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Development of an intelligent controller for robot-aided assessment and treatment guidance in physical medicine and rehabilitation

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Abstract: In this study, an intelligent controller was developed for a rehabilitation robot called DIAGNOBOT, which can be used for assessment and treatment in the rehabilitation of wrist and forearm. The controller has a decision support system structure strengthened with conventional statistical methods and databases. The controller uses the patient's biomechanical parameters to make an assessment and proposes a treatment in line with this. In accordance with the recommended treatment, it produces the control parameters, torque, and position information for the control of the rehabilitation robot. The system's ability of assessment and treatment was tested with voluntary patients. Through these test studies, the treatments recommended by the developed intelligent controller have been proven to have a very high rate of accuracy.

Key words: Decision support system, assessment, intelligent control, rehabilitation robot

1. Introduction

The need for rehabilitation is increasing along with the rising world population. Rehabilitation is needed in order to eliminate, to the maximum possible level, partial or general functional losses in various limbs of individuals due to aging, occupational and traffic accidents, chronic diseases, and wars. Various medical methods and therapies have been developed to compensate for the loss of these limbs and increase the range of motion (ROM) and muscle strength. Therapeutic exercises, which are one of these methods, play an important role in rehabilitation. Therapeutic exercises are divided into two groups as passive and active exercises. These exercises can be performed with the help of various instruments, mechanical or electromechanical devices, as well as performed manually by the physiotherapist or the patient themselves, depending on their condition.

The use of robots in rehabilitation is increasing by the day due to a number of particular qualities, such as their ability to perform repetitive movements with precise accuracy, to make objective measurements and evaluations, and to make positive contributions in terms of cost and time, making the treatment process easily and remotely accessible [1]. Clinical studies have demonstrated the contribution of robots to the rehabilitation processes [2].

Today, computers are an indispensable part of the medical field as in every other field. In parallel with this, unprecedented amounts of data can now be stored. With these data being rendered meaningful by analysis

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through artificial intelligence methods, significant improvements have been made, particularly in the field of medical assessment. The use of artificial intelligence in the fields of medicine and health care is increasing day by day [3].

Many robotic systems developed for treatment purposes can be found in the literature. The most well-known of these is the robotic system MIT-MANUS (Massachusetts Institute of Technology - MANUS), developed by Krebs et al. [4, 5]. This robot, with its 3-DOF motion, has been developed for shoulder and elbow rehabilitation. The system can perform passive, active-assistive, and resistive exercises. Impedance control method [6] was used for controlling the system. In the literature, there are many studies using conventional control techniques such as impedance control, admittance control, and PID control in the control of rehabilitation robots [7–11].

There are various robotic systems developed in the literature for the assessment. A large part of these are on the assessment of ROM and motor skills of stroke patients. Zhang et al. developed a mechanism that can measure and assess wrist passive ROM [12]. They stated that these measurements can help physicians in therapeutic exercises, but treatment recommendations are not made using these measurements. In addition, force measurement is not made either. Guidali et al. [13] developed a system using ARMin robot to measure the level of hemiparesis in patients with moderate to severe hemiparesis after stroke. In the system developed for the shoulder joint, ROM and static torque measurements are performed in 3-dimensional space. Here force and ROM measurements are made, but no results are suggested regarding the treatment. Hingtgen et al. [14] developed a 3D upper limb kinematic model to obtain joint angles of the trunk, shoulder, and elbow using a Vicon motion analysis system. The model computed motion patterns in the affected and unaffected arms. The unaffected arm showed a larger ROM and higher angular velocity than the affected arm. This model has been proposed to assist in the assessment and planning of stroke rehabilitation and to shorten the recovery time. Here joint ROM and velocity are taken into consideration, and an assessment of the force values is not made. In his doctoral dissertation [15], Natarajan developed a system-based robotic rehabilitation system for hemiparetic limbs in stroke patients. With the help of the expert system, the system can monitor such parameters as ROM, movement speed, and trajectory following error during the exercise and make suggestions to the physiotherapists for the next exercise. Here by evaluating the previous exercise performance, it helps to plan the next session. Again, no results regarding force values are revealed. Tojo et al. developed a robotic system to diagnose patients' strength levels and performances [16]. In this system, patients exert force on a handle in two-dimensional space with the given directions and levels shown on the screen. This is done to determine the rate at which patients can reach these target strength levels. These strength values are presented to physicians, but no treatment recommendations are made. Zariffa et al. [17] used measurements from robotic rehabilitation sessions to predict clinical scores in a traumatic cervical spinal cord injury. They explored 14 predictive variables, relating to ROM, movement smoothness, and grip ability. Here the measurements made during the application of the exercises recommended by the doctor are evaluated, but no treatment recommendation is made by the system. Lee et al. [18] describe and evaluate an interactive hybrid approach that integrates a data-driven model with expert's knowledge on kinematic features to assess the quality of motion for stroke rehabilitation. They predict quality of motion on three performance components (ROM, smoothness, compensation) and the comparison between unaffected and affected sides. Joint forces are not taken into account. In addition, no treatment recommendations are made. Zhao et al. [19] developed a real-time motion assessment approach for rehabilitation exercises based on the integration of comprehensive kinematic modeling with fuzzy inference. This approach is based on motion analysis and does not include force assessment. During the exercise, the error is calculated by comparing the movement of the patient with the target position values produced by the system. These values used as inputs to a fuzzy interference system to derive the overall quality of the exercise. The use of regression analysis, to obtain predictions of clinical scores using robotic measurements, has also been studied in the literature [20, 21].

As seen in the literature and Table 1, there is no system that evaluates joint passive and active ROM and force/torque values and recommends appropriate exercise type and parameters. Additionally, no rehabilitation robot controller that can perform assessment and recommend treatment with a single controller structure was found either in the literature. The number of parameters that need to be evaluated in rehabilitation is very high and the essential attributes associated with them tend to be very different [22]. The main purpose of therapeutic exercise is to improve the joint ROM and strength and endurance of the limbs to the highest level possible [23]. For this reason, ROM and strength values are taken into account both in the evaluation and treatment stages. The parameters for wrist and forearm rehabilitation are the passive-active ROM and force/torque values of the flexion, extension, ulnar/radial deviation, pronation, supination, and hand grasping force. Assessments without considering all these parameters remain limited. To solve this problem, it is necessary to create a control structure that takes into account all the mentioned parameters, deducts from healthy human data, and can produce a conclusion about the deficiencies, and suggests the appropriate treatment method and exercise parameters according to this result. This will shorten the diagnosis period of physicians and contribute to the accuracy of diagnosis.

Table 1. Comparison of the assessment-based systems.

Reference	ROM	Force	Evaluated parameters	Exercise type and param. recommendation
Zhang et al.[12]	✓	X	Passive ROM	X
Guidali et al.[13]	✓	✓	ROM, static torque	X
Hingtgen et al. [14]	✓	X	ROM, velocity	X
Natarajan [15]	✓	X	ROM, velocity	X
Tojo et al. [16]	X	✓	Force	X
Zariffa et al. [17]	✓	✓	ROM, smoothness, grip ability	X
Lee et al. [18]	✓	X	ROM, smoothness, compensation	X
Zhao et al. [19]	✓	X	ROM	X
DIAGNOBOT	✓	✓	Active and passive ROM, force/torque	✓

In this study, a unique intelligent controller structure has been developed to support physicians and physiotherapists. This controller determines the exercise type and parameters according to the assessments and performs the chosen therapy. Its fundamental features are making inferences using databases and a decision support system supported by conventional statistical methods, making an assessment about the ROM and force/torque deficiency by comparing the inferences with the physical characteristics of the patient, adapting to the changes that may occur over time in the population thanks to the continuously updated healthy human database. In brief, a controller structure has been created to perform all stages of the rehabilitation process from assessment to treatment. Assessment performance of the intelligent controller has been demonstrated through experiments which were performed with patients. The details on the design and conventional control structure of the system were given in previous studies [24, 25].

The contribution of this study to the literature is that it is the first study to make an assessment and recommend a treatment method for a rehabilitation robot under a unique intelligent controller with a decision support system structure, supported by conventional statistical methods while also including databases. Additionally, a significant contribution was made to the clinical assessment process by the robot performing joint force measurements, which were not carried out by physicians in the clinic and were highly significant in physical therapy and rehabilitation.

2. Robotic system aimed at assessment and therapy: DIAGNOBOT

DIAGNOBOT is a robotic system for wrist and forearm rehabilitation that can be used for both assessment and therapy. It can perform passive, active-assistive, stretching, isometric, isotonic, and resistive exercises. The passive exercise is performed manually or by assistive device within the ROM. It does not include the voluntary muscular contraction of the patient. In the active-assistive exercise, the patient moves his limb to the position where he can move. The rest of the movement is completed by an external force. Stretching exercises are applied to the joints with contractures. The joint is forced to reach the target ROM. In the isometric exercise, the level of muscular contraction is increased without causing a change in the length of the muscle. In the isotonic exercise, the limb is moved along the ROM against a constant force. In the vario-resistive exercise [24], various difficulty levels are applied to the patient depending on the ROM.

The general block diagram of the system is given in Figure 1. There are three robot manipulators on DIAGNOBOT to perform flexion-extension (fle-ext), ulnar-radial (uln-rad) deviation, and pronation-supination (pro-sup) movements in wrist and forearm. The force and position measurements are made with the encoder and the force/torque sensors. There is a grasping force measurement unit to measure the grasping force of the patient. The robotic system communicates with the physician via a mobile application called DIAGNOCONN©. The axis parameters and the units on the robotic system are shown in Figure 2. 1-DOF manipulators carry out exercise movements by rotating around the Z axis. Detailed information and introduction video about DIAGNOBOT can be accessed online[1].

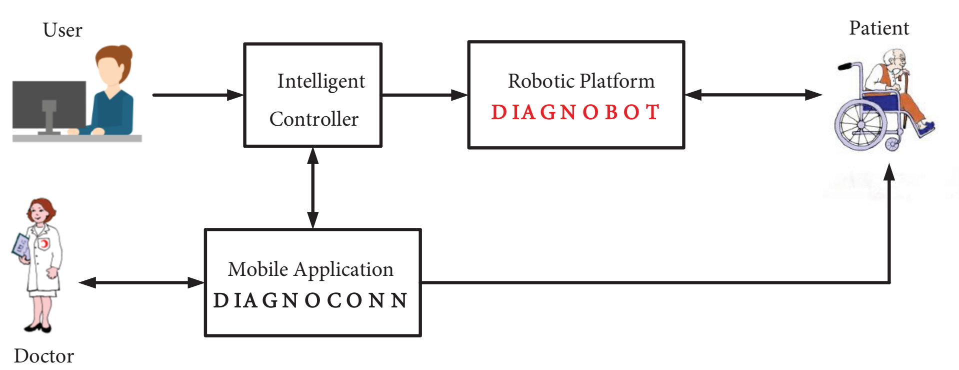

Figure 1. General block diagram of the DIAGNOBOT.

[1] Yıldız Technical University Biomecatronics Laboratory (2017). DIAGNOBOT [online]. Website http://ytubiomechatronics.com/portfolio-item/diagnobot/ [Accessed 06.01.2021].

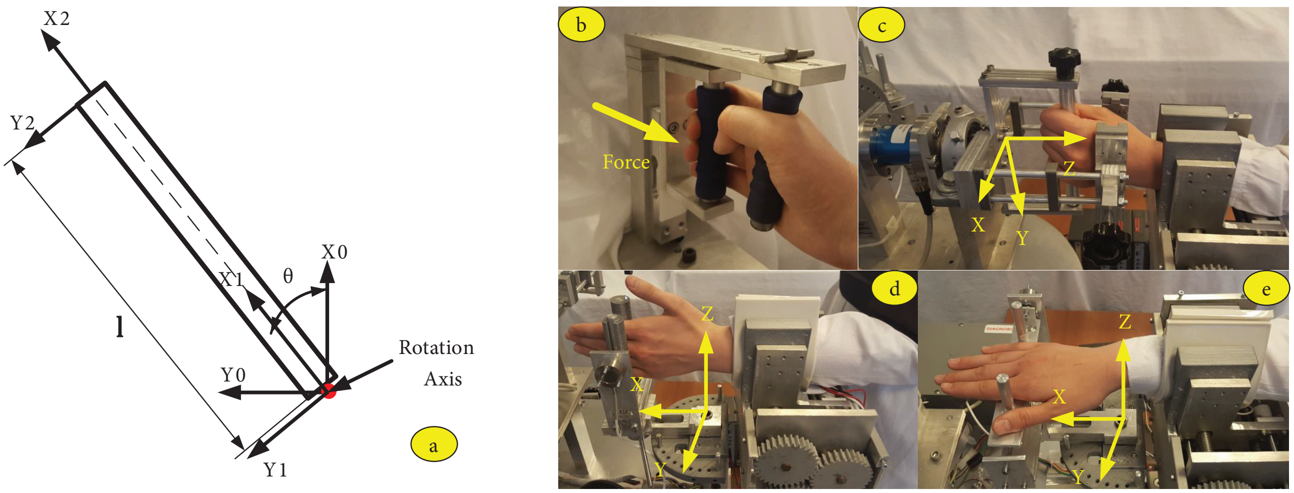

Figure 2. (a) Axis parameters, (b) grasping force meas., (c) pro-sup, (d) fle-ext (e), uln-rad deviation units.

3. Intelligent controller aimed at assessment and therapy

An intelligent controller can detect, comprehend, gather information, learn, make inferences and decisions as well as implement these decisions [26]. The developed intelligent controller has these features. General characteristics of the controller are: 1) It is able to learn the previous (healthy) joint ROM and force/torque values by analyzing the ROM and force patterns in the healthy human database through statistical methods. 2) It produces a result about the joint ROM and force/torque deficiency of the patient. 3) It determines the exercise method and parameters according to this result. 4) Thanks to a continuously updated healthy human database, it adapts to different conditions and different patient populations by making the necessary changes in the algorithm of the inference. 5) With the help of the mobile application [27], it enables communication between the physician, the patient, and the robot.

The units in the system are given in Figure 3. These units are central processing unit, healthy human database, correlation analysis unit, regression analysis unit, biomechanical parameter extraction unit, therapeutic exercise unit, and conventional controller. Patient information is entered in the central processing unit. The correlation analysis unit performs correlation analysis with the data in the healthy human database, determines the independent variables that are related to each other, and sends them to the regression analysis unit. Here, by performing regression analysis, the equation coefficients that establish the relationship between independent variables and dependent variables are calculated and sent to the biomechanical parameter extraction unit. Here, the desired biomechanical parameters (DBP) are determined by using the equation coefficients and patient information and sent to the central processing unit. The central processing unit determines the difference in percentage by comparing the DBP and the patient's biomechanical measurements and then sends these percentages to the therapeutic exercise unit. The exercises and exercise parameters to be applied are determined by the therapeutic exercise unit and sent to the central processing unit. Thus, the deficiencies in the joint ROM and force/torque are determined and an appropriate treatment is suggested in line with this determination. The determined exercise parameters are sent to the conventional controller, where the motor torque values are determined and the exercises are performed. The assessments and exercise suggestions as well as patient's personal information and biomechanical measurements are sent to the physicians via the mobile application. For this purpose, the mobile application infrastructure (DIAGNOCONN) given in [27] is used. The units are explained in detail in the following sections.

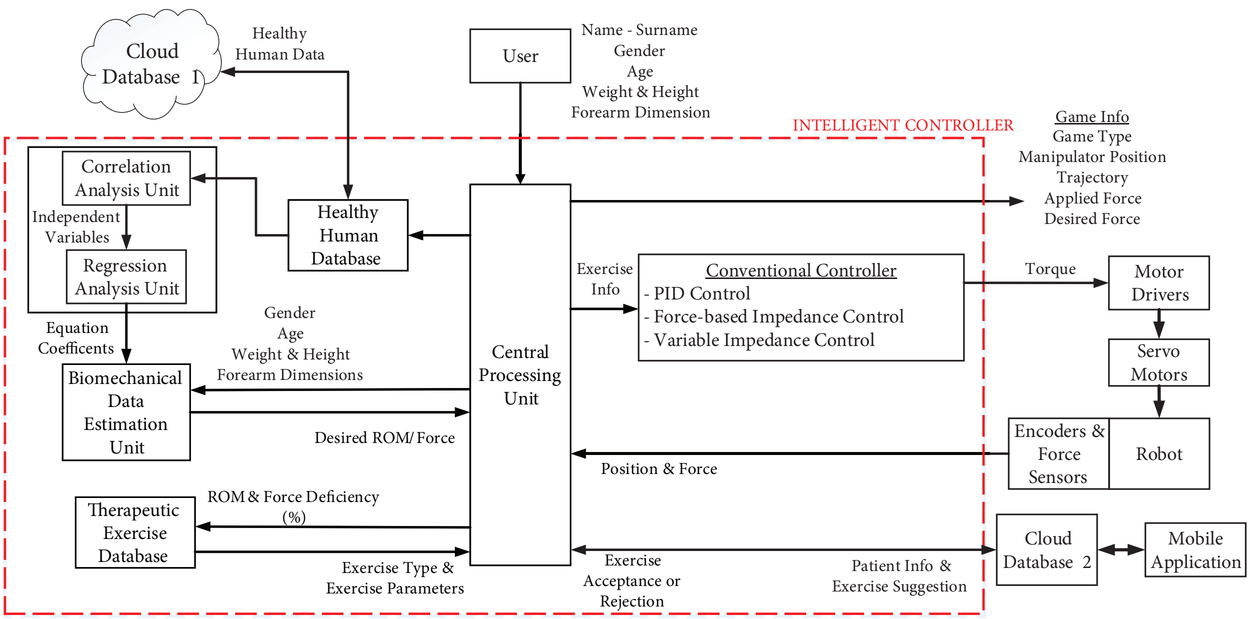

Figure 3. Intelligent controller block diagram.

3.1. Central processing unit

It is the management unit of the intelligent controller. It enables data communication between all units. It determines the joint ROM and the force/torque deficiencies using the information obtained from the peripheral units, and produces parameters for the conventional controller. The tasks of the central processing unit are;

- taking the patient's information entered by the user and the biomechanical measurements made with the robot manipulators,
- sending the data on gender, age, height, weight, forearm length, and forearm circumference to the biomechanical parameter extraction unit,
- subtracting the desired ROM and force/torque values from the patient's values, and thereby identifying the percentages of deficiency in the joint ROM and force/torque,
- sending the exercise type and parameters to the physicians via the mobile application,
- selecting the appropriate control method in the conventional controller according to the approval or corrections from the physician, and calculating the required motor torque and sending it to the motor drives,
- and finally, in game-based exercises, sending the game type, trajectory, manipulator position, applied force, and target force to the patient's computer.

Equation 1 determines the percentage of deficiency of the central processing unit in the patient's biomechanical parameters (i.e. joint ROM, force, torque);

$$DeficiencyPercentage = (DBP - PBP) * 100/DBP \tag{1}$$

Here, DBP stands for "desired biomechanical parameters" while PBP stands for "patient biomechanical parameters". The DBP is calculated by the biomechanical parameter extraction unit. The PBP is the measurements taken from patients. Through this equation, the percentage of ROM and force deficiency in the patient's limb are calculated.

3.2. Healthy human database

This is a database of wrist and forearm biomechanical parameters of healthy people used in order to allow the robotic system to perform an assessment. Data were collected from a total of 150 subjects, 100 males and 50 females. Permission required to collect data from healthy people and to conduct experiments with patients was obtained from the Clinical Research Ethics Committee of Marmara University's School of Medicine.

Data were collected from individuals without diabetes, bone fracture, amputation, thyroid, neck hernia, neuropathy, renal and hepatic insufficiency and rheumatic diseases, all of which adversely affect muscle strength. The independent variables are gender, age, height, weight, arm length, arm circumference, and dominant hand. The dependent variables are grasping force (kg), pro-sup ROM (deg.), fle-ext ROM (deg.), uln-rad dev. ROM (deg.), pronation torque (Nm), supination torque (Nm), flexion force (N), extension force (N), ulnar dev. force (N), and radial revolution force (N). At each measurement, the subject is asked to apply force/torque three times for 3 s. The differences between the resulting three peaks are calculated. In the case of a 10% difference, the measurement is repeated. By taking the average of the peak values, the corresponding force/torque value is determined. The collected data is saved to the cloud database so that any robots that may be added later to the system also have access to it.

3.3. Correlation analysis unit

Correlation indicates the degree of relationship between variables. This degree of relationship is called the correlation coefficient (r). The task of the correlation analysis unit is to determine the independent variables (height, weight, forearm length, and forearm circumference) that affect the dependent variables (grasping force, ROM, and force values) in the healthy human database. Correlation coefficient is calculated with Equation 2.

$$r = \frac{cov(x,y)}{s_x s_y} \tag{2}$$

Here, *cov(x,y)* is the covariance of the variables x and y, s_x is the standard deviation of the variable x, and s_y is the standard deviation of the variable y. r values between 0.6 and 0.8 show high correlation and r values higher than 0.8 show very high correlation. Correlation analysis is performed using data from the healthy human database. As a result of the analysis, variables with high and very high correlations are determined and sent to the regression analysis unit. The healthy human database is constantly updated and the amount of data is continuously increased. Therefore, correlation analysis is performed before each assessment so that the system can adapt to population change.

3.4. Regression analysis unit

The task of this unit is to form the matrix of coefficients using the multivariate regression model for the calculation of dependent variables. Multivariate regression model can be expressed as:

$$Y = a_1 + a_2X_1 + a_3X_2 .... + a_nX_{n-1} \tag{3}$$

Here, Y is the dependent variable, while $X_1, X_2, ..., X_n$ are the independent variables. a_1 is the constant term and is also the average value of the dependent variable when all of the independent variables are zero. The $a_2, a_3, ..., a_n$ coefficients are called partial regression coefficients. A regression model is formed by estimating the partial regression coefficients. The least squares method (LSM) is used for this estimation.

A regression model consisting of "m" number of dependent variables and "n" number of independent variables is expressed as:

$$\mathbf{Y}_{mx_1} = \mathbf{A}_{mx(n+1)}\mathbf{X}_{(n+1)x_1} \tag{4}$$

Here, Y is the vector of dependent variables, X is the vector of independent variables, A is the matrix of coefficients, m is the number of dependent variables, and n is the number of independent variables.

It calculates the matrix of coefficients consisting of partial regression coefficients that establish the relationship between the selected independent variables sent from the correlation analysis unit and the six dependent variables. The number of independent variables here is determined by the correlation analysis unit. A regression model is created according to these independent variables. A regression model consisting of six dependent variables and an "n" number of independent variables is expressed as:

$$\begin{bmatrix} \textit{Flexion Force} \\ \textit{Extension Force} \\ \textit{Ulnar Dev. Force} \\ \textit{Radial Dev. Force} \\ \textit{Pronation Torque} \\ \textit{Supination Torque} \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & .... & a_n \\ b_1 & b_2 & b_3 & .... & b_n \\ c_1 & c_2 & c_3 & .... & c_n \\ d_1 & d_2 & d_3 & .... & d_n \\ e_1 & e_2 & e_3 & .... & e_n \\ f_1 & f_2 & f_3 & .... & f_n \end{bmatrix} \begin{bmatrix} 1 \\ x_1 \\ x_2 \\ x_3 \\ . \\ x_n \end{bmatrix} \tag{5}$$

Assuming that the weight and arm circumference are determined as independent variables as a result of the analysis performed in the correlation analysis unit, the n will be 2. The x_1 and x_2 will be weight and arm circumference, respectively. The calculated coefficients are sent to the biomechanical parameter extraction unit.

3.5. Biomechanical parameter extraction unit

This unit determines the desired biomechanical parameters (ROM and force/torque) using the patient's physical characteristics (gender, age, height, weight, arm length, arm circumference) provided by the central processing unit and the coefficients matrix that comes from the regression unit.

Equation coefficients, which determine the relationship between the independent variables determined in the correlation unit and the six dependent variables, are taken from the regression unit. The independent variables in these equations were determined by the correlation analysis unit. These independent variable values consist of the patient's physical characteristics. By duly placing these values from the central processing unit, the desired ROM and force/torque values (DBP) are obtained for the six movements. These determined values are then sent to the central processing unit.

3.6. Therapeutic exercise unit

The therapeutic exercise unit has a rule-based structure. It has rules about the types of exercise and the situations in which these exercises will be applied, and the ROM and force values to be applied in each set. The therapeutic exercise database was created based on information from an eight-member team of three physical medicine and rehabilitation physicians and five physiotherapists.

The central processing unit sends deficiency percentages of force and ROM to the therapeutic exercise unit. Exercise type and exercise parameters are determined according to this deficiency percentages and sent to the central processing unit. In the therapeutic exercise unit, joint ROM and force deficiency values are categorized in various sections according to their percentages. The structure of the database consists of rules. Each joint ROM and force deficiency value is controlled according to the rules and exercise recommendations are made accordingly. An example rule is given below:

$$\textbf{Rule} \quad If \quad \boldsymbol{f\_a\_ROMx} > 10\% \quad and \quad \boldsymbol{f\_a\_ROMx} > \boldsymbol{f\_p\_ROMx} \quad and \quad \boldsymbol{f\_p\_ROMx} == \boldsymbol{f\_max}, \quad Ex1 = f\_active\_assistive$$

Here, $\boldsymbol{f}$, $\boldsymbol{a}$, and $\boldsymbol{p}$ represent flexion, active, and passive, respectively. $\boldsymbol{f\_a\_ROMx}$ indicates the lack of **active** ROM in the **flexion** direction. $\boldsymbol{f\_p\_ROMx}$ refers to the lack of **passive** ROM in the flexion direction again. $\boldsymbol{f\_max}$ is the ROM of a healthy person should have for flexion. In this rule, the patient's deficiency of active ROM is greater than their deficiency of passive ROM, and the passive ROM equals the ROM of a healthy person. In other words, the patient's joint can passively open to the maximum. This is an indication that there is no contracture in the joint. Therefore, an active-assistive exercise is recommended as the first exercise (Eg1). Another example rule is given below:

$$\textbf{Rule} \quad If \quad \boldsymbol{f\_a\_ROMx} > 10\% \quad and \quad \boldsymbol{f\_a\_ROMx} == \boldsymbol{f\_p\_ROMx} \quad or$$
$$\boldsymbol{f\_a\_ROMx} >= \boldsymbol{f\_p\_ROMx} + \boldsymbol{f\_p\_ROMx} * 1/20, \quad Ex1 = f\_stretching$$

In this rule, the patient's active ROM deficiency value is over 10%. The patient's passive and active ranges of motion are equal to each other or their passive joint ROM is higher by 5%. That is, the limb cannot be passively moved to the maximum ROM, either. This is an indication of contracture in the joint. Therefore, stretching exercise is recommended as the first exercise (Eg1). Another example rule is given below:

$$\textbf{Rule} \quad If \quad \boldsymbol{f\_forcex} > 30\% \quad and \quad \boldsymbol{f\_forcex} < 40\%, \quad Ex1 = f\_isometric, Ex2 = f\_resistive\_medium$$

In this rule, the $\boldsymbol{f\_forcex}$ value refers to the flexion force deficiency value of the patient. The patient's value of force deficiency is between 30% and 40%. Therefore, an isometric exercise is recommended. In addition, since the force deficiency value is not higher than 50%, a resistive exercise is recommended as the second exercise with the difficulty level set to ”moderate”. Once the exercise type has been determined, the exercise parameters are also determined by the rules. An example rule is given below:

$$\textbf{Rule} \quad If \quad \boldsymbol{Ex1{=}{=}f\_stretching}, Ex1p = \boldsymbol{f\_p\_ROM} + 5$$

In this rule, $\boldsymbol{f\_p\_ROM}$ refers to passive joint ROM in the flexion direction. *Eg1p* is the first exercise parameter. As a parameter of flexion stretching exercise, a value 5° higher than the passive joint ROM is suggested. Another example rule is given below:

$$\textbf{Rule} \quad If \quad \boldsymbol{Ex1{=}{=}f\_isometric}, Ex1p = \boldsymbol{f\_force/2}$$

In this rule, ***f__force*** is the maximum force of the patient in the direction of flexion. Half of the maximum force is recommended as the first repetition parameter of the flexion isometric exercise.

3.7. Conventional controller

The task of the conventional controller is to select the appropriate controller according to the exercise type and parameters coming from the central processing unit and to calculate the required torque values and send them to the motor drivers.

The central processing unit sends the exercise type and parameters from the therapeutic exercise database to the conventional controller. The conventional controller selects the appropriate control method according to the type of exercise from the rule-based structure that it has. The impedance control is used for exercises that require force control, and PID control method is used for exercises that require position control. There is a transition between the PID control, force-based impedance control, and variable impedance control modes according to the type of control that each exercise requires. Exercise types and control methods in the rule base of conventional controller are given in Table 2.

Table 2. Control methods and exercise parameters according to exercise types.

Exercise type	Control method	Exercise parameters
Passive	PID control	Movement type, ROM, movement speed
Active assistive	Force-based impedance + PID control	Target position
Stretching	PID control	Target Position
Isometric	PID control	Movement type, target force
Isotonic	Force-based impedance control	Target position, target force
Resistive	Force-based impedance control	Target speed, ROM, manipulator stiffness
Vario-resistive	Variable impedance control	Target speed, ROM, manipulator stiffness

The dynamic behavior of the robotic system in the force-based impedance control mode for fle-ext and uln-rad deviation units given as;

$$M_d\ddot{x} + B_d\dot{x} - F_d = -F_{ext} \tag{6}$$

where M_d, B_d, and F_d are the desired mass, damping, and force, respectively. F_{ext} is the external force applied by the patient. $\dot{x}$ and $\ddot{x}$ are linear velocity and acceleration. By applying the dynamic equations of the robotic system, the torque equation is obtained as follows:

$$\tau = MJ(q)^{\dagger}(M_d^{-1}(F_d - F_{ext} - B_d\dot{x}) - \dot{J}(q)\dot{q}) + G(q) + F(\dot{q}) + J(q)^T F_{ext} \tag{7}$$

where M is the total inertia of the link, motor, and the gear. The q, $\dot{q}$, and $\ddot{q}$ are the angular position, velocity, and acceleration of the robot joint, respectively. $J(q)$ is the Jacobian vector, $J(q)^{\dagger}$ denotes the pseudoinverse of the Jacobian vector. The $G(q)$ and $F(\dot{q})$ are the gravity and friction forces, respectively.

In the variable impedance control equation, the value of B_d changes depending on the ROM.

$$\tau = MJ(q)^{\dagger}(M_d^{-1}(F_d - F_{ext} - [(\theta_{max} - |\theta|)(B_{d_{max}} - B_{d_{min}})(\theta_{max})^{-1}] + B_{d_{min}}\dot{x}) - \dot{J}(q)\dot{q})$$
$$+G(q) + F(\dot{q}) + J(q)^T F_{ext} \tag{8}$$

where θ and θ_{max} are the actual and maximum ROM of the joint. The $B_{d_{max}}$ and $B_{d_{min}}$ are the maximum and minimum values of the desired damping. According to the maximum and minimum value of the joint ROM, B_d varies within the defined limits.

4. Results and discussion

The ability of the developed robotic system to perform therapeutic exercises is given in [24] along with the test studies with healthy subjects. In this study, the assessment and treatment suggestion performance of the controller was demonstrated through test studies conducted with 8 voluntary patients. Each patient was examined at the Şişli Hamidiye Etfal Hospital's Physical Therapy and Rehabilitation ward by a physician, who took their ROM and grasping force measurements manually, and then the exercises that should be applied were determined. Subsequently, the measurements of the patients were performed and a treatment suggestion was made after the joint ROM and force/torque deficiencies were determined by the robotic system. Measurements and treatment recommendations made by the physician were compared with made by the robotic system. As a result of this comparison, the performance of the robotic system as well as the accuracy of its measurement and assessment capability were demonstrated. Figure 4 shows the manual assessment procedures performed by a physician in a clinic and the assessment performed by the system.

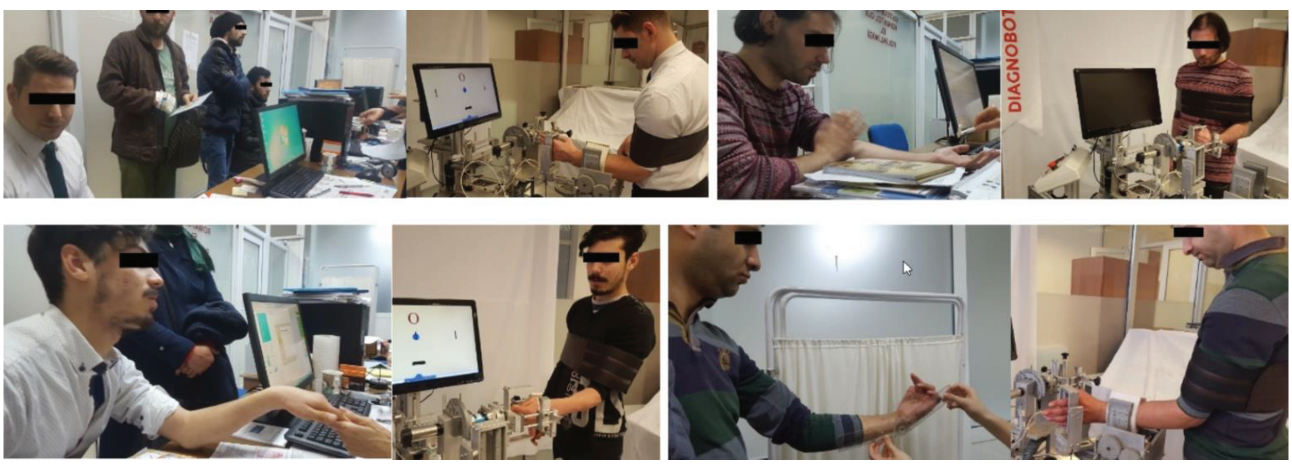

Figure 4. Pictures from the diagnosis and treatment processes.

Patient information is given in Table 3. The first and sixth patients suffered from a carpal bone fracture as a result of falling, the second patient had a brachial plexus laceration, the third patient had an elbow fracture, the fourth and eighth patients had a nerve laceration, and the fifth and seventh patients suffered from a forearm fracture. Each patient experiment consists of two phases. In the first phase, the ROM and grasping force measurements made by the physician in the hospital and the ROM, grasping force and joint force/torque biomechanical measurements taken by the robotic system are provided. The target biomechanical values calculated by the intelligent controller and the percentage of deficiencies identified according to these values are given in this section. In the second phase, the accuracy of the robotic system was determined by comparing the exercise methods suggested by the physician and the exercises suggested by the robotic system.

Table 3. Personal information of the patients.

	P1	P2	P3	P4	P5	P6	P7	P8
Age	29	28	24	28	25	26	22	25
Height (cm)	182	176	177	185	180	175	179	186
Weight (kg)	86	78	61	78	81	64	82	91
Forearm length (cm)	27	25	25	27	26.5	25	26	27
Forearm circum. (cm)	26	25	23.5	25	25.2	24.5	25.5	26
Dominant hand	Right	Left	Right	Right	Right	Right	Left	Right
Treated hand	Left	Left	Left	Left	Left	Right	Right	Right

4.1. Biomechanical measurements and assessment of percentages of deficiency

The measurements made by the physician and by the robotic system are given in Table 4. There are 3 parameters for each patient. These parameters are biomechanical measurements made by the physician, those made by the robotic system, and the difference between the measurements made by the physician and by the robotic system. According to the values given in the table, the differences between the measurements performed by the physician and the robotic system in the ROM of the first patient vary between 2.3% and 10%. For the third patient, there is 38% difference in the radial deviation ROM between the measurements made by the physician and by the robot. The reason for this is that this movement's joint ROM is too small; nonetheless, the robot is capable of very precise measurements. The differences between measurements for the seventh patient ranged from 1% to 21.3%. The 21.3% difference was observed in the ulnar deviation. This is because the patient's ROM is too small and the robot can measure these small values more precisely. As can be seen from the results, the developed robotic system successfully performed measurements for all patients. Joint force measurements not performed by physicians were performed by the robot. This is one of the important contributions of the developed controller to the medical literature. These measurements, which are very significant in rehabilitation, have made a significant contribution to clinical diagnostic procedures.

The deficiencies of the patients are given in Table 5. There are 3 parameters in the table. Desired biomechanical parameters and the difference between the desired and the patient's biomechanical parameters, respectively. The ROM deficiencies are indicated in red and the force/torque deficiencies are indicated in blue. The DBP values for the joint ROMs are taken from the literature. In addition, DBP values related to joint forces are calculated by the controller. The deficiency percentages below 10% are not taken into account on the recommendation by physicians.

For the first patient, except for the ulnar deviation, the deficiency percentages in the joint ROM are 10% or less. For the ulnar deviation movement, the robotic system identified a 40% deficiency in the joint ROM.

The ROM deficiencies for the second patient range from 22% to 93%. The force/torque deficiencies are between 47% and 88%.

The third patient's supination is neutral, i.e. 0°.

For the fourth patient, the percentage of deficiencies in the joint ROM other than flexion is below 10%. Therefore, no exercises have been recommended for these joints. Force/torque deficiencies are between 17% and 43%.

The ROM deficiencies of the fifth patient range from 11% to 60%. The force/torque deficiencies, on the other hand, are between 34% and 76%.

Table 4. Biomechanical measurements performed by the physician and the robotic system (PM: physician measurements, SM: system measurements, D: difference (%)).

	Patient 1			Patient 2			Patient 3			Patient 4		
	PM	SM	D	PM	SM	D	PM	SM	D	PM	SM	D
Flexion ROM(°)	80	72	10	80	73	8.7	70	72.5	3.6	45	54	20
Extension ROM(°)	65	63.5	2.3	50	51	2	25	25.8	3.2	55	63.3	15
Ulnar dev. ROM(°)	20	21	5	0	2.5	0	15	18	20	30	32.2	7
Radial dev. ROM(°)	20	18	10	25	25	0	5	6.9	38	25	28	12
Pronation ROM(°)	70	72	2.8	50	54.7	9.4	75	75	0	90	89.2	0
Supination ROM(°)	80	78	2.5	80	82	0	0	0	0	90	90.6	0
Grasping force (N)	37	39.2	5.9	11	12.1	9.6	0.8	1.27	58	12	12.2	1.6
	Patient 5			Patient 6			Patient 7			Patient 8		
	PM	SM	D	PM	SM	D	PM	SM	D	PM	SM	D
Flexion ROM(°)	55	53	3.6	70	62	11	45	41.4	8	70	68.1	2.7
Extension ROM(°)	40	41.6	4	70	65.2	6.8	50	46	8	75	71.4	4.8
Ulnar dev. ROM(°)	15	14	13	35	34.4	1.7	15	12.8	21.3	30	29.7	1
Radial dev. ROM(°)	10	11.6	16	25	23.3	6.8	10	10.1	1	20	18.8	6
Pronation ROM(°)	70	68.4	2.2	90	86.3	4.1	75	72	4	70	63.8	8.9
Supination ROM(°)	80	75.9	5.1	90	88	2.2	90	83.3	7.4	80	77.4	3.3
Grasping force (N)	24	22.6	5.8	20	19.4	3	4	3.55	11	44	41.6	5.4

For the sixth patient, percentage of deficiencies in the joint ROM other than flexion is below 10%. For the eighth patient, only percentage of deficiency higher than 10% was in the flexion and ulnar deviation.

Considering the results, it is seen that the controller has successfully determined the percentage of deficiency. When we compare it with the examples in the literature, it is not possible to find a controller structure that has an evaluation capability in this scale.

4.2. Treatment recommendations

As a result of the measurements made in the hospital, the necessary exercises were recommended by the physician. As a result of the measurements and calculations made by the robotic system, the necessary exercises were recommended by the intelligent controller. For example, the type and parameters of exercise recommended by the controller for patient 3 are shown in Table 6 in detail. Similar results were obtained for all of the other 7 patients.

As shown in Table 6, isometric and isotonic exercises were recommended by the robotic system in the flexion and extension. The active joint ROM in the extension is 25.8, while the percentage of deficiency is 63%. The passive extension angle is full (70°). This shows that there is no contracture in the joint and it can be opened passively. Therefore, the robotic system recommends an active-assistive exercise at a 70° ROM for the extension movement. The active joint ROM in ulnar and radial deviation are 18° and 6.9° and the deficiencies are 48% and 65%, respectively. Passive ulnar-radial deviation angles are full (35° and 20°). This shows that there is no contracture. Therefore, the robotic system recommended a 35° active-assistive exercise in ulnar deviation and 20° in radial deviation. However, it recommended an isometric exercise with force values of 8N

Table 5. Deficiencies of the patients. (DBP: desired biomechanical parameter, PBP: patient's biomechanical parameter, D: deficiency (%)).

	Patient 1			Patient 2			Patient 3			Patient 4		
	DBP	PBP	D	DBP	PBP	D	DBP	PBP	D	DBP	PBP	D
Flexion ROM(°)	80	72	10	80	73	9	80	72.5	9	80	54	32
Extension ROM(°)	70	63.5	9	70	51	27	70	25.8	63	70	63.3	9
Ulnar dev. ROM(°)	35	21	40	35	2.5	93	35	18	49	35	32.2	8
Radial dev. ROM(°)	20	18	10	20	25	0	20	6.9	65	20	28	0
Pronation ROM(°)	70	72	0	70	54.7	22	70	75	0	70	89.2	0
Supination ROM(°)	85	78	8	85	82	4	85	0	100	85	90.6	0
Flexion force (N)	98.9	77	22	99.8	44	56	76.2	41.9	45	91.7	52.7	43
Extension force (N)	74.4	56	24	77.5	29.8	62	56	19.6	65	68.3	49.7	27
Ulnar dev. force (N)	86.3	49	43	85.5	10.6	88	60.8	17.6	71	78.2	63	19
Radial dev. force (N)	97.3	60	38	97.6	39.5	59	68.8	30.2	56	88.2	67.6	23
Pronation torque (Nm)	6.3	4.4	30	6.2	2.86	54	4	2.09	48	5.5	6.52	0
Supination torque (Nm)	8	5.1	37	7.9	4.22	47	5.5	0.78	86	7.3	6	17
	Patient 5			Patient 6			Patient 7			Patient 8		
	DBP	PBP	D	DBP	PBP	D	DBP	PBP	D	DBP	PBP	D
Flexion ROM(°)	80	53	34	80	62	23	80	41.4	48	80	68.1	15
Extension ROM(°)	70	41.6	41	70	65.2	7	70	46	34	70	71.4	0
Ulnar dev. ROM(°)	35	14	60	35	34.4	2	35	12.8	63	35	29.7	15
Radial dev. ROM(°)	20	11.6	42	20	23.3	0	20	10.1	49	20	18.8	6
Pronation ROM(°)	70	68.4	2	70	86.3	0	70	72	0	70	63.8	9
Supination ROM(°)	85	75.9	11	85	88	0	85	83.3	2	85	77.4	9
Flexion force (N)	94.3	39.6	58	79.8	44.7	44	94.6	24.6	74	104	65	37
Extension force (N)	70.2	33.7	52	57.6	41.5	28	71.7	30.1	58	78.1	61.7	21
Ulnar dev. force (N)	80	28	65	63.9	58.8	8	82.4	43.7	47	91.3	70.3	23
Radial dev. force (N)	91.2	21.9	76	72	64.1	11	93.1	41.9	55	103	74.1	28
Pronation torque (Nm)	5.8	3.81	34	4.3	4.07	5	5.9	3.21	46	6.7	4.72	30
Supination torque (Nm)	7.6	3.97	48	5.8	4.2	28	7.7	3.62	53	8.6	4.91	43

and 15N in the ulnar and radial deviation to increase the strength. The active ROM in supination is 0° and the passive ROM is 47°. This means that the joint cannot passively open up to 80°, the maximum degree to which the joint can open, which shows that there is contracture. For this reason, the robotic system recommended a 52° stretching exercise in supination.

The treatment recommendations made by the physician and the intelligent controller for all the patients are compared in Table 7. As shown, the treatment recommendations made by the robotic system and those made by the physician are compatible. While some patients were recommended a resistive exercise by the physician, the robotic system recommended an isometric or isotonic exercise. The reason for this is that the resistive exercises assigned by the physicians incorporate all the exercises in which resistance is applied to the patient [23]. The controller elaborated the exercise recommendation and suggested isometric and isotonic

Table 6. Exercise types and parameters recommended by the intelligent controller (Patient 3).

Exercise type	Exercise parameters			Exercise type	Exercise parameters		
	Set 1	Set 2	Set 3		Set 1	Set 2	Set 3
Flexion isometric	21 N	31 N	42 N	Rad. dev. act-assistive	20°		
Flexion isotonic	42 N	31 N	21 N	Rad. dev. isometric	15 N	23 N	30 N
Extansion act-assistive	70°			Pronation isometric	1 Nm	1.5 Nm	2 Nm
Extansion isometric	10 N	15 N	20 N	Pronation isotonic	2 Nm	1.5 Nm	1 Nm
Extansion isotonic	20 N	15 N	10 N	Supination stretching	52°		
Uln. dev. act-assistive	35°			Supination isometric	0.4 Nm	0.6 Nm	0.78 Nm
Uln. dev. isometric	8 N	12 N	17 N				

exercises, which are types of resistive exercise. For some patients, while the physician recommended an ROM exercise, the robotic system recommended an active-assistive or stretching exercise. These exercises are also within the scope of ROM exercises. In accordance with the assessment results, the robotic system can suggest exercises. In other words, the controller structure can decide the exercise type in accordance with the purpose of its development. Consequently, the intelligent controller structure successfully carries out an assessment and treatment recommendation.

5. Conclusion

In this study, an intelligent controller that can perform assessment and treatment for a rehabilitation robot has been developed. The controller has a decision support system that also incorporates a powerful database supported by statistical methods. The controller interprets the patient's biomechanical measurements at the stage of assessment and treatment recommendation. Using these measurements and the healthy human database, it produces a result according to the joint ROM and the force/torque deficiencies provided by the correlation and regression analysis. Based on this result, it determines the exercise type and parameters for each movement using the therapeutic exercise database. The performance of the controller was demonstrated by tests with patients. Test results have shown that the developed controller can perform assessment and treatment suggestion with very high accuracy.

In the future work, the amount of data in the healthy human database will be increased. In this way, a deep learning algorithm can be integrated into the developed controller by using this large data pool. Besides, we are planning to incorporate artificial neural network-based learning methods into the control structure. All databases in the developed controller are kept on the internet. This makes it possible to integrate more robots into the system. All robots will be able to access these databases and the mobile application infrastructure to perform assessment and treatment.

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Table 7. Exercise recommendations made by the physician and the robotic system.

	Patient 1		Patient 2		Patient 3		Patient 4	
	Doctor	System	Doctor	System	Doctor	System	Doctor	System
Fle	Isometric Resistive	Isometric Resistive	Isometric Resistive	Isometric Isotonic	Isometric Resistive	Isometric Isotonic	ROM Isometric Resistive	Active asi. Isometric Resistive
Ext	Isometric Resistive	Isometric Resistive	ROM Isometric Resistive	Active asi. Isometric Isotonic	ROM Isometric Resistive	Active asi. Isometric Isotonic	Isometric Resistive	Isometric Resistive
Uln	ROM Isometric	Active asi. Isometric	ROM Isometric	Stretching Isometric	ROM Isometric	Active asi. Isometric	Isometric Isotonic	Isometric Isotonic
Rad	Isometric	Isometric	Isometric	Isometric	ROM Isometric	Active asi. Isometric	Isometric Isotonic	Isometric Isotonic
Pro	Isometric Resistive	Isometric Resistive	ROM Isometric	Stretching Isometric	Isometric Resistive	Isometric Isotonic	Resistive	Resistive
Sup	Isometric Resistive	Isometric Resistive	Isometric Resistive	Isometric Isotonic	Stretching Isometric	Stretching Isometric	Isometric Resistive	Isometric Resistive
	Patient 5		Patient 6		Patient 7		Patient 8	
	Doctor	System	Doctor	System	Doctor	System	Doctor	System
Fle	ROM Isometric Resistive	Active asi. Isometric Isometric	ROM Isometric Resistive	Active asi. Isometric Resistive	ROM Isometric Isotonic	Stretching Isometric Isotonic	ROM Isometric Resistive	Active asi. Isometric Resistive
Ext	ROM Isometric Resistive	Active asi. Isometric Isotonic	Isometric Resistive	Isometric Resistive	ROM Isometric Resistive	Stretching Isometric Isotonic	Isometric Resistive	Isometric Resistive
Uln	ROM Isometric	Active asi. Isometric			ROM Isometric	Stretching Isometric	ROM Isometric	Active asi. Isometric
Rad	ROM Isometric	Active asi. Isometric	Isometric	Isometric	ROM Isometric	Stretching Isometric	Isometric	Isometric
Pro	Isometric Resistive	Isometric Resistive	Resistive	Resistive	Isometric Resistive	Isometric Isotonic	Isometric Resistive	Isometric Resistive
Sup	ROM Isometric Resistive	Active asi. Isometric Resistive	Isometric Resistive	Isometric Resistive	Isometric Resistive	Isometric Isotonic	Isometric Resistive	Isometric Resistive

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