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Design of Adaptive PID Controller for Lower Limb Rehabilitation Robot Based on Particle Swarm Optimization Algorithm

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Abstract

The proportional-integral-derivative (PID) is still the most common controller and stabilizer used in industry due to its simplicity and ease of implementation. However, in most of the real applications, the controlled system has parameters that slowly vary or are uncertain. Thus, PID gains must be adapted to cope with such changes.

In this research, an Adaptive Proportional-Integral-derivative controller (APID) is proposed to verify the APID succeeds to control the 2-DoF lower limb rehabilitation robot system with efficiently or no. The parameters gains of the proposed controller are optimized using the Particle Swarm Optimization algorithm (PSO). The simulation results show no overshoot and zero steady-state error, but large settling time (t_s=3.654 sec. for hip link and t_s=2.844 sec. for knee link) for linear path, and the actual path tracks the desired path with a large error for the nonlinear path. The results illustrate that the robot's performance is inefficient for linear and nonlinear paths when using the APID controller to control the lower limb rehabilitation robot. Therefore, the controller needs to modify for controlling the robot efficiently.

Keywords: Adaptive PID, Lower limb, Rehabilitation robot, Particle swarm optimization algorithm.

الخلاصة: لا يزال مسيطر ال (PID) هو المتحكم الأكثر شيوعاً في الصناعة نظراً لبساطته وسهولة تنفيذه. ومع ذلك، في معظم التطبيقات الحقيقية، يحتوي نظام المسيطر على معاملات تتغير ببطء أو غير مؤكدة. وبالتالي، يجب تكييف معاملات PID للتعامل مع هذه التغييرات.

في هذا البحث، تم اقتراح وحدة تحكم تكيفي (APID) للتحقق هل ينجح مسيطر APID بالتحكم في نظام روبوت إعادة تأهيل الأطراف السفلية ٢-DOF بكفاءة أم لا ينجح. تم تحسين معاملات وحدة التحكم المقترحة بإستخدام خوارزمية السرب (PSO). تظهر نتائج المحاكاة عدم وجود overshoot وعدم وجود خطأ ولكن وقت الإستقرار كبير (ts = 3.654 ثانية لوصلة الورك و ts = 2.844 ثانية لوصلة الركبة) للمسار الخطي، والمسار الفعلي يتتبع المسار الخطي المطلوب مع وجود خطأ كبير في المسار غير الخطي. اظهرت النتائج أن أداء الروبوت غير فعال للمسارات الخطية وغير الخطية عند استخدام وحدة تحكم APID للتحكم في روبوت إعادة تأهيل الطرف السفلي. لذلك، يحتاج هذا المسيطر إلى التعديل والتحسين للتحكم بالروبوت بكفاءة.

1. INTRODUCTION

Spinal cord injury, accidents, and stroke are the significant sources of disability for the athletics, drivers, and elderly persons that create troubles in their life's. Rehabilitation tools were focused on recovering full/partial functionality by enhancing their motion capabilities using different techniques. Recently, wearable robots of lower-limb exoskeletons have been employed for helping disabled people with mobility issues.

A rehabilitation robot is a robot that helps patients recuperate from strokes or other types of extremity injuries. The goal of developing a rehabilitation robot is to assist individuals with daily living problems. Since robots are suited to provide a precise and reproducible physiotherapy, they are excellent tools for providing high-quality treatment at a low cost with minimal intervention [1].

Both conventional PID and adaptive PID controllers are utilized effectively rehabilitation robot procedures.

(Zahid et al., 2017) in [2] proposed reference model adaptive PID controller for 1-DOF rehabilitation robot to reduce positioning error and make the robot beneficial for a wide range of stroke patients.

(Proietti et al., 2019) in [3] proposed an Adaptive PID (APID) controller to control the upper limb rehabilitation exoskeleton robot for neurorehabilitation. Their results show the different features allowed by our controller with respect to controllers commonly used for neurorehabilitation with exoskeletons.

(Roy et al., 2021) in [4] proposed a PID (PID) controller to control the 2-DoF upper limb rehabilitation robot for elbow rehabilitation. Their simulation results show good performance of the robot with zero steady state error and 0% overshoot and undershoot.

Although the mentioned controllers are claimed to have good performance, the Only few control strategies such as optimal PID, Adaptive PID controllers are used to control the rehabilitation robots.

This research focuses on designing an Adaptive Proportional-Integral-Derivative Controller (APID) based on Particle Swarm Optimization Algorithm (PSO) to track the path of a two-link lower-limb rehabilitation robot by using dynamic equation for a human two-joint during-walk lower-limb model. PSO is used to tune the parameters of the suggested controller. The dynamic model of this robot was derived by (Rezage & Tokhi, 2016) [5] depended on anthropometric data (described by Winter (2009) [6]). The stability analyses of both joints of a closed-loop controlled system based on the dynamic robot equations are explained by Lyapunov stability.

The rest of this paper is organized as follows, the dynamic mathematical model of the two-link lower-limb rehabilitation robot is given in section 2, the suggested controller is detailed in section 3, the PSO is illustrated in section 4, simulation results are presented in section 5; finally, the conclusions are provided in section 6.

2. LOWER LIMB REHABILITATION ROBOT DYNAMIC MODEL

The structure of a two degree of freedom (2-DOF) rehabilitation robot is shown in Figure 1, this robot consists of two links with two joints of the lower limb: a joint at the hip and a joint at the knee, link1 assists the rehabilitation of the hip and link2 for the knee. The dynamic model of this robot is was derived by (Rezage & Tokhi, 2016) depended on anthropometric data (described by Winter (2009)) for person with 74 kg in weight and 1.69 m in height.

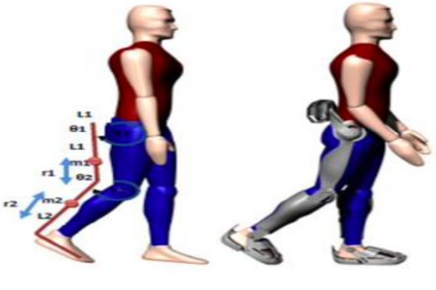

Figure 1 2-DOF Rehabilitation Robot [5].

The dynamic model of the 2-DOF robot given by (Rezage & Tokhi, 2016) is expressed in matrix form as:

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) = u(t) \quad (1)$$

where $\theta, \dot{\theta}$, and $\ddot{\theta}$, respectively represent the angle, angular velocity, and acceleration of a robot joint vector. Matrices of human limbs for each inertia $M(\theta)$, Coriolis and centrifugal torque $C(\theta,\dot{\theta}) \in R^{(2*2)}$. The torque of gravity $(G(\theta))$ has one-dimensional vector $\in R^{(2*1)}$, $u(t)$ indicates the control signal. The obtained $M(\theta)$ are given in Eq. 2:

$$M(\theta) = \begin{bmatrix} I_1 + I_2 + m_1(L_{c1})^2 + m_2(L_1)^2 + m_2(L_{C2})^2 + 2m_2L_1L_{C2}\cos(\theta_2) & I_2 + m_2(L_{C2})^2 + m_2L_1L_{C2}\cos(\theta_2) \\ I_2 + m_2(L_{C2})^2 + m_2L_1L_{C2}\cos(\theta_2) & I_2 + m_2(L_{C2})^2 \end{bmatrix} \quad (2)$$

$C(\theta, \dot{\theta})$ matrix elements can be given by Eq. 3:

$$C(\theta, \dot{\theta}) = \begin{bmatrix} -m_2L_1L_{c2}\sin(\theta_2)\dot{\theta}_2 & -m_2L_1L_{c2}\sin(\theta_2)(\dot{\theta}_1 + \dot{\theta}_2) \\ m_2L_1L_{c2}\sin(\theta_2)\dot{\theta}_1 & 0 \end{bmatrix} \quad (3)$$

The gravitational vector $(G(\theta))$ elements are given in Eq. 4:

$$G(\theta) = \begin{bmatrix} m_1L_{c1}g\sin(\theta_1) + m_2gL_1\sin(\theta_1) + m_2gL_{c2}\sin(\theta_1 + \theta_2) \\ m_2gL_{c2}\cos(\theta_1 + \theta_2) \end{bmatrix} \quad (4)$$

The variables of these equations and physical parameters are defined by Table 1.

Table 1 The variables and physical parameters for lower limb rehabilitation robot.

Parameters	Notation	Unit	Value
Length of link 1	L_1	**m**	**0.54**
Length of link 2	L_2	**m**	**0.48**
Link (1) center of mass	L_{c1}	**m**	**0.2338**
Link (2) center of mass	L_{c2}	**m**	**0.241**
Mass of link 1	m_1	**Kg**	**8**
Mass of link 2	m_2	**Kg**	**3.72**
Inertia of link 1	I_1	**Kg.m^2**	**0.42**
Inertia of link 2	I_2	**Kg.m^2**	**0.07**
Gravity acceleration	**g**	**m /s^2**	**9.8**
Angular Displacement of link 1	θ_1	**Rad**	**/**
Angular Displacement of link 2	θ_2	**Rad**	**/**
Angular Velocity of link 1	$\dot{\theta}_1$	**Rad/s**	**/**
Angular Velocity of link 2	$\dot{\theta}_2$	**Rad/s**	**/**
Angular acceleration	$\ddot{\theta}$	**Rad/s^2**	**/**

3. ADPTIVE PID CONTROLLER DESIGN

The PID controller is a control loop feedback mechanism which is widely used in industrial control system. Based on the investigation of conventional PID controller, the adaptive PID controller adopts online parameter adjustment method according to the state of the system, therefore it has better system adaptability [7].

The structure of the APID controller that is suggested by (Ebel, 2011) [8] is used here to build an adaptive controller for the two-link rehabilitation robot is shown in Figure 2.

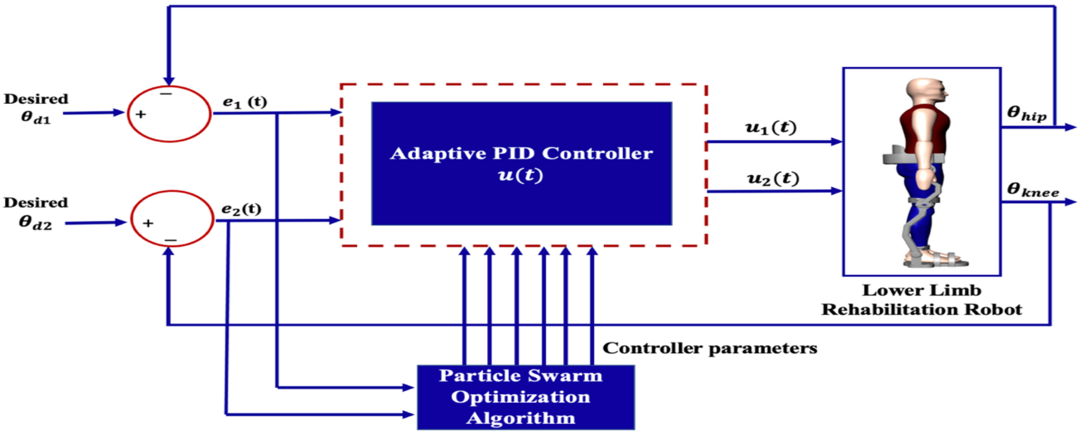

Figure 2 The block diagram of the suggested APID controller.

Sigma function is defined as stated in Eq. (5):

$$\sigma^i(t) = X_P{}^i e^i(t) + X_D{}^i \dot{e}^i(t) \tag{5}$$

where i=1, 2 is the link number. e^i is the instantaneous error which represents the difference between the current desired path $\theta_d{}^i$ and actual output θ^i of link (i) as in Eq. (6):

$$e^i = \theta_d{}^i - \theta^i \tag{6}$$

The control law for this controller is given by Eq. (7):

$$u(t) = M(\theta, \dot{\theta}) * u_{pid}{}^i(t) \tag{7}$$

Also, $u_{PID}{}^i(t)$ is defined in Eq. (8):

$$u_{PID}{}^i(t) = K_P{}^i(t)\, e^i(t) + K_I{}^i(t) \int_0^t e^i(t)\, dt + K_D{}^i(t)\, \dot{e}^i(t) \tag{8}$$

where $K_P{}^i(t), K_I{}^i(t), and\ K_D{}^i(t)$ are self-tune parameters obtained by Eq. (9) through Eq. (11):

$$K_P{}^i(t) = \int \dot{K_P}{}^i(t) \Longrightarrow \dot{K_P}{}^i(t) = -\eta_1{}^i\, \sigma^i(t)\, e^i(t) \tag{9}$$

$$K_I{}^i(t) = \int \dot{K_I}{}^i(t) \Longrightarrow \dot{K_I}{}^i(t) = -\eta_2{}^i\, \sigma^i(t)\, \int e^i(t)\, dt \tag{10}$$

$$K_D{}^i(t) = \int \dot{K_D}{}^i(t) \Longrightarrow \dot{K_D}{}^i(t) = -\eta_3{}^i\, \sigma^i(t)\, \dot{e}^i(t) \tag{11}$$

where $\eta_1{}^i$, $\eta_2{}^i$, and $\eta_3{}^i$ represent positive learning rate. It is crucial to choose the appropriate learning rates and initial values for the controller gains.

The Lyapunov function candidate is set to be as in Eq. (12) and Eq. (13):

$$V^i = \tfrac{1}{2}(\sigma^i(t))^2 \tag{12}$$

$$\dot{V}^i = \sigma^i(t)\dot{\sigma}^i(t) < 0 \tag{13}$$

when $\dot{V}^i < 0$ it is guaranteed that $\sigma^i \to 0$ as $t \to \infty$. From Eq. (5), it can be written:

$$\dot{\sigma}^i(t) = ({X_P}^i e^{\cdot i}(t) + {X_D}^i \ddot{e}^i(t)) \tag{14}$$

Substituting Eq. (14) into Eq. (13):

$$\dot{V}^i = \sigma^i(t)[({X_P}^i e^{\cdot i}(t) + {X_D}^i \ddot{e}^i(t))\,] < 0 \tag{15}$$

The optimal parameters of the APID controller $u(t)$ of link1 (${\eta_1}^1, {\eta_2}^1, {\eta_3}^1, {X_P}^1,$ and ${X_D}^1$), and link2 (${\eta_1}^2, {\eta_2}^2, {\eta_3}^2, {X_P}^2,$ and ${X_D}^2$) will be determined by the PSO algorithm.

4. OPTIMISATION ALGORITHM

Optimization is defined as the process of identifying the best solution for a specific problem to obtain the desired cost function properties to reach the global optimum. The optimization algorithms use multiple agents (solutions), to move through the search space in the process of solving an optimization problem. In this paper we use PSO technique (Particle Swarm Optimization algorithm) [9]. The PSO fitness function ITAE (Integral Time Absolute Errors) is given by Eq. (16) for each rehabilitation robot link (1, 2) [10]:

$$F = ITAE = \int_0^\infty t|e(t)|dt \tag{16}$$

4.1. Particle Swarm Optimization Algorithm (PSO)

PSO was developed by Kennedy and Eberhart in 1995, an evolutionary optimization technique. PSO is based on the social behaviour of birds and fish that flock together in search of food. This behaviour is based on the intellect of each individual and the flock as a whole. Creating a swarm is the basic phenomenon of PSO. Particles are potential solutions to the problem that moves in the problem space. Each particle has its own velocity and position. Particles updated their velocity and position after each iteration, going towards the swarm's best value. pbest and gbest are two components of the particle's updated position. The updated position of the particle is pbest, while the global best position of the whole swarm is gbest [11]. For more details see [12,13].

5. SIMUATION RESULTS

With the aid of the facility included in the MATLAB software version (R2019b), various lower limb rehabilitation robot simulations are performed for linear and nonlinear desired paths with 10% uncertainties to demonstrate the efficiency of the APID based on PSO algorithm. The PSO parameters for each rehabilitation robot link (1, 2) are given in Table 2, and final optimal parameters in APID for link 1 and 2 are given in Table 3.

Table 2 The parameters of PSO algorithm.

Particle swarm optimization algorithm	Parameters
No. of iterations	50
No. of search agents	15
Dim (number of variables)	10
Lower bound of variable n (lb)	[29; 29; 24; 29; 24; 29; 29; 24; 29; 24]
Upper bound of variable n (ub)	[31; 31; 26; 31; 26; 31; 31; 26; 31; 26]

Table 3 Optimal parameters of the APID obtained by PSO algorithm.

Links	Controller parameters	APID
Link1 (hip)	$\eta_1{}^1$	30.0000
	$\eta_2{}^1$	30.0000
	$\eta_3{}^1$	25.0000
	$X_P{}^1$	30.0000
	$X_D{}^1$	25.0000
Link2 (knee)	$\eta_1{}^2$	30.0000
	$\eta_2{}^2$	30.0000
	$\eta_3{}^2$	24.0000
	$X_P{}^2$	29.9113
	$X_D{}^2$	24.0000

5.1.Simulation Results of Linear Trajectory

The step response (positive unity step for hip link, and negative unity step for knee link) of the controlled lower limb rehabilitation robot (position and control signal) with 10% uncertainty are shown in Figure 3 and Figure 4. These results show that the actual path of the robot tracks the desired path with no overshoot and zero steady-state error, with a smooth control signal (less than 200 N for link1 and less than 65 N for link2), but the settling time (t_s=3.654 sec. for link1 and t_s=2.844 sec. for link2) and rising time (t_r= 4.520 sec. for link1 and t_r=3.813 sec. for link2) is quite large. The evaluation parameters of simulation results for the suggested controller are given in Table 4.

Table 4 The simulation result's evaluation parameters for the APID.

Parameters	Link1(hip)	Link2 (knee)
$M_p(\%)$	0	0
$t_s\,(sec.)$	3.654	2.844
$e_{s.s}$	0	0
$t_r\,(sec.)$	4.520	3.813

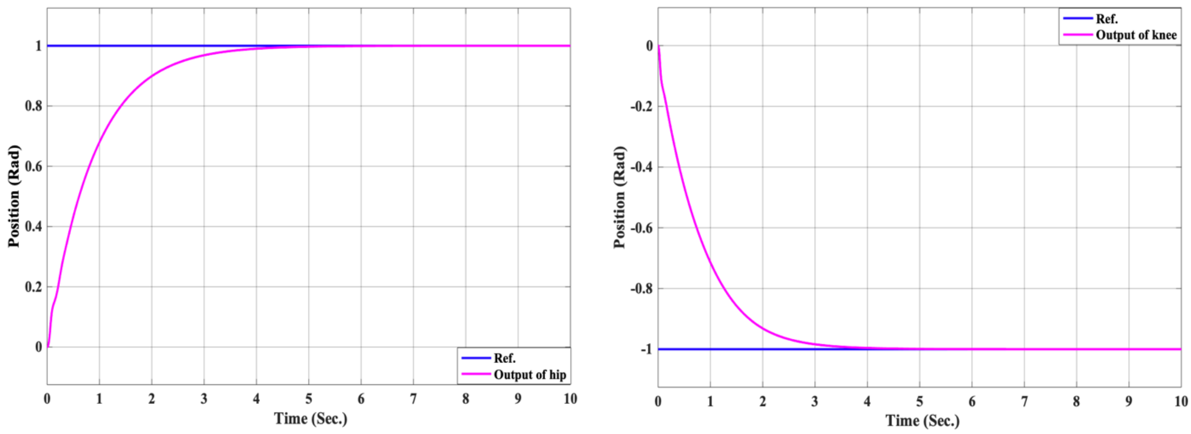

Figure 3 The position of hip link and knee link for linear path with APID.

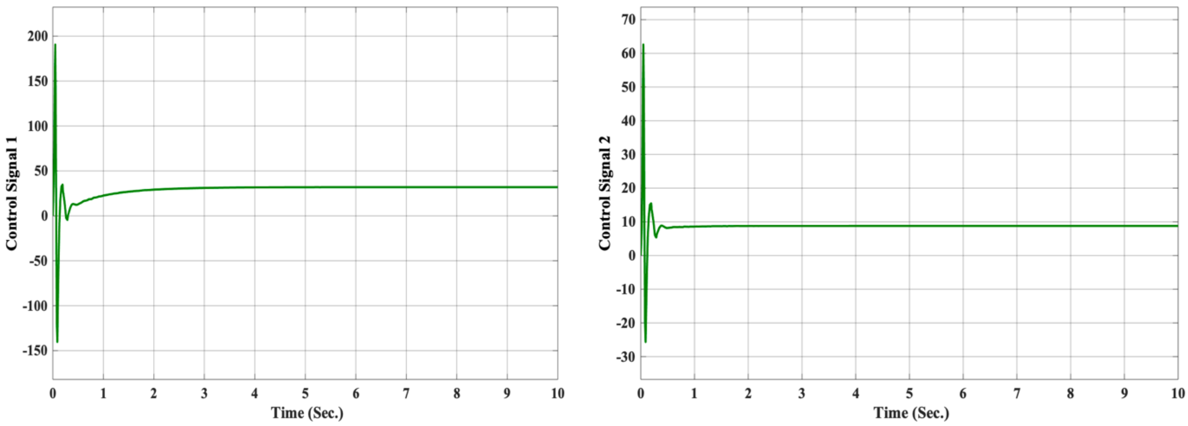

Figure 4 The control signals for linear path with APID.

5.2. Simulation Results of Nonlinear Trajectory

The simulation results of the lower limb rehabilitation robot with the suggested APID tested by the desired nonlinear input signal ($x_{d1} = {}^{\pi}/_{4} + (1 - cos3t)$ for link1 and $x_{d2} = {}^{\pi}/_{6} + (1 - cos5t)$ for link2) with 10% uncertainty are illustrated in Figure 5 and Figure 6; these results show a smooth control signal (less than 180 N for link1 and less than 60 N for link2), but the actual path track the desired path with large error.

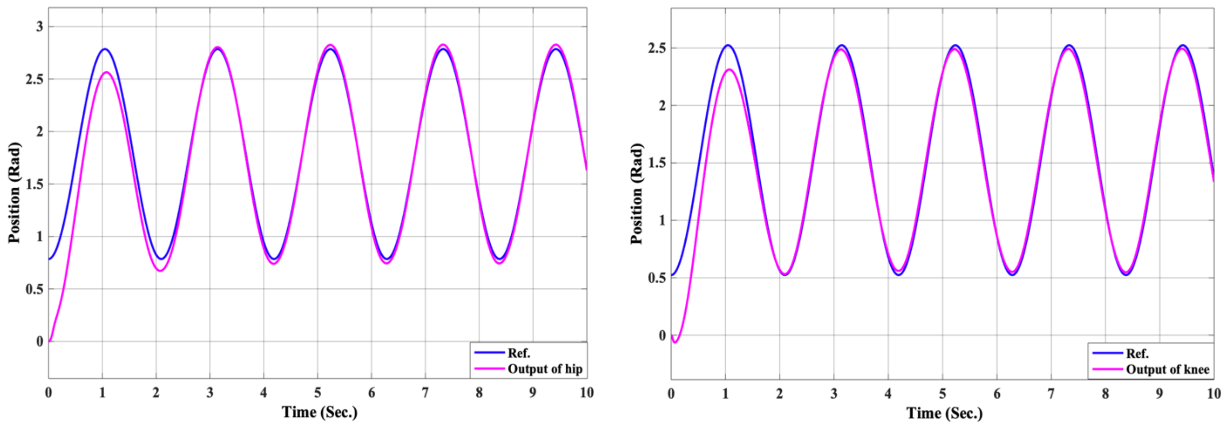

Figure 5 The position of hip link and knee link for nonlinear path with APID.

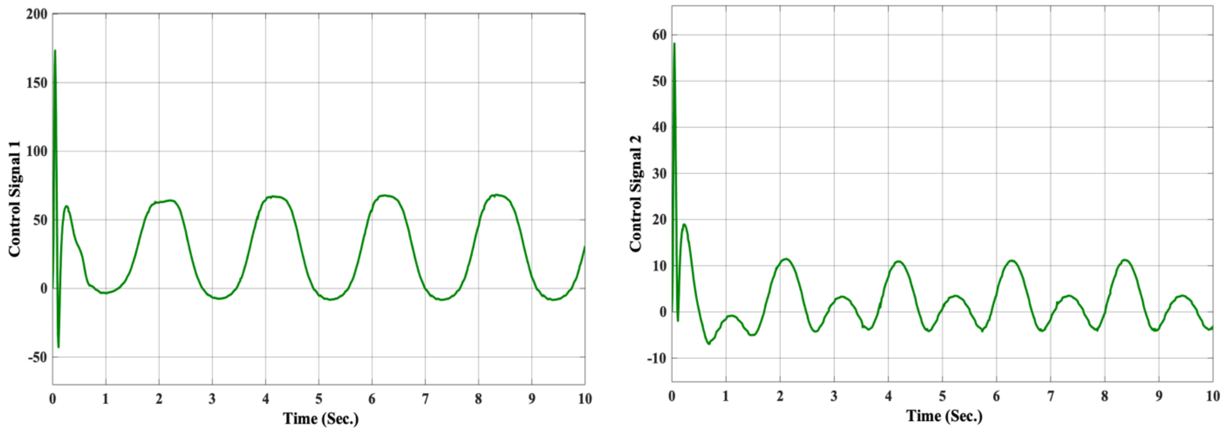

Figure 6 The control signals for nonlinear path with APID.

The obtained results for linear and nonlinear paths illustrate that the APID controller is inefficient in controlling the lower limb rehabilitation robot. Therefore, the controller needs to be modified to control the robot efficiently.

6. CONCLUSIONS

The main aim of this work was to design an Adaptive Proportional-Integral-Derivative (APID) to verify the APID succeeds in tracking the desired path and improving the performance of a two-link lower limb rehabilitation robot with efficiently or no. The parameters of the APID were optimized by using a Particle Swarm Optimization algorithm (PSO). The transient parameters of the obtained results show zero steady-state error in two links, no overshoot, but the settling time (t_s=3.654 sec. for hip link and t_s=2.844 sec. for knee link) is high, and the nonlinear path results show the actual path tracks the desired path with large error. Furthermore, the simulation results illustrate that the APID is inefficient in controlling the lower limb rehabilitation robot, and the controller needs to modify it for controlling the robot efficiently.

7. RECOMMENDATIONS

In order to enhance the efficiency of the adaptive PID controller and improve its performance, a modified adaptive PID controller is suggested to reduce the tracking error, the sigma function in Eq. (5) must be modified to PID controller equation, and the control law must be modified by adding the part ($\boldsymbol{tanh}\,(\boldsymbol{\sigma^i}(\boldsymbol{t})) * \boldsymbol{K_M}^{\boldsymbol{i}}$) to Eq. (7).

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