Variable Impedance Control for Rehabilitation Robot using Interval Type-2 Fuzzy Logic

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ABSTRACT

In this study, a novel variable impedance control for a lower-limb rehabilitation robotic system using voltage control strategy is presented. The majority of existing control approaches are based on control torque strategy, which require the knowledge of robot dynamics as well as dynamic of patients. This requires the controller to overcome complex problems such as uncertainties and nonlinearities involved in the dynamic of the system, robot and patients. On the other hand, how impedance parameters must be selected is a serious question in control system design for rehabilitation robots. To resolve these problems this paper, presents a variable impedance control based on the voltage control strategy. In contrast to the usual current-based (torque mode) the use of motor dynamics lees to a computationally faster and more realistic voltage-base controller. The most important advantage of the proposed control strategy is that the nonlinear dynamic of rehabilitation robot is handled as an external load, hence the control law is free from robot dynamic and the impedance controller is computationally simpler, faster and more robust with negligible tracking error. Moreover, variable impedance parameters based on Interval Type-2 Fuzzy Logic (IT2Fl) is proposed to evaluate impedance parameters. The proposed control is verified by a stability analysis. To illustrate the effectiveness of the control approach, a 1-DOF lower-limb rehabilitation robot is designed. Voltage-based impedance control are simulated through a therapeutic exercise consist of Isometric and Isotonic exercises. Simulation results show that the proposed voltage-based variable impedance control is superior to voltage-based impedance control in therapeutic exercises.

1. Introduction

Nowadays, neurological impairments such as Stroke and Cerebral Palsy are the most common forms of disability in adults and children, respectively. People with neurological impairment often have compromised volitional control of their arm and legs limiting their ability to undertake activities of daily living such as walking. The core mechanisms of rehabilitation interventions to promote lower limb function involve intensive practice of functional tasks, which drives neural plasticity to improve motor skills. However

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weakness of the lower limb makes it difficult for the neurologically impaired to practice at the necessary intensity. One-way of providing the required support for the neurologically impaired is to utilize rehabilitation robotic technology to enable practice of useful lower limb movements. The rehabilitation robotics enable the control of the spatial and temporal characteristics of movements [1].

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. The hybrid control was successfully implemented on the LOKOMAT robotic system [2-4]. Compared with other control methods, the impedance control is more effective and flexible to apply a wide range of rehabilitation exercises in the presence of uncertainties [5]. The therapeutic robots such as MIT-MANUS employ impedance control for passive and resistive exercises [6]. An impedance control law is a desired dynamics, which a rehabilitation robot should show in contact with human to perform a commanded therapeutic exercise. Because of applying impedance control, the robotic system will interact with the environment such a mass-spring-damper system in response to the applied force from the environment.

In rehabilitation robot and other case that the environment's dynamics changing in during task execution has been observed that impedance control with fixed impedance parameters is not effective [7]. Moreover, how impedance parameters must be selected is great question in control system design for rehabilitation robots. Parameters of impedance control are often tuned empirically and intuitively; hence, the system designers have to adjust them according to individuals. Due to this issue, users sometimes have to adapt themselves to the controlled machine when the tuning condition given by the designer is not adequate for the user [8].

To resolve these problems variable impedance has been proposed which impedance parameters adapted according to various characteristics in real time. Impedance parameters have been regulated by some different ways such as varying impedance parameters with fuzzy logic systems [9] adaptive strategies [10] and switching mechanisms [11]. Selsuk et al. proposed impedance control, which gain of mechanical impedance was modified by a fuzzy logic PID controller [12].

G. Xu et al have used fuzzy and fuzzy neural network impedance controller to regulate impedance parameters‹. In this studies control method needs to impaired limb parameters for regulate impedance parameters [13, 14]. Also G. Xu et al presented adaptive hierarchical control for upper limb rehabilitation which combines the high-level progressive resistive supervisory controller with a low-level adaptive resistive force triggered controller [15]. Y. Choi et al have proposed a novel robotic adaptive and automatic presentation of tasks. In this study, the high-level adaptive task scheduler regulated task and difficulty of exercise according to physiotherapist, prior practice database and task bank. Then function task model generated desired trajectory for admittance controller [16].

Impedance control is basically defined as a torque control scheme. In the other words, the joint torques of robot are commended to implement impedance control. For this purpose, the controller should overcome complex problems such as uncertainty and nonlinearity involved in the dynamics of the robotic system. Also in torque control scheme, control system design depends on dynamics of patient's limb. Dynamics of patient's limb is nonlinear, unknown and Varies with time. Furthermore, majority of the proposed control approaches have ignored the dynamics of actuators, which are important in motion control and generally this proposed control approaches need to use estimator to estimate patient's limb parameters [15, 16]. In the torque based control approaches, it is assumed that the actuators can provide the commanded torques for the robot joints. However, this assumption may not be satisfied perfectly due to some practical problems such as the actuator dynamics, actuator saturation and sensing limitations.

In order to overcome nonlinearity of the robotic system and considering the actuators and moreover to create a robot with the ability to adapt to the patient's status in real-time, this paper presents a novel adaptive impedance control for a rehabilitation robot, which can be less dependent on the model of robot dynamics. The impedance parameters are regulated in real-time by IT2FLS according to position error, velocity error and error of force. The proposed control is developed based on the voltage control strategy [17] that differs from the commonly used strategy called, torque control strategy. Compared with a torque control scheme, it is simpler, less computational and more efficient.

The remaining of this paper is organized as follows: Section 2 formulates the dynamics of the rehabilitation robot. Section 3 develops Interval Type-2 Fuzzy Logic Systems. In section 4, we presented the impedance control to perform recommended exercises by a physiotherapist specializing in knee therapies. Section 5 presents stability analysis and evaluates the control

performance. Section 6 illustrates the simulation results. Finally, Section 7 concludes the paper.

2. System Dynamics

In general, an electrically driven rehabilitation robot consists of n links interconnected at n joints into an open kinematic chain. Each link is driven by a permanent magnet dc motor through the gears. We assume that both the links and the couplings between the electric motors and links are perfectly rigid. The dynamic model [9] can thus be described by n generalized coordinates representing the degrees-of-freedoms of the n joints as

$$D_r(q)\ddot{q} + C_r(q,\dot{q})\dot{q} + g_r(q) + \tau_e = \tau_r \qquad (1)$$

where $q \in R^n$ is the vector of joint positions, $D_r(q) \in R^n$ is the matrix of manipulator inertia, $C_r(q,\dot{q})\dot{q} \in R^n$ is the vector of centrifugal and Coriolis torques, $g_r(q) \in R^n$ is the vector of gravitational torques, $\tau_e \in R^n$ is the vector of load torque, and $\tau_r \in R^n$ is the torque vector of robot. Note that vectors and matrices are bold for clarity.

The load torque is actually provided by the human lower limb located on the robot express as

$$D_e(q)\ddot{q} + C_e(q,\dot{q})\dot{q} + g_e(q) + \tau_h = \tau_e \qquad (2)$$

where associated with human body, $D_e(q) \in R^n$ is the inertia matrix, $C_e(q,\dot{q})\dot{q} \in R^n$ is the vector of centrifugal and Coriolis torques, $g_e(q) \in R^n$ is the vector of gravitational torques, $\tau_h \in R^n$ is the vector of generated torque by human. Note that vectors and matrices are bold for clarity.

The mechanical section of the rehabilitation robot is obtained by substituting (2) into (1) to obtain

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + \tau_h = \tau_r \qquad (3)$$
where

$$D(q) = D_r(q) + D_e(q) \qquad (4)$$
$$C(q) = C_r(q,\dot{q}) + C_e(q,\dot{q}) \qquad (5)$$
$$g(q) = g_r(q) + g_e(q) \qquad (6)$$

The electric motors provide the joint torques of the robot as follows

$$J_m r^{-1}\ddot{q} + B_m r^{-1}\dot{q} + r\tau_r = \tau_m \qquad (7)$$

where $\tau_m \in R^n$ is the torque vector of motors, J_m, B_m and r are the $n \times n$ diagonal matrices for motor coefficients namely the inertia, damping, and reduction gear, respectively. Vectors of the joint velocities $\dot{q}$ and the motor velocities $\dot{\theta}_m \in R^n$ are related through the gears to yield

$$\dot{q} = r\dot{\theta}_m \qquad (8)$$

In order to obtain the motor voltages as the inputs of system, we consider the electrical equation of geared permanent magnet dc motors in the matrix form,

$$RI_a + L\dot{I}_a + K\dot{q} + \varphi = V \qquad (9)$$

where $K = K_b r^{-1}$, $V \in R^n$ is the vector of motor voltages, $I_a \in R^n$ is the vector of motor currents, and $\varphi \in R^n$ is the vector of external disturbances. R, L and K_b represent the $n \times n$ diagonal matrices for the coefficients of armature resistance, inductance, and back-emf constant, respectively.

The motor torque vector τ_m as the input for dynamic equation (14) is produced by the motor current vector,

$$\tau_m = K_m I_a \qquad (10)$$

where K_m is a diagonal matrix of the torque constants. The state-space model of the electrically driven robot manipulator is introduced by the use of equations (1)-(10) as

$$\dot{z} = f(z) + bW + b\varphi \qquad (11)$$

where $W = \begin{bmatrix} \tau_h \\ V \end{bmatrix}$ is considered as the inputs, $z = [q\ \dot{q}\ I_a]^T$ is the state vector, b and $f(z)$ are of the form

$$f(z) = \begin{bmatrix} z_2 \\ A(-(B_m r^{-1} + rC(z_1,z_2))z_2 - rg(z_1) + K_m z_3) \\ -L^{-1}(K_b r^{-1}z_2 + Rz_3) \end{bmatrix}$$

where

$$A = (J_m r^{-1} + rD(z_1))^{-1}$$

$$b = \begin{bmatrix} 0 & 0 \\ (J_m r^{-1} + rD(z_1))^{-1} rJ_e^T(z_1) & 0 \\ 0 & L^{-1} \end{bmatrix}_r \qquad (12)$$

The state-space equation (11) shows a highly coupled nonlinear large multivariable system. Complexity of the model has been a serious challenge in the literature of robot modelling and control.
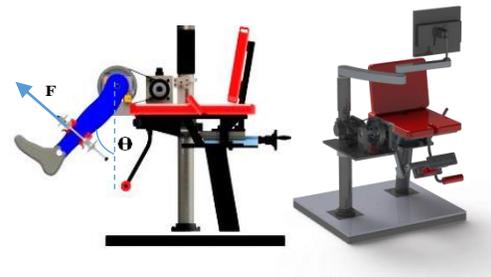

Fig. 1. A schematic of rehabilitation robot

It can be obtained by using (9) and (12) that

$$RI_a + L\dot{I}_a + K\dot{q} = V \qquad (13)$$

3. Interval Type-2 Fuzzy Logic Systems

A fuzzy logic system that uses at least one type-2 fuzzy set is called a type-2 fuzzy logic system. It is very useful in circumstances, where the determination of an exact membership grade for a fuzzy set is difficult [18]. As illustrated in Fig. 2, a type-2 fuzzy MF can be obtained by starting with a type-1 MF and blurring it. The extra mathematical dimension provided by the blurred area represents the uncertainties in the shape and

position of the type-1 fuzzy set and is referred to as the footprint of uncertainty (FOU).

The FOU is bounded by upper and lower MFs, and points within the "blurred area" have membership grades given by type-1 MFs. The most frequently used type-2 fuzzy sets are interval fuzzy sets, where each point in the FOU has unity secondary membership grade [19].

An interval type-2 fuzzy set $\tilde{A}$ in X is defined as [20]

$$\tilde{A} = \frac{\int_{x \in X}\left[\int_{x \in J_x} \frac{1}{u}\right]}{x}, J_x \subseteq [0 - 1] \tag{14}$$

where x is the primary variable with domain X, u the secondary variable which has domain J_x, J_x is called the primary membership of x. Uncertainty about $\tilde{A}$ is conveyed by

the union of all the primary memberships called the footprint of uncertainty (FOU) of $\tilde{A}$, i.e., [21]

$$FOU(\tilde{A}) = J_x, x \in X \tag{15}$$

The structure of a typical type-2 fuzzy logic system is shown in Fig. 3. It is similar to its type-1 counterpart. The major difference is that at least one of the fuzzy sets is type-2 and a type-reducer is needed to convert the type-2 fuzzy output sets into type-1 sets so that they can be processed by the defuzzifire to give a crisp output [18]. General type-2 fuzzy logic systems (FLSs) are computationally intensive because type-reduction is very intensive [18, 22].
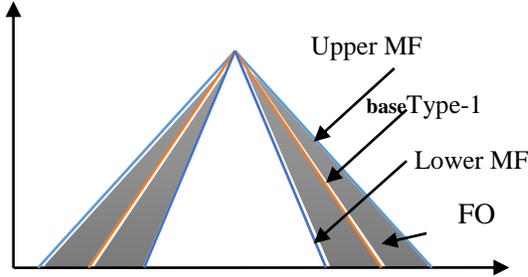

Fig. 2. Type-2 fuzzy logic membership function

Therefore, we will use in this work the interval type-2 fuzzy logic systems for their simplicity and efficiency. We design the fuzzy systems by the use of two inputs. If we select three fuzzy sets for each input, the whole control space will be covered by 9 fuzzy rules. The fuzzy rules are of the form of

R^i : if x_1 is $\tilde{X}_1^i$ and x_2 is $\tilde{X}_2^i$ then $y^i = a_{i1}x_1 + a_{i2}x_2 + a_{i0}$

$$i = 1,2,\dots,m \tag{16}$$

where $\tilde{X}_j^i (j = 1,2)$ is an interval type-2 fuzzy set and the inputs of rule R^i is $x = (x_1, x_2) \in U \in \mathbf{R}^2$, U is the universe of discourse. M is the number of rules, and in the i-th rule (R^i), a_{i1} and a_{i2} are the gains in

consequent part for $i = 1, 2$, y_i is the crisp output. The proposed interval type-2 fuzzy system is for the case when antecedents are interval type-2 fuzzy sets (A2) and consequents are crisp numbers (C0) [23]. The inference engine combines all the ring rules and gives a nonlinear mapping from the input interval type-2 fuzzy sets to the output interval type-2 fuzzy sets.

The firing strength set of the i-th rule is [22]

$$F^i(x) = \left[\underline{f}^i(x), \bar{f}^i(x)\right] = \left[\underline{f}^i, \bar{f}^i\right] \tag{17}$$

where

$$\underline{f}^i = \underline{\mu}_{\tilde{X}_1^i(x1)} \times \underline{\mu}_{\tilde{X}_2^i(x2)} \tag{18}$$

$$\bar{f}^i = \bar{\mu}_{\tilde{X}_1^i(x1)} \times \bar{\mu}_{\tilde{X}_2^i(x2)} \tag{19}$$

The terms $\underline{\mu}_{\tilde{X}_j^i(j=1,2)}$ and $\bar{\mu}_{\tilde{X}_j^i(j=1,2)}$ are the lower and upper membership grades of $\mu_{\tilde{X}_j^i}$, respectively. The type-2 fuzzy inference engine produces an aggregated output type-2 fuzzy set. The type reduction block operates on this set to generate a centroid type-1 fuzzy set known as the type-reduced set " of the aggregate type-2 fuzzy set. Several type-reduction methods have been suggested in the literature, such as the center-of-sums, the height, the modified height and the center-of-sets [18; 22]. The most commonly used one is the center-of-sets type-reducer due to its computational efficiency. That may be expressed as [18, 22]
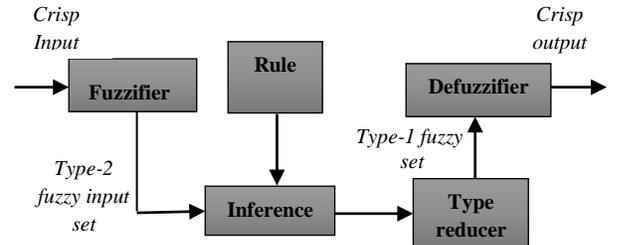

Fig.3. Scheme of a type-2 fuzzy logic system

$$Y_{cos}(x) = [y_l, y_r] = \bigcup_{f^i \in F^i(x)} \frac{\sum_{i=1}^M f^i y^i}{\sum_{i=1}^M f^i} \tag{20}$$

where Y_{cos} is the interval set determined by two end points y_l and y_r, and firing strengths $f^i = \left[\underline{f}^i, \bar{f}^i\right] \in F^i(x)$. y_l and y_r can be expressed as

$$y_l = \frac{\sum_{i=1}^L \bar{f}^i y^i + \sum_{i=L+1}^M \underline{f}^i y^i}{\sum_{i=1}^L \bar{f}^i + \sum_{i=L+1}^M \underline{f}^i} \tag{21}$$

$$y_r = \frac{\sum_{i=1}^R \underline{f}^i y^i + \sum_{i=R+1}^M \bar{f}^i y^i}{\sum_{i=1}^R \underline{f}^i + \sum_{i=R+1}^M \bar{f}^i} \tag{22}$$

Two end points y_l and y_r can be computed efficiently using the Karnik-Mendel (KM) algorithms [22]. Since

the type- reduced set is an interval type-1 set, the defuzzifire output is [18]

$$y(x) = 0.5(y_l + y_{r)}) \qquad (23)$$

4. Control strategy

An impedance rule is proposed as

$$D_d(t)(\dot{q_d} - \dot{q}) + K_d(t)(q_d - q) = \tau_h \qquad (24)$$

where $D_d(t)$ and $K_d(t)$ are the diagonal matrices, which include the desired impedance parameters that regulate by IT2FL systems. From (24), we have

$$\dot{q_d} + D_d^{-1}(t)K_d(t)(q_d - q) + D_d^{-1}(t)\tau_h = \dot{q} \qquad (25)$$

An impedance controller which establishes the impedance rule (14) is proposed as

$$RI_a + L\dot{I}_a + K(\dot{q_d} + D_d^{-1}K_d(t)(q_d - q) + D_d^{-1}(t)\tau_h) = V \qquad (26)$$

The closed loop system is formed by substituting the control law (16) into the system (9) as

$$RI_a + L\dot{I}_a + K(\dot{q_d} + D_d^{-1}(t)K_d(t)(q_d - q) + D_d^{-1}(t)\tau_h) = RI_a + L\dot{I}_a + K\dot{q} \qquad (27)$$

We design IT2FL system to determined impedance parameters adaptively, we consider the $X_{1K} = F_d - F_h$ and $X_{2K} = e$ as inputs. Where e is a position error and defined as $e = X_d - X$. The IT2FL takes these two inputs and provides an impedance parameters K_d .

The membership functions of an IT2FL can be assumed as triangular functions, trapezoidal functions, Gaussian functions, etc [24]. In this study, Gaussian functions are used. The membership functions for K_d and D_d are shown in Figure 4 and Figure 5, respectively. Note that "N" stands for negative, "E" stands for 0, and "P" stands for positive. All the universes of discourses are normalized and arranged in [-1 1] for inputs. The rules of the fuzzy systems are given in Section table 2 and 3.
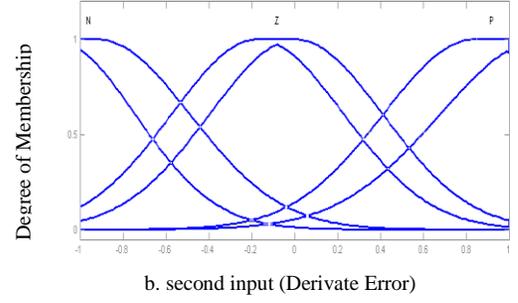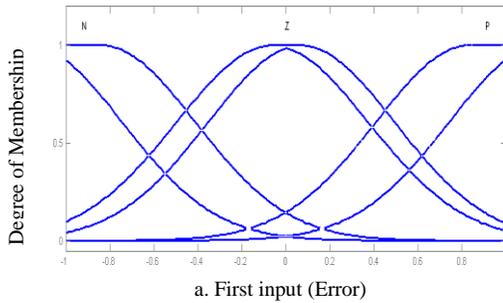

a. First input (Error)

b. second input (Derivate Error)

Fig. 4. Membership function of the type-2 FLS for K_d

a. First input (Error)

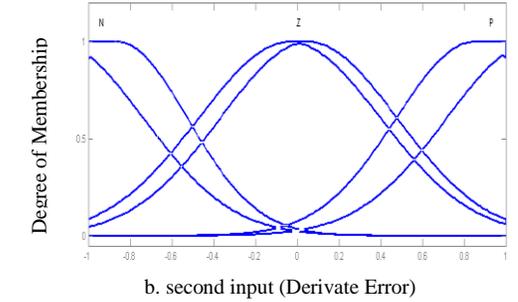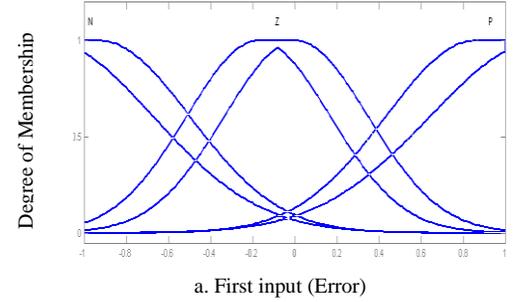b. second input (Derivate Error)

Fig. 5. Membership function of the type-2 FLS for D_d

Table 1 : Fuzzy Rules ($D_d(t)$)

$D_d(t)$		Second input $X_{2D} = \dot{X}_d - \dot{X}$		
		N	Z	P
First input $X_{1D} = F_d - F_h$	N	2	4	6
	Z	4	6	8
	P	6	8	10

Table 2. Fuzzy Rules ($K_d(t)$)

$k_d(t)$		Second input ($X_{2K} = X_d - X$)		
		N	Z	P
First input $X_{1K} = F_d - F_h$	N	50	70	90
	Z	70	90	110
	P	90	110	130

5. Stability Analysis

A proof for the boundedness of state variables is given by stability analysis. In order to analyze the stability, the following assumptions are made:

$$D_d(t)(\dot{q}_d - \dot{q}) + K_d(q_d - q) = \tau_h \qquad (28)$$

Assumption 1 The desired trajectory in the joint-space q_d must be smooth in the sense that q_d and its derivatives up to a necessary order are available and all uniformly bounded [22]. Equation (28) shows a linear second order system with a bounded input τ_h. In (28) the suggested matrices $D_d(t)$ and $K_d(t)$ are positive diagonal matrices. Therefore, the linear system (28) is stable based on the Ruth-Hurwitz criteria. Because the input τ_h is bounded as a consequence

Result 1: $q_d - q$ and $\dot{q}_d - \dot{q}$ are bounded.

In addition, Assumption 1 states that q_d and $\dot{q}_d$ are bounded. Thus, using Assumption 1 and Result 1 yields to

Result 3: The variables q and $\dot{q}$ are bounded.

In (3), the boundedness of q, $\dot{q}$ and τ_h yields to

Result 4: The joint torque vector τ_r is bounded.

In (7), vectors of $\dot{q}$, $\ddot{q}$ and τ_r are bounded and matrices J_m, B_m and r are constant. Thus,

Result 5: The motor torque vector τ_m is bounded.

From (10), it can be written that $I_a = K_m^{-1}\tau_m$. K_m is a constant matrix and τ_m is bounded in Result 5. Therefore,

Result 6: The motor current vector I_a is bounded.

The robotic system is stable since all system states q, $\dot{q}$ and I_a are bounded.

6. Simulation Results

In this study, the Impedance Voltage Control with constant impedance parameters (IVC) [10] is compared with proposed Variable Impedance Control using IT2FL system based on Voltage Control (VIVC), which has been shown in Figure 6.
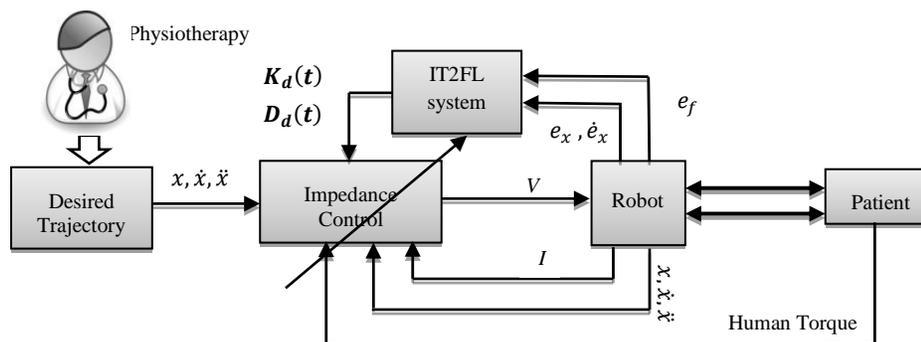
The rehabilitation robotic system is a single link robot driven by a permanent magnet dc motor as shown in Figure 1. Parameters of rehabilitation robotic system and the patient are given in Table 3, where m_r is the mass of link, m_h is the mass of patient's leg, l_r is the length of link, l_p is the length of patient's leg, and $r_c = [x_c, y_c, z_c]$ is the center of mass for the link. The inertia tensor in the center of mass is expressed as

$$I = \begin{pmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{pmatrix} \qquad (29)$$

Parameters of the motor are given in Table 4. For the tracking control, the desired trajectory should be sufficiently smooth such that all its derivatives up to the required order are bounded.

In addition, tracking the desired trajectory in the given exercise should be suitable for the patient. The desired trajectory for isotonic exercises starts from zero and goes up to 80° for the extension and stays this position for several seconds.

Table 3. Parameters of Manipulator and Patient

I_{yz}	I_{zx}	I_{zy}	I_{zz}	m_r	m_h	l_h	l_r
0	0	0	0.91	2	4	0.5	0.5

x_c	y_c	z_c	I_{xx}	I_{xy}	I_{xz}	I_{yx}	I_{yy}
0.09	-0.16	0	0.91	-0.12	0	-0.12	0.23

Table 4. The Electric Motor Parameters

V_{max}	R	K_b	L	J_m	B_m	r
40	1.6	0.26	0.001	0.0002	0.001	0.02

Fig. 6. Block diagram of the proposed control scheme

6.1. Isometric exercise

The aim of this exercise is that the specified resistance force applied to the patient while the limb angle not change. The force is determined individually for each patient by physiotherapist. In this type of exercise limb move to the desired angle, without applied any resistance force to the patient, after that the desired force applied to the patient and he or she try to not be changed the angle of limb.

Simulation results show a comparison between the proposed IVC and VIVC in Figure 7. The IVC tracks the desired trajectory very well until that in specified time desired force must be applied to the patients. In this time, constant potion error is created which according to control impedance theory is predictable. With cursory glance at the graph, we can clearly state that in comparison with IVC, the proposed adaptive impedance voltage control has less position error. The impedance control can be evaluated according to how well the impedance law is performed. For this purpose, the force that applied to the patient is shown in Figure 8. The IVC and VIVC have similar results in impedance that applied to the patient. The IVC and VIVC shows a force error with a maximum value of 1.6 *N* and 1.4 *N* respectively.
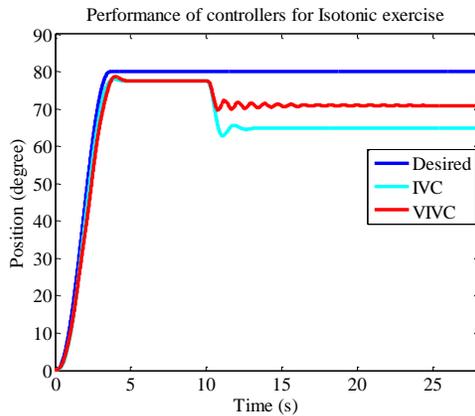

Fig. 7. A comparison between the IVC and the VIVC for the isometric exercise
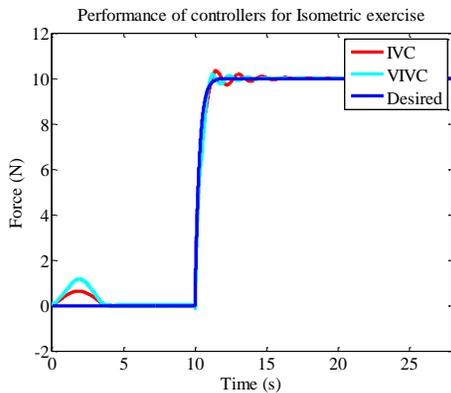

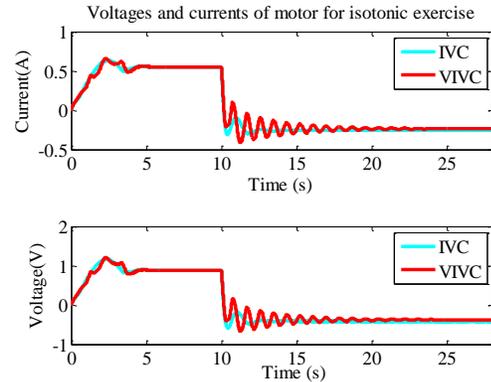Fig. 8. A comparison between IVC and VIVC for isometric exercise

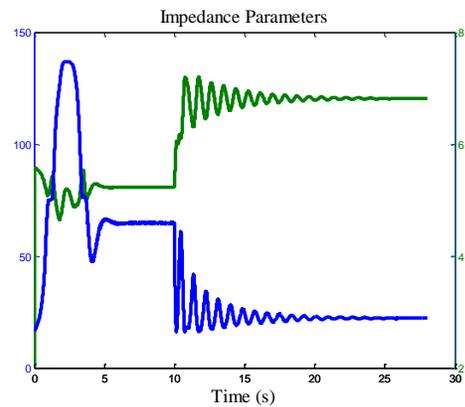Fig. 9. A comparison between IVC and VIVC for the isometric exercise

Fig. 10. Impedance parameters tuned by the IT2FLS

In control methods with using voltage control strategy the motor voltage and motor currents of controllers must be in valid range without suddenly changed. For isometric exercise they are shown in Figure 9, respectively. Adaptive Impedance parameters for the VIVC method has been shown in Figure 10.

6.2. Isotonic exercise

Isotonic exercise is one method of muscular exercise where a constant resistance force is applied to the patient for duration of the movement. In contrast, in the isometric exercise the muscular contractions occur without movement of the involved parts of the body. In this study, the Impedance Voltage Control (IVC) expressed by (20) with constant impedance parameters of $D_d(t)$ and $K_d(t)$ is simulated and compared with the proposed VIVC with the variable impedance parameters.

Simulation results, shown in Figure 11, compares the proposed VIVC and the IVC. The IVC and the VIVC have the same efficient with respect to tracking trajectory. Additionally, the impedance control should be evaluated according to how well the impedance law is performed. The force applied to the patient is shown in Figure 12. The art of proposed control has been shown in the force applied to the patient. The IVC results in a force error with a maximum value of 4.1 N

while the proposed VIVC shows a significantly lower force error of 2.2 N.

The motor voltage and motor current of robot for isotonic exercise are shown in Figure 13. As shown in this figure, they perform well without oscillations under the permitted values. The Adaptive Impedance parameters for the AIVC method is shown in Figure 14. As shown, these parameters are fluctuated according to the isotonic exercise, while remaining in a valid range.
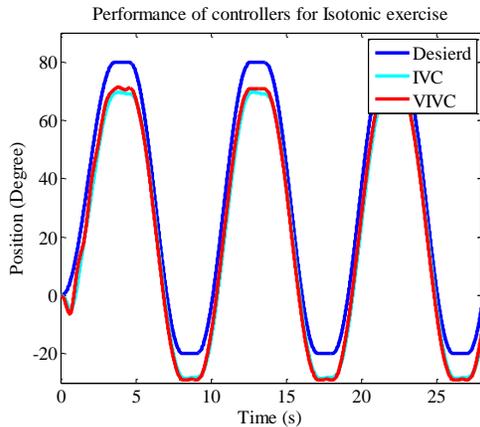

Fig. 11. A comparison between the IVC and the VIVC for isotonic exercise
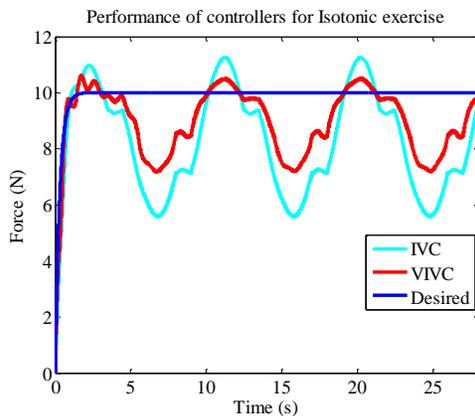

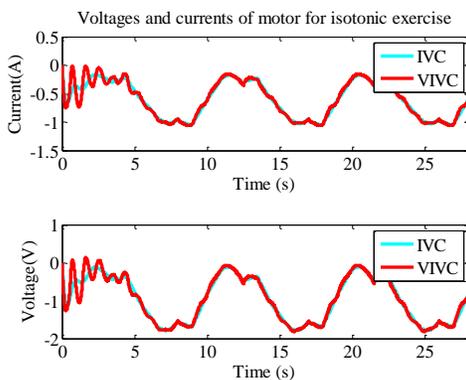Fig. 12. A comparison between the IVC and the VIVC for isotonic exercise

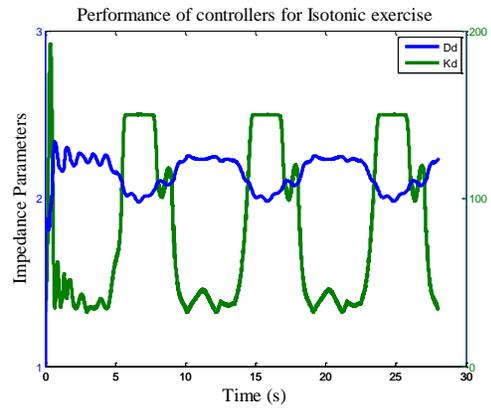Fig. 13. A comparison between IVC and VIVC for isotonic exercise

Fig. 14. Impedance parameters tuned by IT2FLS

7. Conclusion

Impedance control is an effective method in controlling the rehabilitation robots. The therapeutic exercises are performed well with satisfactory performances. The previous impedance control approaches were developed based on the torque control strategy whereas the proposed impedance control is based on the voltage control strategy. The proposed approach is free of manipulator dynamics, thus is simpler, less computational, and more effective compared with the torque based control approaches. Additionally, since it is difficult to be sure about the ideal value of the impedance parameters, interval type-2 fuzzy logic systems are used to regulate impedance parameters. The proposed technique for applying the adaptive impedance parameters is shown to be more efficient than using the constant impedance parameters. The control approach has been verified by stability analysis. The simulation results show the superiority of the proposed control approach over a constant impedance control scheme.

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