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Modelling and Hybrid Fuzzy controller for Knee Passive Rehabilitation Robotic

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Abstract: Recently, the requirement for rehabilitation robotics for human legs has been increasing worldwide. Knee rehabilitation robotics (R-Knee) is one of the robotics used to recover a patient's legs due to disease, injury or surgery. It can provide effective rehabilitation training and reduce the burden to therapists. The R-Knee usually dealt with difficulties in controller development due to its non-linearity and uncertainty in dynamics characteristics. A fuzzy logic controller (FLC) provides robustness and compliance for non-linearity and uncertainty in dynamics characteristics. However, the performance of FLC with fixed parameters is not optimal. Therefore, this article pays inclusivity to formulate the R-Knee mathematical modeling and optimizes the FLC using the derivative (Fuzzy-D) and Integral (Fuzzy-I) controller. The R-Knee modeling consists of a mechanical structure, direct current motor, and human leg model. The trajectory tracking performance of FLC, Fuzzy-D and Fuzzy-I is compared by simulation, which showed by the integral absolute error. As a result, the Fuzzy-D and Fuzzy-I controllers are significantly improving performance, which reducing trajectory error by 55.942% and 71.626% respectively compared to FLC. This developing control system is useful for use in development of actual device which used in passive mode rehabilitation exercises.

Keywords: *Fuzzy logic, Fuzzy-D, Control System, Rehabilitation, Knee Exoskeleton*

1. Introduction

The rehabilitation robotic for knee joint (R-Knee) has attracted the attention of researchers over the past years because of its ability to provide repetitive and consistent therapeutic exercises for patients over a long time. The R-Knee is a device attached to the patient's shank for knee limb rehabilitation purposes for those suffering neurological problems such as spinal cord injury or other factors contributing to such services. The R-Knee is inspired by the human musculoskeletal system to work in harmony with the patient, naturally transferring power from the actuator to the limb [1-2].

The demand for rehabilitation services is growing rapidly due to the rising global number of patients. Health facts annual report 2021 by the Malaysian Ministry of Health reported that the ratio of physiotherapists to Malaysia's population as of 31 December 2019 is 1: 22,864 [3]. Conventionally, a patient therapeutic exercise requires the aid of at least two physiotherapists during the rehabilitation process. It is a significant burden on physiotherapists in treating the growing number of patients. Advances in robotic rehabilitation technology have reduced treatment costs and produced better treatment results than traditionally [4].

Therapeutic exercises using rehabilitation robotics usually consist of three-stage physical movement, i.e., passive, assistive, and resistive exercises [5-6]. Typically for users

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without exciting muscles, especially those who lose most of the motion capacity after spinal cord injury or stroke, the patient is proposed to undergo passive assistance training. In passive assistance training, R-Knee uses mechanical actuators to help patients generate movements based on the trajectory recommended by a physiotherapist [7].

The desired trajectory of the joints requires a robust control system to achieve satisfactory motion exercise for various rehabilitation treatments. However, the dynamic of rehabilitation robotics usually deals with nonlinear characteristics due to parameter variations and unknown uncertainties. Therefore, the control system plays a vital role in minimizing steady-state errors and reducing disturbances. The high-performance controller is required to make the R-Knee motion track the desired trajectory in passive exercises [8].

There are many types and control system schemes that researchers have developed such as proportional-derivative-integral (PID) controller [8], Hybrid model reference adaptive control and PID controller [9], PID Gain tuning [10], adaptive control [11] and fuzzy-based impedance control [12]. A fuzzy logic controller (FLC) provides an advantage for non-linearity and uncertainty in dynamics characteristics. However, the performance of FLC will be degraded by parameter changes and disturbances. Therefore, this article pays inclusivity to the development of R-Knee mathematical modeling and optimizes the FLC trajectory tracking by using the derivative function (Fuzzy-D) and integral function (Fuzzy-I). Next, the performance of Fuzzy-D and Fuzzy-I on R-Knee are compared.

2. Literature Review

There have been controllers developed for the rehabilitation robotics. Rezage et al. [13] proposed the fuzzy logic controller (FLC), where the optimization method is done by adjusting the input-output scaling factor. The result indicates that superior performance and more accurate tracking on the proposed controller.

Zhong et al. [14] proposed the fuzzy compliance adaptive controller, which was integrated with the multi-input multi-output sliding mode controller. This controller is used for an assist-as-needed strategy for pneumatic muscle-driven gait rehabilitation exoskeleton. Results via experiment reveal that the maximum angular deviations from desired joint angle trajectory are 10.89°.

Besides, Sadjadi et al. [15] has been studied the adaptive fuzzy sliding mode controller for used in trajectory tracking of knee rehabilitation orthosis. The result shown the superior performance, which the maximum angular deviations from desired joint angle trajectories is 9.809°. The result shown by Zhong et al. [14] and Sadjadi et al. [15] is consistent with the other rehabilitation orthoses such as Lokomat, for which the maximum trajectory tracking errors during the position control mode must be less than 15° [16].

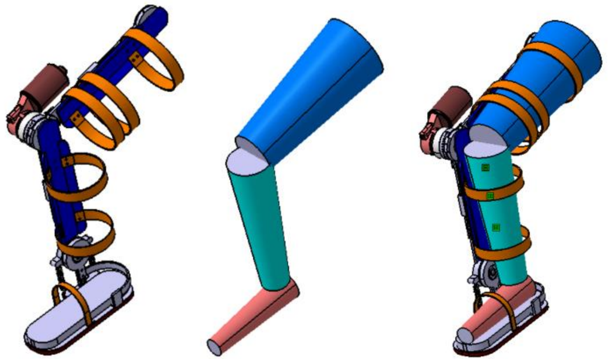
In another work, the Takagi-Sugeno fuzzy adaptive controller for generating assisting torque of knee-ankle orthosis was studied by Kumar & Mishra [17]. The adaptive frequency oscillator using adaptive law is used to adjust the singleton output of the rule. These studies included trajectory tracking, parametric uncertainty handling, and disturbance rejection capabilities. The result has shown that superior performance and more accurate tracking on the proposed controller.

3. Methodology

In this work, there have two stage of development: first, develop the R-Knee dynamic modelling; and second, develop control system design.

3.1 R-Knee Dynamic Modelling

The R-Knee modelling consists of a mechanical structure with a direct current (DC) motor installed at the knee joint, illustrated in Figure 1(a), and the human leg is modeled as shown in Figure 1(b). The human leg is tight on the mechanical structure of the R-Knee, as shown in Figure 1(c). The human leg was developed with a 50% percentile of Malaysian human anthropometric data [18]. This work only shows the right leg of the R-Knee.



(a) (b) (c)

Fig. 1 (a) DC motor and Mechanical structure of R-Knee (b) Human model (c) R-Knee

In this paper, the free body diagram of R-Knee link and human leg is modelled as one degree of freedom of the pendulum as shown in Figure 2. The total physical effect of each lower link, such as inertia and mass, is considered to

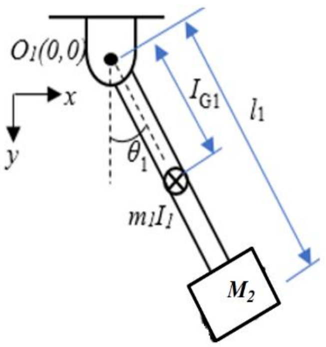


Fig. 2 Pendulum model

be *M1*. The dynamic model of the pendulum is determined by Lagrangian formulation as shown as below [17],

$$L_1 = E_{k1} - E_{p1} \tag{1}$$

$$\tau_1 = \frac{d}{dt}\left(\frac{\partial L_1}{\partial \dot{\theta}_1}\right) - \left(\frac{\partial L_1}{\partial \theta_1}\right) \tag{2}$$

where L_1 represent the Lagrangian function, τ_1 represent the torque of joint, E_{k1}, E_{p1}, θ_1 and $\dot{\theta}_1$ are kinetic energy, potential energy, angles of the knee, and angular position of the knee, respectively. Thus the dynamic equation of link is shown as follows,

$$\tau_1 = \left(m_1 l_g^2 + M_1 l_1^2 + I_1\right)\ddot{\theta}_1 + a\dot{\theta}_1 + \left(l_1 M_1 + l_g m_1\right) g sin\theta_1 \tag{3}$$

where m_1 is the mass of link, M_1 is the mass of lower link, l_1 and lg are the length of the link and the center of gravity, a is the friction coefficient, g gravitational acceleration, $\ddot{\theta}_1$ represent acceleration position of the knee respectively. The $sin\theta_1$ is approximated as θ_1. The τ_{R-Knee} is defined as a combination torque of patient shank, τ_P and mechanical link, τ_L . Thus the τ_{R-Knee} can be represented as,

$$\tau_{R-Knee} = \tau_P + \tau_L \tag{4}$$

Table 1 shown the physical features of the mechanical R-Knee link and human leg model.

Table 1 R-Knee Structure

Model	Part Name	Mass,m (kg)	Length, l (m)	Inertia, I (Kg.m^2)	Center of mass, l_g
R-Knee	Shank	0.222	0.410	0.0042	0.110
	Foot	0.121			
Human leg	Shank	3.160	0.440	0.0512	0.190
	Foot	1.081			

The torque to rotate the R-Knee joint is actuated by the DC motor, which consists of an electrical part, i.e., resistance and inductance. The mathematical model of DC motor determined by Kirchhoff's Voltage Law is shown as below,

$$v = L_I\left(\frac{di}{dt}\right) + Ri + e \tag{6}$$

where v is the input voltage, L_I, R and i are inductance, resistance and current of the DC motor, respectively. The e is back electromotive-force which is proportional to the motor velocity shown as follows,

$$e = K_b\dot{\theta}_r \tag{7}$$

where $\dot{\theta}_r$ and K_b are velocities of DC motor shaft and voltage constant of the DC motor, respectively. The torque of the DC motor that rotates the R-Knee joint is shown as,

$$\tau_m = Ki \tag{8}$$

where, K and τ_m are torque sensitivity and torque of DC motor, respectively. The torque of DC motor shaft is express as,

$$\tau_r(t) = J_r\ddot{\theta}_r + B_r\dot{\theta}_r \tag{9}$$

where τ_r is shaft rotation of DC motor, J_r and B_r are the inertia of the DC motor shaft and friction of the DC motor shaft, respectively. The dynamic equation of gear shaft is express as,

$$\tau_{shaft}(t) = J_{shaft}\ddot{\theta} + B_{shaft}\dot{\theta} \tag{10}$$

where J_{shaft} is the inertia of the DC motor gear and B_{shaft} is the constant of the friction gear. The R-Knee joint structure is the rotary part that is connected to the DC motor, is written as follows,

$$\tau_m = \tau_r + \frac{1}{n}\left(\tau_{shaft} + \tau_{R-Knee} + d\right) \tag{11}$$

where *n* is a gear ratio and *d* is disturbance. Therefore, the motor torque at knee joint including R-Knee link and patient knee limb is determined as,

$$\tau_m = J_r S^2\theta_r(s) + \frac{1}{n}\Big(J_{shaft} + \left(m_P {d_P}^2 + M_P {l_P}^2 + I_P\right) + \left(m_L {d_L}^2 + M_L {l_L}^2 + I_L\right)\Big) s^2\theta(s) + B_r s\theta_r(s) + \frac{1}{n}\left(B_{shaft} + q_P + q_L\right)s\theta(s) + \frac{1}{n}\Big((l_P M_P + d_P m_P) + (l_L M_L + d_L m_L)\Big)g\theta(s) + d \tag{12}$$

where the subscript of L and P denote for R-Knee link and knee patient limb, respectively. Thus, the DC motor modelling is formulated as,

$$v = \frac{(L_I s + R)\tau_m(S)}{K} + K_b s\theta(s) \tag{13}$$

Thus, the transfer function of the R-Knee joint including DC motor, mechanical link and patient knee limb is shown as follows,

$$G_{R-Knee} = \frac{\theta}{V} = \frac{w}{S^3 q_{11} + S^2 q_{12} + S^1 q_{13} + q_{14}} \tag{14}$$

where,

$w = nK$

$$q_{11} = \big(J_{shaft} + n^2 J_r + (m_P {d_P}^2 + M_P {l_P}^2 + I_P) + \qquad (15)$$

$$(m_L {d_L}^2 + M_L {l_L}^2 + I_L)\big) L_I q_{12} = (B_{shaft} + n^2 B_r + \qquad (16)$$

$$q_L) L_I + \big(J_{shaft} + n^2 J_r + (m_P {d_P}^2 + M_P {l_P}^2 + I_P) + \qquad (17)$$

$$(m_L {d_L}^2 + M_L {l_L}^2 + I_L)\big) R q_{13} = ((l_L M_L + d_L m_L) +$$

$$(l_P M_P + d_P m_P)) L_I g + (n^2 B_r + B_{sh} + q_L) R + n^2 K K_b +$$

$$L_I d q_{14} = \big((l_P M_P) + (l_L M_L)\big) R g + \big((d_P m_P) +$$

$$(d_L m_L)\big) R g + R d \qquad (18)$$

The Parameters of the DC motor are shown in Table 2.

Table 2 Parameter of DC Motor

Model	Symbol/Unit	Value
Resistance	R (Ω)	1.031
Inductance	L_I (H)	0.019
Torque sensitivity	K (Nm/A)	1.844
Voltage constant	K_b (v/rad.sec^{-1})	0.185
Friction of the DC motor	B (N.m/rads^{-1})	0.029
Momen of inertia of rotor	J_r (Kgm^2)	0.046
Inertia of the DC motor gear	J_{shaft} *(Kgm^2)*	0.011
Constant of the friction gear	B_{shaft} *(N.m/rads^{-1})*	0.013
Gear ratio	n	20

3.2 Control System Design

In the R-Knee system, G(s) is a combination of a transfer function of the R-Knee structure, G_R (s) and the human leg, G_H (s). The G_R (s) and G_H (s) are coupled together and the joints angles are equal; thus, it is assumed parallel to each other. The FLC employs the input error and change of error between desire and actual trajectories, while the output is the voltage for the DC motor. The FLC membership functions of input and output are shown in Figure 3, while the rules are shown below:

$R1$: $if\ (e\ is\ N)\ and\ (\Delta e\ is\ N)\ then\ (output\ is\ N)$
$R2$: $if\ (e\ is\ Z)\ and\ (\Delta e\ is\ N)\ then\ (output\ is\ N)$
$R3$: $if\ (e\ is\ P)\ and\ (\Delta e\ is\ N)\ then\ (output\ is\ P)$
$R4$: $if\ (e\ is\ N)\ and\ (\Delta e\ is\ Z)\ then\ (output\ is\ N)$
$R5$: $if\ (e\ is\ Z)\ and\ (\Delta e\ is\ Z)\ then\ (output\ is\ Z)$
$R6$: $if\ (e\ is\ P)\ and\ (\Delta e\ is\ Z)\ then\ (output\ is\ P)$
$R7$: $if\ (e\ is\ N)\ and\ (\Delta e\ is\ P)\ then\ (output\ is\ N)$
$R8$: $if\ (e\ is\ Z)\ and\ (\Delta e\ is\ P)\ then\ (output\ is\ P)$
$R9$: $if\ (e\ is\ P)\ and\ (\Delta e\ is\ P)\ then\ (output\ is\ P)$

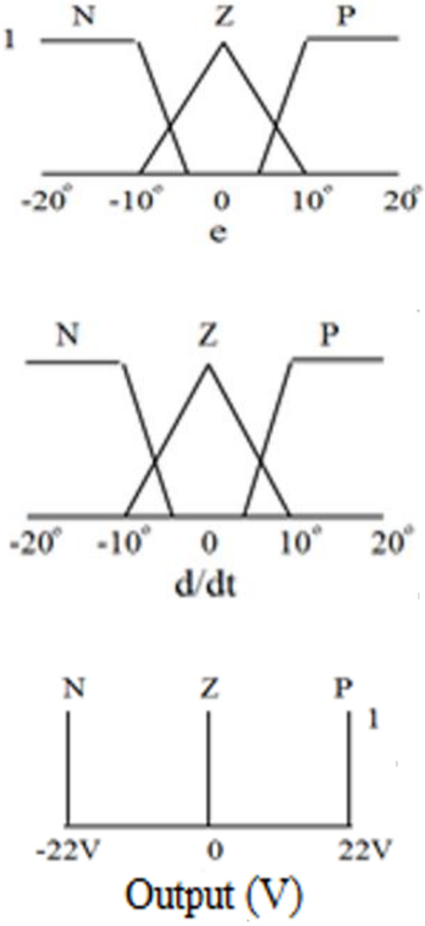


Fig. 3 Fuzzy membership functions

The design structure of the FLC, Fuzzy-D and Fuzzy-I is depicted in Figures 4(a), 4(b) and 4(c), respectively. The torque disturbance, *d* is attached to evaluate and controller performance are compared on R-Knee modelling. The parameters of proportional gain *A*, change of error gain *B*, proportional function *P*, derivative function, *D* and integral function, *I* were tuned manually until the value of integral absolute error reached the minimum value. Finally, the result shows the lowest error when the *A*, *B*, *D* and *I* parameters are set to 1.2, 0.01, 7 and 7, respectively. The value of *P* is set to 1.

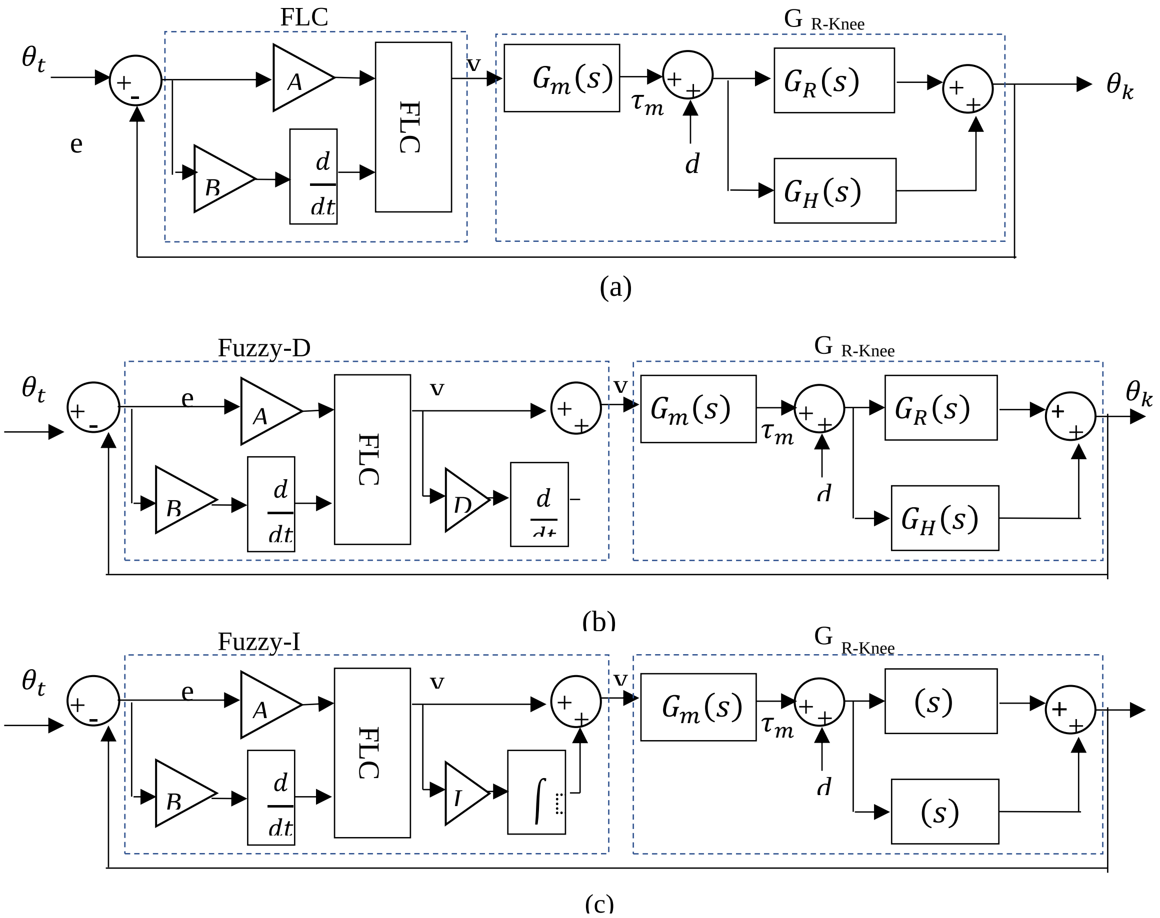


Fig. 4 Control schema (a) FLC (b) Fuzzy-D (c) Fuzzy-I

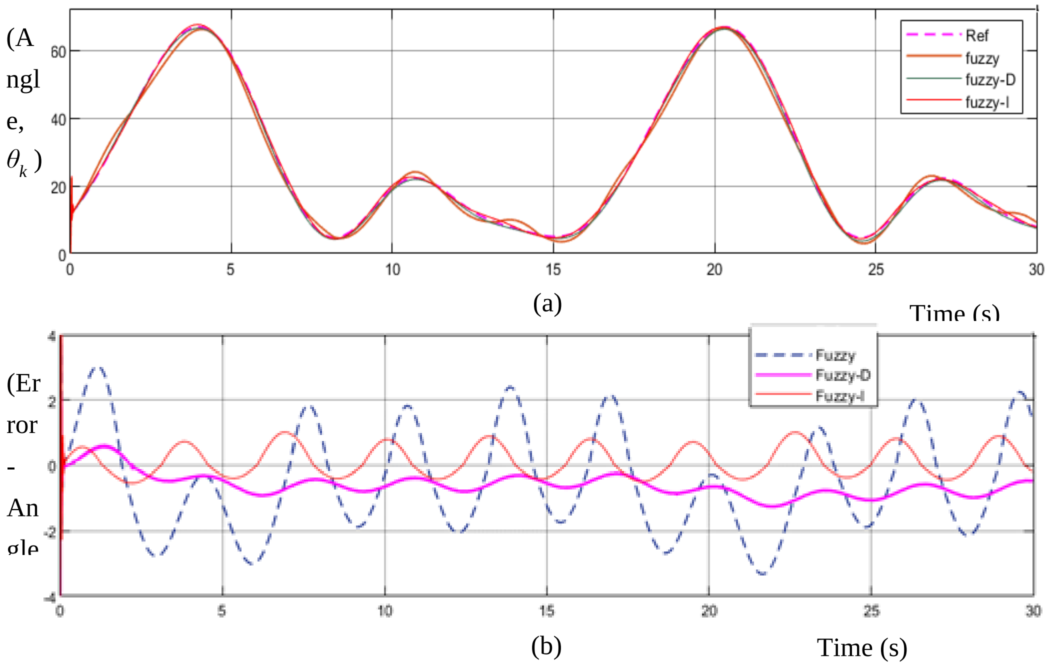


Fig. 5 (a) Trajectory tracking the performance of FLC, Fuzzy-D and Fuzzy-I (b) Comparison of error between FLC, Fuzzy-D and Fuzzy-I

4. Result and Discussion

In this paper, the objective is to improve the performance of FLC, which gives the outstanding tracking trajectory on the knee joint. The R-Knee modelling with FLC, Fuzzy-D and Fuzzy-I controller was created in simulation by Matlab. The comparison of the controllers is discussed in this section.

Figure 5(a) shows the trajectory tracking of knee joint of R-Knee so that actual trajectory followed the desired trajectory. The disturbance, d is represented by sin wave signal. The result demonstrates that the Fuzzy-I were track the input trajectory with less error compared to the FLC and Fuzzy-D. An input trajectory is defined as a reference trajectory for the R-Knee joint. In the other view, the performance of Fuzzy-I in Figure 5(b) shows that it provides less peak-to-peak error compared to the FLC and Fuzzy-D. The maksimum error do not exceed 15° which are still in the acceptable range [16].

Table 3 shows the comparison of FLC, Fuzzy-D and Fuzzy-I in term of numerical analysis performance on the R-Knee joint. The error measured using Integral absolute error (IAE) indicates that Fuzzy-I exhibits an increased efficiency by 55.942 % compared to FLC, while Fuzzy-I increase efficiency by 71.626 % compared to FLC. This result is shown that the Fuzzy-I has an advantage in reducing the tracking trajectory and more robust compared to FLC and Fuzzy-D in the non-linear system. The integral function has improved FLC's performance in error correction with virtually less overshoot compared to FLC, causing the error to be quickly corrected.

Jadual 3 Controller comparison and performance

Controller Types	IAE	Percentage Improvement of Performance (%)
FLC	43.42	-
Fuzzy-D	19.13	55.942
Fuzzy-I	12.32	71.626

5. Conclusion

R-Knee is used by patients suffering neurological problems such as spinal cord injuries and stroke undergoing physiotherapy training. In this study, the dynamic modeling of R-Knee, which consists of mechanical R-Knee structure, DC motor, and couple with human model as a patient were shown. The trajectory tracking controller using FLC, Fuzzy-D and Fuzzy-I was developed and compared. The result was shows, the Fuzzy-I controller minimizes the trajectory tracking error and robust to the non-linear system. The performance of Fuzzy-D was improved by 55.942 %, while Fuzzy-I was improved by 71.626 % compared to FLC. In future work, the Fuzzy-D and Fuzzy-I can be tested in another non-linear system such as arm robot and the other types of exoskeleton joint. The results obtained have strengthen the study done in this paper. In future work, the comparison and analysis of the actual R-Knee prototype will investigate.

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