Trajectory Tracking Control of Pneumatic Cylinder-Actuated Lower Limb Robot for a Gait Training System

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ABSTRACT

This article presents the design of a control strategy for a lower limb gait training system catering to patients with Spinal Cord Injury (SCI) or stroke. The system operates by driving the hip and knee joints individually through pneumatic cylinders. The focus lies on the study and development of a control strategy for the pneumatic actuators within the gait training system, specifically targeting trajectory tracking control of pneumatic double-acting cylinders utilizing a PID Controller. The experiment setup comprises a pneumatic cylinder regulated by a proportional valve, incorporating feedback via position and pressure sensors. The experimental results show that the system exhibits good trajectory-tracking performance, particularly at low frequencies.

Keywords-trajectory tracking; pneumatic control; gait training system; PID control

I. INTRODUCTION

Individuals with mobility difficulties, such as those resulting from stroke or Spinal Cord Injury (SCI), often face significant challenges in regaining their ability to walk independently. The rehabilitation process for these individuals typically involves repetitive and intensive exercises aimed at restoring mobility and functionality. Recent studies found that incorporating gait training exercises into rehabilitation programs can significantly enhance both speed and effectiveness of patients' recovery processes [1, 2]. However, the accessibility of traditional therapy methods and high-tech rehabilitation systems remains limited, primarily due to their prohibitive costs and availability only in high-end hospital settings. Consequently, there is a pressing need for cost-effective lower limb gait training systems that can be widely accessible to individuals in need of rehabilitation.

Several existing rehabilitation systems and controlling strategies have been developed to address the challenges faced by individuals with mobility impairments. Soft robots have become rapidly evolving in the field of rehabilitation robotics because of their high degree of flexibility and suitability for biomedical design [3]. Soft actuators, such as McKibben type pneumatic artificial muscles [4, 5], offer capabilities for extension, contraction, bending, and twisting, albeit with complex structures and multiple degrees of freedom (DoFs). Despite these advantages, soft robots face several challenges due to their unique characteristics such as complexity of material and structure, sensor integration and control difficulty [6]. Electromagnetic actuators, such as the LOPES exoskeleton robot [7] and the Lokomat exoskeleton [8], are common rehabilitation devices. They utilize servo motors and electric actuators to facilitate guided limb movement. Pneumatic actuators, widely applied in industrial applications for their affordability, lightweight nature, and favourable force-to-weight ratio [9]. Authors in [10] demonstrated a 1-DoF robot to support the movement of lower limb at sitting position using a pneumatic double acting cylinder. A pneumatic -driven robot gait training system, comprising a lower-limb exoskeleton, a weight support system, and a treadmill can offer continuous passive gait motion for patients while also reducing the need for therapist assistance [11]. However, pneumatic actuators present challenges in achieving high-precision position control due to the compressive properties of air and nonlinearity of control valves [12]. Several methods have been proposed to regulate the trajectory tracking of pneumatic actuators. Authors in [13, 14] demonstrated PID controllers tailored for pneumatic McKibben actuator and pneumatic cylinder, respectively. While PID controllers offer simple approaches, more advanced and nonlinear controllers such as Sliding Mode Control (SMC) [15-17] and adaptive control [18, 19] have emerged. Despite their complexity, these advanced controllers show better tracking accuracy, especially in the presence of uncertainties and disturbances.

Due to the prohibitive cost and intricate design of existing gait training systems, our research endeavours to explore alternative approaches aimed at reducing both expense and complexity while maintaining effective gait training functionality. Our locomotion training approach aims to focus on regaining walking ability by simulating the natural motion of human legs. Leveraging the two primary joints of the human leg, the hip and knee, our proposed system utilizes pneumatic cylinders to actuate these rotational joints, enabling trajectory tracking control for rehabilitation purposes. Each joint can be controlled independently and synchronized to replicate the desired trajectory of a normal walking cycle, thereby facilitating repeatability in gait training and specific lower limb rehabilitation tasks. Importantly, our approach prioritizes safety, reliability, and affordability, making it suitable for long-term operation and widespread adoption.

This paper presents a study on a pneumatic actuator system comprising a pneumatic double-acting cylinder controlled by a proportional directional control valve. The performance of PID control with various desired reference inputs is investigated through simulations and experiments. By evaluating the effectiveness of this control strategy, we aim to contribute to the development of more accessible and efficient rehabilitation solutions for individuals with mobility impairments.

II. SYSTEM OVERVIEW

Figure 1 demonstrates the designed lower limb robot component within the gait training system. This robot consists of two pivotal joints, mirroring the functionality of the human hip and knee joints. Movement initiation within these joints is facilitated by a rack and pinion mechanism. Specifically, the rack is affixed to the rod of a pneumatic cylinder, while the pinion is centrally mounted to the shaft of the joint. Consequently, manipulation of the pneumatic cylinder regulates the joint angle, enabling precise control over the motion dynamics of the robotic leg. Controlling this robot requires synchronized management of the trajectory angle of both the hip and the knee joints. In essence, each joint of the robot should be controlled to adhere a specific trajectory. Figure 2 illustrates the schematic diagram of the experimental setup.

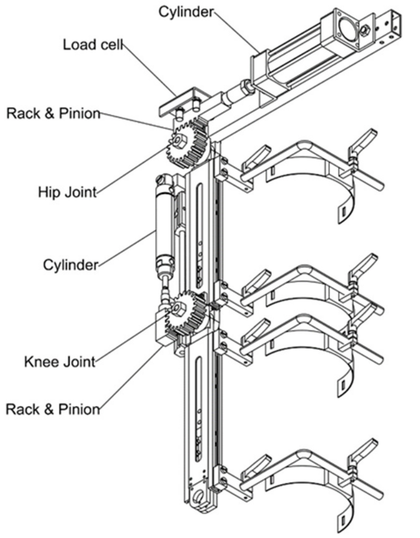

Fig. 1. Configuration of the lower limb rehabilitation robot for gait trainning.

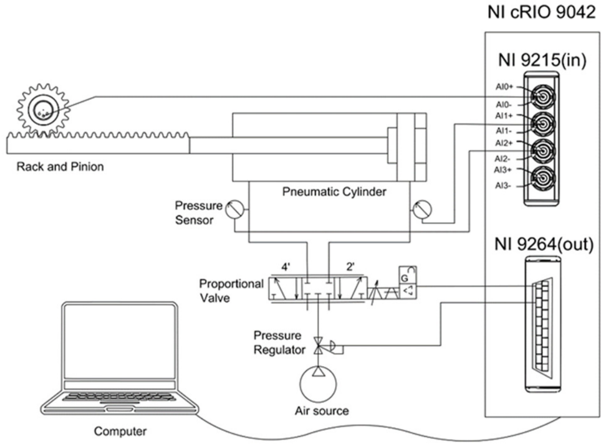

Fig. 2. Schematic diagram of the experimental setup.

The objective of this testbench is to study the control of pneumatic cylinder piston's position, enabling it to track various reference trajectories for gait training purposes. The initial point (0) of the cylinder is designated as the right-most position of the piston where the rod is at its shortest position. The linear motion of the piston is transmuted into rotational motion via the rack and pinion mechanism. The rotation angle is quantified using an angular sensor (P3022-V1-CW360-SPI) affixed to the pinion shaft. Air flow rates into and out of the pneumatic cylinder's chambers are managed by the proportional valve (FESTO MPYE-5-1/8-HF-010-B). This valve modulates the air flow to and from the actuator's chambers in response to variations in electrical voltages, with the effective orifice area adjusting according to input voltage. A pneumatic regulator at the air source maintains a constant pressure supplied to the valve. Chamber pressures are gauged using pressure sensors (SMC PSE540 R04). The valve, pressure sensors, and angular sensor interface with a Real-time target NI cRIO 9042 controllers, which executes system control tasks via signal input module NI9215 and signal output module NI9264. The physical setup of the system is depicted in Figure 3. The system parameters are listed in Table I.

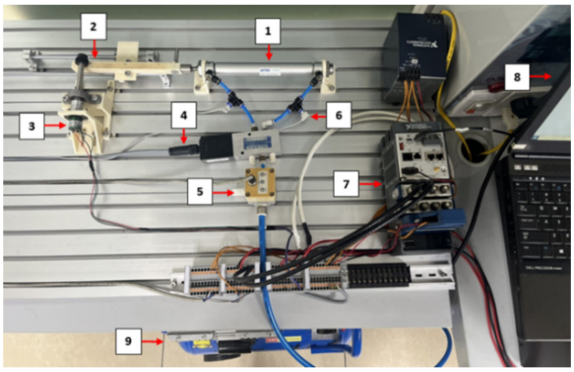

Fig. 3. Photo of the experimental setup: 1) Pneumatic cylinder, 2) rack and pinion, 3) angular sensor, 4) valve, 5) regulator, 6) pressure sensor, 7) controller, 8) computer, 9) pressure source.

TABLE I. SYSTEM PARAMETERS

Parameter	Value	Parameter	Value
P_S	500000 Pa	C_d	0.8
P_{atm}	100000 Pa	T	293 K
A_a	314 mm^2	R	287 J/(KgK)
A_b	268.3 mm^2	C_r	0.528
A_r	8 mm^2	l	150 mm
M_L	_	w	2.52 mm^2

III. MODELING AND CONTROL SYSTEM

The characteristics of airflow in pneumatic systems are highly intricate, due to the complicated characteristic of air and pressure, the nonlinearity of pneumatic components such as valves, cylinders, air tube, and friction. The theoretical analysis is a widely used method for finding the mathematical model of the pneumatic actuator and components [20, 21]. Commonly, there are three major considerations for obtaining the pneumatic actuator system: (1) the mass flow rate of the air through the valve, (2) the pressure, volume and temperature of the air in the cylinder, and (3) the dynamic of the load. Friction force [22, 23] and thermodynamics inside the actuator chambers [24] can also be modeled to increase the accuracy of the pneumatic actuator system model. Simplifications are often needed for mathematical analysis and trajectory control tracking. The following hypotheses are employed to streamline the modeling process: treating the air as an ideal gas, assuming uniform pressure and temperature within cylinder chambers, disregarding kinetic and potential energy terms, neglecting air leakages from chambers, maintaining constant supply and exhaust pressures, and ignoring the effects of connecting tubes when the air supply is close to the valve and cylinder. These assumptions are essential for developing models and analyzing pneumatic systems, enabling researchers to navigate the complexities of airflow dynamics more effectively.

Figure 4 shows the dynamic representation of the pneumatic cylinder. The detailed derivation of the estimated dynamic model is given in [25]. The main equations of the dynamic model are summarized as follows:

$$M_L\ddot{x} + \beta\dot{x} + F_f + F_L = P_aA_a - P_bA_b - P_{atm}A_r \quad (1)$$

$$\dot{m}_a = q_a(X_a, p_a) \quad (2)$$

$$\dot{m}_b = q_b(X_b, p_b) \quad (3)$$

$$\dot{m}_a = (P_a\dot{V}_a + V_a\dot{P}_a/k)/(RT) \quad (4)$$

$$\dot{m}_b = (P_b\dot{V}_b + V_b\dot{P}_b/k)/(RT) \quad (5)$$

where x is the piston position of the pneumatic cylinder, $\dot{x}$ represents the velocity, and $\ddot{x}$ the acceleration, M_L is the external load (kg), β is the viscosity coefficient, F_f is the friction force inside the cylinder, F_L is the external force, P_a and P_b are the absolute pressures in chamber A and B, A_a and A_b are the piston effective areas of chamber A and B, respectively, P_{atm} is the atmospheric pressure, and A_r is the area of the piston rod.

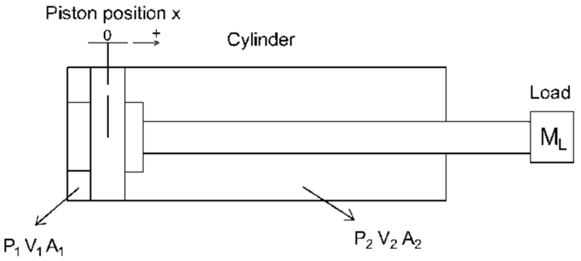

Fig. 4. Dynamic representation of pneumatic cylinder.

By neglecting the effect of friction force, the state-space representation of the system is obtained:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{1}{M}(A_ax_3 - A_bx_4 - K_fx_2) \\ \dot{x}_3 = -\frac{kx_3}{(l/2+x_1)}x_2 + \frac{kRT}{A_a(l/2+x_1)}C_dC_0wX_a\,f(P_u, P_a) \\ \dot{x}_4 = \frac{kx_4}{(l/2-x_1)}x_2 + \frac{kRT}{A_b(l/2-x_1)}C_dC_0wX_b\,f(P_u, P_b) \\ y\ =\ x_1 \end{cases} \quad (6)$$

where $x_1 = x$, $x_2 = \dot{x}$, $x_3 = P_a$, and $x_4 = P_b$, and y is the system output. The spool displacement of valve has a linear relationship with the control signal u of the valve. We can estimate the relationship by $u = X$. Thus, for a single five-port valve of the system $u_a = -u_b$. Based on the physical properties of the system, the position x_1 and pressures x_3 and x_4 are bounded by $x_1 \in [\frac{-l}{2}, \frac{l}{2}]$ and $x_3, x_4 \in [P_{atm}, Ps]$.

In this study, we implement a PID controller to govern the movement of a pneumatic piston. The PID controller is a widely used method for achieving precise control in pneumatic systems. This controller is designed to regulate the position of a piston, ensuring that it tracks the desired position effectively. The control law u is calculated as follows:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \qquad (7)$$

where u is the control signal of the proportional valve, $e = x_d - x$ is the error between desired position x_d and actual position x of the cylinder's piston. The controller's parameters, including proportional, integral, and derivative coefficients (K_p, K_i, K_d), are tuned through a combination of trial-and-error methods.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Our experiments aim to assess the control efficacy of the pneumatic actuator system. The objective is for the pneumatic cylinder's piston to accurately track specified reference signals. These signals include sinusoidal waves with amplitudes of 70 mm at frequencies of 0.1 Hz and 0.5 Hz, as well as hip-joint and knee-joint reference signals also at 0.1 Hz and 0.5 Hz, respectively. These joint signals, sourced from [5], represent the complete gait cycle of leg movement. Additionally, we performed experiments with varied frequency reference trajectories.

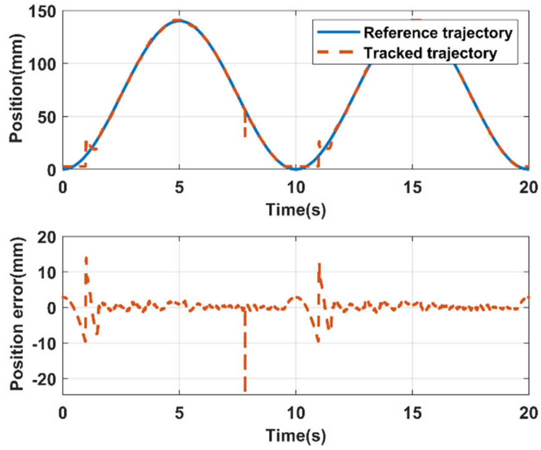

Fig. 5. Experimental results for sine wave reference trajectory at 0.1 Hz.

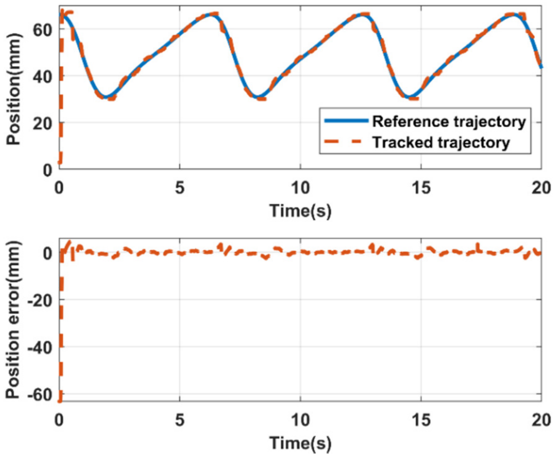

Fig. 6. Experimental results for hip-joint reference trajectory at 0.1 Hz.

Figures 5-7 show the tracking of desired trajectories at 0.1 Hz using the PID control method. Throughout these experiments, the pressure was maintained at 5 bar, and no load was applied to the rack and pinion system. To reduce sudden pressure changes within the cylinder, the control signal of the proportional valve was capped between 4 V and 6 V. Figures 8-10 depict tracking results at 0.5 Hz under identical conditions. To optimize performance, only PI parameters were used and individually tailored for each case. The specific control parameters utilized were: $K_p = 0.04$, $K_i = 0.1$ for 0.1 Hz and $K_p = 0.04$, $K_i = 0.2$ for 0.5 Hz. The tracking performance for varied frequency is shown in Figure 11.

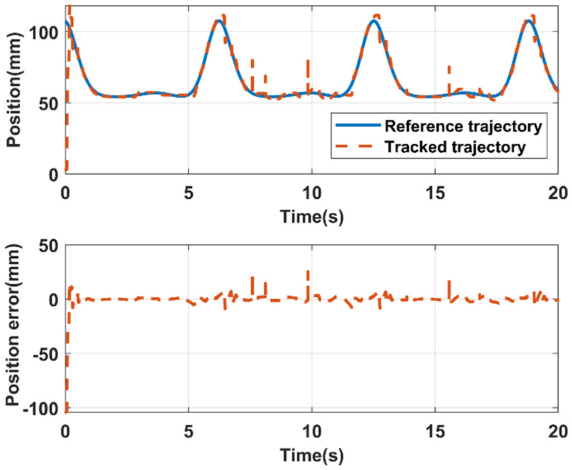

Fig. 7. Experimental results knee-joint reference trajectory at 0.1 Hz.

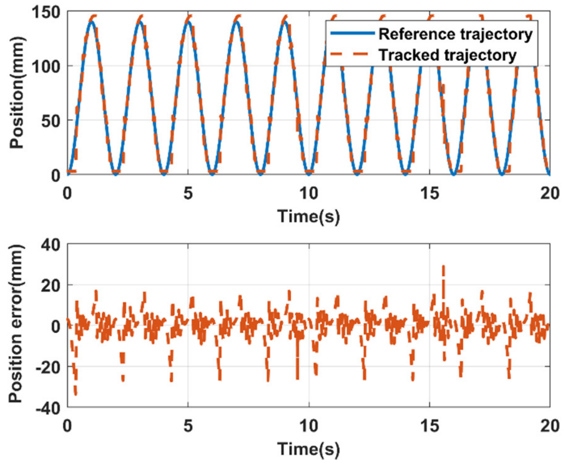

Fig. 8. Experimental results for sine wave reference trajectory at 0.5 Hz.

The RMSE values for trajectory tracking are listed in Tables II and III. From the results, the system exhibits a rapid response to reach steady-state conditions. The system's fast response capabilities make it well-suited for dynamic clinical environments, where timely adjustments are essential for effective patient rehabilitation.

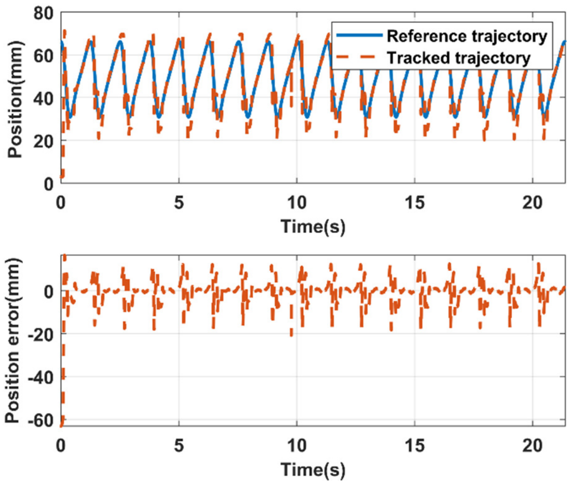

Fig. 9. Experimental results hip-joint reference trajectory at 0.5 Hz.

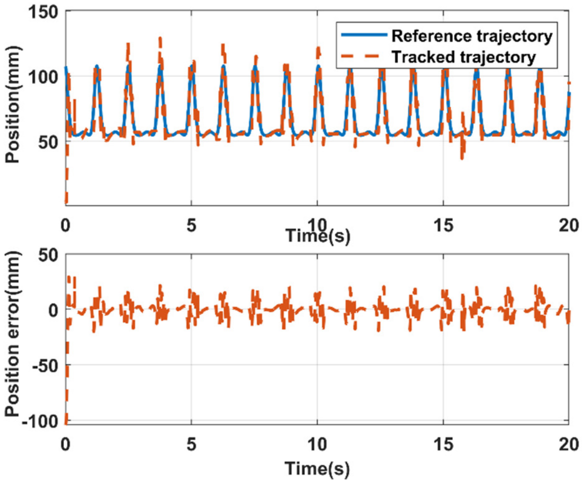

Fig. 10. Experimental results for knee-joint reference trajectory at 0.5 Hz.

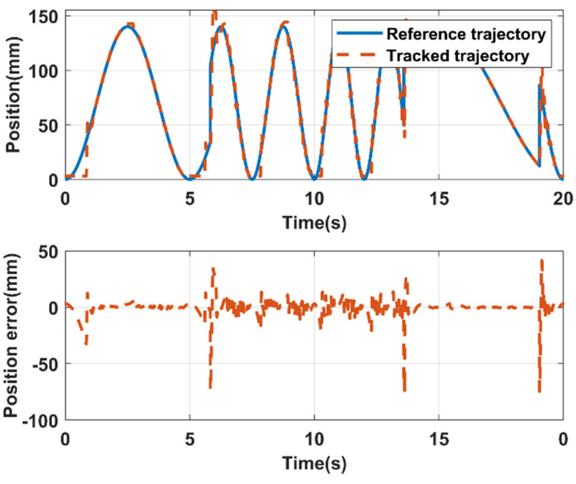

Fig. 11. Experimental results for varied frequency reference trajectory.

The analysis of tracking error percentages reveals an interesting trend: tracking performance is notably robust at lower frequencies, such as 0.1 Hz, but declines as the frequency increases to 0.5 Hz. This observation underscores the sensitivity of the system's tracking accuracy to frequency variations, highlighting the need for careful consideration and optimization of control parameters across different operating frequencies. In comparison to the tracking results presented in [11], our finding shows comparable tracking performance for both hip and knee joint at 0.1 Hz, utilizing identical reference signals. Given that the purpose of gait training system is to aid patients in improving and assisting their functionality, which can vary among individuals, this level of motion error is satisfactory and acceptable in clinical practice [26].

TABLE II. ROOT MEAN SQUARE ERROR OF TRAJECTORY TRACKING AT 0.1 HZ

	Sinusoidal wave	**Hip-joint reference**	**Knee-joint reference**
RMSE (mm)	2.29	4.04	6.45
RMSE percentage	1.65%	6.12%	6.03%

TABLE III. ROOT MEAN SQUARE ERROR OF TRAJECTORY TRACKING AT 0.5 HZ

	Sinusoidal wave	**Hip-joint reference**	**Knee-joint reference**
RMSE (mm)	7.11	6.30	8.35
RMSE percentage	5.12%	9.55%	7.81%

A significant finding is the occurrence of elevated errors during transitions in cylinder direction. This phenomenon is attributed to several factors, including the delay induced by pressure changes and the inherent deadband of the valve used for directional control. These factors influence the system's response during directional changes, contributing significantly to the rise in RMSE. Addressing these factors is crucial to enhance overall performance and reliability. This can be achieved through the design of a controller capable of predict pressure changes and make necessary adjustments.

Our pneumatic gait training system, utilizing rack and pinion mechanisms, leverages the benefit of pneumatic technology in biomedical application, while remaining convenient to implement and control. This characteristic holds relevance in developing countries like Vietnam, where access to advanced gait training systems is restricted due to cost and technological constraints. This project carries significant humanitarian implications, addressing a pressing need within society.

In future work, we will focus on enhancing both the control system and the physical structure to minimize tracking errors and conduct experiments under varying conditions. Additionally, we plan to implement the system on a real gait training robot to further validate its efficacy and real-world applicability.

V. CONCLUSION

In conclusion, this paper presents a comprehensive design and implementation of a control strategy for a lower limb gait training system tailored for patients with Spinal Cord Injury (SCI) or stroke. The system, driven by pneumatic cylinders, focuses on individual control of the hip and knee joints. The primary objective is to develop effective trajectory tracking control for the pneumatic actuators employing a PID controller, while keeping it robust and reliable. The experimental results demonstrate the system's good trajectory tracking performance, particularly notable at lower frequencies. These results underscore the efficacy and potential of the proposed control strategy in enhancing gait training outcomes for individuals with lower limb impairments. Further research and refinement of the control system hold promise for advancing rehabilitation techniques and improving patient outcomes in clinical settings.

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REFERENCES

[1] T. Mikolajczyk *et al.*, "Advanced technology for gait rehabilitation: An overview," *Advances in Mechanical Engineering*, vol. 10, no. 7, , Jul. 2018, Art. no. 1687814018783627, https://doi.org/10.1177/1687814018783627.

[2] A. Guzzetta *et al.*, "Brain Representation of Active and Passive Hand Movements in Children," *Pediatric Research*, vol. 61, no. 4, pp. 485–490, Apr. 2007, https://doi.org/10.1203/pdr.0b013e3180332c2e.

[3] M. S. Xavier *et al.*, "Soft Pneumatic Actuators: A Review of Design, Fabrication, Modeling, Sensing, Control and Applications," *IEEE Access*, vol. 10, pp. 59442–59485, 2022, https://doi.org/10.1109/ACCESS.2022.3179589.

[4] S. Z. Ying, N. K. Al-Shammari, A. A. Faudzi, and Y. Sabzehmeidani, "Continuous Progressive Actuator Robot for Hand Rehabilitation," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5276–5280, Feb. 2020, https://doi.org/10.48084/etasr.3212.

[5] D. G. Caldwell, N. G. Tsagarakis, S. Kousidou, N. Costa, and I. Sarakoglou, "'soft' exoskeletons for upper and lower body rehabilitation — design, control and testing," *International Journal of Humanoid Robotics*, vol. 04, no. 03, pp. 549–573, Sep. 2007, https://doi.org/10.1142/S0219843607001151.

[6] P. Polygerinos *et al.*, "Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot Interaction," *Advanced Engineering Materials*, vol. 19, no. 12, 2017, Art. no. 1700016, https://doi.org/10.1002/adem.201700016.

[7] J. F. Veneman, R. Kruidhof, E. E. G. Hekman, R. Ekkelenkamp, E. H. F. Van Asseldonk, and H. Van Der Kooij, "Design and Evaluation of the LOPES Exoskeleton Robot for Interactive Gait Rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 379–386, Sep. 2007, https://doi.org/10.1109/TNSRE.2007.903919.

[8] K. van Kammen, A. M. Boonstra, L. H. V. van der Woude, H. A. Reinders-Messelink, and R. den Otter, "The combined effects of guidance force, bodyweight support and gait speed on muscle activity during able-bodied walking in the Lokomat," *Clinical Biomechanics (Bristol, Avon)*, vol. 36, pp. 65–73, Jul. 2016, https://doi.org/10.1016/j.clinbiomech.2016.04.013.

[9] D. Saravanakumar, B. Mohan, and T. Muthuramalingam, "A review on recent research trends in servo pneumatic positioning systems," *Precision Engineering*, vol. 49, pp. 481–492, Jul. 2017, https://doi.org/10.1016/j.precisioneng.2017.01.014.

[10] R. Goergen, A. C. Valdiero, L. A. Rasia, M. Oberdorfer, J. P. De Souza, and R. S. Goncalves, "Development of a Pneumatic Exoskeleton Robot for Lower Limb Rehabilitation," in *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, Toronto, ON, Canada, Jun. 2019, pp. 187–192, https://doi.org/10.1109/ICORR.2019.8779522.

[11] I.-H. Li, Y.-S. Lin, L.-W. Lee, and W.-T. Lin, "Design, Manufacturing, and Control of a Pneumatic-Driven Passive Robotic Gait Training System for Muscle-Weakness in a Lower Limb," *Sensors*, vol. 21, no. 20, Jan. 2021, Art. no. 6709, https://doi.org/10.3390/s21206709.

[12] E. Richer and Y. Hurmuzlu, "A High Performance Pneumatic Force Actuator System: Part I—Nonlinear Mathematical Model," *Journal of Dynamic Systems, Measurement, and Control*, vol. 122, no. 3, pp. 416–425, Jun. 1999, https://doi.org/10.1115/1.1286336.

[13] S. Yamamoto, Y. Shibata, S. Imai, T. Nobutomo, and T. Miyoshi, "Development of gait training system powered by pneumatic actuator like human musculoskeletal system," in *2011 IEEE International Conference on Rehabilitation Robotics*, Zurich, Jun. 2011, pp. 1–4, https://doi.org/10.1109/ICORR.2011.5975452.

[14] T. X. Bo, "PID Control for a Pneumatic Servo System," *Journal of Science and Technology - Technical Universities*, vol. 29, no. 7, pp. 12–17, Nov. 2019.

[15] T. Nguyen, J. Leavitt, F. Jabbari, and J. E. Bobrow, "Accurate Sliding-Mode Control of Pneumatic Systems Using Low-Cost Solenoid Valves," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 2, pp. 216–219, Apr. 2007, https://doi.org/10.1109/TMECH.2007.892821.

[16] V. T. Jouppila, S. A. Gadsden, G. M. Bone, A. U. Ellman, and S. R. Habibi, "Sliding mode control of a pneumatic muscle actuator system with a PWM strategy," *International Journal of Fluid Power*, vol. 15, no. 1, pp. 19–31, Jan. 2014, https://doi.org/10.1080/14399776.2014.893707.

[17] D. M. Duc, T. X. Tuy, and P. D. Phuoc, "A Study on the Response of the Rehabilitation Lower Device using Sliding Mode Controller," *Engineering, Technology & Applied Science Research*, vol. 11, no. 4, pp. 7446–7451, Aug. 2021, https://doi.org/10.48084/etasr.4312.

[18] D. Meng, G. Tao, and X. Zhu, "Integrated direct/indirect adaptive robust motion trajectory tracking control of pneumatic cylinders," *International Journal of Control*, vol. 86, no. 9, pp. 1620–1633, Sep. 2013, https://doi.org/10.1080/00207179.2013.792002.

[19] O. Aydogdu and M. L. Levent, "Kalman State Estimation and LQR Assisted Adaptive Control Of a Variable Loaded Servo System," *Engineering, Technology & Applied Science Research*, vol. 9, no. 3, pp. 4125–4130, Jun. 2019, https://doi.org/10.48084/etasr.2708.

[20] O. Olaby, "Characterization and Modeling of A Proportional Value for Control Synthesis," *Proceedings of the JFPS International Symposium on Fluid Power*, 2005, https://doi.org/10.5739/isfp.2005.771.

[21] Shu Ning and G. M. Bone, "Development of a nonlinear dynamic model for a servo pneumatic positioning system," in *IEEE International Conference Mechatronics and Automation, 2005*, Niagara Falls, Ont., Canada, 2005, pp. 43–48, https://doi.org/10.1109/ICMA.2005.1626520.

[22] A. Saleem, C. B. Wong, J. Pu, and P. R. Moore, "Mixed-reality environment for frictional parameters identification in servo-pneumatic system," *Simulation Modelling Practice and Theory*, vol. 17, no. 10, pp. 1575–1586, Nov. 2009, https://doi.org/10.1016/j.simpat.2009.06.016.

[23] A. S. Lafmejani, M. T. Masouleh, and A. Kalhor, "An experimental study on friction identification of a pneumatic actuator and dynamic modeling of a proportional valve," in *2016 4th International Conference on Robotics and Mechatronics (ICROM)*, Tehran, Iran, Oct. 2016, pp. 166–172, https://doi.org/10.1109/ICRoM.2016.7886840.

[24] D. Meng, G. Tao, J. Chen, and W. Ban, "Modeling of a pneumatic system for high-accuracy position control," in *Proceedings of 2011 International Conference on Fluid Power and Mechatronics*, Beijing, China, Aug. 2011, pp. 505–510, https://doi.org/10.1109/FPM.2011.6045817.

[25] J. Wang, D. J. D. Wang, P. R. Moore, and J. Pu, "Modelling study, analysis and robust servocontrol of pneumatic cylinder actuator systems," *IEE Proceedings - Control Theory and Applications*, vol. 148, no. 1, pp. 35–42, Jan. 2001, https://doi.org/10.1049/ip-cta:20010238.

[26] M. H. Schwartz, J. P. Trost, and R. A. Wervey, "Measurement and management of errors in quantitative gait data," *Gait & Posture*, vol. 20, no. 2, pp. 196–203, Oct. 2004, https://doi.org/10.1016/j.gaitpost.2003.09.011.