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PID Control of a Lower Limb Rehabilitation Exoskeleton

***Abstract**.: In this paper, our objective is to design a robust control system for an exoskeleton (orthosis) intended for rehabilitation assistance, which could potentially extend to addressing mobility issues. It is important to note that, within the scope of our work, rehabilitation assistance is specifically focused on the lower limbs (legs), as the knee is a crucial joint in the human body and, consequently, requires both significant stability and mobility. The primary goal is to develop a control system for the exoskeleton at the knee level. To achieve this, several factors must be taken into account the disturbances and the nature of human muscle movements: Human movement is facilitated by muscle contractions and relaxations.*

***Streszczenie.** W tym artykule naszym celem jest zaprojektowanie solidnego systemu sterowania egzoszkieletem (ortezą) przeznaczonym do celów rehabilitacyjnych, który mógłby potencjalnie rozszerzyć się na rozwiązywanie problemów z poruszaniem się. Warto zaznaczyć, że w zakresie naszej pracy pomoc rehabilitacyjna koncentruje się w szczególności na kończynach dolnych (nóżkach), gdyż kolano jest kluczowym stawem w organizmie człowieka i co za tym idzie wymaga dużej stabilności i mobilności. Podstawowym celem jest opracowanie systemu kontroli egzoszkieletu na poziomie kolan. Aby to osiągnąć, należy wziąć pod uwagę kilka czynników, zaburzenia i naturę ruchów mięśni człowieka: Ruch człowieka jest ułatwiony przez skurcze i rozluźnienia mięśni. (**Sterowanie PID egzoszkieletu rehabilitacyjnego kończyn dolnych**)*

Keywords: knee exoskeleton-assistant system, dynamic modeling, stability analysis, PID controller.
Słowa kluczowe: układ egzoszkielet-asystent kolana, modelowanie dynamiczne, analiza stabilności, kontroler PID.

Introduction

The partial or total loss of mobility in human limbs, also known as hemiplegia, can result from various causes such as aging, strokes, sports injuries, occupational injuries, or spinal cord traumas. Over the last decade, there has been a notable evolution in the approach to rehabilitating this condition. The emergence of concepts like brain plasticity and grip motor control has paved the way for new therapeutic approaches. These approaches have demonstrated real potential for neurological recovery and significant functional improvements in patients. However, the hemiplegic leg has often been an exception, with a naturally unfavorable prognosis and a relatively limited response to conventional therapies. As a result, researchers have sought new alternatives, encouraging collaboration between technology and medical professionals [1], [2], [3].

This collaboration has led to the development of innovative therapies, often based on the use of technological tools such as functional electrical stimulation, virtual reality, and transcranial magnetic stimulation to facilitate movements. Robotics has naturally come into play in the field of rehabilitation, enhancing the quality of treatments, particularly in terms of intensity. Initially focused on lower limb rehabilitation, robotic rehabilitation has gradually extended to the upper limb. It is in the context of neuromotor lower limb rehabilitation robotics that our paper contributes [4], [5].

The primary objective of this study is to craft a resilient control system tailored for an exoskeleton dedicated to enhancing lower limb rehabilitation, with a specific emphasis on the knee, given its pivotal role in human mobility [6]. Given the intricate nature of the leg exoskeleton system, a meticulously designed approach is imperative. The robustness of the control system is paramount, as it must exhibit efficacy across various leg models. The chosen control method to be developed and evaluated is the PID control [6]. The utilization of the PID controller is motivated by its simplicity of implementation, offering a pragmatic solution. Additionally, PID control ensures stability, precision, and agility within the study's system, aligning with the multifaceted requirements of lower limb rehabilitation [7], [8].

PID controllers offer simplicity, ease of implementation, and intuitive parameter tuning compared to sliding mode control, predictive control, and internal model control. Their robust performance across diverse operating conditions, cost-effectiveness, and balanced trade-off between simplicity and effectiveness make PID controllers a preferred choice in various industrial applications [9], [10], [11].

This paper is organized as follows. Section II presents a Dynamic Modeling of the Exoskeletal Knee Assistance System. Section III presents PID Controller-Based Control Strategy for Exoskeleton. In Section VI, we will implement the PID control on the exoskeleton to accurately track the desired trajectories. Some conclusions are drawn in section V.

Dynamic Modeling of the Exoskeletal Knee Assistance System

An exoskeleton is an articulated structure that supports the body externally, contrasting with the human skeleton, which provides internal support to the body. In the realm of robotics, an exoskeleton refers to an articulated and motorized device that attaches to specific parts of the body. It enhances the user's movements by supplementing strength through electric motors [1], [5].

The exoskeletal knee assistance system consists of two links, as illustrated in Fig.1.

A single link, affixed to the thigh, remains stationary, while the other link, connected to the shin, undergoes angular movement within a specified range. The mobility of the second link is facilitated by a DC motor situated at the knee joint, enabling controlled rotation. This configuration is particularly relevant in situations where the knee is affected by a disability, the motor is tasked with generating the required torque to precisely rotate the leg to the desired position.

As shown in Fig.1, the exoskeletal system has been configured to operate within the range of [0° - 90°]. Full leg extension is indicated by 0°, while 90° represents the resting position of the leg.

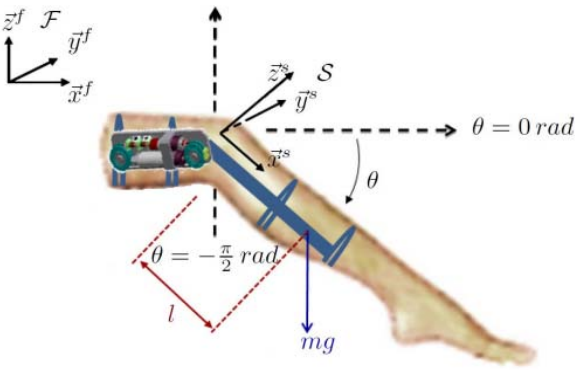

Fig.1. Geometric representation of the exoskeleton knee [12]

For the geometric modeling of the human leg, we opted for the direct geometric modeling. This approach enables the calculation of operational coordinates, i.e., the position and orientation of the end effector, based on joint coordinates. It allows determining the configuration of a robot, including its position and orientation, based on the configuration of its joints. In our case, we considered the top of the thigh as a fixed reference, the leg rotating relative to it, and the ankle being embedded in the leg (Fig.1).

Table 1. Geometric parameters of the prototype according to the Denavit-Hartenberg convention

	a_{i-1}	α_{i-1}	d_i	θ_i
Thigh	l_{Thigh}	0	0	θ_i
Leg	l_{Leg}	0	0	0
Knee Joint	0	$-\dfrac{\pi}{2}$	0	θ_i

The dynamic model of the human leg and exoskeleton is intricately crafted through the application of the Lagrangian method, with its expression elegantly delineated by the following equation [12], [13]:

(1) $$l_i = E_{ki} - E_{gi}$$

where $E_{ki} = \frac{1}{2} J_i \dot{\theta}^2$ and $E_{gi} = m_i\, g\, l_i \left(1 - \sin\theta\right)$: represent respectively the kinetic energy and the gravitational energy of the elements of the system.

In this context, $\dot{\theta}$ denotes the angular velocity of the exoskeleton system, J stands for the moment of inertia of the leg, while m_i and l_i represent the mass and length of the leg at the center of gravity and knee, respectively. G denotes the gravitational force, and θ signifies the angular position of the knee.

By employing the Euler-Lagrange differential equation for l_i, the dynamic model of the coupled system components can be obtained [12]:

(2) $$J_i \ddot{\theta} = m_i\, g\, l_i \left(1 - \sin\theta\right) - \tau_{exti}$$

where τ_{exti} Serves as a representation of the overall external torque exerted on the system. The expression of this torque is given by the following equation:

(3) $$\tau_{exti} = \tau_{fi} + \tau_i$$

Here, τ_i represents the control torque generated by the DC motor, and τ_{fi} is the frictional torque provided by:

(4) $$\tau_{fi} = -f_{si}\, sign\left(\dot{\theta}\right) - f_{vi}\, \dot{\theta}$$

where f_{vi} and f_{si} represent, respectively, the coefficients of viscous friction and solid friction

The dynamical model of the exoskeleton system is meticulously articulated through a comprehensive set of equations, capturing the intricate interplay of forces, moments, and dynamic variables that govern its behavior, it's gives by the following equation:

(5) $$J_i\, \ddot{\theta} = -\tau_g \cos\theta - f_s\, sign\left(\dot{\theta}\right) - f_v\, \dot{\theta} + \tau_h + \tau$$

PID Controller-Based Control Strategy for Exoskeleton

The PID controller is a powerful tool for lower limb exoskeletons, offering stability, precision, and adaptability crucial for rehabilitation. Its proportional component ensures accurate trajectory tracking, while integral and derivative components contribute to robustness, accommodating variations in system dynamics and handling external disturbances. The controller's simplicity facilitates real-time implementation, making it efficient for diverse exoskeleton models. Reduced settling time enhances rehabilitation exercise efficiency, and proper tuning minimizes overshooting for smoother movements [7], [8]. The PID controller's versatility allows for customization to different user profiles, ensuring an individualized rehabilitation experience. Its compatibility across various models and proven track record in control applications make PID controllers a reliable choice for achieving optimal performance in lower limb exoskeletons. Real-time adjustments enable dynamic responses to changes in user gait patterns, emphasizing the controller's adaptability in diverse rehabilitation scenarios.

The equation of the PID controller, representing a Proportional-Integral-Derivative device, is formulated as follows [7], [14]:

(6) $$u\left(t\right) = k_p\, e\left(t\right) + k_i \int e\left(t\right) dt + k_d \frac{de\left(t\right)}{dt}$$

where : u(t) represents the control to be applied to the system at time t.

e(t) represents the error between the setpoint value and the system output at time t.

k_p, *k_i*, and *k_d* are the tuning coefficients for the proportional, integral, and derivative controller components, respectively.

To determine the parameters of the PID controller, we need to linearize the exoskeleton system around a stable equilibrium point $\theta_0 = -\frac{\pi}{2}$

The dynamic model of the exoskeleton is linearized around the stable equilibrium point using the first-order Taylor series expansion technique. In this context, approximations will be employed to craft the linearized model of the study system, providing a tractable representation for analysis and control design.

(7) $$\begin{cases} \theta = \theta_0 + \Delta\theta \\ \dot{\theta} = \dot{\theta}_0 + \Delta\dot{\theta} \\ \ddot{\theta} = \ddot{\theta}_0 + \Delta\ddot{\theta} \\ sign\left(\theta\right) \approx sign\left(\theta_0\right) = -1 \\ \cos\left(\theta\right) \approx \cos\left(\theta_0\right) + \sin\left(\theta_0\right)\left(\theta - \theta_0\right) - \sin\left(\theta_0\right)\Delta\theta_0 \end{cases}$$

By applying the approximations provided by Equation (7) into Equation (5) and neglecting higher-order terms (products of $\Delta\dot{\theta}$ and $\Delta\ddot{\theta}$), the linearized model of the exoskeleton is expressed by the following equation:

$$0.3598\,\Delta\ddot{\theta} + 0.963\,\Delta\dot{\theta} + 2.192\,\Delta\theta = \Delta u \tag{8}$$

This simplified representation captures the essential dynamics of the exoskeleton, enabling a more manageable analysis while disregarding higher-order complexities introduced by the product of $\Delta\dot{\theta}$ and $\Delta\ddot{\theta}$ terms.

By linearizing our exoskeleton around the equilibrium point and applying the Ziegler-Nichols technique, we determined the PID controller gains as follows: kp=150, ki=5, kd=1. This selection of proportional (kp), integral (ki), and derivative (kd) gains is crucial for achieving stability and optimal performance in the control system. These values were derived through systematic analysis and tuning to enhance the exoskeleton's response to various operating conditions.

Simulation results

Within this section, we conduct numerical simulations for the Exoskeleton knee-assisted system under the influence of a PID controller. The exoskeleton system is subjected to a desired trajectory defined by the following equation:

$$\theta_{ref}(t) = \sin(t) \tag{9}$$

By taking the derivative of equation 3, we obtain the desired reference velocity defined as follows:

$$\dot{\theta}_{ref}(t) = \cos(t) \tag{10}$$

Fig. 2 provides a captivating visualization of the temporal evolution of the knee's angular position. The continuous blue trace represents the actual trajectory, while the reference is elegantly symbolized by discontinuous red points. A careful observation eloquently reveals that the system's output remarkably adheres to the setpoint, demonstrating a coherent convergence between the desired trajectory and the actual response. This synchronization between reality and the ideal underscores the efficiency and precision of the system in faithfully tracking the established reference parameters.

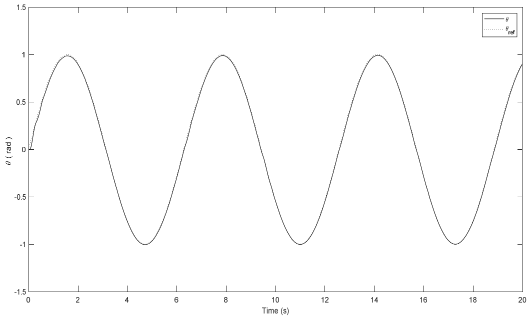

Fig.2. Evolution of the knee's angular position

Fig.3 illustrates the evolution of the error between the desired position (θ_{ref}) and the actually measured position (θ) of the knee joint at each moment. The error fluctuates between -0.01 and 0.07, indicating a minimal deviation in position tracking that remains close to zero. This observation underscores the remarkable ability of the PID control applied to the exoskeleton to guide the output θ with remarkable precision toward the reference θref, even in the presence of potential systemic variations such as external disturbances, changes in load, or uncertainties in system parameters. Thus, the PID controller maintains consistent stability in trajectory tracking performance, thereby attesting to its robustness in the face of varying dynamic conditions.

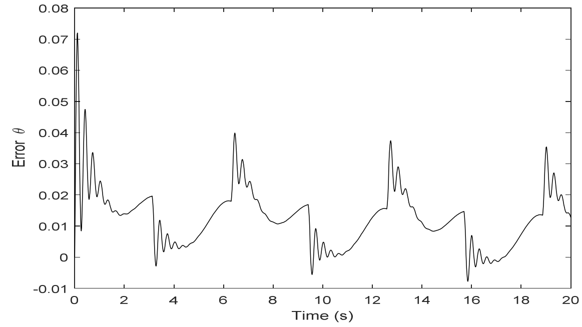

Fig.3. Position tracking error.

Fig.4 highlights the trajectory of the knee's angular velocity evolution. A careful observation reveals that the velocity $\dot{\theta}$ faithfully tracks its reference, exhibiting synchronized oscillations at the maximum and minimum points of the sinusoidal setpoint. This detailed observation provides insight into the system's ability to consistently adjust the knee's angular velocity, emphasizing the precision of tracking relative to the imposed reference.

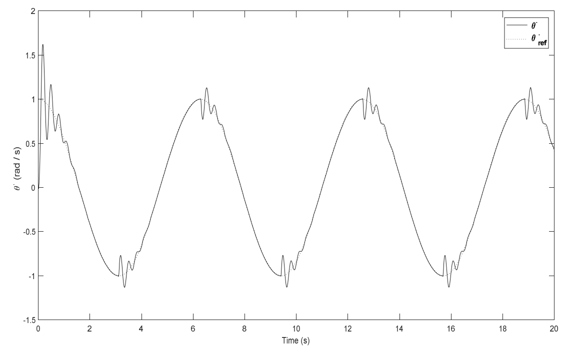

Fig.4. Evolution of the angular velocity of the knee.

Fig.5 provides a graphical representation of the temporal evolution of the angular velocity error of the knee. A careful analysis reveals that the tracking error of θ˙ oscillates between -0.6 and 1 but gradually converges to a narrower range, aligning between -0.2 and 0.2 from the 4-second mark. This convergence demonstrates the system's ability to regulate and diminish the error over time, thereby enhancing the stability and precision of tracking the angular velocity of the knee within the exoskeleton system.

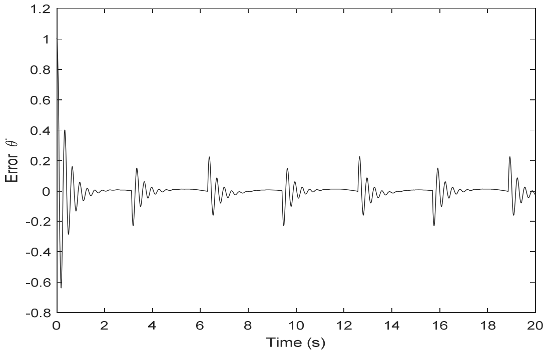

Fig.5. Evolution of the tracking error in the angular velocity of the knee.

Fig.6 provides a dynamic temporal view of the evolution of the torque exerted by the exoskeleton. Initially, at the start of the simulation, the torque amplitude oscillates between -0.3 and 1.3 Nm, demonstrating significant variability. However, from the 4-second mark onward, this variation remarkably adjusts, narrowing down to a more confined range, now spanning from -0.1 to 0.7 Nm. This detailed temporal observation highlights the system's ability to refine and stabilize the exerted torque, thereby offering a more precise and consistent performance over time.

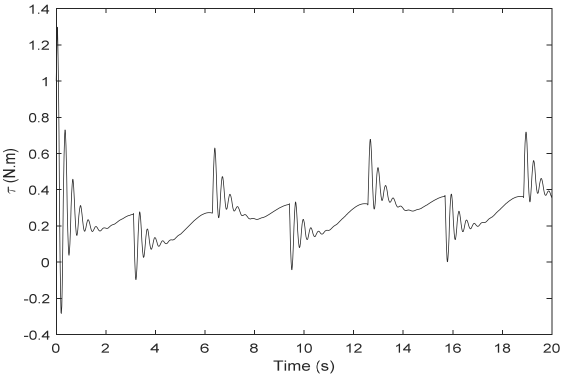

Fig.6. Torque applied to the exoskeleton.

Conclusion

In the paper, we embarked on an in-depth exploration of an exoskeletal robot meticulously crafted for the intricate dynamics of the human knee joint, featuring a singular degree of freedom (DDL). Our principal aim revolved around the conceptualization and realization of a robotic rehabilitation structure tailored specifically to address the unique needs of individuals grappling with knee disabilities. Our research journey prominently emphasized the intricate process of dynamic modeling applied to the exoskeleton, coupled with the subsequent deployment of a PID controller for precise control. The meticulous calibration of controller parameters was conducted through the nuanced approach of linearizing the system model, ensuring a fine-tuned response. The outcome of our simulations not only attests to the commendable performance of the system but also underscores its prowess in critical aspects such as stability, precision, and speed when subjected to the PID controller. These compelling findings substantiate the belief that our innovative approach stands as a beacon of promise in furnishing an effective and sophisticated rehabilitation solution for individuals contending with knee disabilities through the utilization of this advanced exoskeletal robot.

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