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Fractional proportional derivative-based active disturbance rejection control of knee exoskeleton device for rehabilitation care

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ABSTRACT

The use of rehabilitation exoskeleton by physiotherapists in their daily practice is becoming more common. In this study, the active disturbance rejection controller (ADRC) is proposed to ensure high performance of trajectory tracking for asstitve exoskeleton at the level of knee-joint. The controlled medical robot has to mimic the actual physical training and application for knee-rehabilitation. Two versions of ADRC is presented to control the rehabilitation system. One version is based on conventional ADRC, while the other version is based on fractional proportional-derivative PD-ADRC. A comparison study in performance has been conducted between two versions of ADRCs in terms of robustness against disturbances. According to numerical simulations, the results showed that the fractional PD-based ADRC ouptperforms the ADRC in terms of robustness characteritics based on the index root mean square error (RMSE).

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1. INTRODUCTION

Exoskeleton technology has progressed to the point where those with less athletic capabilities can enhance their mechanical energy with exoskeletons. The most of generator control regulation systems work by calculating a real-time estimate of the user's planned motion [1]. Following treatment with any of these devices, the participant's performance is tracked, and a comparison of progress on the measured values can be used to justify the treatment.

Many control methods are being used in the field of artificial knee joint therapy, and human support exoskeletons have already been designed. Proportional-derivative (PD) based control behaves well when there is no disruption in the process [2], but it performed badly when there is a perturbation in the process [3]. In respect of regulation development and hypothesis validation, intelligent control techniques [4] need a considerable amount of time and effort. Sensitive enhancement involves the presence of disturbance, demanding the application of an adequate inverse model structure [5]. In these kind of cases, one alternative is to employ powerful control systems that are conservative that handle worst-case possibilities at the tradeoff of immediate responsiveness. Taha *et al.* [6] offers a particle swarm optimization (PSO)-based add significantly rejecting regulatory for removing disturbances in locomotory trajectory tracking, which involves a wide range of variable measurements but has higher computational requirements. Yang *et al.* [7] used a radial basis function network to compensate the disturbance. Sliding mode control can help avoid against faults and driven environment, but it can noisy if the transitioning is disrupted [8]. Lu *et al.* [9] used computed-torque method which relies on the system's particular machine and may require extra control to compensate for prototype issues. To overcome such present control issues, the active disturbance rejection controller (ADRC) methodology is introduced by Gao *et al.* [10], which is the first one to recommend the ADRC controller, which has a number of benefits. The advancement and quick implementation of ADRC in industry over the last three decades demonstrates its appeal in autopilots [11], production control [12], [13], motion tracking systems [14], [15], and other areas [16]. Its utility as a proportional integral derivative (PID) alternative is being investigated in industry. The PID and ADRC are comparable, however ADRC has better features. The technology developed by ADRC is intended to improve options by actively eliminating all local and global constraints [17]. The method organization and estimated quantities of process variables are all that is required for ADRC to act as a model-free controller [18]. This concentrates on error rather than structure control approach [19], and it does not necessitate substantial structure or system knowledge, such as a detailed model of the system [20]. Robotic machines, assistive devices, prosthetic limbs, and implants are being developed in the field of lower leg recovery to help clinicians with therapeutic interventions and many other behaviors such as seating, standing, and so on. For clinical locomotor statistics, a linear extended state observer (LESO) based ADRC with simply the lower extremity effector for the hip and knee joints was employed like a guide.

ADRC has been utilized in a wide range of autonomous assist humans for tracking progress in recent decades [21], because to its increasing influence and dependability. The outcomes of PID and ADRC are evaluated, and the results show that ADRC improves PID in terms of knee paths and failures tests. The findings also suggest that ARDC is beneficial. Non - linearities are handled by ADRC [22]. Some of the control systems utilized in rehabilitation are location tracking, power and resistivity control, biological signals oriented control, and optimal control [23]. Location monitoring is among the most fundamental control schemes for autonomous therapy systems, where in the controller enhances movement regularity and accuracy for the diagnosis [24]. The goal of this study is to compare the performance of a sinusoidal tracking system for exoskeleton joint output to linear active disturbance rejection control (LADRC) and fractional active disturbance rejection control (FADRC), and to show which system performs better. In recent years, more emphasis has been placed on enhancing the outputs of LADRC controllers by using the fractional order concept, which has been developed as non - integer order LADR controller (FADRC).

A comparison study has been established to investigate the effectiveness of proposed controllers. In addition, the PSO technique is introduced for tuning the designed parameters of FADRC. The contributions of the work can be summarized by the following points:

- To develop FPD-ADRC algorithm to solve the tractability LADRC problem.
- Perform regular a comparative studies of LADRC and FADRC for tracking error in terms of some performance indices.
- Using new performances indices for control effort evaluation, integral square of the control signal (ISU), whereas ISU relates to denote control effort required for a controller and Integral absolute of the control signal (IAU), where IAU performance index reflects a measure of chattering reduce in control signal.

The remainder of this work is laid out as follows. The suggested limb-rehabilitation device is described in section 2. The exoskeleton system is shown in section 3 with two configurations of the ADRC control approach. Section 4 gives the particle swarm optimization (PSO) for parameters tuning. In section 5, you can view the experimental results and discussion for two ADRC settings. Finally, in section 6, the conclusion is presented, along with some additional views on future research on the subject at hand.

2. EXOSKELETON MODEL

The thigh segment is rigidly fastened to the sitting surface and body segment forces are fully backed for robotic surgery during the seated leg extension and flexion training. As a result, robotic support of the knee joint for these workouts can be represented as a pendulum with knee joint dynamics, with the entire system in synchronous locomotion, as shown in Figure 1. The dynamic model of lower knee joint motion in general is [25]:

$$J\ddot{\theta} = -\tau_g \cos\theta - A sign\dot{\theta} - B\dot{\theta} + \tau_e + \tau_h \tag{1}$$

θ is the knee joint angle between the actual position of the shank and the full extension position, $\dot{\theta}$and $\ddot{\theta}$ are respectively the knee joint angular velocity and acceleration. $J, A, B, \tau_g, \tau_e, \tau_h$ are Inertia, solid friction coefficient, viscous friction coefficient, gravity torque, controller torque and human torque respectively.

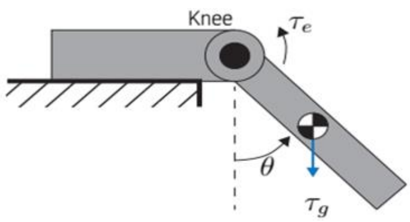

Figure 1. Knee exoskeleton prototype

3. PRINCIPLES OF ADRC

The tracking differentiator (TD), the extended state observer (ESO), and the linear state error feedback loop (LSEF) are the three necessary aspects of the ADRC. The ESO receives the component's specific output to measure the item's error variation and distortion, while the profile generator (PG) or TD prepares the transitional process that provides differential input. Lastly, the $C(s)$ or PD controller is fed the error between the overall input and the overall output, and the control action is created to adjust for every disruption [10]. The design parameter (b_o) is depend on dynamic system. Figure 2 depicts the layout of an exoskeleton system $P(S)$ employing LADRC structure.

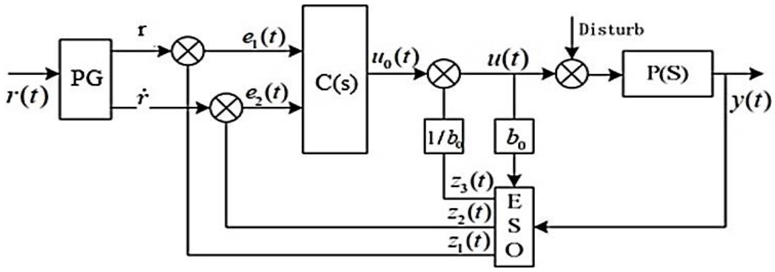

Figure 2. General LADRC structure

3.1. Linear TD

The TD is extensively used to eliminate overflow and improve system reliability. It employs a differential impermanent feature of the input signal to remove quick shifts, producing in a progressive instead of a sudden increase in output, with just the signal and its derivative (linear TD) being used in this section:

$$\begin{aligned} v_1 &= r \\ v_2 &= \dot{r} \end{aligned} \tag{2}$$

where $r, \dot{r}$ are desired input and its derivative.

3.2. Linear ESO

The dynamic model for a regulated system exposed to unpredictable local and global perturbations is as follows [26], [27]:

$$\begin{cases} \dot{\zeta}_1 = x_2 \\ \dot{\zeta}_2 = f(\zeta, w, t) + bu \\ y = \zeta_1 \end{cases} \tag{3}$$

the input and output signals are u and y, the unpredictable dynamic systems functional incorporating perturbation is $f(\zeta, w, t)$, and the control gain is b. $\zeta_3 = f(\zeta, w, t) + \Delta bu$ is the new extended state variable, which contains the total disturbance of the system, $\dot{\zeta}_3 = g(t)$, then in (4).

$$\begin{cases} \dot{\zeta}_1 = \zeta_2 \\ \dot{\zeta}_2 = \zeta_3 + bu \\ \dot{\zeta}_3 = g(t) \\ y = \zeta_1 \end{cases} \tag{4}$$

The extended state observer of the system in (3) is:

$$\begin{cases} \dot{\hat{\zeta}}_1 = \hat{\zeta}_2 + \beta_1 \left(\zeta_1 - \hat{\zeta}_1\right) \\ \dot{\hat{\zeta}}_2 = \hat{\zeta}_3 + b_0 u + \beta_2 \left(\zeta_1 - \hat{\zeta}_1\right) \\ \dot{\hat{\zeta}}_3 = \beta_3 \left(\zeta_1 - \hat{\zeta}_1\right) \end{cases} \tag{5}$$

where $\hat{\zeta}_1$ and $\hat{\zeta}_2$ are the estimations of ζ_1 and ζ_2, respectively.$\hat{\zeta}_3$ is the estimation of ζ_3. β_1, β_2 and β_3 are selected as $[\beta_1,\ \beta_2,\ \beta_3] = [3w_o,\ 3{w_o}^2\ ,\ {w_o}^3]$ to ensure the stability of the ESO. w_o is the observer bandwidth.

Now, let $\check{\zeta}_1 = \zeta_1 - \hat{\zeta}_1$, $\check{\zeta}_2 = \zeta_2 - \hat{\zeta}_2$ and $\check{\zeta}_3 = \zeta_3 - \hat{\zeta}_3$ the state errors. From (5), the system can be refered as:

$$\begin{cases} \dot{\check{\zeta}}_1 = \dot{\zeta}_1 - \dot{\hat{\zeta}}_1 = -3w_o\check{\zeta}_1 + \check{\zeta}_2 \\ \dot{\check{\zeta}}_2 = \dot{\zeta}_2 - \dot{\hat{\zeta}}_2 = -\ 3{w_o}^2\check{\zeta}_1 + \check{\zeta}_3 \\ \dot{\check{\zeta}}_3 = \dot{\zeta}_3 - \dot{\hat{\zeta}}_3 = -{w_o}^3\check{\zeta}_1 + \dot{\zeta}_3 \end{cases} \tag{6}$$

the state error $\check{\zeta} = \left[\check{\zeta}_1, \check{\zeta}_2, \check{\zeta}_3\right]^T$ is defined to rewrite (6) as:

$$\begin{gathered} \dot{\check{\zeta}} = A\check{\zeta} + B \\ \begin{bmatrix} \dot{\check{\zeta}}_1 \\ \dot{\check{\zeta}}_2 \\ \dot{\check{\zeta}}_3 \end{bmatrix} = \begin{bmatrix} -3w_o & 1 & 0 \\ -\ 3{w_o}^2 & 0 & 1 \\ -{w_o}^3 & 0 & 0 \end{bmatrix} \begin{bmatrix} \check{\zeta}_1 \\ \check{\zeta}_2 \\ \check{\zeta}_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot{\zeta}_3 \end{bmatrix} \end{gathered} \tag{7}$$

according to (7), selecting w_o in such a way that the eigenvalues of A are on the left-hand plane is always possible [28].

3.3. Linear PD controller

The generalized PD controller for LADRC as shown in Figure 2 is linear as:

$$u_o = K_p e + K_d \dot{e} = K_p\left(r - \hat{\zeta}_1\right) + K_d(\dot{r}\_\hat{\zeta}_2) \tag{8}$$

where (K_p) is proportional gain and (K_d) is derivative gain.$(e, \dot{e})$ are error and its derivative.The controller bandwidth (w_c) and damping ratio (ξ) are used to determine the gains (k_p, k_d). These parameters are determined by the design specifications [29], [30].

$$\begin{gathered} k_p = \omega_c^2, \\ k_d = 2\zeta\omega_c \end{gathered} \tag{9}$$

The observer gains $(\beta_1,\ \beta_2,\ \beta_3)$ values for LADRC and PD controller can be calculated according to the analysis from [29], the bandwidth w_c is related to settling time τ_s of closed-loop system according to the following formula:

$$w_c = \frac{10}{\tau_s} \tag{10}$$

In this application, the specification of settling time of controlled system is chosen to be $\tau_s = 0.408sec$. The observer and PD controller gains can be calculated according to above equation with $(w_c = 24.5rad/sec)$.

3.4. Fractional PD controller

In this case, only needs to rewrite (8) in Fractional mode FPD:

$$u_o = K_p e + K_d D^{\alpha_c} e \tag{11}$$

one parameter to optimize for FADRC is the fractional term of derivative (α_c).

4. PARTICLE SWARM OPTIMIZATION (PSO) BASED- PARAMETER TUNING METHOD

In PSO, a system is evaluated by a particle, and a swarm of particles is the aggregate of solutions. Position and velocity are the two most significant attributes of each particle. Using the velocity, each particle goes to a new location. The optimal position of each particle and the best position of the swarm are adjusted as necessary once a new location is attained [31]-[33]. In this work PSO parameters are chosen according to the trial and error method as follows:

$$\text{Iterations} = 30;\ \text{inertia} = 1.5; \text{c1} = 2; \text{c2} = 2; \text{swarm\_size} = 30; \text{no\_of\_param} = 1.$$

the PSO optimization result gives the best value of Fractional controller term (α_c) as (0.10612).

5. COMPUTER SIMULATION AND ANALYSIS

For the Exoskeleton device, the transient behaviour and performance evaluation of LADRC and ADRC with FPD controller are investigated under two different scenarios: nominal and disturbance. A MATLAB experiment was used to confirm the findings. The numerical values of parameters for the human leg-exoskeleton system are given as [25]:

$$J = 0.314\ kg.m^2,\ A = 1.243\ N.m,\ B = 0.784\ N.m.sec.rad^{-1} \text{ and } \tau_g = 3.912\ N.m.$$

5.1. Nominal case

To evaluate the performance of the FADRC controller, with no payload condition, it works normally (no human torque effect $\tau_h = 0$) and without any disturbances and noises. Figure 3 shows performance of the FADRC and LADRC (Desired vs Real output). Figure 4 show knee position error between the desired and actual positions for both FADRC and LADRC. Comparative experiment results show that the FADRC control method achieves the smallest tracking error which verifies its effectiveness and superiority to LADRC as listed in Table 1. Due to the extra degree of freedom, the FADRC controller achieves better performance than the integer ADRC (LADRC) controller. To study the required control torque (τ_c) or $u(t)$ for both control strategies, Figure 5 shows the control efforts. Comparative experiment results show that the FADRC control method achieves the smallest control effort required for a controller (ISU) and smallest measure of chattering reduce in control signal index (IAU), when compared with LADRC due to present fractional function in PD controller.

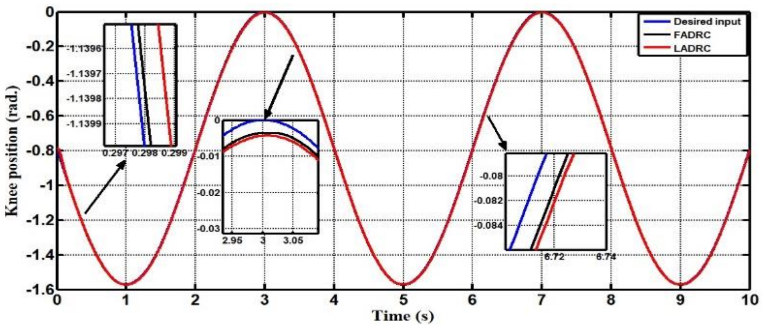

Figure 3. Knee position trajectory for comparison between FADRC and LADRC

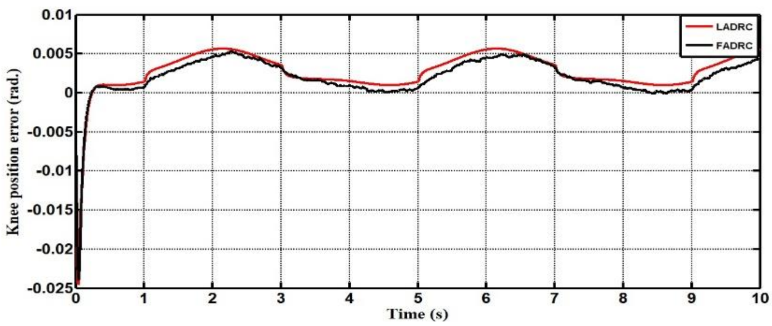

Figure 4. Knee position error for comparison between FADRC and LADRC

Table 1. Performance indices for LADRC and FADRC

Control Method	R.M.S.E(rad.)	ISU(N.m)	IAU(N.m)
LADRC	0.0038	121.2	28.36
FADRC	0.0013	120.1	28.1

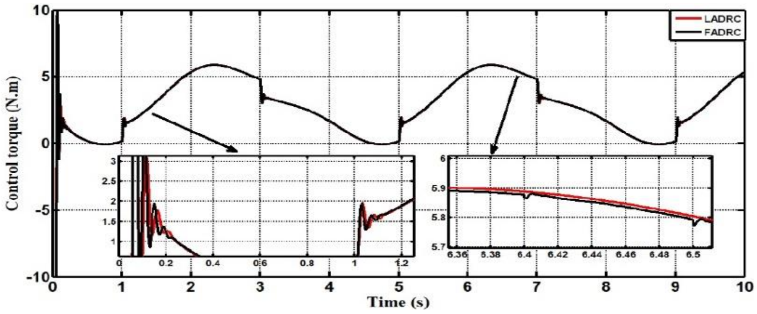

Figure 5. Control torque required for comparison between FADRC and LADRC

5.2. Disturbance case

In this case, the user's effort is considered with $\tau_h \neq 0$ or 0.5 Kg of payload is introduced on the beginning of the flexion/extension cycle (at time=2sec), which is applied at the output knee position moving. According to the control strategies are tested with a desired trajectory representing flexion and extension movements. Figure 6 show the trajectories tracking performance, it appears all position responses are tracked the desired trajectory. Figure 7 show knee error between the desired and actual positions. Comparative experiment results show that the FADRC control method achieves the smallest tracking error which verifies its effectiveness and superiority.

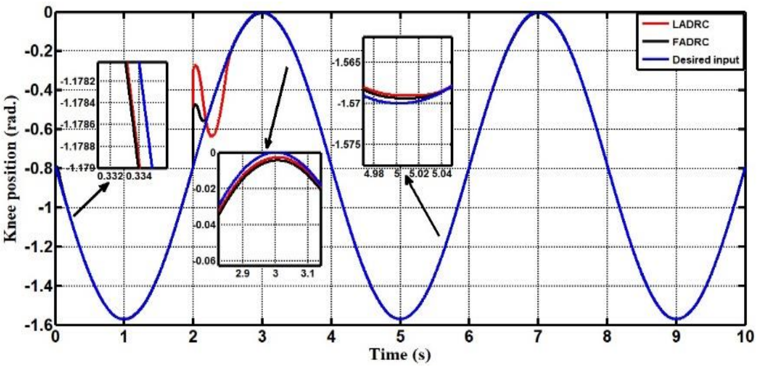

Figure 6. Knee position trajectory for comparison between FADRC and LADRC with disturbance

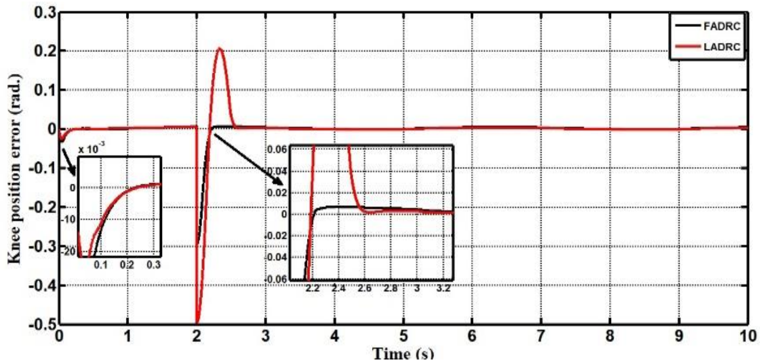

Figure 7. Knee position error for comparison between FADRC and LADRC with disturbance

To study the required control torque (τ_c) or $u(t)$ for both control strategies, Figure 8 shows the control efforts. Comparative experiment results show that the FADRC control method achieves the smallest control effort required for a controller (ISU) and highest measure of chattering reduce in control signal index (IAU), when compared with LADRC due to present fractional function in PD controller. It appears more vibration than LADRC, as listed in Table 2. In order to extend the present work for future work, one may suggest other control techniques for motion control of leg shank and a comparison study in performance with this study [34]-[43].

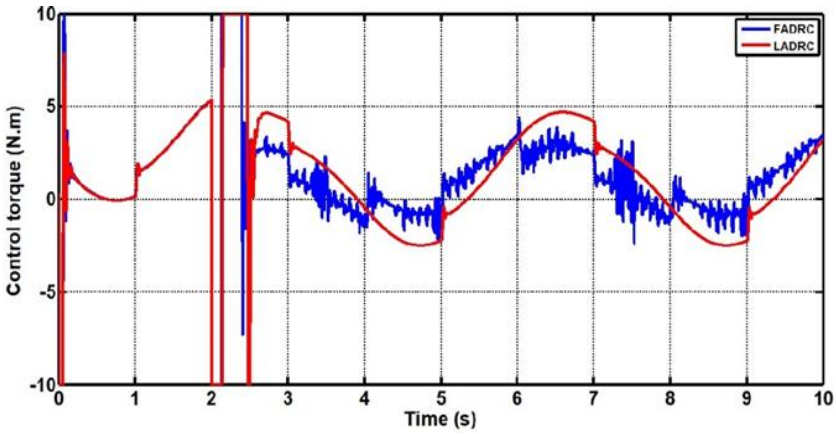

Figure 8. Control torque required for comparison between FADRC and LADRC with disturbance

Table 2. Performance indices for LADRC and FADRC with disturbance

Control Method	R.M.S.E(rad.)	ISU(N.m)	IAU(N.m)
LADRC	0.0547	115.2	25.11
FADRC	0.0459	80.74	25.15

6. CONCLUSION

This study has presented modified version of ADRC to enhance the dynamic performance of exoskeleton device dedictated to rehabilitate the disabled persons who suffering weak mobility in their lower-limbs. The effect of adding fractional order proportional derivative (FPD) in the feedfoward of conventional ADRC has been investigated. Moreoevr, the comparison study has been conducted between FPD-based ADRC and conventional ADRC in terms of robustness characteristics under uncertainity of system parameters. The results based on numerical simulation showed that the modified ADRC based on FPD outperforms the performance of FPD-free ADRC in terms of robustness characteristics.

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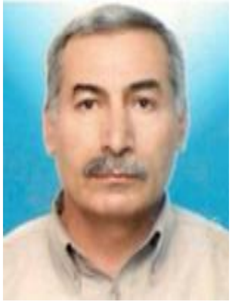

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