Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 911 – 934
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doi:10.3906/elk-1310-50

Upper limb rehabilitation robot for physical therapy: design, control, and testing

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Received: 06.10.2013 • **Accepted/Published Online:** 21.01.2014 • **Final Version:** 23.03.2016

Abstract: In recent years, the treatment process of patients and disabled people who need rehabilitation and physical medicine has become more effective with the use of new devices and developing technology. The rehabilitation robot is one of the most important developments in new technology. The right therapeutic exercises and the objectivity of the evaluation of the range of motion (ROM; generated torque and muscular activation measurement of the patient) are extremely important factors during treatment. In this study, a lower limb rehabilitation robot was modified and controlled for upper limbs. The retrofitted robot system is able to do passive, active, and active-assistive therapeutic exercises. On the other hand, it performs active-assistive exercises using muscular activation. A web-based human machine interface, which can support home-care service, was developed to control the robotic system. This interface includes a performance evaluation unit, which is able to use not only ROM and torque, but also muscular activation of patients for the assessment of therapy results. Thanks to this system, assessment and physical therapy can be realized by a single robotic system for both upper and lower limbs using physical parameters such as ROM, generated torque, and muscular activation of the limbs. Satisfactory performance of the system is observed in the tests performed with a healthy subject.

Key words: Rehabilitation robot, electromyography, human-machine interface, therapeutic exercise, assessment

1. Introduction

Cases of physical disability emerge as a result of hemiplegia, paralysis, muscular diseases, etc. Physical medicine and rehabilitation are the most important treatment methods, because these methods help patients to reutilize their limbs at maximum capacity. Intensive therapies and task-based exercises are very effective treatment forms for the recovery of the motor skills [1]. One of the most important processes of physical therapy requires manual exercises, in which the physiotherapist (PT) and the patient must be in a one-to-one interaction. The goal of the physiotherapist in this process is to help patients achieve normal standards of range of motion (ROM) in their limbs and to strengthen their muscles. The following issues are also noted in physical therapy:

- The number of physiotherapists is lower than the number of patients. This limited number means a ratio of 16 patients per 1 physiotherapist in Turkey [2].
- Difficulties in manual therapy, which needs repeated movements.
- Mechanical and software inadequacies in the current therapy devices.

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- Problems with the objective evaluation of the results and with recording therapy data.
- Problems of the patients regarding their transportation to the therapy centers.

In order to overcome these problems, physical medicine and rehabilitation need new technologies.

The most featured technology in the research and development of rehabilitation technology is the rehabilitation robot. The advantages provided by robots during treatment are outlined below [3]:

- Robots easily fulfill the requirements of the cyclic movements in rehabilitation.
- Robots are able to successfully control the forces applied.
- Robots can record therapy results objectively using their sensors.
- Robots can be more precise regarding the required therapy conditions.

Moreover, a more objective evaluation or measurement can be performed when the robots are compared to a PT. The patients' ROM of the joints and the force or torque value of the limbs can be measured accurately with the help of the sensors; as a result, they can also be recorded with great precision. Furthermore, therapy robots can be operated through web-based interfaces. These features of therapy robots make the home care of patients possible. Home care of patients is important in countries such as Turkey, where the number of sickbeds is insufficient due to the large population. The Ministry of Health has addressed this problem, and since February 2010 the "Featured Home Health Services in the Ministry of Health Guidelines on Procedures and Principles" has been promulgated [4]. Therefore, rehabilitation robots can support the concept of home care services.

The effectiveness of robot-assisted rehabilitation has been shown in previous studies [5–7]. However, the robot-assisted rehabilitation systems are available on the market only in limited numbers. The most important reason is that the costs of these systems are very high. These systems are mostly found in the United States, Japan, and Switzerland, where they are in practical use. The common trait of these countries is their high welfare level. These systems need low-cost production in order to be used in countries with lower incomes. In order to realize this aim, research and development studies in the field of rehabilitation robotics should be spread over a wider range of fields.

Researchers have conducted studies on rehabilitation robots especially in the last 15 years. Some robotic systems are intended for lower and higher extremity rehabilitation. Robots intended for higher extremity rehabilitation are able to accomplish active and passive bilateral and unilateral motor skills training for the wrist, forearm, and shoulder [5,8–12]. MIT-Manus is the most well-known upper limb rehabilitation robot [5]. It was developed for unilateral shoulder or elbow rehabilitation. While the patient is performing a number of tasks, these can be followed on the patient's monitor. MIME is another well-known upper limb rehabilitation robot, developed for elbow rehabilitation using the master-slave concept [9,10]. The movement of the master side of the robot is reproduced on the slave side. Therefore, the healthy side of the subject treats the paretic side. The 2-DOF robot can perform flexion-extension and pronation-supination movements. The Assistive Rehabilitation and Measurement (ARM) Guide is a bilateral rehabilitation system for upper limb rehabilitation using an industrial robot [8]. It assists the patient in following a trajectory. It also supports a basis for the evaluation of several key motor impairments, including abnormal tone, incoordination, and weakness. The GENTLE/s system uses a haptic interface and virtual reality techniques for rehabilitation. The patients can move their limbs in a three-dimensional space with the direction of the robot [11]. In the aforementioned studies,

the positive clinical effects of the robot-assisted rehabilitation were shown. These systems are able to accomplish active, active-assistive, and passive exercises in motor skills training in rehabilitation.

Robots intended for walking training [13,14] and exoskeletal robots [15–19], which also give walking support, are developed by researchers. Moreover, there are robotic systems, which accomplish active, passive, and resistive exercises, that play an important role in lower extremity rehabilitation. Okada et al. developed a 2-DOF robotic system. In this system, the position and force data are received and recorded for the robotic system during the learning phase [20]. The aim of this phase is to learn the PT's movements. In the therapy phase, the robotic system imitates the corresponding motions. MotionMaker (Swortec SA) is a robotic system that can perform fitness exercises with the active participation of the patient with paralyzed limbs [21]. It has position and force sensors, which can work with an electrostimulation device that functions according to patient performance. Bradley et al. developed a 2-DOF autonomous system known as NeXOS [22]. It can perform passive, active-assistive, and resistive exercises for knee and hip extension-flexion movements. Moughamir et al. developed a 1-DOF system, Multi-Iso, used for knee limb and extension-flexion movements [23]. Multi-Iso can perform assistive, resistive, and passive exercises.

The evaluation of the physical therapy process is another important issue for rehabilitation. The response of the patients to the treatment process regarding its mechanical parameters, such as the range of the joint mobility and the force or torque value produced by the limb, as well as other biological parameters, such as electromyography (EMG), are able to make a major contribution to the recording and evaluation of the rehabilitation. In manual treatments, the rehabilitation process is evaluated according to the PT's abilities, and these kinds of assessments are not entirely objective. Simple devices, such as the goniometer and dynamometer, are used for the ROM and for strength measurement. On the other hand, a robotic system is able to provide force, position, and velocity data. These can be used very effectively for the assessment of the rehabilitation process. Therefore, clinicians obtain a ROM, torque generated by the limb, maximum velocity, etc. Even if there is no joint movement, muscle palpation can occur. Therefore, muscular activation should be taken into account in order for a correct and successful evaluation to be made. In order to measure muscular activation, the EMG technique is used [24]. On the other hand, muscular activation must be used as a feedback signal for effective control of the robot manipulator for active assistive exercises.

Recently, a number of studies were performed on rehabilitation robotics and its use in assessment. Bosecker et al. tested the performance of linear regression models in order to predict clinical scores for the upper limbs from robot-based metrics [25]. Guidali et al. developed a new assessment tool for the qualitative measurement of abnormal couplings [26]. Ball et al. designed a 3-DOF upper limb exoskeletal robot manipulator for assessment and physical therapy [27]. Its actuating method is cable-driven. In these studies, classical robot-based metrics were usually used, such as torque, joint angle, etc., whereas muscular activation was not used for assessment.

Briefly, the upper limb rehabilitation systems are developed with respect to motor training skills, such as task-based robots. During these trainings, passive, active-assistive, and resistive exercises are used. In the process of rehabilitation, the measurement and the record of the physical parameters of the patient, such as ROM, generated torque, etc., are especially important. In this respect, the developed robotic systems bring out the results of the evaluation by taking the robot-based metrics. However, the place where the movement occurs is actually the muscles. Therefore, in order to obtain an accurate assessment and control, muscle activation must be considered. The robotic systems developed for rehabilitation are intended to rehabilitate either the upper or the lower limbs. Thus, a system could promote the rehabilitation process in a new and useful way if it

were able to provide an evaluation of ROM, generated torque, and muscular activation of the patient, and also a processing of the rehabilitation of both upper and lower limbs in a single mechanism.

Akdoğan and Adli designed a 3-DOF lower limb therapeutic exercise robot, called Physiotherabot™ [28]. The main purpose of Physiotherabot™ is to learn and imitate PT exercise motions. Additionally, it has a high exercise capacity. It can perform active, passive, and active-assistive exercise motions. Physiotherabot™ uses only robot metrics, such as position and force, to evaluate patient performance during a rehabilitation session [28]. It also uses position and force feedback. However, it does not have a specific performance evaluation unit; instead, evaluation results are performed through the use of simple graphical and numerical values.

In this study, the design modification and control of the Physiotherabot™ for upper limb rehabilitation is analyzed. This modified system is able to make flexion-extension for the forearm and internal-external rotation for the shoulders. It is also able to process isotonic, isometric, and isokinetic exercises, known as active, passive, and active-assistive exercises. It uses muscular activation signals as feedback for active-assistive exercises. Additionally, this system can process isotonic exercises during the movement, and when it stops, the system can process isometric exercises. This feature of the system, which is described as hybrid exercise in this study for the first time, has an important differential role among the other rehabilitation systems. In order to serve in home care therapy, the robot controller was developed in accordance with web-based control. The modified system has a specific performance evaluation unit. It can assess ROM, generated torque, maximum velocity, and muscular activation. The differences between Physiotherabot™ and the retrofitted system are given in Table 1. The Physiotherabot™ rehabilitation capability increased with the modification process performed in this study. Therefore, the difference of this system is that it processes all of the following: rehabilitation of the upper and lower limbs, recording and evaluation of the ROM, and generated torque and muscular activation of the patients, which means the development of a therapeutic robotic system. The exercise types of this system are shown in the experiments made with a healthy subject. The result of the exercises is given in robotic metrics (position and force), and also jointly with the muscle activation signals.

Table 1. Difference between Physiotherabot™ and retrofitted system.

System / Subject	Physiotherabot™	Retrofitted system
Limb	Hip and knee	Elbow and shoulder
Exercise movement capacity	• Flexion-extension for knee and hip • Abduction-adduction for hip	• Flexion-extension for elbow • Internal-external rotation for the shoulder
Feedback types	Force and position	Force, position, and muscular activation
Specific performance evaluation unit	Nonexistent	Existent
Performance evaluation parameters	Force and position	Force, position, and muscular activation
Web-based operating	Limited	Flexible

2. Descriptions for physical therapy and rehabilitation

In this study, the robotic system's mechanical structure is modified as processing flexion-extension for the forearm and internal-external rotation for the shoulder. The extension movement is the extending and opening

of a limb, and the flexion movement is the bending or closing of a limb. The rotation movement is the turning or rotating of a limb [29]. There are 3 types of therapeutic exercises: passive, active-assistive, and active exercises. Active exercises are divided into 3 groups: isometric, isokinetic, and isotonic [30]. The robotic system has a human–machine interface (HMI) that can perform passive, active-assistive, and active (isotonic, isometric, and isokinetic) therapeutic exercises. In rehabilitation, the movements of the exercises are made by considering the results of the manual muscle tests performed by the PT. The classification of the muscle test and the related exercise movements are given in Table 2. The details of the exercise types can be seen in Section 5.

3. System architecture

The system has 4 main elements, which can be seen in Figure 1. The PT is the primary user of the system. The HMI is the main controller of the system. It receives the rehabilitation information from the PT, such as the patient's physical features, therapy mode, duration of therapy, movement type, etc., and provides the therapy results. The therapeutic exercises are realized via position and force control methods. Control parameters are generated and sent to the robot manipulator by the HMI. In addition, the HMI is able to conduct a performance analysis of the patient by using feedback parameters such as ROM, generated torque, and muscular activation. The 2 DOF of the robot manipulator is used for elbow and shoulder rehabilitation (the origin of the robot manipulator has 3 DOF). It is able to perform flexion-extension and internal-external rotation movements for the elbow and the shoulder, respectively. It also moves the patient's limb according to the therapy data. If the patient reacts to the movement, the robot manipulator detects this through sensors, and then it tunes the therapy tone in terms of force and position. The system is able to perform passive, active (isotonic, isometric, isokinetic), and active-assistive exercises. The detailed explanation of the exercise types, robot manipulator, and HMI are given in the following sections.

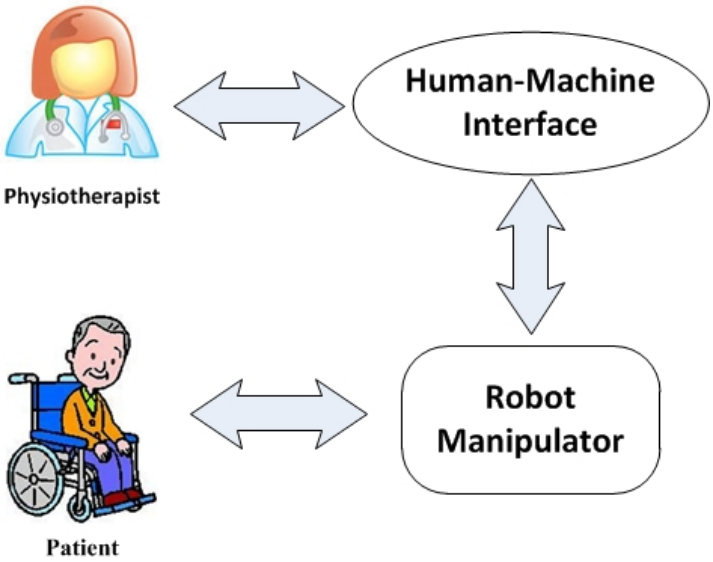


Figure 1. System architecture.

The hardware of the system is shown in Figure 2. The system includes a National Instrument 6024E Multi-function DAQ card for analog-digital data conversion and a National Instrument 6602 8-Channel Counter/Timer card for acquiring position feedback. The sampling time of the system is 1 ms. Force feedback is obtained

through a 6-axis ATI Delta force/torque system. Servo drivers and servo motors with a gear-box are used as actuators. A Kollmorgen AKM31C servo motor was used in this study. Muscular activation is taken via an EMG amplifier and electrodes. In this regard, the DELSYS-Bagnoli-8 EMG system was used.

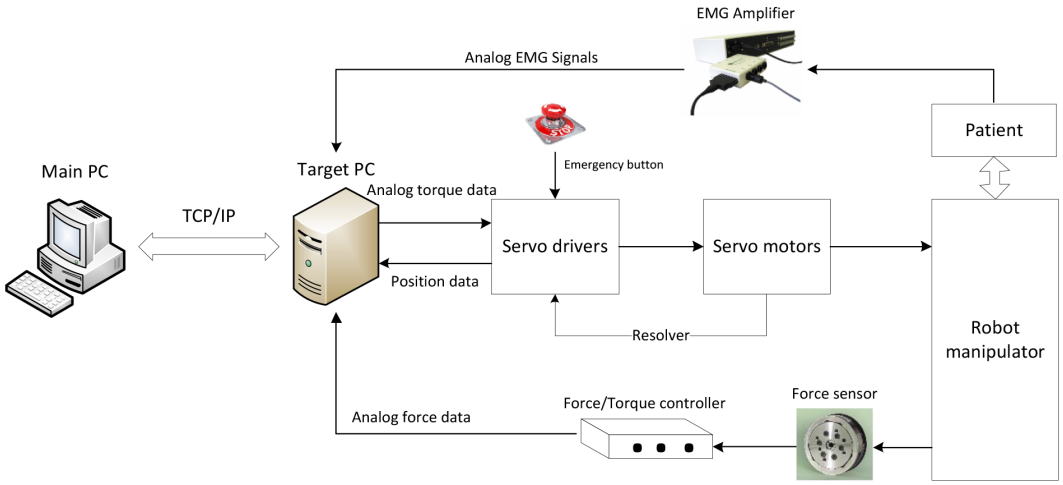


Figure 2. System hardware.

Table 2. Manual muscle test classification and exercise types [31,32].

Class	Description	Exercise type
(0) Zero	Nonpalpation of any spasm	Passive
(1) Very weak	No movement of any joint, but small amount of spasm	Passive
(2) Weak	Muscle spasm; when gravity is removed, the completion of the movement occurs	Active assistive
(3) Moderate	Completion of joint mobility against gravity	Active (no resistance)
(4) Good	Completion of full joint movement against a middle-level resistance and gravity	Active (resistive)
(5) Normal	Completion of full joint mobility against the maximum resistance and gravity	Active (resistive)

3.1. Robot manipulator and mechanical analysis

Physiotherabot^{TM} is a 3-DOF lower limb rehabilitation robot, which was developed by the author [28,33–35]. In this study, the robot was modified in order to perform rehabilitation of the upper limbs. With the new design, a patient is able to perform elbow flexion-extension for the elbow and shoulder internal-external rotation movements for the shoulder. To this end, an apparatus was designed and produced (Figures 3 and 4). The previous and modified version of the robot manipulator is shown in Figure 3 with motion axes.

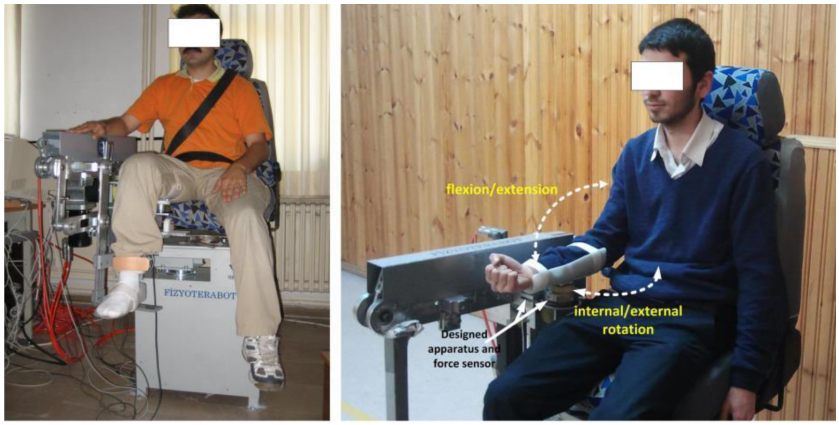
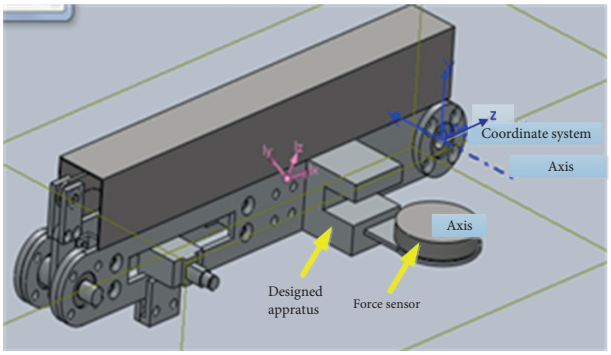
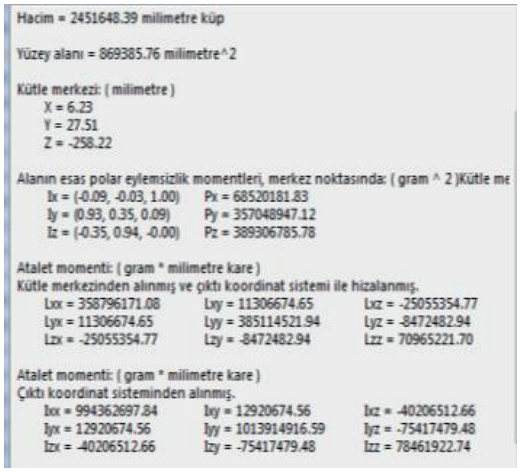


Figure 3. (a) Physiotherabot^{TM} [28], (b) modified version of robot manipulator motions.



(a)



(b)

Figure 4. (a) CAD drawing of robot manipulator link, (b) calculations of inertia and center of mass via 3D CAD software (in Turkish).

In order to obtain a mathematical model for the robotic mechanism, several calculations were made. CAD software was used for inertia and center of mass calculations (Figure 4). In order to calculate body segment masses, a well-known method described by Zatsiorsky and Seluyanov was used in this study [36]. It uses body weight, height, and 3 coefficients, which are described for each body segment (Table 3). Body segment mass (m_i) is given in Eq. (1):

$$m_i = B_0 + B_1.m + B_2.v, \tag{1}$$

where m is the body weight and v is the body height. According to this equation, upper limb mass is calculated as follows:

$$m_{upperlimb} = m_{(forearm)} + m_{(hand)}. \tag{2}$$

Gravity compensation is an important parameter for high accuracy in robotic engineering. For this purpose, mechanism weight and the effect of the human body segments on the gravity torque are taken into account in the system. The center of the mass of human body segments was obtained from [36].

$$\tau_{gravity} = \tau_{Link} + \tau_{upperlimb}, \tag{3}$$

$$\tau_{upperlimb} = (r_{hand}.m_{hand+}r_{forearm}.m_{forearm}).g.sin\theta, \tag{4}$$

$$r_{hand} = l_{hand} \times 0.51 + l_{forearm}, \tag{5}$$

$$r_{forearm} = l_{forearm} \times 0.43, \tag{6}$$

where $\tau_{gravity}$ is the total gravity torque, τ_{Link} is the gravity torque of link, $\tau_{upperlimb}$ is the gravity torque of the upper limb, θ is the limb angle, r_{hand} is the distance between the center of the mass of the hand and the rotational point, m_{hand} is the mass of the hand, $r_{forearm}$ is the distance between the center of the mass of the forearm and the rotational point, $m_{forearm}$ is the mass of the forearm, l_{hand} is the length of the hand, $l_{forearm}$ is the length of the forearm, and g is the gravitational constant.

Table 3. Body segment coefficients.

Segment name	B_0[kg]	B_1	B_2[kg/cm]
Hand	–0.1165	0.0036	0.00175
Forearm	0.3185	0.01445	–0.00114
Upper arm	0.25	0.03012	–0.0027

Total inertia of the system is given in Eqs. (7) and (8):

$$I = I_{mechanism} + I_{upperlimb}, \tag{7}$$

$$I_{upperlimb} = I_{hand} + I_{forearm}, \tag{8}$$

where I is total inertia, $I_{mechanism}$ is inertia of the robotic mechanism, $I_{upperlimb}$ is the inertia of the limb, I_{hand} is the inertia of the hand, and $I_{forearm}$ is the inertia of the forearm. The inertia of body segments was determined using [37]. According to [37], the inertia of the hand and forearm is as follows:

$$I_{hand} = (134.m - 2599).10^{-7} + m_{hand}.r_{hand}^2, \tag{9}$$

$$I_{forearm} = (1397.m - 26562).10^{-7} + m_{forearm}.r_{forearm}^2. \tag{10}$$

3.2. Human–machine interface

A HMI controls the entire system. All communications between system units are provided through the HMI. A block diagram of the HMI is shown in Figure 5.

The HMI consists of 6 units. The information concerning these units is given below.

Main controller: This is the main control unit of the HMI. Communication among all units is made via this unit.

GUI (graphical user interface): The physiotherapist enters the data of the patient, the exercise types, and the parameters via the GUI. Afterwards, this information is sent to the main controller. The PT follows the data about the results of the treatment via this unit.

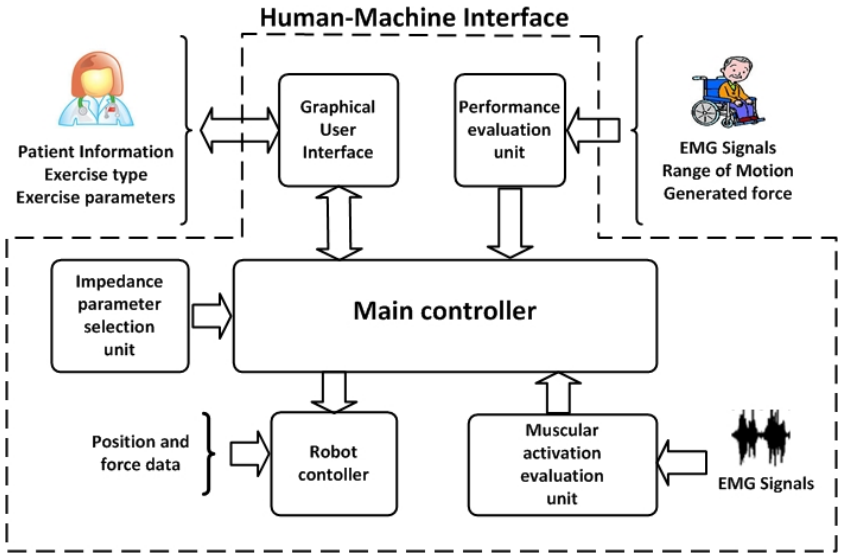


Figure 5. Human–machine interface block diagram.

Robot controller: This unit consists of the algorithms that establish the control of the robot during the exercises. In this system, the proportional-integral-derivative (PID) control method is used for the exercises requiring the position control, and the impedance or direct torque control methods are used for the exercises requiring the force control. Since the active-assistive exercises need both the position and the force controls, they are used with PID and impedance control through the switching method. On the other hand, force, position, and muscular activation feedback data coming from sensors are evaluated by this unit in order to realize force and position control. The choice of the control methods is processed by the main controller. The details of the control methods are given in Section 4.

Impedance parameter selection unit: The impedance control method is used in the isometric, isotonic, and active-assistive exercises. In the isotonic exercises, different resistance levels are achieved by the shifting of the impedance parameters. The isometric and isotonic exercises are performed by the system in one operation mode. This process is realized in such a way that the patient moves his limbs and creates resistance in the opposite direction of the limb. Namely, the patient performs the isotonic exercise. When the limb reaches the boundary of the ROM, the system generates a fixed force effect. This effect is referred to as the isometric exercise. Isotonic and isometric exercise levels are selected by the PT from the GUI before the exercise session. In comparison to other robotic systems, this is an innovative feature of the system. In the active-assistive exercises, the lowest impedance parameter values, which do not lead to system instability, are used during the active movement of the patient. The main control unit sends the impedance parameter values (to the kind of the exercise by means of the rules made in the impedance parameter selection unit) to the robot controller.

Muscular activation evaluation unit: This unit processes the muscular activation signals (EMG). In order to realize this process, the EMG signals are sampled, amplified, and filtered according to ISEK standards [38]. The sample frequency is chosen as 1 kHz. These signals are filtered by a 10-Hz Butterworth low-pass filter. The muscular activation level (MAL) is one of the performance evaluation parameters of the patient. The muscular activation level is defined in Eq. (11) [39]:

$$MAL\left(t\right)=\frac{1}{L}\sum_{i=1}^{L}\frac{EMG_i\left(t\right)-EMG_i^{rest}}{EMG_i^{\max}-EMG_i^{rest}}, \tag{11}$$

where L is the number of pairs of electrodes, $EMG_i\ (t)$ is sampled signals (i = 1, 2,..., L), EMG_i^{rest} is the mean value of $EMG_i(t)$ while the resting position of the limb is maintained, and $EMG_i^{\max}$ is the mean value of $EMG_i(t)$ while the maximum voluntary contraction is provided.

During the active-assistive exercise, when the muscular activation level of the patient reaches the level of the completion of the movement, the case is determined by the muscular activation level, and then the robot manipulator leads the patient to complete the movement.

Performance evaluation unit: This unit evaluates the therapeutic performance of the patient. The mechanical and biologic parameters are obtained via sensors. In this regard, the EMG signals, muscular activation level, joint angle, generated torque, and velocity parameters are measured or computed. These parameters have 3 different values [40]:

- instant value depending on time;
- time average value for each trial;
- ensemble average value for all trials.

The instant value of these parameters reflects the patient's performance depending on session duration, whereas their average value reflects the patient's performance for each session. The ensemble average value for all the trials of one day can be used for evaluating the training effects. Therefore, the daily, weekly, and monthly performances of the patient can be followed. These parameters are evaluated with 2 different versions: patient index and error index. The patient index reflects the performance of the patient. The error index shows the differences between patient performance and commands from the system. All parameters can be tracked by the PT through the GUI. The equations of the related indexes are given in Tables 4 and 5.

4. The control of the robot manipulator

In the control of the robot manipulator, two control methods are generally used. These methods are impedance control for the exercises requiring force control, and PID control for the exercises requiring position control. The PID control rule is given in Eq. (12):

$$\tau = K_p\theta_e + K_i \int \theta_e dt + K_d\dot{\theta}_e, \tag{12}$$

where θ_e is the difference between the desired and the actual positions, and K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. The PID position control is especially used in the passive and active-assistive exercises. The PID position control is responsible for monitoring the predefined trajectory of position in the passive exercise. In addition, it moves the patient's limb to the limit of the ROM when he/she cannot carry his/her limb in the active-assistive exercise.

The impedance control, developed by Hogan, is aimed at the adjustment of the mechanical impedance of the robotic arm's end-effector [41]. It is known as the most effective control method in interactive human–robot systems and in rehabilitation robots [28]. In the system, the impedance control is used in the active-assistive, isotonic, and isometric exercises. The impedance control has been processed in different forms by researchers. In this study, Yoshikawa's force-based impedance control model is taken as the reference [42]. In this regard, the torque equation is given in Eq. (13):

Table 4. Patient index parameters.

Parameters	Type	Value	Equation
Biological parameter index	EMG pattern index	Instant value of EMG for kth trial	$EMG_i{}^t(n)$
		Time average value for each trial	$EMG_{mean}^k = \frac{1}{N.T_s}\sum_{k=1}^{K} EMG_i^k(n)$
		Ensemble average value for all trials	$EMG_{ens} = \frac{1}{K}\sum_{k=1}^{K} EMG_{mean}^k$
	Muscular activation level	Instant value of MCL	$MAL^k(n) = \frac{1}{L}\sum_{i=1}^{L} \frac{EMG_i^k(n) - EMG_{rest}^k}{EMG_{max}^k - EMG_{rest}^k}$
		Time average value for each trial	$MAL_{mean}^k = \frac{1}{N.T_s}\sum_{k=1}^{K} MAL^k(n)$
		Ensemble average value for all trials	$MAL_{ens} = \frac{1}{K}\sum_{k=1}^{K} MAL_{mean}^k$
Biomechanical parameter index	Joint angle (Θ^k) / Generated torque (τ^k) / Velocity (V^k)	Instant value of parameter for kth trial	P^k(n)
		Time average value for each trial	$P_{mean}^k = \frac{1}{N.T_s}\sum_{k=1}^{K} P^k(n)$
		Ensemble average value for all trials	$P_{ens} = \frac{1}{K}\sum_{k=1}^{K} P_{mean}^k$

n: sample number, n = 1,2,…,N; k: trial number, k = 1,2,…,K; i: electrode number, i = 1,2,…,L; T_s: sampling time.

Table 5. Error index parameters.

Parameters	Type	Value	Equation
Biological parameter index	Muscular activation level	Instant value error of MAL	$MAL_e(n)$=$MCL^k(n) - MAL_{comm}^k$
		Mean square error for all trials	$MSE_{musc} = \frac{1}{K}\sum_{k=1}^{K}(MCL_e)^2$
Biomechanical parameter index	Joint angle (Θ^k) / Generated torque (τ^k) / Velocity (V^k)	Instant value error of parameter for kth trial	P^k(n)- P_{comm}^k
		Mean square error for all trials	$MSE_{mech} = \frac{1}{K}\sum_{k=1}^{K} E_{mech}^k$

n: sample number, n = 1,2,…,N; k: trial number, k = 1,2,…,K; i: electrode number, I = 1,2,…,L; T_s: sampling time; *comm*: command; *e*: error; *musc*: muscular; *mech*: mechanical.

$$\tau = \mathbf{h_N}(\mathbf{q},\dot{q}) - \mathbf{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q})\dot{J}_\mathbf{y}(\mathbf{q})q - \dot{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q})\mathbf{M_d^{-1}}(\mathbf{D_d}\dot{y}_\mathbf{e} + \mathbf{K_d y_e}) +$$

$$\left[\mathbf{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q})\mathbf{M_d^{-1}} - \mathbf{J_y^T}(\mathbf{q})\right]\mathbf{F_{ext}}, \tag{13}$$

where τ is the torque matrix; $\boldsymbol{h_N}$ is Coriolis effect, the centrifugal force, and other effects; $\boldsymbol{q}$ is the joint angle matrix; $\boldsymbol{J_y}$ is the Jacobian matrix; $\boldsymbol{M(q)}$ is the inertia matrix; $\boldsymbol{M_d}$ is the desired inertia coefficient matrix; $\boldsymbol{K_d}$ is the desired stiffness coefficient matrix; $\boldsymbol{D_d}$ is the damping coefficient matrix; $\boldsymbol{y_e}$ is the position error; and $\boldsymbol{F_{ext}}$ is the external force. According to Eq. (13), the impedance control rule of a degree of freedom manipulator, shown in Figure 6, is given as follows:

$$\tau = \tau_{gravity} - \frac{I.n}{L_g.M_d}(D_d\dot{\theta}_e + K_d\theta_e) + \left(\frac{I.n}{L_g.M_d} - L_g\right)F_{ext}n \tag{14}$$

where $\tau_{gravity}$ is the gravity torque, I is inertia, θ_e is the position error, F_{ext} is the external force, n is the gear ratio, and L_g is the distance from the center of the mass.

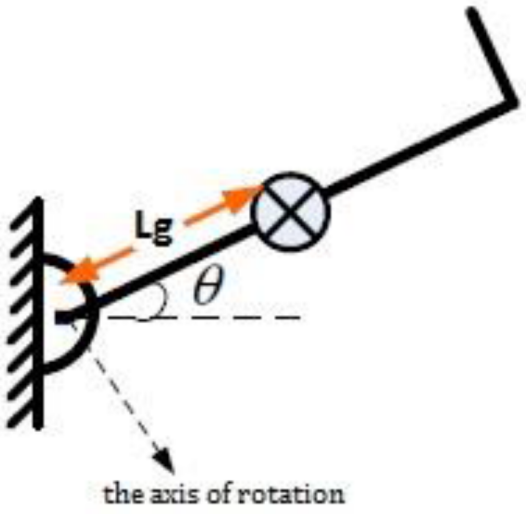


Figure 6. Robot manipulator with 1 DOF.

5. Results

In order to demonstrate the system performance, some experiments are conducted with a healthy subject, aged 23 years. In these experiments, the control algorithms developed for the exercise types are tested for elbow flexion-extension movements. During the experiments, the results of the measure are obtained by the force and position sensors, which are on the robot, and by EMG electrodes mounted to the experimental subject's upper limbs. Three pairs of electrodes were mounted to the subject's limbs. As can be seen in Figure 7, these electrodes were positioned on the biceps brachii (Channel 1 for elbow flexion), brachioradialis (Channel 2 for elbow extension), and triceps brachii (Channel 3 for elbow extension).

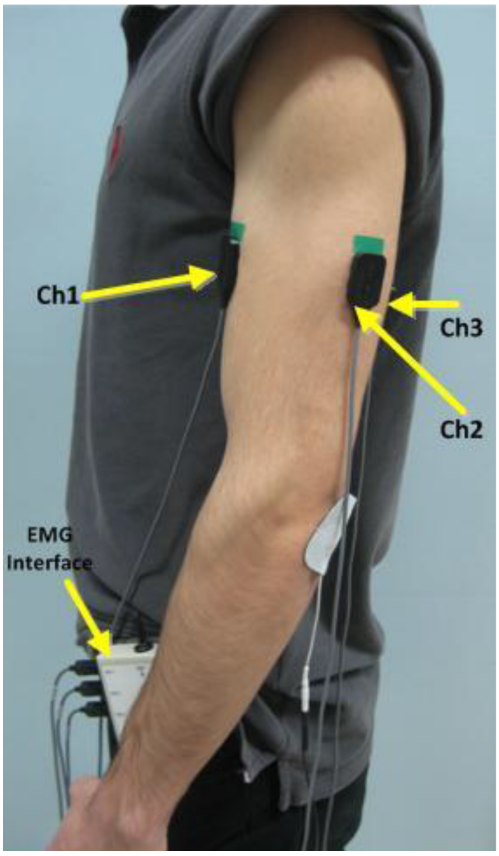


Figure 7. EMG electrode positions.

5.1. Range of motion (passive) exercises

The passive exercises are processed in the motion range of the joint without any resistance. This is done in order to protect the flexibility and the motion of the joint. In the system, these exercises are made by the PID position control. The required parameter values for the exercises, such as velocity, repetition number, and motion range of the joint, are determined by the PT. The optimum parameter values in the design of the PID controller are determined as $K_p = 0.8$, $K_i = 0.001$, and $K_d = 0.1$ using the simple trial and error technique. The step response of the system to these values is given in Figure 8. According to this figure, the steady state error is 2.79 degrees. This error is acceptable within the norms of physical therapy.

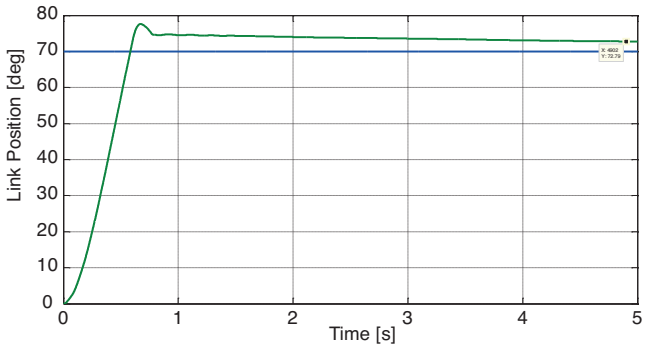


Figure 8. Step response of PID controller.

The results regarding the sinusoidal motion trajectory devised for the passive exercises and tracking by the system are given in Figure 9. In the graphics, the position error of the system is given. Hence, the system can follow a 2-degree error in the direction of the extension and a 1-degree error in the direction of the desired trajectory. In Figure 10, the EMG signals' accordance with the channel number for the passive exercises is given. According to this, the amplitude of the EMG signals in the passive exercises averages 0.1 mV. This value is the lowest signal level compared to the active exercise EMG signals.

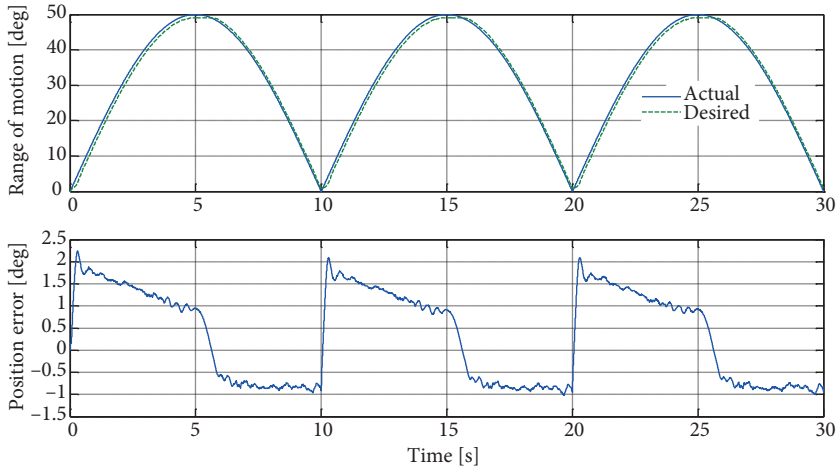


Figure 9. Passive exercise.

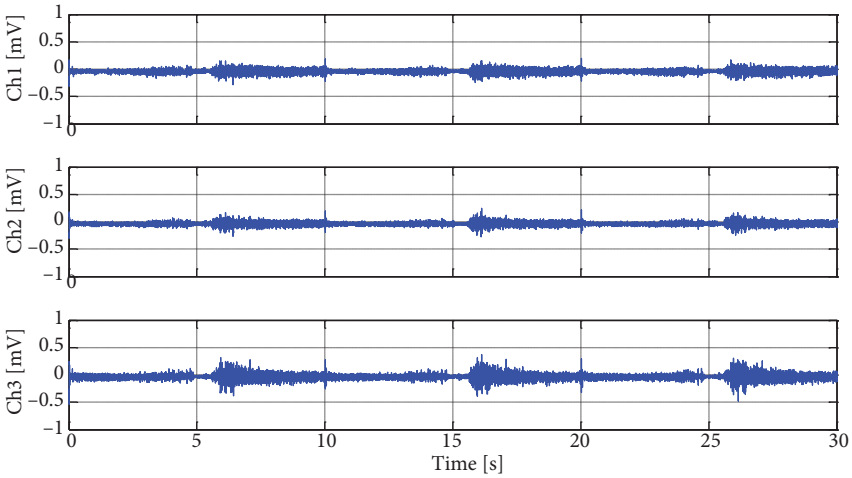


Figure 10. EMG signal during passive exercise.

5.2. Active assistive exercise

In the active-assistive exercise, the patient moves his limb by himself until the present motion range of the joint. After this point, he completes the movement with the help of the PT. Muscle contraction can occur despite the occurrence of the joint motion. Therefore, muscular activation-controlled active-assistive exercise is required for the realization of a more effective treatment. The author used the force feedback method for the active-assistive exercise in previous studies [28,33–35]. In these studies, he mentioned that evaluating muscular contraction is necessary for effective treatment. The author proposed a human-machine interface, developed on the basis of the evaluation of muscular activation for a lower limb rehabilitation robot in another of his studies [43].

Due to the reasons set forth above, muscular activation has been used in order to realize active-assistive exercises in this study. To this end, an algorithm has been developed for two different scenarios, which are required by the active-assistive exercise. The first scenario is that the patient can carry his limb but cannot move it, and a muscle contraction occurs. Force feedback cannot be used for the first scenario, so the use of EMG is necessary. The second scenario is that the patient cannot carry his limb and his muscular contraction is not at a sufficient level. In the event of these scenarios, the behavior of the system is as given in Figure 11.

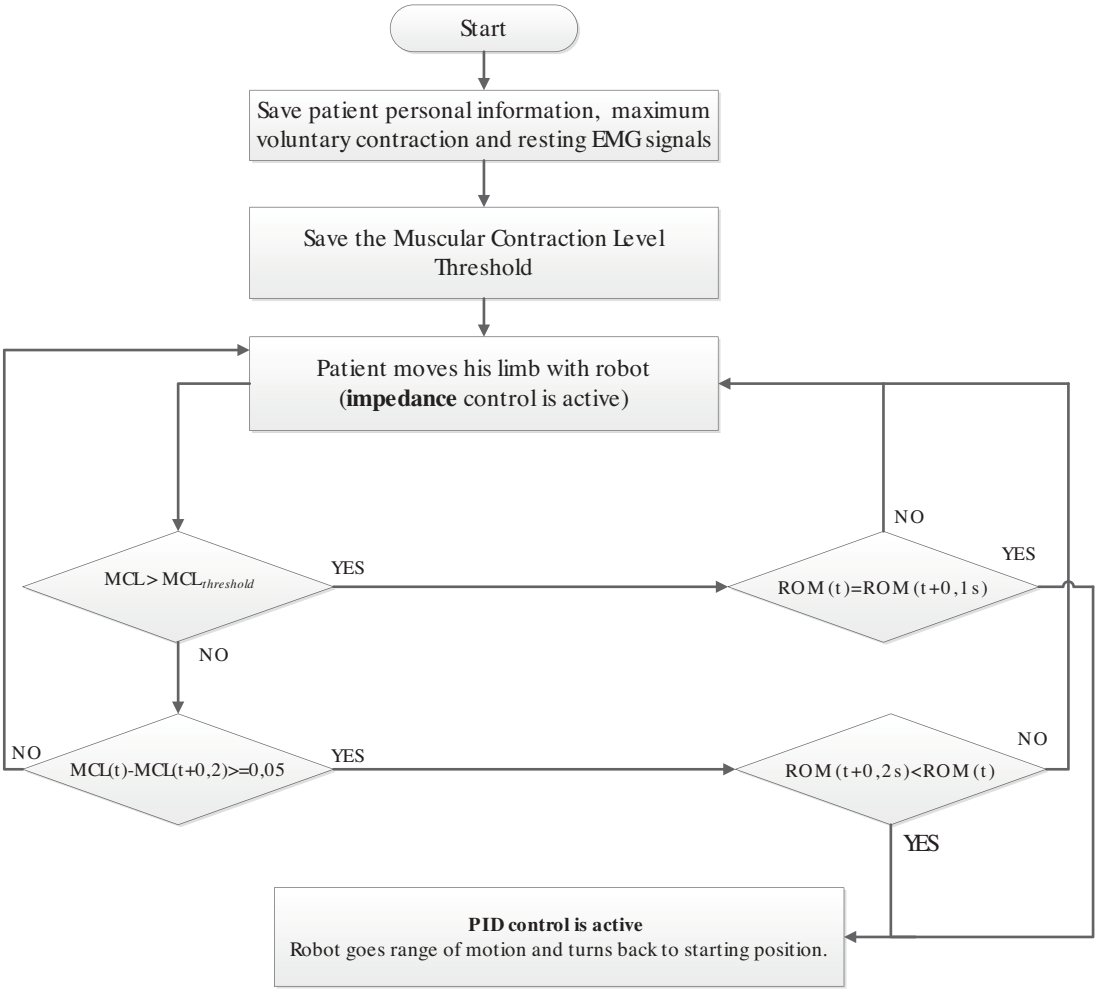


Figure 11. Algorithm of active-assistive exercise.

In Figures 12a and 12b, the test results of the active-assistive exercise are given with respect to the 2 different scenarios mentioned above. In Figure 12a, the first scenario shows the conduct of the robot manipulator in the case of occurrence of muscular contraction, although the joint movement does not happen.

5.2.1. First scenario

The muscular activation level at the 6.884th second is observed as 30.5%. This observed level exceeds the threshold of the muscular activation level, which is 30.487% on the individual's learning phase. While the position data taken from the encoder at the 6.884th second are at the degree of 26.49, 100 samples (0.1 s) before, that is to say at the 6.784th second, they are also at the degree of 26.49. Thus, no change in the position

can be observed. As a result of the algorithm, when the angle change is smaller than 0.5 degrees and the muscular activation level exceeds the threshold level, the manipulator comes into play; by doing so, the patient can complete his/her movement. The related values are highlighted in the figure.

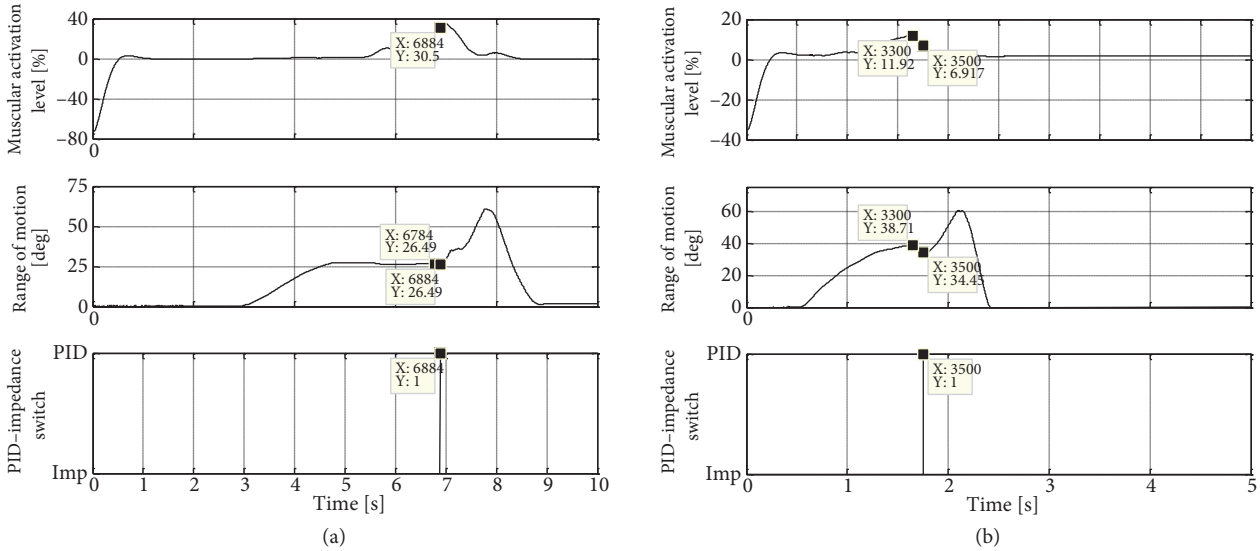


Figure 12. Active assistive exercise results: (a) scenario 1, (b) scenario 2.

In Figure 12b, the second scenario shows the conduct of the robot manipulator in the case when the muscular contraction is not at a sufficient level and the patient is not able to carry his/her arm.

5.2.2. Second scenario

There is a 5% decline in the muscular activation level between second 3.5, in which the muscular contraction level is 6.917%, and 200 samples (0.2 s) earlier, second 3.3, when the muscular activation level is 11.920%. The position at second 3.5 is at 34.45 degrees, and at second 3.3 it is at the degree of 37.86. Hence, the robot arm moves in the negative direction. The occurrence of decline in the muscular activation level and of movement in the direction of the closure in the limb's range of motion lead the robot manipulator to come into play in accordance with the algorithm. As a result of the robot manipulator, the patient can complete his/her movement. The related values are marked in the figure.

According to the test results, the robot manipulator can be controlled via muscular activation. By using this method, the active-assistive exercise can be modeled successfully.

5.3. Isotonic exercises

The isotonic exercises are also known as progressive resistance exercises. In these kinds of exercises, the resistance is kept stable while the velocity of the movement changes. With these exercises, the ability of the muscle to carry resistance is increased [44]. In the system, this kind of exercise is generated by different resistance levels and is achieved through the change of the impedance parameter values. The impedance parameter values suited to the resistance levels, which are chosen by the PT with the GUI, are taken by the main controller from the impedance parameter selection unit and then are sent to the robot controller. These parameter values are suited to the resistance values and are given in Table 6. In the 0–90 degree range of the motion, the average reverse force value produced by the system according to the chosen resistance level is as given in Table 7. As seen in

Tables 6 and 7, when the numerical values of the impedance parameters increase, the reverse resistance value of the system also increases. The EMG signals, together with the force and position values of the forearm flexion-extension movement regarding the isotonic exercise levels, are given in Figures 13–16. As seen in these figures, when the resistance level is increased, the joint force generated by the limb also increases. Concordantly, the activation in the muscle signals also increases.

Table 6. Parameter values.

Resistance level	Impedance parameter		
	M [kg]	K [N/deg]	D [Ns/deg]
Low	0.02	1	0.05
Medium	0.02	5	0.1
High	0.03	6	0.04
Very high	0.03	10	0.03

Table 7. Average opposite force values.

Resistance level	Ratio [N/deg]
Low	0.803640
Medium	0.971757
High	1.158597
Very high	1.438636

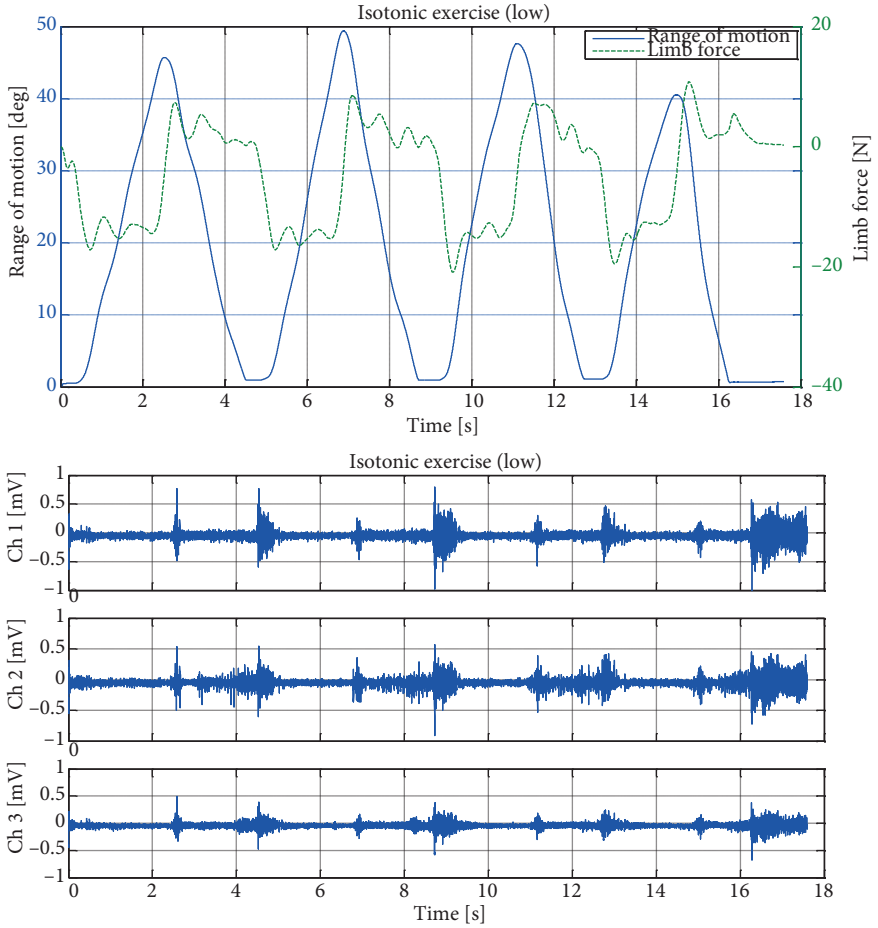


Figure 13. Isotonic exercise (low level).

5.4. Isometric exercise

Isometric exercise is performed against a fixed resistance without change of motion range [30]. This exercise is realized through the occurrence of a fixed load effect at the ROM in the system. The patient smoothly moves his limb with the impedance control. A fixed load value such as 2.5 kg entered by the PT with the GUI is applied

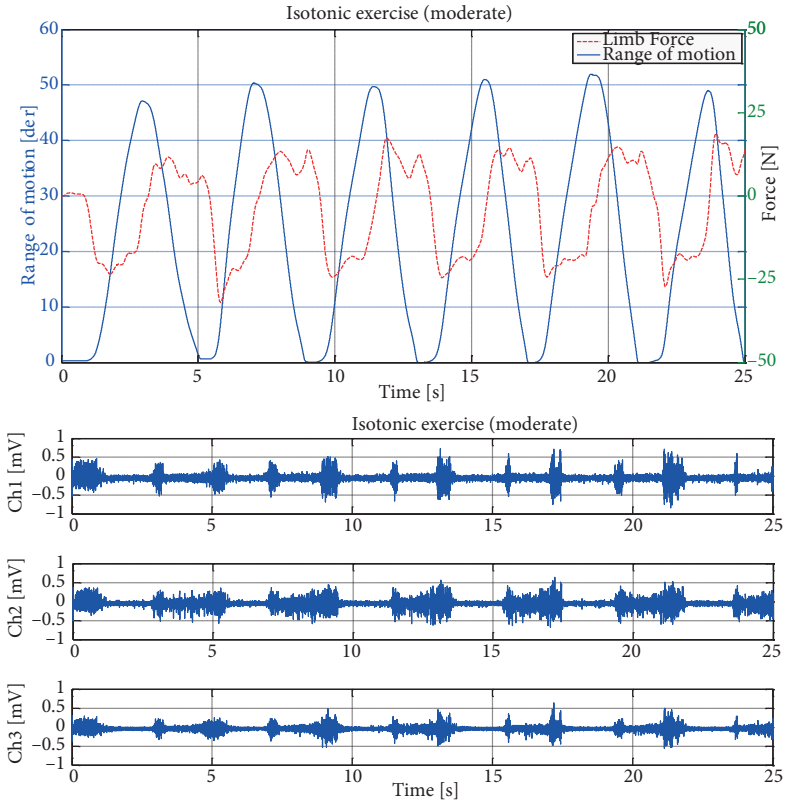


Figure 14. Isotonic exercise (moderate level).

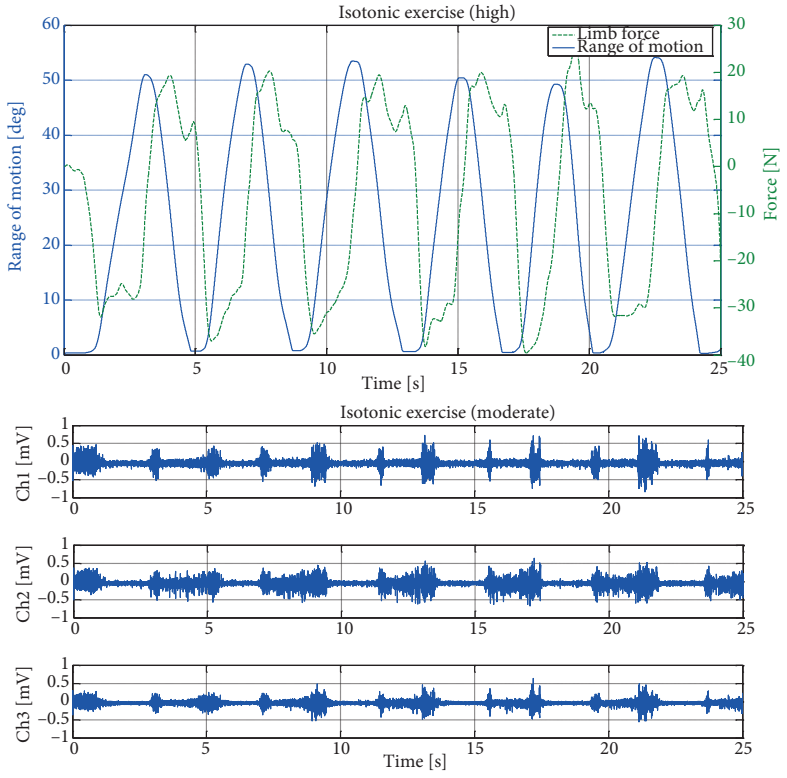


Figure 15. Isotonic exercise (high level).

to the patient's limb when he stops his limb movement. The force value generated by the robot manipulator is calculated by the HMI according to Eq. (15):

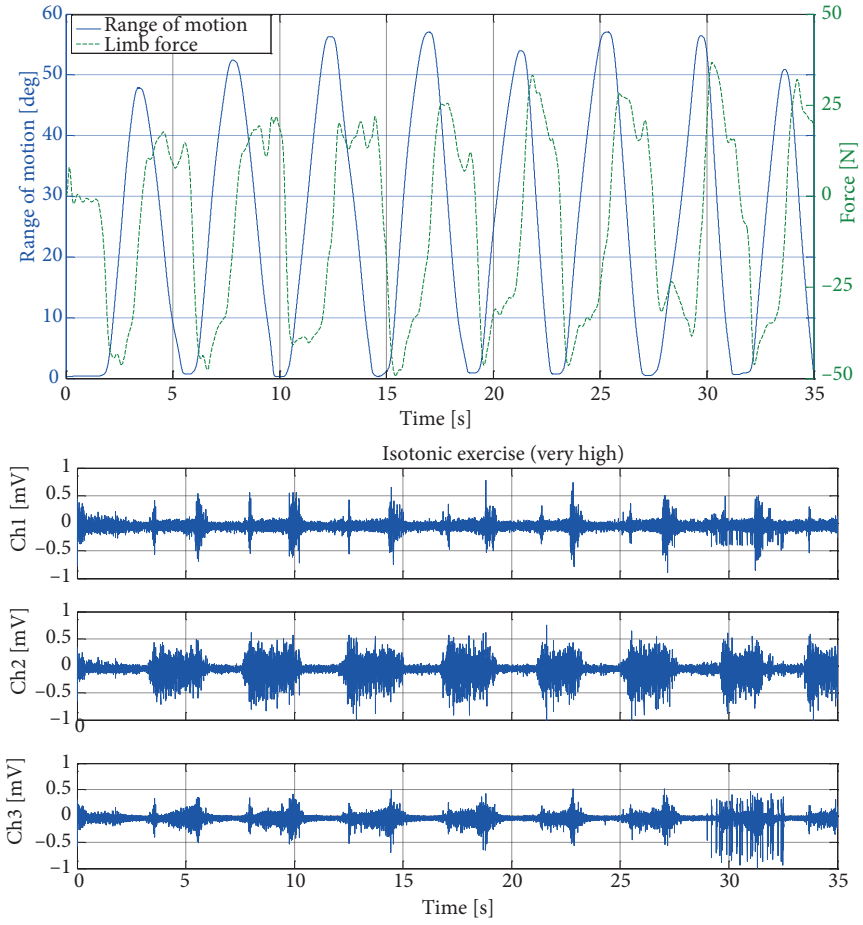


Figure 16. Isotonic exercise (very high level).

$$F_{load} = m.g.sin\theta, \tag{15}$$

where m is the load effect (mass), g is the gravitational force constant, and θ is the robot manipulator angle. The direct torque control method is used for the fixed load effect.

The exercise results of the isometric exercise for 2.5-kg load effect are given in Figure 17. The system moves the limb of the patient and stops it at approximately 27 degrees. One second (predetermined value) after this point, the robot manipulator starts to apply the force in the opposite direction. In the last image of Figure 17a, the motor voltage is given. As from second 3.15 (shown with a black square block in the figure), constant voltage is applied to the motor. As seen in the joint force graphics, after second 3.15, the force applied to the limb of the patient rapidly increases. As can be seen in Figure 17b, at this time the muscular contraction suddenly increases.

5.5. Isokinetic exercises

Isokinetic exercise is a resistance exercise performed at a fixed speed [30]. This technique was invented in the 1960s, and its main goal is to obtain the maximum muscular effort from the limb through a full range of motions.

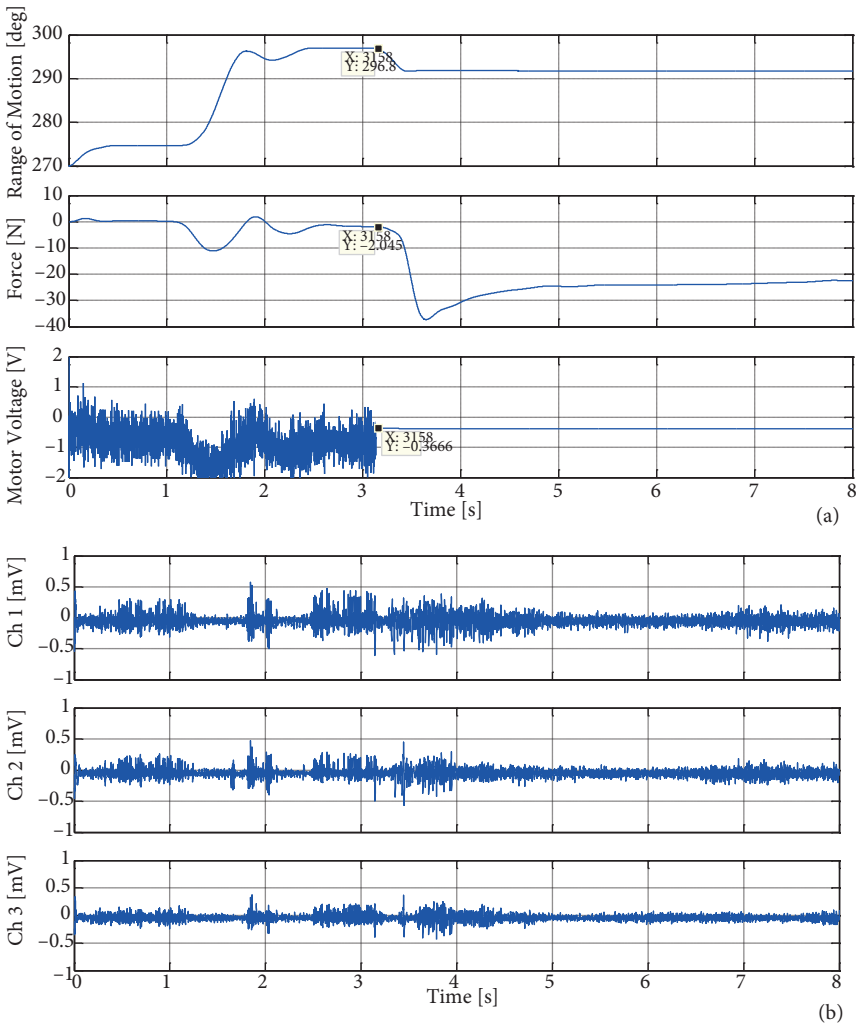


Figure 17. Isometric exercise for 2.5-kg load affect: (a) (from top to bottom) range of motion, limb force, and motor voltage; (b) EMG signals.

This type of exercise is usually applied to athletes. This exercise is carried out in the system as follows: a fixed speed value is entered by the PT, the person moves his limb, and, at the same time, the impedance controller controls the manipulator. When it reaches a fixed speed value, a torque value equaling the torque generated by the limb is produced in the opposite direction by the system. In this manner, a constant limb speed is obtained. In Figure 18, the results of the isokinetic exercise are given for a ratio of 30 degrees per second. As seen in Figure 18a, while the position is increasing, the velocity of the joint remains stable. As the joint force increases in the direction of the flexion, the force in the direction of the extension is lower. The oscillation in the velocity signal on the 30 degrees/second scale takes place due to the mechanical vibration. The amplitude of these vibrations is in the lower levels; thus, they cannot be felt by the patient during the exercise. The present regularity in the position sign shows this fact. The increase of the muscle signals during the movement in the direction of the flexion and the increase of the force can be clearly seen. On the other hand, as can be seen in Figure 18b, muscular activation increases in Channel 1 for extension and Channel 2 for flexion.

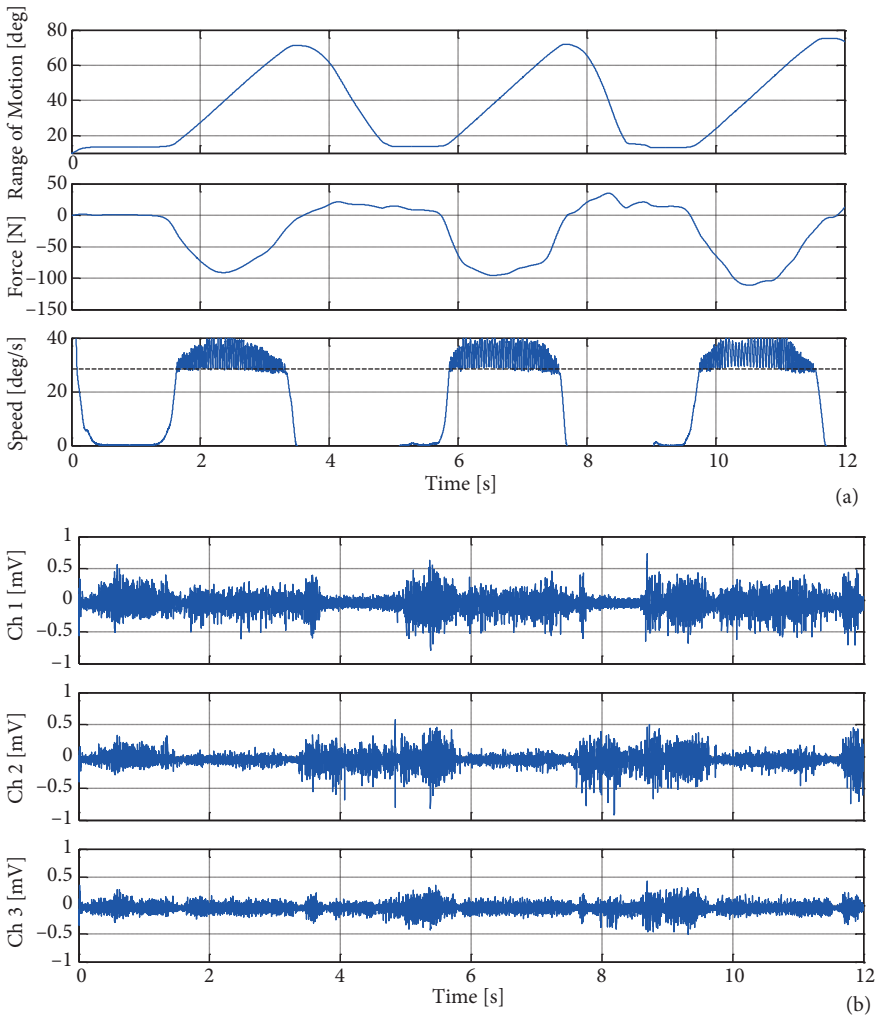


Figure 18. Isokinetic exercise, 30 degree/s: (a) (from top to bottom) range of motion, limb force, and limb speed; (b) EMG signals.

6. Conclusion

In this study, the modification, mechanical analysis, and control of a robot retrofitted for forearm rehabilitation are explained. With this modified system, the passive, active-assistive, and active exercise movements for the upper limbs are generated. The active-assistive exercise was realized using muscular activation feedback. The performance of the system is shown on the basis of the tests conducted with a healthy subject. The feedback data are provided with both mechanical and biological parameters. For this purpose, the position, force values, and muscle signals are used. A human-machine interface is developed for the control of the system. A full control of the system is carried out with this interface; in addition, the interface processes a detailed performance analysis. The evaluation of the mechanical parameters and the biological feedback is very useful with respect to rehabilitation. The measurements made by proprioception tests play an important role in the follow-up of the condition of the patient by the physiotherapists. The prototype robot used in this study is a modification of a rehabilitation robot that was developed for lower limb rehabilitation. By this modification, the newly developed robot has become suitable for upper limb rehabilitation. It is the only system that is able to fulfil both upper and lower rehabilitation within a single robotic system. If it is compared with other rehabilitation

robot systems, this developed system has high usage potential in clinical applications in terms of mechanics, ergonomics, and cost. In future studies, the test of the system is going to be realized with patients.

Acknowledgments

This work was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK), Grant No. 104M018. The author would like to thank Hakan Coşkun for his participation in the experiments.

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