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Optimizing the Torque of Knee Movements of a Rehabilitation Robot

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Abstract

The aim of this study is to employ the novel adaptive network-based fuzzy inference system to optimize the torque applied on the knee link of a rehabilitation robot. Given the special conditions of stroke or spinal cord injury patients, devices with minimum error are required for performing the rehabilitation exercises. After examining the anthropometric data tables of human body, some parameters such as the length of shins, weight, force, joint angle etc. were chosen as the input data. The torque is considered as the output of the system. Errors at any stage of the treatment can harm the patients or disrupt their recovery process. Therefore, after examining different numbers of various fuzzy inference system membership functions and their consequent error, cases with the lowest error were chosen to be the best possible conditions for the system. As a result, it can be said that a robot using the adaptive network-based fuzzy inference system offers negligible errors.

Keywords: Rehabilitation, Optimizing, Adaptive Network-based Fuzzy Inference System (ANFIS), Fuzzy Logic, Anthropometry.

1- Introduction

Today, with advancements in biomedical engineering and mechatronics, many different robots and devices are being fabricated in these fields for fulfilling the needs of mankind. Many rehabilitation aid robots have been designed and used for patients with lower body movement disorders. Control is great challenge in rehabilitation robot because the robot is interacting with patients and always a lot of uncertainty is been in this field. Widespread research activities have been performed to control system design of rehabilitation robot in recent years. To perform therapeutic exercises, various control methods such as position control, force control, hybrid position force control and impedance control have been applied for the rehabilitation robots. Hybrid control and impedance control are two commonly used control methods [1]. The main idea in impedance control is execution of a pre-determined dynamic behavior by the robot; such that the robot is affected by its environment [2, 3]. Simplicity and robustness when facing uncertainty in parameters can be named as features of impedance control. The procedure of strengthening muscles back to normal conditions (rehabilitation) is time consuming, costly and requires high precision. Therefore, the need for implementation of robots in rehabilitation is evident [4]. Many robots were developed for the purpose of rehabilitating patients with disabilities. The first group of such robots is those incorporating treadmills. These devices are only capable of simulating walking on flat surfaces. Based on the previous researches, walking solely on a treadmill does not have a significant impact in rehabilitating stroke or SCI patients since it is not capable of simulating many situations such as climbing stairs, ankle joint rotation etc. That is why other supplementary mechanisms are used in addition to the treadmill. One the most prominent of such designs is the Lokomat [5]. In another type of these mechanisms, moving platforms are placed under patient's feet, creating the desired motion. In such mechanisms, the whole leg or a part of is made to move or is helped in making the desirable maneuvers. An example of such designs is the Haptic Walker. The whole leg or a part of it is made to move or helped to do a maneuver in this device by programming the moving platform. This device was developed by researchers at Berlin University and is capable of moving the whole of patient's body forward [13]. The other group consists of mechanisms that utilize an external skeleton. The skeleton is attached to the patient's body at multiple points and is often composed of multiple pneumatic actuators that consistently help the patient's muscles to make natural moves. CPM can be named as one of the first machines that were used for rehabilitation purposes. This device, which is extensively used in Health centers, was first introduced in 1970. One of its usage can be rehabilitation after total knee arthroplasty [6,7]. NeXOS, Motion Maker, and Multi-Iso are the members of this category [8-10]. The Lambda, as a parallel robot, made the utilization of parallel robotic systems possible in this field. Position control was employed in this robot with the capability of excluding the effect of gravity. The robot has three degrees of freedom and was introduced in 2009 [11]. The other group, are the mechanisms in which the whole leg or a part of it is made to move or helped to do a maneuver by programming the moving platform. An example of such designs is the Haptic Walker. The whole leg or a part of it is made to move or helped to do a maneuver in this device by programming the moving platform. This device was developed by researchers at Berlin University and is capable of moving the whole of patient's body forward [13]. The Physiotherabot is one of the most comprehensive robots available which was designed and fabricated by Akdogan et al. in 2011 [12]. They proposed impedance control as one of the most effective control methods and implemented it in their robot. This robot is capable of performing most of rehabilitation exercises for the patients, thus replacing the physiotherapist to some extent. Indeed, it is clear that a physiotherapist is required as the conductor for any robot. The distinction of this robot from others is that it has three degrees of freedom and is capable of performing the complete format of stretching and bending exercises for knees and thighs, and also pushing thighs away and drawing them in. Adaptive neuro-fuzzy inference system (ANFIS) was used in this study. The advantage of ANFIS to other neural network is that by simultaneous use of fuzzy logic, makes the highly sophisticated and uncertain systems more intelligent. The innovation of this approach is the simultaneous use of neural networks and fuzzy logic which complement each other for optimization. Optimization of the torque applied to the knee link of the robot was addressed in this research. Parameters such as shin length, weight, force, joint angle, etc. that are effective on the therapy were considered as inputs of the neural network. Moreover, the minimum system error can be attained by setting the adequate number and type of the input and output membership functions for the fuzzy inference system. Furthermore, for the system to be capable of covering patients of different physical conditions, it was tried to consider a wide range of physiques in the system. For instance, the system covers patients of 1.4m to 2m height and 40kg to 120kg weight.

2- Governing Equations

The knee link of Physotherabot is shown in Fig.1, The mechanical impedance considered to control the final operator of this three degree-of-freedom robot is presented as in (1) [14]:

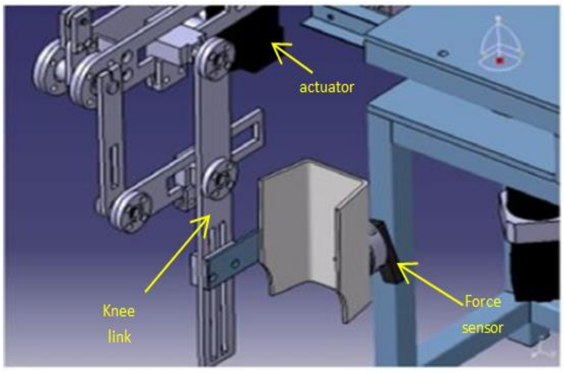

Fig. 1. Knee link of Physiotherabot

$$\mathbf{M_d}\ddot{\mathbf{y}} + \mathbf{D_d}\dot{\mathbf{y}}_\mathbf{e} + \mathbf{K_d}\mathbf{y_e} = \mathbf{F} \quad (1)$$

$$\mathbf{y_e} = \mathbf{y_d} - \mathbf{y} \quad (2)$$

where $\mathbf{F}$, $\mathbf{y}$ and $\mathbf{y_d}$ are the vectors of force, actual position and the desired position respectively, and $\mathbf{M_d} \in R^{n\times n}$, $\mathbf{D_d} \in R^{n\times n}$ and $\mathbf{K_d} \in R^{n\times n}$ are the inertia, damping and hardness matrices respectively.

Equation (3) shows the dynamic equation of control without external force:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h_n}(\mathbf{q},\dot{\mathbf{q}}) = \boldsymbol{\tau} \quad (3)$$

where $\mathbf{M}(\mathbf{q})$ is the inertia matrix and $\mathbf{h_n}(\mathbf{q},\dot{\mathbf{q}})$ consists of Coriolis force, centrifugal force and other effects including gravitational force (by the help of which the patient does not feel the weight of the mechanism). $\mathbf{q} \in R^n$ is the vector of joint position and $\boldsymbol{\tau} \in R^n$ represents the torque required for control. $\mathbf{y}$ and $\mathbf{q}$ are related according to (4) the second and third derivatives of which are presented as in (5).

$$\mathbf{y} = \mathbf{f_y}(\mathbf{q}) \quad (4)$$

$$\dot{\mathbf{y}} = \mathbf{J_y}(\mathbf{q})\dot{\mathbf{q}} \quad (5)$$
$$\ddot{\mathbf{y}} = \dot{\mathbf{J}}_\mathbf{y}\dot{\mathbf{q}} + \mathbf{J_y}\ddot{\mathbf{q}}$$

Where $\mathbf{J_y} = \partial\mathbf{y}/\partial\mathbf{q}^\mathbf{T}$ is the Jacobian matrix for the joint angle control of the final operator. The joint torque equivalent to the external force $\mathbf{F}$ can be expressed as

$$\boldsymbol{\tau}_\mathbf{F} = \mathbf{J}_\mathbf{y}^\mathbf{T}(\mathbf{q})\mathbf{F} \quad (6)$$

with the help of the Jacobian matrix. Based on (3) and (6), the dynamic equations of control can be obtained as in (7) in case the external force $\mathbf{F}$ exists.

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h_n}(\mathbf{q},\dot{\mathbf{q}}) = \boldsymbol{\tau} + \mathbf{J}_\mathbf{y}^\mathbf{T}(\mathbf{q})\mathbf{F}. \quad (7)$$

Assuming $\mathbf{J_y}(\mathbf{q})$ to be non-singular, as in (8-10) can be obtained for any $\mathbf{q}$ at the desired point based on (5) and (7):

$$\mathbf{M_y}(\mathbf{q})\ddot{\mathbf{y}} + \mathbf{h}_{\mathbf{N_y}}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{J}_\mathbf{y}^{\mathbf{-T}}(\mathbf{q})\boldsymbol{\tau} + \mathbf{F} \quad (8)$$

$$\mathbf{M_y}(\mathbf{q}) = \mathbf{J_y^{-T}}(\mathbf{q})\mathbf{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q}) \quad (9)$$

$$\mathbf{h_{N_y}}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{J_y^{-T}}(\mathbf{q})\mathbf{h_N}(\mathbf{q},\dot{\mathbf{q}}) - \mathbf{M_y}(\mathbf{q})\dot{\mathbf{J}}_\mathbf{y}(\mathbf{q})\dot{\mathbf{q}} \quad (10)$$

Using (1-10) and making the necessary substitution, the required torque for attaining the desirable impedance for control is obtained as in (11).

$$\boldsymbol{\tau} = \mathbf{h_N}(\mathbf{q},\dot{\mathbf{q}}) - \mathbf{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q})\dot{\mathbf{J}}_\mathbf{y}(\mathbf{q})\dot{\mathbf{q}} - \mathbf{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q})\mathbf{M_d^{-1}}(\mathbf{D_d}\dot{\mathbf{y}}_\mathbf{e} + \mathbf{K_d}\mathbf{y_e}) + \left[\mathbf{M}(\mathbf{q})\mathbf{J_y^{-1}}(\mathbf{q})\mathbf{M_d^{-1}} - \mathbf{J_y^{T}}(\mathbf{q})\right]\mathbf{F} \quad (11)$$

For knee rehabilitation, we obtain Equation (12) for the knee link after substituting $M = I_2$, $J_y = J_y^T = r$ and $J_y^{-1} = 1/r_2$ in (11):

$$\tau = \tau_{gravity} - \frac{I_2}{r_2 M_d}\left(D_d \dot{\theta}_e + K_d \theta_e\right) + \left(\frac{I_2}{r_2 M_d} - r_2\right)F \quad (12)$$

where

$$\tau_{gravity} = mg\sin\theta_2 l_{g2}. \quad (13)$$

In (12) and (13), m represents the mass of the link, g is the gravitational acceleration on earth, I_2 is the inertia of the knee link, J_y is the Jacobian of the knee link, θ_2 is the actual angle, θ_e is the difference between actual and desirable angle, l_{g2} is the distance between the knee joint and the knee link center of mass, and r_2 represents the distance between knee joint and the location of the force sensor. The muscular capacitance of the patient can be evaluated by applying force sensors on their limbs. Moreover, the reaction force of the patient, which affects the torque applied by the robot, can be determined.

3- Optimization

The aim of optimization is to find the best acceptable solution, considering the limitations and requirements of the problem. Advancements in computer science during the last fifty years resulted in development of optimization methods and numerous commands. The optimization methods can be generally categorized into three groups: numerical, computational and random search [15].

In recent years, fuzzy systems have become an attractive approach for creating intelligent complex systems of high uncertainty [16-18]. Since the time fuzzy logic was first introduced to describe complex systems, it has been successfully applied in different problems especially automatic controllers. However, the main problem with fuzzy logic is that it lacks the systematic trend needed for designing a fuzzy controller. On the other hand, a neural network has the capability of learning from the environment, organize its structure and adjust its interactions [19,20]. The Adaptive Network-based Fuzzy Inference System (ANFIS) was presented as a system capable of combining the advantages of both methods. ANFIS was introduced by Dr. Rogger Jang in 1993 [21]. ANFIS is a sugeno fuzzy inference system the rules of which are determined and optimized based on a series of available learning data. In fact, ANFIS is a fuzzy inference system that adapts itself to the learning data.

Given the different physical conditions of patients, also in order to improve the control process and consequently to accelerate patients' recovery, it was tried to consider all the parameters that are effective on rehabilitation, in all stages of this study.

Parameters such as the mass of knee link, the distance between knee joint and the knee link center of mass, the actual angle, the difference between the desirable and the actual angles, derivative of angle difference, the distance between knee joint and the force sensor, and the knee link inertia and force were the input data, and torque the output of ANFIS.

3-1- Creating the Initial Model

The ANFIS tool box of MATLAB was utilized to create the initial model of the adaptive network-based fuzzy inference. The ANFIS was created considering the special conditions of patients who need rehabilitation and the factors effective on their recovery. Fig.2 shows an overall view of the sugeno adaptive network-based fuzzy inference system.

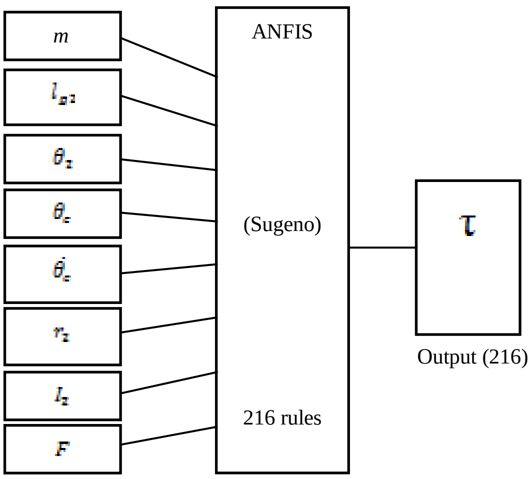

Fig. 2. overall view of the ANFIS

There are different choices of membership function type and number and the best choice is to be picked. The number of membership functions for each input is chosen based on its significance. For instance, for an input with high significance a larger number if membership functions are considered. Given that the force and the angle of joint during rehabilitation are important parameters in controlling rehabilitation devices, special attention was given to force and angle inputs. The final goal in choosing the type and the number of membership functions is to minimize system error.

The membership functions assumed for each of the ANFIS inputs is shown in Table.1.

Table 1- Input Variables and Number of Membership Functions of the Anfis System

Input	Variable	Number of membership functions
Input1	m	2
Input2	l_{g2}	1
Input3	θ_2	3
Input4	θ_e	3
Input5	$\dot{\theta}_e$	1
Input6	r_2	2
Input7	I_2	2
Input8	F	3

Different membership functions are available for fuzzy sets such as Gaussian, Trapezoidal-shaped, Triangular-shaped and bell membership functions that can be applied to different systems. Various membership functions of fuzzy sets were examined in this research and the function that yielded the lowest error was chosen as the ANFIS membership function. In the system that was created, the Gaussian membership function was found to offer the lowest error. The membership functions pertaining to each input is demonstrated in Figs .3-10.

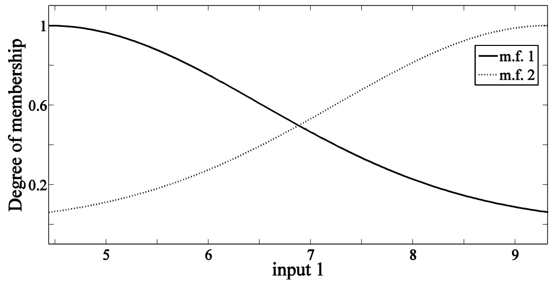

Fig .3. Input1 membership functions

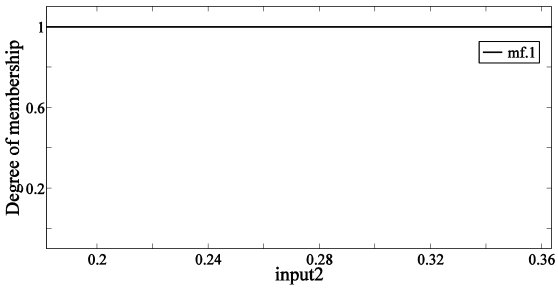

Fig .4. Input2 membership functions

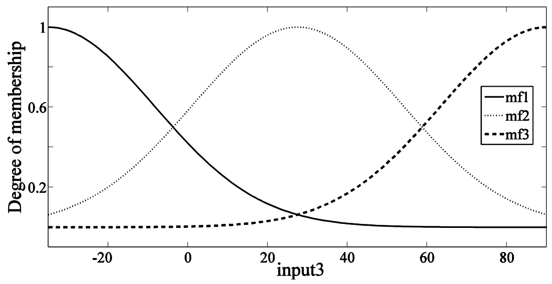

Fig .5. Input3 membership functions

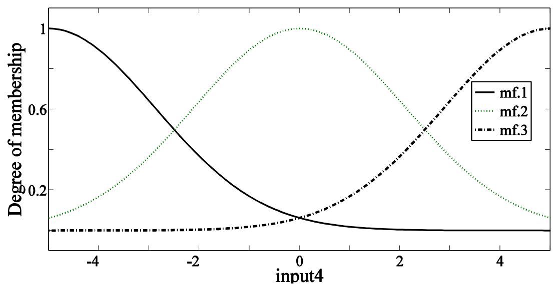

Fig .6. Input4 membership functions

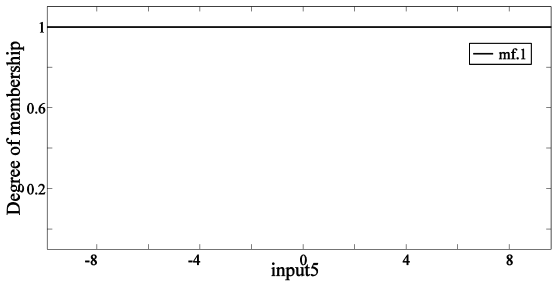

Fig .7. Input5 membership functions

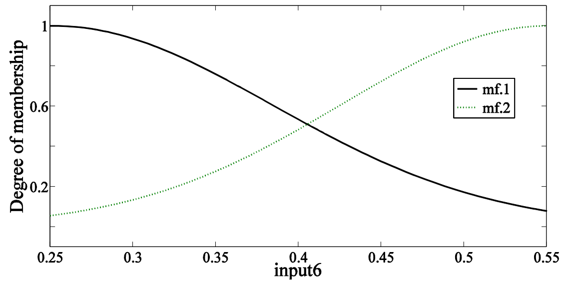

Fig .8. Input6 membership functions

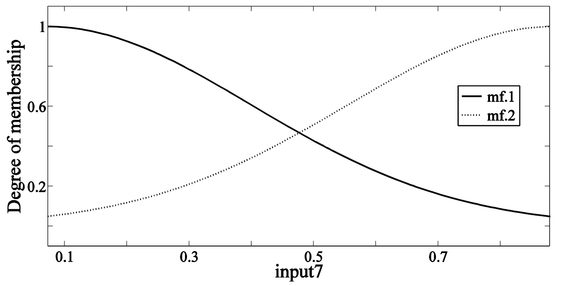

Fig .9. Input7 membership functions

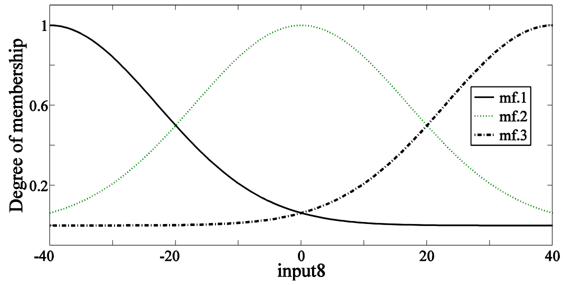

Fig .10. Input8 membership functions

3-2- System Rules

Fuzzy rules are linguistic IF-THEN-constructions that have the general form "IF A THEN B" where A and B are (collections of) propositions containing linguistic variables. A is called the premise and B is the consequence of the rule. In effect, the use of linguistic variables and fuzzy IF-THEN- rules exploits the tolerance for imprecision and uncertainty. In this respect, fuzzy logic mimics the crucial ability of the human mind to summarize data and focus on decision-relevant information. Fuzzy inference systems are based on knowledge or rules. The heart of a fuzzy inference system is the knowledge base which is composed of fuzzy If-Then rules. The number of fuzzy rules is determined based on the product of the number of input membership functions in a fuzzy inference system [22]. Therefore, one rule is considered for each of the 216 cases in the present problem. When choosing the number of membership functions, it is important to have in mind that MATLAB is capable of considering 256 rules at maximum. Therefore, the number of membership function should be selected such that the maximum number of rules does not exceed this value.

3-3- Testing the Designed ANFIS

Anthropometry tables were used in order to set an accurate range for parameters such as m, l_{g2}, r_2 etc. Anthropometry is the study of the measurement of the human body in terms of the dimensions of bone, muscle, and adipose (fat) tissue. Generally speaking, anthropometry consists of different measurements of different body parts such as weight and volume of the limbs, and their motion space and angles. The statistics and information derived from these tables is employed for designing tools and equipment used in workspace [23,24]. The training data were obtained by Minitab 16.2 (that yields random data) after extracting the formulas, governing relations and accurately determining the range of input variables. It should be noted that 500 pieces of data were extracted, 400 of which was used for network learning and the remaining 100 for testing the neural network. The learning error and ANFIS test results (with the Gaussian membership function) are presented in Table 2. The selection criterion for the best scenario of number and type of membership functions is considering maximum error and average error together. As table 2 shows, for testing the system average error is 4×10^{-1} and maximum error is 3.1 and Gaussian function has less error than other functions (bell-shaped, sigmoid). Training error is also visible.

Table 2- Gaussian function results for Anfis system

	Min Error	Max Error	Avg Error
Train	9.7×10^{-6}	1.2	5.6×10^{-2}
Test	8.5×10^{-3}	3.1	4×10^{-1}

The results of system learning and testing are presented in Figs. 11 and 12 in which the horizontal axis represents system data and the vertical axis represents system outputs. As it is specified in the figures, the "+" assigned to ANFIS outputs and the "●" shows the desirable torque. Given that values are very close, it is safe to say the system error was low and acceptable. The dotted lines in Figs. 11 and 12 show the error which is seen to be almost zero and insignificant.

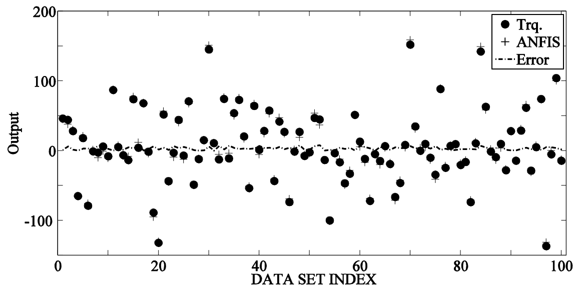

Fig .11. results of system testing

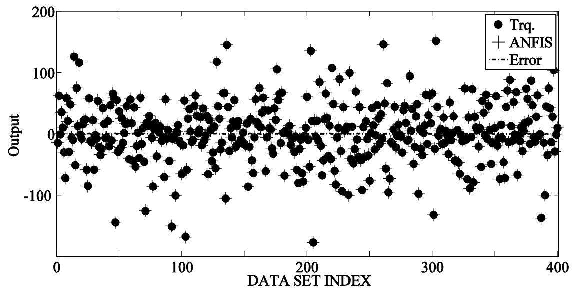

Fig .12. results of system learning

4- Conclusion

Given the special conditions of the recovering patients, it is important for the system to offer low error at most of the rehabilitation stages. Errors at any of these stages can harm the patient or disrupt their recovery. Therefore, in the present study, the novel Adaptive Network-based Fuzzy Inference System (ANFIS) was employed to reduce error in decisions made by the robot. Force and joint angle are two important parameters in rehabilitation process. It is also tried to consider most parameters which are effective in the patient rehabilitation in the system and as the input for ANFIS. The torque imposed to the knee link was considered as the system output. 400 data considered for training and 100 data for the test. Finally, regarding the physical conditions of different patients (height and weight) and diagnosing the disease by the patient and needs of the patient for recovery, the information of each patient can be entered in ANFIS and then, obtain the optimal torque imposed to knee link from the system. After creating the initial ANFIS model and testing the criteria for the number and type of membership functions that are involved in the ANFIS, the number and type of the membership functions were chosen in a way that yield the minimum error. Furthermore, for the system to be capable of covering patients of different physical conditions, it was tried to consider a wide range of physiques in the system. For instance, the system covers patients of 1.4 to 2m height and 40 to 120kg weight. Test results pertaining to the adaptive fuzzy inference system that was designed suggest its high accuracy and negligible error in estimating the required control torque for rehabilitation exercises. The conditions were considered for the system which result in the minimum error. Finally, results show a low and acceptable error for the system.

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