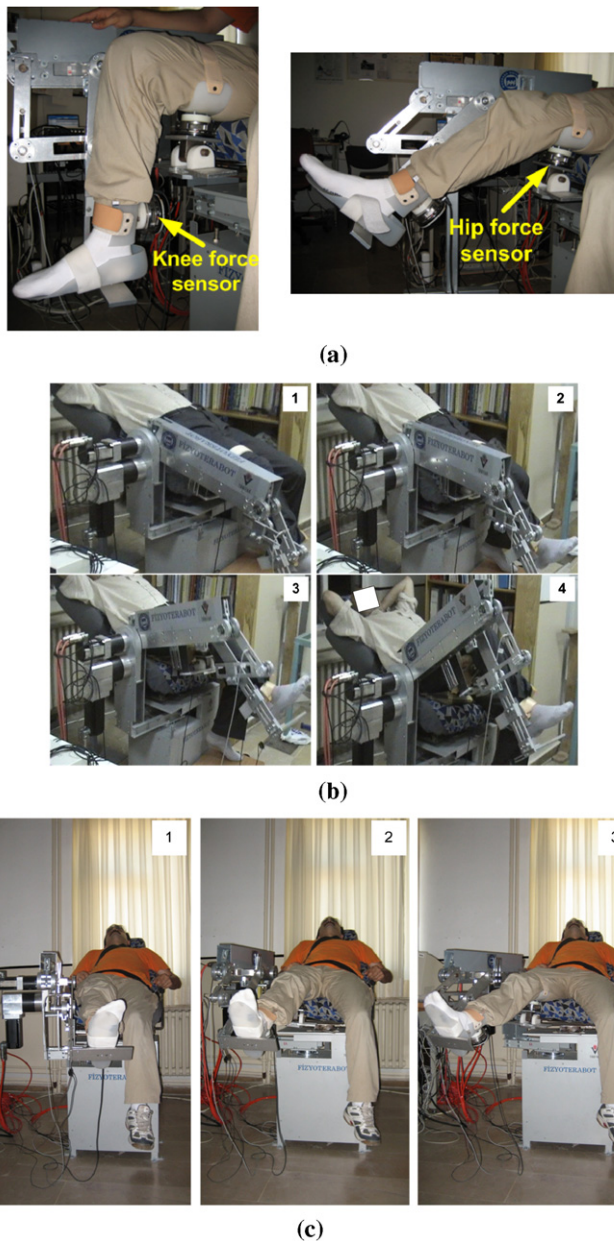


Fig. 3. Exercise movement capacity of robot manipulator. (a) Knee flexion-extension, (b) hip flexion-extension, (c) hip abduction-adduction.

- The movement range of the RM is appropriate for the physical features of lower limbs and characteristics of exercise movements. The range of movement of a limb and the Physiotherobot is given in Table 2.
- The mechanism can be adjusted for the patient's limb size and used for both the left and right leg.
- In order to decrease the weight of the mechanism, most of the moving parts of the RM were produced from duralumin.

3.1.2. The hardware configuration

The block diagram of the system hardware is shown in Fig. 4 and a detailed explanation is given below.

3.1.2.1. Actuators (servomotors), servo drivers and gearboxes. The system has three servomotors (Kollmorgen) as actuators, servomotor drivers (Servostar S Type) and gearboxes (Neugart). These motors are able to move the lower limbs of a patient who weighs up to

Table 2

The range of motion (ROM) of a limb and the Physiotherobot.

Limb	Movement	ROM of limb	ROM of Physiotherobot
Knee	Flexion–extension	–45°/90°	–35°/90°
Hip	Flexion–extension	–15°/45°	–15°/45°
	Abduction–adduction	0°/120°	0°/120°

100 kg. All the motors are located on the base. The model and parameter information of servomotors and gearboxes are given in Tables 3 and 4.

3.1.2.2. Force and position feedback (measurement). The system has two force/torque sensors and their controllers (ATI – Delta). They are positioned at the calf and thigh locations (see Fig. 3a). The position of force sensors can easily be modified according to the patient's limb size. Voluntary and involuntary forces exerted by the patient and forces applied by the PT to the patient are measured via these sensors. Position data are obtained via encoder emulation that is provided by servo-drivers.

3.1.2.3. Data acquisition. The system has two DAQ cards (National Instruments 6024E Multifunction Data Acquisition) for analog/digital data conversion. In this study, the sampling time was selected to be 1 ms.

3.1.2.4. Safety. Safety is provided through hardware and software. This allows for a dual layer of safety. The hardware comprises limit switches and an emergency button. The second layer involves software, which limits the servomotors' torque and rotation angles through servomotor drivers. Furthermore, mechanism movement angles and current values sent to motors are limited with developed system software.

3.2. Human–Machine Interface

The Human–Machine Interface is the central unit between the PT and the RM. Passive, active assistive, isotonic, isometric, and isokinetic types of exercises are performed by the RM for which control is provided by the HMI. Furthermore, especially with this architecture, the RM can learn the actions performed by the PT for each patient and imitate these actions in the absence of the PT. In this paper, this exercise type is named “robototherapy”. *Robototherapy* has two phases: teaching and therapy. The teaching process is performed based on the physical characteristics of the patient and the position and force data obtained from the patient. Treatment requirements change from patient to patient. On the other hand, the medical needs of a patient can differ from day to day. That is why the PT teaches necessary movements to the patient before each rehabilitation session with the robot manipulator. The existing safety precautions were developed to prevent abrupt situations that would occur during the rehabilitation session. If a serious change occurs in the patient's situation and a need arises for a change in the movements that are applied to the patient, the PT can easily re-teach the system and continue the rehabilitation.

There are two modes in the therapy phase. These modes are *direct therapy* and *reactive therapy*. In the direct therapy mode, the system can repeat movements taught it by the PT for any required duration. In the reactive therapy mode, joint open exercise of PT with force is modeled and the system responds according to the patient's reactions. The boundary conditions of the exercise carried out continuously change over the duration of therapy.

A detailed explanation of exercise performing methods is given in Section 5. The HMI consists of a graphical user interface, a central interface unit, an impedance and PID controller, a rule base and

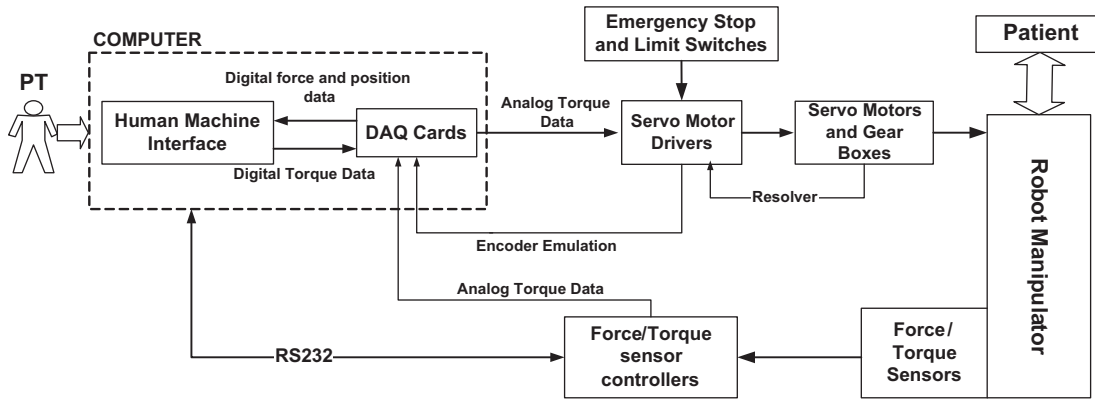


Fig. 4. System hardware.

Table 3
Model and parameter information of servo motors.

Model	Servomotor		
	0	1	2
	AKM 31C	AKM 43E	AKM 31C
<i>Parameter</i>			
Max. operating voltage (Vdc)	640	640	640
Stall torque (N m)	1.15	4.7	1.15
Stall current (ARms)	1.37	2.76	1.37
Max. mechanical speed (Rpm)	6000	6000	6000

Table 4
Model and parameter information of gearboxes.

Model	Gearbox		
	0	1	2
	PLE80-80	WPLE120	PLE80
<i>Parameter</i>			
Gear ratio	80	40	100
Nominal output torque (N m)	120	230	120
Max. output torque (N m)	192	368	192
Inertia moment (kg cm ²)	0.5	2.84	0.44

a database (Fig. 5). Also, the architecture of the HMI allows monitoring the position, reaction force of the patient, and the force applied by the robot manipulator to the patient, and records the results of the exercises so that the treatment period can be followed.

The central interface unit provides for the management of the system and communication between all system components. The GUI enables the user to communicate with the HMI. The main menu of GUI is used to input the patient's data. The data is used in order to calculate several mechanical parameters. The limb which is to be exercised and the exercise type are selected from the main menu as well. Results from completed exercises can be accessed from the main menu and are displayed graphically. The graphics display the patient's range of motion (ROM) numerically, the patient's limb trajectory during the exercise sessions and the corresponding forces. These results are stored in the database for documentation and can be printed out if necessary.

Impedance control is the main control method of the system. According to the exercise type, the central interface unit determines impedance control parameters using rules and the database. A detailed explanation of impedance control is given in Section 4. For exercise types which require only position control, the PID control method is used. The patient's personal data, saved exercise data from the teaching phase, and exercise results are stored in the database. The rule base contains rules that are used to choose proper impedance parameters in accordance with the exercise type. Also, for the reactive therapy phase, the rule base determines the data file stored in the database that contains the desired exercise trajectory realized according to different patient weights.

The PT is the main user of the system. S/he decides the necessary exercises and teaches the RM the exercise movements. First, the PT inputs the patient's information using the GUI. This information consists of the patient's age, height, weight, and foot length. S/he then inputs the information on the type of exercise,

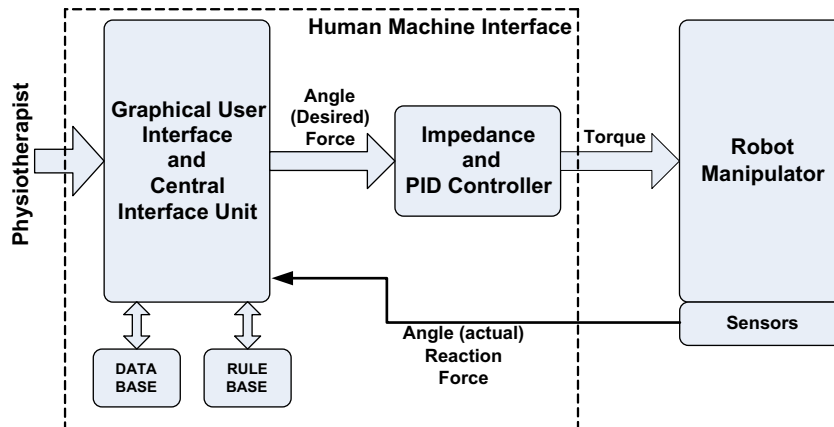


Fig. 5. Human-Machine Interface structure.

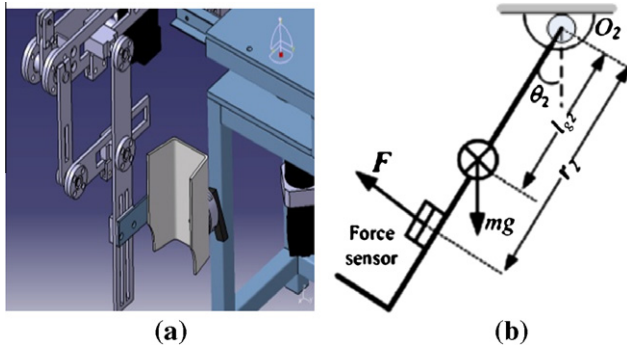


Fig. 7. Knee link: (a) Pictorial view [45] and (b) schematic model.

tual (θ_2), l_{g2} is the distance between the knee joint and the mass center of the knee link and r_2 is the distance between the knee joint and the knee force sensor (Fig. 7b), respectively.

4.2. Control of hip movements

The RM can perform related exercises for the hip with flexion–extension and abduction–adduction movements. The force measurement is realized by F1 and F2 sensors that are located on Links 1 and 2 (Fig. 8). The position of the force sensors can be adjusted according to patient limb size.

4.2.1. Flexion–extension movement

The hip flexion–extension is a 2-DOF movement. The schematic model that shows the links which perform the hip flexion–extension movement of the RM are shown in Fig. 8.

The impedance control law is applied to hip flexion–extension movements using Eq. (11). Because the force is applied to the RM at two different points (one at the thigh and the other at the calf, see Fig. 8) the necessary variables and parameters in Eq. (11) are adjusted as needed, as follows:

$$q^T = [\theta_1 \quad \theta_2] \quad \tau^T = [\tau_1 \quad \tau_2] \quad F_1 = \begin{bmatrix} f_{1x} \\ f_{1z} \end{bmatrix} \quad F_2 = \begin{bmatrix} f_{2x} \\ f_{2z} \end{bmatrix}$$

$$J_{y1} = \begin{bmatrix} -r_1 \sin \theta_1 \\ -r_1 \cos \theta_1 \end{bmatrix} \quad J_{y2} = \begin{bmatrix} -l_1 \sin \theta_1 & -r_2 \sin \theta_2 \\ -l_1 \cos \theta_1 & -r_2 \cos \theta_2 \end{bmatrix}$$

$$h_N = \begin{bmatrix} h_{N1} \\ h_{N2} \end{bmatrix} \quad M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

$$M_d = \begin{bmatrix} M_{dx} & 0 \\ 0 & M_{dz} \end{bmatrix} \quad D_d = \begin{bmatrix} D_{dx} & 0 \\ 0 & D_{dz} \end{bmatrix} \quad K_d = \begin{bmatrix} K_{dx} & 0 \\ 0 & K_{dz} \end{bmatrix}$$

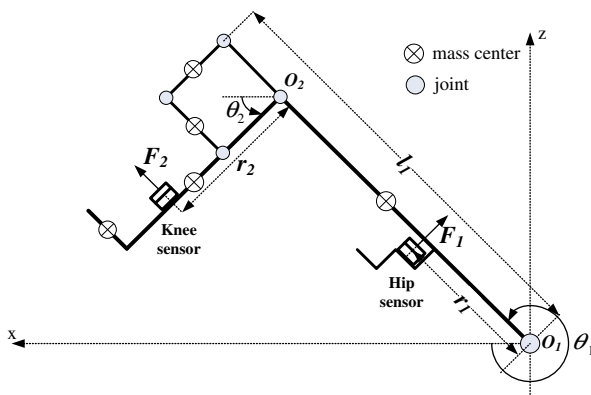


Fig. 8. Schematic model of the hip link.

4.2.2. Abduction–adduction movement

The hip abduction–adduction movement is a one-DOF movement about the z-axis and is performed by the motor (actuator 0) placed on the base (see Fig. 2). In this study, the abduction–adduction movement has been modeled for only passive (ROM) exercises and the position control is enough to perform this exercise. By implication, since the movement needs a position control, the PID control method given in (14) is used.

$$\tau = k_p \theta_e + k_i \int \theta_e dt + k_d \dot{\theta}_e \tag{14}$$

where θ_e is the difference between the desired and actual position and k_p , k_i , k_d are the proportional, integral and derivative gains, respectively.

5. Results

In this study, except in the passive (ROM) exercises, impedance control has been employed in all exercise types. Usage of impedance control for exercise types in this study is given as follows: In the isotonic exercise, various resistance levels were obtained by changing the impedance parameters. The isometric exercise was combined with the isotonic exercise and the patient was helped to complete the isotonic exercise during the limb movement and isometric exercise on the extension limit. The impedance control was used to eliminate the effects that stem from the mechanism – such as friction and gravity – in order for the patient to move his/her limb at the desired speed in the isokinetic exercise. For the active assistive exercise, the impedance parameters were selected suitably in a way that makes the patient move his/her limb easily. As for the robototherapy, the smallest impedance parameter values that do not generate any vibration were selected for the PT to teach the exercise motions to the RM with great ease.

At first, the impedance parameters were selected by the trial and error method. A series of experiments were carried out in order to detect the effects of the impedance parameters during the control phase. In those experiments, regarding knee flexion–extension, motion speed was also taken into account. However, the same experiments were not conducted for the hip since the exercise movements for the hip were not at the same speed.

For the flexion–extension movement of the knee, the experiments were carried out on healthy subjects whose physical specifications are given in Table 5. Weight differences in these subjects were taken into consideration as the selection criterion. During the experiments, three different speed levels – low (16 °/s), moderate (32 °/s) and fast (48 °/s) – were used. The impedance parameters were changed in the range of values given in Table 6 and their combinations amongst themselves were taken into account.

Table 5
The physical specifications of subjects for the knee exercise.

Subject	Height (cm)	Weight (kg)	Age
I	172	74	21
II	180	80	23
III	175	86	24

Table 6
Knee flexion–extension impedance parameter values.

	Robotherapy									
M_d (kg)	3	4	5	6	7	8	9	10	3	
K_d (N/°)	1	20	40	60	80	100	20			
D_d (Ns/°)	0	0.001	0.01	0.1	1	0.001				

Since two links are used during the flexion–extension of the hip, the impedance parameters are specified in (2×2) matrices. These parameters were experimentally determined as was done for the knee. First, parameters of Link 2 were determined and the parameter values that do not cause any vibration and that apply the lowest-level counter resistance were experimentally determined. These parameters were then kept constant while the parameters of Link 1 were determined. The impedance parameter values were changed in the ranges given in Table 7, and their combinations amongst themselves were taken into account. The hip abduction–adduction movements were performed in this study for only the passive exercises. The impedance parameter values selected for the *robototherapy* are given in the last column of Tables 6 and 7 for knee and hip extension–flexion movements.

5.1. Passive exercise mode (ROM exercises)

This type of exercise is specifically applied to patients with little or no muscle contraction. The limb of the patient is moved around the ROM with no resistance. The PT inputs the angles of the ROM, the number of repetitions and the movement speed through the GUI. The passive exercises basically require position control. Therefore, the RM makes its moves using the PID position control method for the passive exercises in this system. In this mode, the system works like a CPM device. Since the ROM of the exercise is entered by the PT before the exercise, the RM never exceeds these predetermined ranges. Additionally, the RM has limit switches and the patient and/or the PT can use the emergency stop button at any time to terminate the program.

Fig. 9 provides the experimental result of the passive exercise for the knee, with the extension being 80° , the flexion 20° and the RM's movement speed $20^\circ/\text{s}$. In this figure, the solid lines show

the desired trajectory, while the dashed lines show the actual position of the RM. As shown in Fig. 9, the RM can perform the passive exercises successfully at the designated speed and trajectory.

5.2. Isometric exercise mode

This exercise involves the application of constant resistance to the patient on the ROM (limb angle does not change). In this study, isometric exercise is realized for only the knee. The PT enters a load value (m [kg]) that will be applied to the patient on the ROM through the GUI. This load value can be changed according to the physical situation of the patient. The patient moves his/her limb without applying any resistance. This exercise uses the impedance control method. If the patient's limb reaches the ROM, the position sensors see it. The RM then applies the predefined load (force) by the PT to the limb. The application of constant resistance to the patient's limb is realized according to Fig. 7b for the knee. The gravitational force F_g is given in Eq. (15);

$$F_g = mg \sin \theta_2 \quad (15)$$

where m is the load value that is entered by the PT, g is the gravitational acceleration, and θ_2 is the angle of the knee link. However, in practical application, the mass value of the patient's knee affects F_g . This is why the measured force value differs from the theoretical force value. This difference is shown in Fig. 10 and the necessary explanation is given in the following paragraph.

The required actuator torque that will compensate for F_g on the tip of the foot is given in Eq. (16);

$$\tau = F_g l_{calf} \quad (16)$$

where l_{calf} is the calf length of the patient.

An isometric exercise experiment result for a subject with a weight of 80 kg, a height of 180 cm and a calf length of 55 cm is shown in Fig. 10. This experiment was done with a load effect of 4 kg. The first graph in Fig. 10 shows the position of the subject's limb, the second graph shows the generated forces. The solid lines in this graph show the **desired force** computed using Eq. (15) and the dashed lines show the **force generated by the subject**. The last graph shows the torque values generated by the motor.

The experimental method is as follows: First, the subject moves his/her limb to the extension limit of 70° and waits for the application of counter-resistance by the RM. After 5.25 s, the RM applies a 4-kg load effect. (This value was selected as a test. It can be mod-

Table 7
Hip flexion–extension impedance parameter values.

		Robotherapy			
M_{dx} (kg)	5 and 10	5			
K_{dx} (N/°)	50	50			
D_{dx} (N s/°)	50	50			
M_{dz} (kg)	10 50 75 100	10			
K_{dz} (N/°)	5 50 100	5			
D_{dz} (N s/°)	25 50 75 100	25			

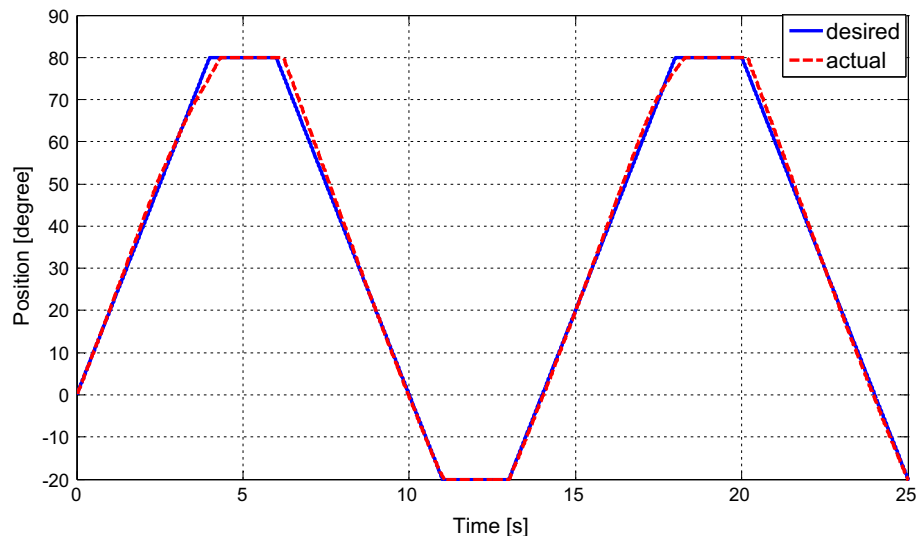


Fig. 9. Knee flexion–extension passive exercise.

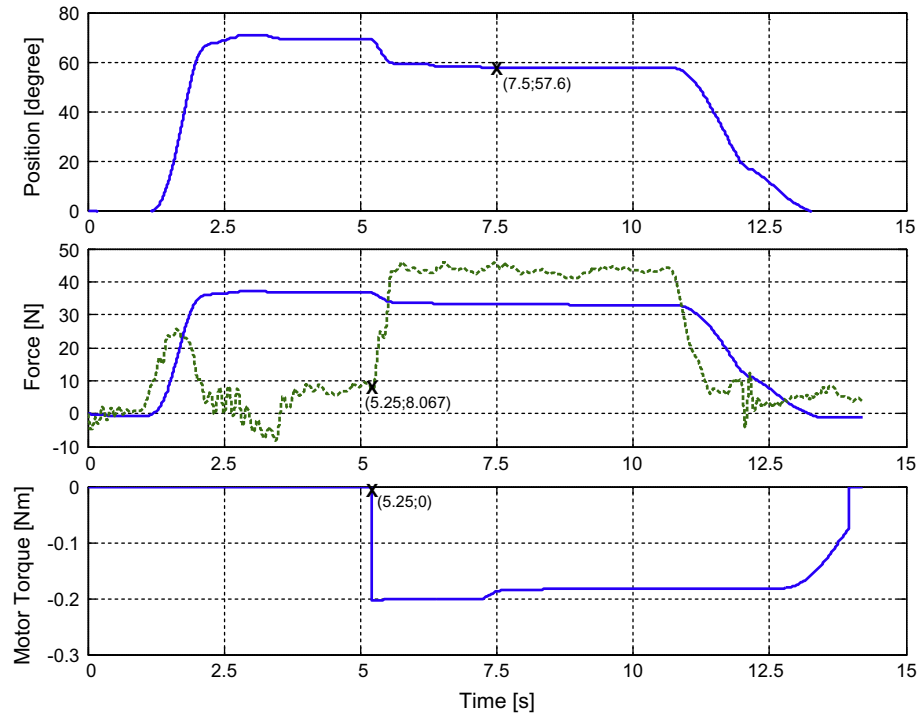


Fig. 10. Isometric exercise for the knee.

ified by the PT for each patient.) to the patient on the ROM. This load value is 33.07 N for 57.6°. Namely, the force value that should be applied to the limb on the ROM is 33.07 N. The subject should generate a force equal to 33.07 N. In order to keep his/her limb in the same position, the subject should generate an equal force.

The force value generated by the subject varies between 40 N and 44 N, as can be seen in Fig. 10. The nearly 7–10 N difference between the force generated by the RM and that which is necessary for the patient to keep his/her limb in the ROM stems from the efforts made by the subject to keep his/her limb in the stationary position. In this system, gravity compensation is realized by impedance control. For the isometric exercises, gravity compensation of the limb is not taken into account because **it is an active exercise**. As seen in Fig. 10, the force generated by the subject before the RM starts generating a torque in the reverse direction for the duration of 5.25 s is 8.067 N. (In this graph, there is a difference between the desired force and the subject's force in the range of 0 and 5.25 s because the RM starts applying the force 2 s after the subject moves his/her limb to the extension limit and stops.)

5.3. Isotonic exercise mode

The isotonic exercise is applied to strengthen patients who suffer muscle contractions. Unlike isometric exercise, a constant resistance force is applied to the patient for the duration of the movement. The RM is controlled using the impedance control, with impedance parameters assigned according to the resistance level to be applied. For the isotonic exercise, four different resistance levels were assigned in cooperation with the PT. These are stated as *low*, *medium*, *high*, and *very high*. The aim of this determination is to obtain different force values that are applied by the system. The counter-force values that are to be applied by the system were determined using experimental methods. Owing to this, the PT has the knowledge about the force values that are applied by the system. If necessary, the force value can easily be increased. In future studies, tests will be done with real patients using these resistance

values under the supervision of a PT. The impedance parameter values to be assigned in a rule-based manner according to the selected resistance level are determined when the PT selects the resistance level using the GUI. These rules are given for the knee and the hip as follows:

For knee flexion–extension:

- 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 $M_d = 10$, $K_d = 100$, $D_d = 1$ >

For hip flexion–extension:

- Rule1 <If Resistance Level is **Low** then $M_{dx} = 10$, $K_{dx} = 50$, $D_{dx} = 50$, $M_{dz} = 10$, $K_{dz} = 50$, $D_{dz} = 25$ >
- Rule2 <If Resistance Level is **Medium** then $M_{dx} = 10$, $K_{dx} = 50$, $D_{dx} = 50$, $M_{dz} = 50$, $K_{dz} = 50$, $D_{dz} = 50$ >
- Rule3 <If Resistance Level is **High** then $M_{dx} = 10$, $K_{dx} = 50$, $D_{dx} = 50$, $M_{dz} = 75$, $K_{dz} = 50$, $D_{dz} = 75$ >
- Rule4 <If Resistance Level is **Very High** then $M_{dx} = 10$, $K_{dx} = 50$, $D_{dx} = 50$, $M_{dz} = 100$, $K_{dz} = 100$, $D_{dz} = 100$ >

5.3.1. Evaluation of experiments on isotonic exercise for knee flexion–extension

The M_d , K_d and D_d parameter values assigned as a result of the isotonic exercise experiments and the force values that emerged as a result of the movement speed are given in Table 7. In these experiments, three different speed levels (slow (16 °/s), moderate (32 °/s), fast (48 °/s)) were used. Table 8 was formed according to the experimental results measured using three subjects. The force values given in Table 8 show the highest approximate force level the RM can apply while the limb moves within the extension and flexion limits. As seen in Table 8, the resistance generated by

Table 8

Parameter values for resistance levels in isotonic exercise for knee flexion–extension.

Level	Parameter			Force (N)					
	M_d (kg)	K_d (N/°)	D_d (Ns/°)	Extension Speed (°/s)			Flexion Speed (°/s)		
				Slow	Moderate	Fast	Slow	Moderate	Fast
Low	4	20	0	8–10	10–13	15–20	17–20	20–22	30
Medium	5	60	0	10–15	21	20–25	23–26	30	40
High	8	40	0	11–18	26–27	30–35	30–45	40–42	50
Very high	10	100	1	23–36	27	40–45	40–50	50–55	55–60

the RM increases parallel to the rise in the impedance parameter values. Additionally, the resistance force shown by the RM expectedly increases when movement speed increases. The reason for the force values in the direction of flexion being higher than extension is due to the effect of the limb weight on the motor torque.

5.3.2. Evaluation of experiments on isotonic exercise for hip flexion–extension

The impedance parameters assigned according to resistance levels at the end of the isotonic exercise experiments and the forces exerted by two subjects on the z-axis in the direction of hip flexion and extension are given in Table 9. These force values show the maximum values measured from subjects. In addition, the net force values generated by the human limb during the flexion–extension movement are also included in the table because the subject generates a certain level of force in order to keep the manipulator balanced at the beginning of the experiment; this force value changes from one subject to another. The counter-resistance force that is generated by the RM is determined when the patient goes through these exercise motions at the relevant parameter values by using these net force values. Consequently, the PT knows the opposite force value that will be generated by the RM. As seen in Table 9, the resistance generated by the RM increases parallel to the rise in the impedance parameter values, as in the knee isotonic exercise.

5.4. Isokinetic exercise mode

The aim of this type of exercise is to facilitate the exercise by countering the maximum resistance and by keeping the movement speed of the patient's limb at a stable level [57]. For this exercise, the PT inputs the movement speed through the GUI. When the exercise begins, impedance control starts operating and the patient moves his/her limb. The movement speed of the limb is continuously tracked by the RM. If the movement speed reaches the speed determined by the PT, an equivalent counter-resistance force is generated for the limb movement by calculating the force value detected by the force sensor. In so doing, the force generated in the reverse direction of the limb helps to maintain the movement speed at the same level, even if the limb accelerates its movement.

Fig. 11 shows the experimental result for the knee flexion–extension isokinetic exercise with Subject I at a speed of 20 °/s. In this figure, the first graphic shows the position of Link 2, the sec-

ond graphic shows the value of force measured from the calf and the third graphic shows the limb speed.

As seen in Fig. 11, after the movement speed reaches 20 °/s, the force value generated by the limb increases while the limb cannot change its movement speed.

The experimental results on the isokinetic exercises performed for the hip flexion–extension movement with Subject I at a speed of 30 °/s are shown in Fig. 12. In this figure, the first plot shows the position of Link 1 (hip position), the second plot shows the force measured from the thigh, and the third plot shows the limb speed. As observed from Fig. 12, the RM has the patient perform an isokinetic exercise by keeping the limb at a stable speed which was specified by the PT. The limb speed oscillates between 31 and 34 °/s. The reason for this 1 to 4 °/s error is that the patient's limb generates a greater force than the counter-resistance generated by the RM.

5.5. Active assistive exercise mode

The active-assistive exercise is a type of exercise performed by the PT. In this type of exercise, the patient moves his/her limb to the extent that s/he is able to move it. The patient is helped to move the limb to the required extent by the RM, which functions like a PT, from the position from where the patient is unable to move his/her limb any further. The patient's limb is moved with the impedance control by the RM to the range of the motion limit and, after this point, the RM moves the patient's limb with the PID position control. Figs. 13 and 14 show the experimental results regarding the active-assistive exercises for the knee and the hip in addition to indicating the force and position differences therein (the left scale belongs to position and the right scale to force data). As seen in these figures, the ROM was selected as 60° for the knee and 30° for the hip in the extension direction. When the value in the force sensor drops below zero, which indicates that the patient has no ability to move any further, the position control algorithm steps in and helps the patient complete the required ROM and brings the limb back to the starting position.

5.6. Robototherapy

The aim of this mode is to learn the action of the PT for each patient and to imitate this behavior in the absence of a PT. The robototherapy has two phases: *teaching mode* and *therapy mode*. The RM

Table 9

Parameter values of resistance levels in isotonic exercise for hip flexion–extension.

Level	Parameter			Force (N)				f_{1znet} (N)	f_{2znet} (N)
	M_{dz} (kg)	K_{dz} (N/°)	D_{dz} (Ns/°)	Extension		Flexion			
				f_{1z} (N)	f_{2z} (N)	f_{1z} (N)	f_{2z} (N)		
Low	10	5	100	50–55	75–78	–5 to –7	5–6	55–62	70–72
Medium	500	50	5	60–63	90–95	–10 to –12	10–14	70–75	80–81
High	500	50	100	75–77	100–105	–10 to –13	15–18	85–90	85–87
Very high	1000	100	5	75–79	105–112	–25 to –27	18–19	100–106	87–93

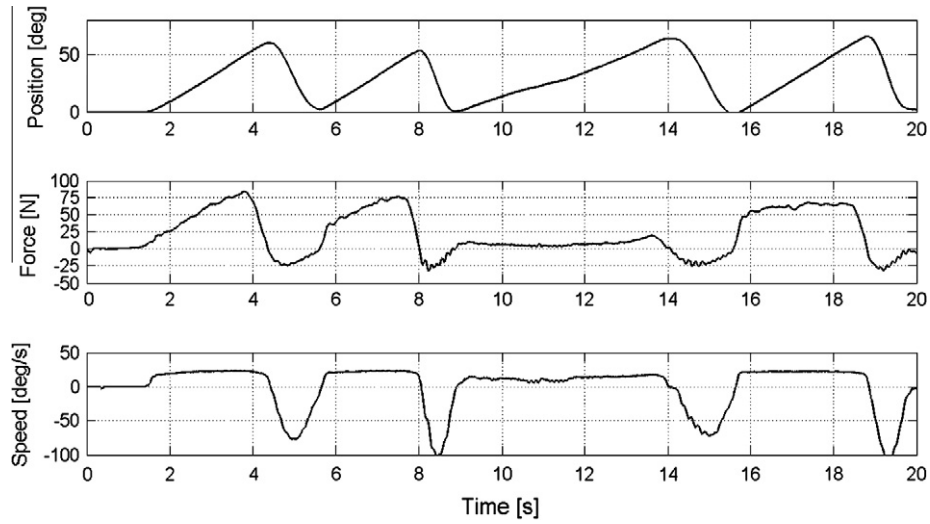


Fig. 11. Knee flexion–extension isokinetic exercise for 20 °/s.

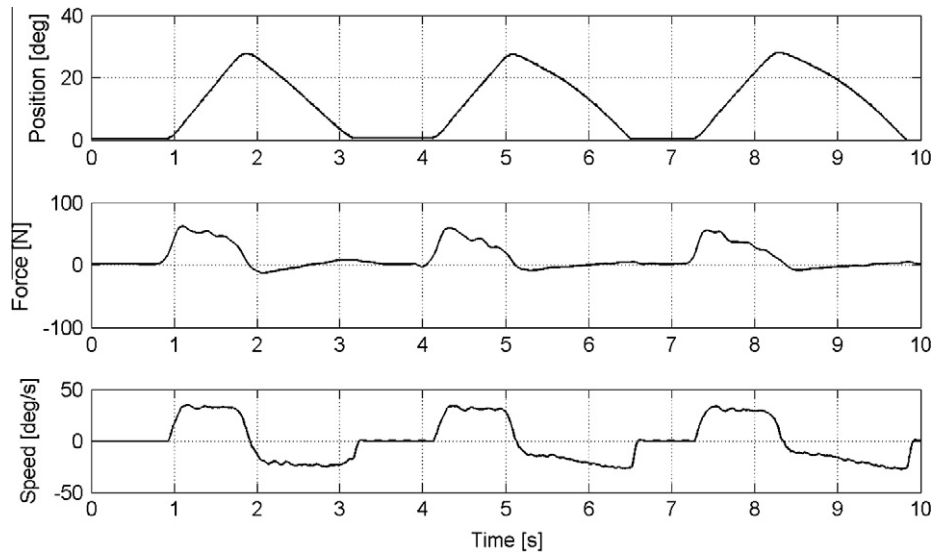


Fig. 12. Hip flexion–extension isokinetic exercise for 30 °/s.

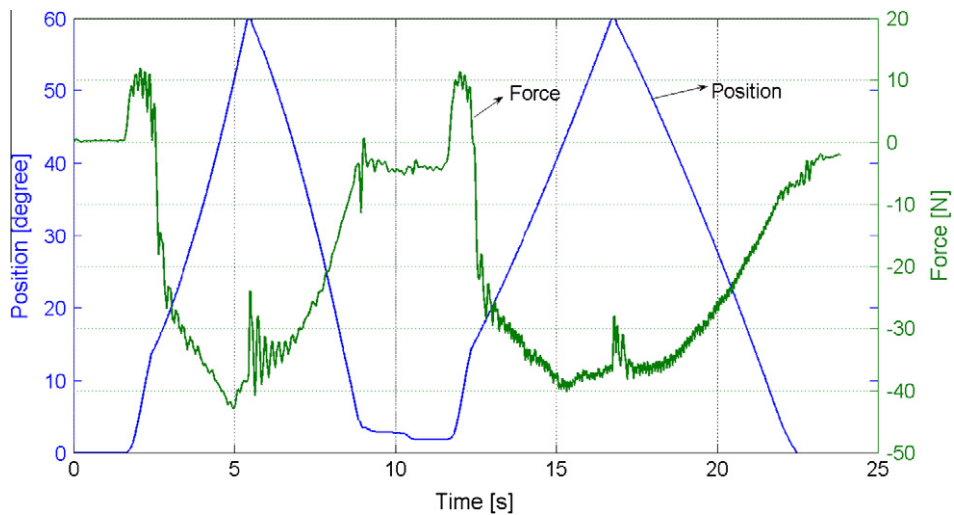


Fig. 13. Knee flexion–extension active assistive exercise (force and position data are shown together).

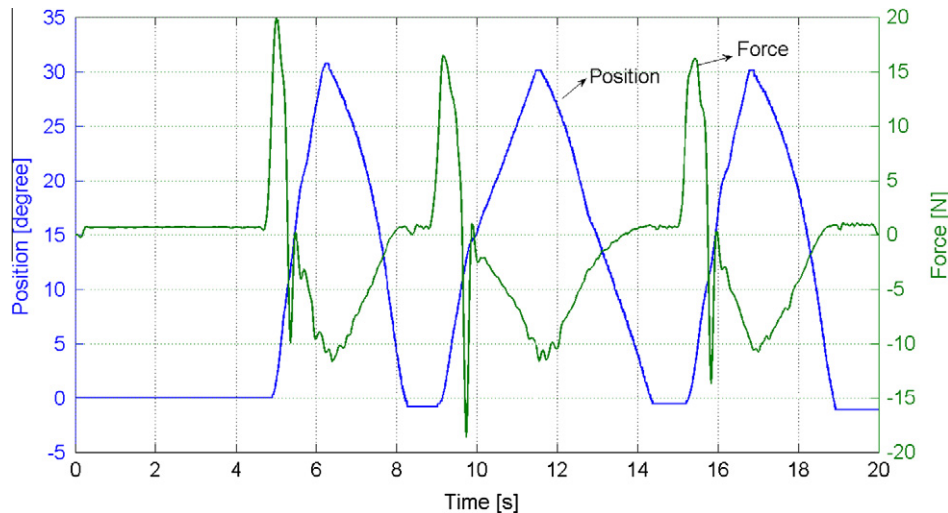


Fig. 14. Hip flexion–extension active assistive exercise (force and position data are shown together).

learns the PT's exercise movement in the teaching mode and performs these exercise movements in the therapy mode.

The PT selects the teaching mode at the start of the rehabilitation session using the GUI. S/he then assists the patient manually to perform the required motion with the RM. The maximum force/position values and time history of force and position data are recorded in the database in real time. These data are used to generate the same behavior by the RM and used in therapy mode to model the PT. For the therapy mode, the PT selects this mode via the GUI. In the *therapy mode*, the RM performs the therapy in the absence of a PT using the force and position data obtained during teaching mode. This data involve the reaction force of the patient that may or may not exist, depending on the kind of disability. Additionally, the therapy mode has two different modes: *direct* and *reactive* therapy. If the patient cannot resist, then the RM forces the patient's knee or hip to move within the limits learned from the PT during teaching mode; this action is called "direct therapy." In direct therapy mode, the RM simply repeats the motion of the PT. The direct therapy mode is applied to all possible movements of the knee and hip. Passive exercises for hip movements are performed with this mode. The aim of reactive therapy is to imitate the PT's *joint open exercise with force*. In this mode, the RM assists the patient to complete the motion. However, if the patient resists the motion, then the RM forces the limb to move up to the limit based on the corresponding desired force and position values stored in the database. Force and position limits are determined by the HMI during teaching mode. The maximum positions and force values of the corresponding data file are used as limit values for the "reactive therapy." In "direct therapy" and "reactive therapy," the RM stops and the position is initialized when the limits of force values are reached. Test results of the robot-therapy mode were published in [45,46].

6. Conclusion

In this study, a therapeutic exercise robot was designed and controlled for lower-limb rehabilitation. The robot manipulator was controlled through a "Human–Machine Interface" that operates on a rule-based control structure combined with impedance control. Manual and active-assistive exercises performed by the PT as well as all other active and passive exercises can be modeled with this interface. It was demonstrated through experiments done on healthy subjects that the RM can perform the necessary exercise movements as well as imitate manual exercises performed by the

PT. The RM can function as both a therapeutic exercise device and as a PT.

Force sensors were used to sense the reactions of the patient in the present study. However, since the patients' EMG (electromyography) signals carry more information than force data about the patient's reaction, our next study will include EMG signals from the patients' muscles as well in reaction force data. In order for PT movements to be fully modeled, it is necessary to determine what impedance parameters are produced as a result of the exercise movements of the PT and the patient's condition. The next study will undertake necessary research in this regard. During the course of the following studies, the RM will be tested in medical centers.

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