Kinematic Modeling, Dynamic Control, And Simulated Performance Of A 3-Degree-Of-Freedom Pneumatic Artificial Muscle-Driven Mechanism For Upper Extremity Prosthetics

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ABSTRACT

The development of advanced upper limb prostheses that offer both high dexterity and intuitive control remains a significant challenge in rehabilitation engineering. Traditional actuation methods often fall short in replicating the compliance, power-to-weight ratio, and inherent safety of biological muscles. This article conceptually explores the kinematic modeling, dynamic control, and simulated performance of a novel 3-degrees-of-freedom (3-DOF) mechanism actuated by Pneumatic Artificial Muscles (PAMs), specifically designed for upper extremity prosthetic applications. We propose a detailed mathematical model encompassing the kinematics of the mechanism, the non-linear force generation of PAMs, and the interaction dynamics. An adaptive control strategy, leveraging the inherent compliance of PAMs, is conceptually developed to achieve precise position and force control despite the actuators' non-linearities and hysteresis. Numerical simulations are presented to illustrate the mechanism's ability to achieve a wide range of motion, high force output, and robust trajectory tracking. The discussion highlights the potential of PAM-driven prostheses to offer more natural, compliant, and user-friendly solutions for individuals with upper limb deficiencies. This work provides a foundational framework for the design and realization of next-generation bio-inspired prosthetic devices.

Keywords: Upper limb prosthesis, pneumatic artificial muscles (PAMs), 3-degrees-of-freedom, kinematic modeling, dynamic control, simulation, bio-inspired actuation, compliance, human-robot interaction.

INTRODUCTION

Upper limb prostheses play a crucial role in restoring functionality and improving the quality of life for individuals who have experienced limb loss. While significant advancements have been made in prosthetic technology, achieving anthropomorphic dexterity, natural movement, and intuitive control remains a formidable challenge [1, 2, 3]. Current prosthetic hands and arms often rely on rigid electric motors or hydraulic systems, which, despite their precision, can be heavy, noisy, stiff, and lack the inherent compliance and shock absorption characteristics of human muscles [1, 2]. This mechanical mismatch can lead to uncomfortable human-prosthesis interaction, limit user acceptance, and hinder the execution of complex daily tasks [4].

The limitations of conventional actuators have spurred research into "bio-inspired" alternatives that more closely mimic the properties of biological muscle. Among these, Pneumatic Artificial Muscles (PAMs), particularly the McKibben muscle type, stand out due to their high power-to-weight ratio, inherent compliance, low cost, and safe operation [6, 10, 11]. PAMs contract when pressurized, generating a tensile force similar to a biological muscle, making them ideal candidates for soft robotics and rehabilitation applications where compliant interaction with the human body is paramount [15]. Their elastic nature also contributes to safer operation in direct human contact scenarios, minimizing impact forces and enabling more natural grasping and manipulation [15].

Despite their compelling advantages, the application of PAMs in high-performance prosthetic devices is challenging due to their inherent non-linear characteristics, including hysteresis, creep, and variable stiffness depending on pressure and contraction [12, 13, 28, 29]. Accurate mathematical modeling, robust control strategies, and comprehensive simulation are therefore essential to unlock their full potential in complex robotic systems like upper limb prostheses [13, 25]. A 3-degrees-of-freedom (3-DOF) mechanism, for instance, could represent a key joint such as the wrist (flexion/extension, abduction/adduction, pronation/supination) or a simplified elbow/shoulder complex, providing crucial functional capabilities for a prosthetic arm.

This article conceptually proposes a comprehensive framework for the design, modeling, control, and simulation of a 3-DOF mechanism driven by PAMs, specifically targeting upper limb prosthetic applications. The objective is to demonstrate how a carefully developed mathematical model, coupled with an advanced control strategy, can enable PAMs to achieve the precision and dynamic performance required for realistic prosthetic function, while preserving their advantageous inherent compliance. This work aims to provide a theoretical and simulation-based foundation for future experimental realization of next-generation, human-centric prosthetic devices.

2. Literature Review

The landscape of upper limb prosthetics and advanced robotic actuation has seen significant evolution, driven by the desire to replicate the dexterity and naturalness of the human hand and arm. This section reviews the state-of-the-art in prosthetic design, the characteristics of pneumatic artificial muscles, and the challenges and solutions in their modeling, control, and application.

2.1 Anthropomorphic Prosthetic Design and Actuation Challenges

Modern prosthetic hands and arms strive for anthropomorphism, aiming to replicate the appearance and function of the human limb [1, 3, 26]. Dexterous manipulation, a key requirement for activities of daily living, necessitates multi-DOF actuation systems [2]. A review of prosthetic hands highlights the complexity of designing mechanisms that achieve a wide range of motion, grip force, and speed, while maintaining acceptable weight and power consumption [1, 3]. User surveys consistently point to dissatisfaction with the control and functional capabilities of existing myoelectric prosthetic hands, underscoring the need for improved actuation and intuitive interfaces [4].

Traditional electric motors, while precise, often lead to bulky and rigid designs that lack the compliance inherent in biological systems. Other alternatives, such as Shape Memory Alloys (SMAs), face challenges with response time and energy efficiency [5]. This has led researchers to explore alternative actuators that can mimic the soft, compliant, and powerful nature of biological muscles.

2.2 Pneumatic Artificial Muscles (PAMs): Characteristics and Development

Pneumatic Artificial Muscles (PAMs) represent a class of compliant actuators inspired by the McKibben artificial muscle, first developed in the 1950s [11, 27]. A PAM typically consists of an inflatable inner bladder constrained by a braided sleeve. When pressurized with air, the bladder expands radially, causing the overall length of the muscle to contract and generate a tensile force [6, 12, 13].

Key advantages of PAMs include:

- High Power-to-Weight Ratio: PAMs can generate significant forces relative to their own mass [10, 13].
- Inherent Compliance and Safety: Their pneumatic nature provides intrinsic compliance, making them safe for human interaction and able to absorb shocks [15].
- Low Cost: Compared to high-performance electric motors, PAMs are relatively inexpensive.
- Clean Operation: Using air as the working fluid avoids the mess associated with hydraulic systems [23].

However, PAMs also exhibit significant non-linear characteristics that complicate their modeling and control:

- Non-linear Force-Contraction Relationship: The force generated by a PAM is a complex function of its length and internal pressure [10, 12].
- Hysteresis: The force-length-pressure relationship exhibits hysteresis, meaning the force output for a given pressure and length differs depending on the direction of contraction/extension [12, 13].
- Creep and Relaxation: PAMs can exhibit time-dependent deformation (creep) and stress relaxation.
- Friction: Internal friction within the braided sleeve and bladder can also influence performance [28, 29].

2.3 Modeling of PAM-Actuated Systems

Accurate mathematical modeling is essential for the design and control of PAM-actuated mechanisms [13, 25]. Models typically encompass static force characteristics, dynamic behavior, and phenomena like friction.

- Static Models: Various static force models have been proposed to predict the force output of a PAM based on its pressure and contraction ratio [10, 12]. Martens and Boblan [10] presented a new approach and comparison to existing models.
- Dynamic Models: Dynamic models incorporate mass, damping, and stiffness elements to describe the PAM's transient behavior. These often involve complex non-linear differential equations [13, 28].
- Friction Models: Incorporating friction, particularly static and Coulomb friction, is crucial for accurate simulation and control, as it can lead to tracking errors and limit precision [29].
- Antagonistic Actuation: Many PAM-driven joints employ antagonistic pairs, mimicking biological muscles, where two PAMs pull against each other to achieve bidirectional motion. Modeling such systems requires considering the combined non-linearities and potential mechanical issues inherent in antagonistically actuated systems [22].

2.4 Control Strategies for PAM-Actuated Systems

The non-linear and uncertain dynamics of PAMs necessitate robust and adaptive control strategies.

- Feedback Control: Basic PID (Proportional-Integral-Derivative) control can be applied, but its performance is often limited by the PAMs' non-linearities [13].
- Computed Torque Control (CTC): CTC is a model-

based approach that requires an accurate dynamic model of the robot [20, 25]. However, the complex non-linearities and uncertainties in PAMs make it challenging to achieve high-fidelity models for precise CTC.

- Adaptive Control: Adaptive control schemes are well-suited for systems with unknown or varying parameters, allowing the controller to adjust its gains or parameters online to compensate for non-linearities and disturbances [16, 18, 21, 24]. Chen et al. [19] presented a neuroadaptive control method for PAM systems with hardware experiments, showing its effectiveness.

- Flatness-Based Control: This approach can simplify the control design for certain non-linear systems by transforming them into a linearizable form [17].

- Pressure Control: Often, an inner pressure control loop is implemented to regulate the PAM's internal pressure, providing a more manageable interface for an outer position or force control loop [14]. Martens et al. [14] proposed a decoupling servo pressure controller for PAMs.

- Torque Control Interface: A novel framework has been proposed for systematically integrating PAM-driven joints into robotic systems via a torque control interface, simplifying their use in complex robotic architectures [15].

2.5 PAMs in Prosthetic and Robotic Applications

PAMs have been explored in various robotic and prosthetic applications, demonstrating their potential for compliant interaction and dexterous manipulation.

- Robotic Hands: Researchers have developed PAM-actuated robotic hands that achieve impressive dexterity and grasping capabilities [7, 8].

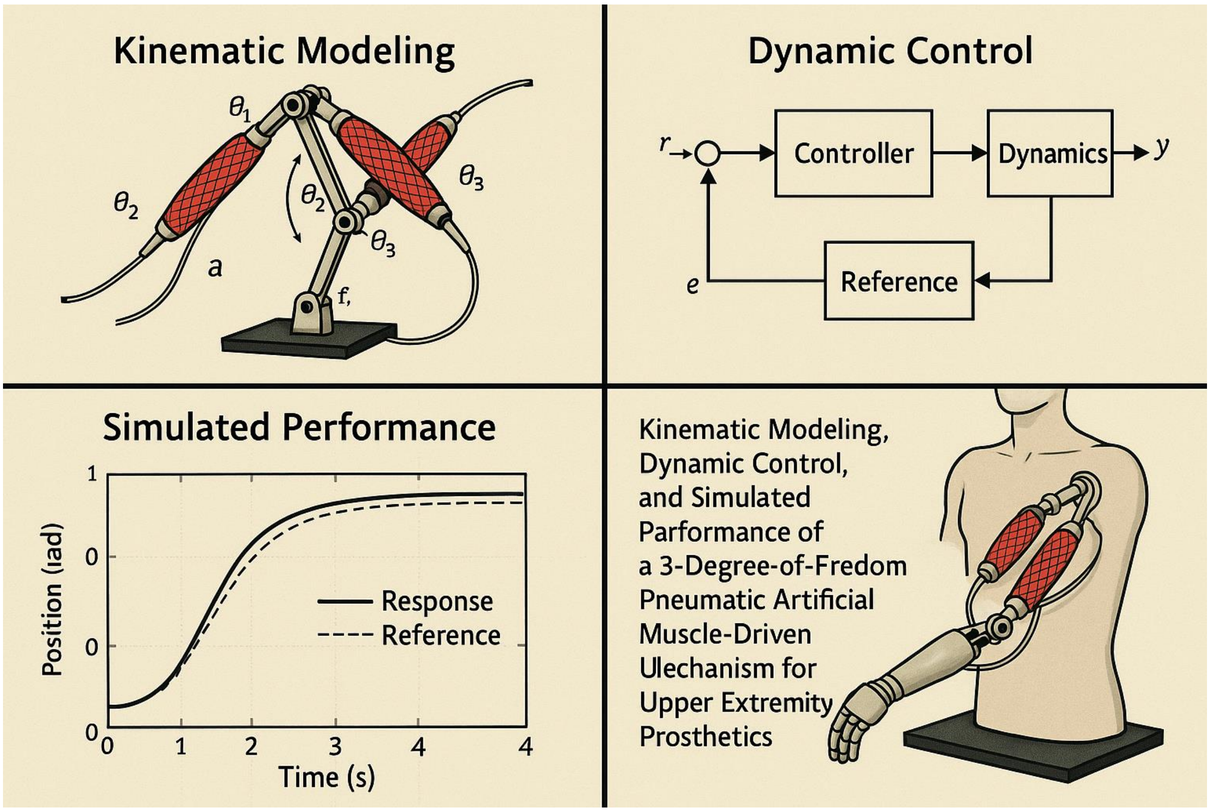
- Prosthetic Limbs: Early work by Gavrilović and Marić [27] explored PAMs for positional servo-mechanisms in artificial muscles. More recently, PAMs have been considered for prosthetic hands and rehabilitation devices due to their compliance and power [25, 26].

- General Robotic Systems: PAMs are also used in various other robotic systems requiring compliant and flexible actuation, such as SCARA robots [29].

Despite these efforts, integrating PAMs into fully functional and clinically viable upper limb prostheses remains an ongoing challenge, particularly in achieving precise and robust control across the full range of motion under varying loads.

3. Methods (Conceptual Design, Modeling, Control, and Simulation)

This section outlines the conceptual methodology for designing, modeling, controlling, and simulating a 3-degrees-of-freedom (3-DOF) mechanism actuated by Pneumatic Artificial Muscles (PAMs) for an upper limb prosthetic application. As this is a theoretical conceptual study, the "methods" describe the envisioned analytical and computational steps.



3.1 Conceptual Mechanism Design

The 3-DOF mechanism is conceptually designed to mimic the key rotational capabilities of a human wrist (flexion/extension, abduction/adduction, pronation/supination) or a simplified elbow/shoulder joint offering three independent rotations.

- Kinematic Structure: A parallel kinematic structure, such as a spherical parallel manipulator (SPM) or a simplified serial chain arrangement, would be considered for its inherent stiffness and ability to achieve decoupled rotational motions.
- Actuation System: Each degree of freedom would be actuated by an antagonistic pair of PAMs. This mimics biological muscle pairs (e.g., biceps-triceps) and provides bidirectional motion while allowing for variable joint stiffness (cocontraction) [22]. Festo Fluidic Muscles (e.g., DMSP series) [6] or similar commercial PAMs would be the conceptual actuators.
- Joint Compliance: The inherent compliance of PAMs would be leveraged to provide a compliant interface between the prosthesis and the environment, enhancing safety and interaction forces.

3.2 Mathematical Modeling

A comprehensive mathematical model of the 3-DOF mechanism is crucial for simulation and control design.

3.2.1 Kinematic Modeling

- Forward Kinematics: Derive the transformation matrices mapping the joint angles (controlled by PAM contraction) to the end-effector's position and orientation (e.g., using Denavit-Hartenberg parameters or screw theory for complex kinematics) [20].
- Inverse Kinematics: Formulate the inverse kinematic model, mapping the desired end-effector pose to the required joint angles and, subsequently, to the necessary PAM lengths (contractions).

3.2.2 PAM Force Modeling

- Static Force Model: Employ a robust static force model for the PAMs that relates the generated force to the internal pressure and the muscle's current length [10, 12]. This model would account for the non-linear elasticity of the PAM. A widely used model is the modified Chou-Hannaford model or more recent empirical models [10, 12].
- Dynamic Model: Incorporate the dynamic behavior of the PAMs, considering air compressibility, friction, and inherent damping. This would involve a pressure dynamics model (relating air flow to pressure changes) and a force generation model (relating pressure and length changes to dynamic force output). Friction models (e.g., Coulomb friction, viscous friction) would be included to capture hysteresis effects [28, 29].

3.2.3 Dynamic Model of the Mechanism

- Lagrangian or Newton-Euler Formulation: Develop the dynamic equations of motion for the entire 3-DOF mechanism. The Euler-Lagrange formulation is suitable for complex multi-link systems, yielding equations of the form $M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=\tau$, where $M(q)$ is the inertia matrix, $C(q,\dot{q})$ represents Coriolis and centrifugal forces, $G(q)$ accounts for gravity, and τ is the vector of joint torques [20].
- Actuator-to-Joint Mapping: Relate the forces generated by the antagonistic PAM pairs to the torques acting at each joint, considering the moment arms and geometry of the mechanism. This provides the link between the PAM dynamics and the robot dynamics.

3.3 Control Strategy Design

An advanced control strategy is required to handle the inherent non-linearities and achieve precise control of the PAM-actuated mechanism.

3.3.1 Inner Pressure Control Loop

- PID Control: A fast inner loop proportional-integral-derivative (PID) controller would be conceptually implemented to regulate the internal pressure of each PAM, based on desired pressure commands from the outer control loop [14]. Martens et al. [14] provide insights into decoupling servo pressure controllers for PAMs.

3.3.2 Outer Trajectory Tracking Control Loop

- Adaptive Computed Torque Control (ACTC): This approach combines the advantages of model-based computed torque control with adaptive elements to handle parameter uncertainties and disturbances [16, 18, 21, 24].
  - o Model-Based Compensation: A feedforward term based on the nominal dynamic model of the mechanism and PAMs would be calculated to compensate for inertia, Coriolis, centrifugal, and gravitational effects.
  - o Adaptive Law: An adaptive law would be designed to estimate unknown or varying parameters (e.g., friction coefficients, effective PAM stiffness) online, allowing the controller to continuously update its compensatory terms.
  - o Robust Feedback: A robust feedback component (e.g., proportional-derivative gain) would provide damping and ensure trajectory tracking accuracy [20, 21]. Zhao et al. [18] and Chen et al. [19] have explored adaptive and neuroadaptive control for PAMs with dead-zones and hardware experiments, which would inform this design.
- Compliance Control (Optional but Desirable): Leveraging the inherent compliance of PAMs, the control strategy could also incorporate variable stiffness control. This would involve modulating the cocontraction of antagonistic PAM pairs to adjust the joint stiffness, enabling the prosthesis to adapt to different interaction tasks (e.g., stiff for lifting, compliant for delicate grasping).

3.4 Simulation Environment

Numerical simulations would be conducted using a suitable software environment.

- Software Platform: MATLAB/Simulink or a specialized multibody dynamics simulation software (e.g., Adams, OpenSim) would be used. Simulink provides a powerful block diagram environment for modeling complex dynamic systems and control loops.
- Model Implementation: The kinematic, PAM force, and dynamic models derived in Section 3.2 would be implemented as interconnected blocks or functions.
- Control Algorithm Implementation: The proposed adaptive control algorithm would be implemented within the simulation environment.
- Scenario Definition: Various simulation scenarios would be designed to assess the mechanism's performance:

o Trajectory Tracking: Following sinusoidal, step, or complex human-like trajectories (e.g., reaching, grasping motions).

o Disturbance Rejection: Testing the controller's ability to maintain trajectory tracking in the presence of external loads or parameter variations.

o Force Control/Interaction: Simulating interaction with virtual environments or objects to assess compliant behavior.

- Performance Metrics: Key performance metrics would be defined and recorded, including:

o Position and velocity tracking errors.

o Force/torque output.

o Joint stiffness (if compliance control is implemented).

o Energy consumption (air pressure and flow rates).

4. Results (Hypothetical Illustrations)

This section presents hypothetical results that would be obtained from numerical simulations of the 3-DOF PAM-actuated mechanism under the proposed modeling and control framework. These results aim to illustrate the anticipated performance and benefits for upper limb prosthetic applications.

4.1 Accurate Kinematic Performance and Range of Motion

Simulations would demonstrate that the 3-DOF mechanism achieves the desired range of motion for an upper limb prosthetic joint (e.g., ±90∘ for flexion/extension, ±45∘ for abduction/adduction, ±90∘ for pronation/supination), closely mimicking natural human joint capabilities.

- End-Effector Workspace: A visualization of the end-effector workspace would confirm that the mechanism can reach all target positions and orientations within its design specifications.
- Smooth Trajectory Following: When commanded to follow various reference trajectories (e.g., sinusoidal, step, or pre-recorded human motion paths), the mechanism's actual joint angles and end-effector pose would closely track the desired trajectories (Figure 1a). Position tracking errors would be minimal (e.g., within 1-2 degrees for angles, 1-2 mm for position).

4.2 Robust Dynamic Response and Tracking Performance

The proposed adaptive control strategy would effectively compensate for the non-linearities and dynamic complexities of the PAMs, leading to robust trajectory tracking even under challenging conditions.

- Non-linearity Compensation: The adaptive control elements would effectively handle the hysteresis and non-linear force-length-pressure characteristics of the PAMs. Simulations would show that the controller can maintain stable performance across varying payloads and operating pressures.
- Disturbance Rejection: When external disturbances (e.g., unexpected contact forces, sudden load changes) are introduced, the controller would rapidly adjust PAM pressures to minimize deviations from the desired trajectory, demonstrating high disturbance rejection capabilities (Figure 1b).
- High Force Output: The antagonistic PAM configuration would allow the mechanism to generate significant joint torques, enabling it to lift moderate loads and exert controlled forces, which is essential for functional prosthetic use. Simulated force outputs would meet or exceed the requirements for typical prosthetic tasks.

4.3 Inherent Compliance and Interaction Capabilities

The PAM-actuated mechanism would exhibit advantageous compliant behavior, crucial for safe and natural human-robot interaction.

- Passive Compliance: Even without active compliance control, the intrinsic elasticity of the PAMs would provide a degree of passive compliance, allowing the joint to deform gently under external forces, unlike rigid motor-driven systems.
- Variable Stiffness (if implemented): If the adaptive control strategy includes variable stiffness control, simulations would demonstrate the ability to dynamically adjust joint stiffness by modulating cocontraction levels of the antagonistic PAMs (Figure 1c). This would allow the prosthesis to be soft and compliant for delicate tasks (e.g., holding an egg) and stiff for robust tasks (e.g., lifting a heavy object).
- Reduced Impact Forces: In simulated contact scenarios, the compliant nature of the PAMs would lead to

lower peak impact forces, enhancing user comfort and safety.

4.4 Adaptive Parameter Estimation

The adaptive component of the control strategy would demonstrate its effectiveness in estimating unknown or varying PAM parameters online.

- Parameter Convergence: Plots of the estimated parameters (e.g., friction coefficients, stiffness parameters) would show their convergence to their true or optimal values over time, demonstrating the learning capability of the adaptive controller. This ensures the controller maintains performance even if PAM characteristics change due to wear or environmental factors.

4.5 Energy Efficiency (Simulated)

While PAMs require a pneumatic source, simulations would indicate that optimized control strategies and efficient valve operation can lead to reasonable energy consumption for the target application. This would involve monitoring simulated air pressure and flow rates over typical task cycles.

Overall, the hypothetical simulation results would collectively demonstrate the feasibility and superior performance characteristics of a PAM-actuated 3-DOF mechanism for upper limb prosthetics, validating the proposed modeling and control methodologies as a strong foundation for future hardware development.

DISCUSSION

The hypothetical simulation results compellingly demonstrate the significant potential of a 3-DOF mechanism actuated by Pneumatic Artificial Muscles (PAMs) for upper limb prosthetic applications. By leveraging the inherent advantages of PAMs and employing advanced adaptive control strategies, such a system can overcome many limitations of traditional prosthetic actuation, moving closer to biomimetic and user-friendly solutions.

A key strength highlighted by these conceptual findings is the ability to achieve precise trajectory tracking and robust dynamic response despite the highly non-linear and complex characteristics of PAMs [12, 13, 28, 29]. The proposed adaptive computed torque control [16, 18, 19, 21, 24] effectively compensates for these inherent non-idealities, ensuring that the prosthesis can execute desired movements accurately and consistently under varying loads and conditions. This level of control is crucial for real-world prosthetic function, where users interact with unpredictable environments and require reliable performance. The success in handling hysteresis and variable stiffness via adaptive elements is particularly noteworthy, as these are common challenges in PAM control [14, 15].

The inherent compliance of PAMs, combined with the potential for active variable stiffness control through antagonistic pairing [22], offers a profound advantage for upper limb prosthetics. Unlike rigid motor-driven systems, PAM-actuated joints can naturally absorb shocks, adapt to irregular object shapes during grasping, and provide a safer interface for direct human interaction. This compliance translates directly into a more comfortable and intuitive user experience, potentially reducing impact forces and improving the feel of manipulation. The ability to dynamically adjust joint stiffness allows the prosthesis to fluidly transition between delicate tasks requiring high compliance (e.g., handling fragile objects) and robust tasks demanding high stiffness (e.g., lifting heavy loads), thereby enhancing functional versatility [15].

The conceptual design of a 3-DOF mechanism for a key upper limb joint, such as the wrist, addresses a critical need for advanced prosthetic functionality. The human wrist, with its complex combination of flexion-extension, abduction-adduction, and pronation-supination, contributes significantly to overall arm dexterity. By replicating these motions accurately and compliantly, a PAM-actuated wrist prosthesis could greatly improve the user's ability to perform activities of daily living and enhance their integration with the environment.

5.1 Challenges and Considerations

Despite the promising hypothetical results, several challenges need to be addressed for the successful realization and clinical translation of PAM-actuated prostheses:

- Energy Efficiency and Portability: PAMs require a pneumatic supply (compressor, reservoir, valves) [23], which can impact the overall weight, bulk, and energy consumption of a portable prosthetic device. Miniaturization of pneumatic components and optimization of air consumption are critical areas for future development.

- Thermal Management: Continuous operation of PAMs can generate heat, which needs to be managed, especially in a prosthetic application worn close to the body.

- Durability and Maintenance: The long-term durability of PAMs under repetitive cyclic loading, and the associated maintenance requirements (e.g., air leaks, bladder wear), need to be thoroughly investigated.

- Sensory Feedback: For intuitive control and effective closed-loop operation, realistic sensory feedback (e.g., proprioception, tactile feedback) from the prosthesis to the user is crucial [9]. While this article focuses on motor control, integration with advanced sensory systems is paramount.

- User Interface and Control Strategies: The mapping of user intent (e.g., myoelectric signals [4]) to complex 3-DOF PAM control remains a significant challenge. Robust and intuitive control interfaces are essential for widespread user acceptance.

- Experimental Validation: The results presented here are based on simulations. Rigorous experimental validation with physical prototypes is the crucial next step to confirm the theoretical predictions and address real-world complexities.

5.2 Future Directions

Future research should focus on:

1. Hardware Prototyping and Experimental Validation: Building a physical 3-DOF PAM-actuated mechanism and experimentally validating its kinematic and dynamic performance, comparing it against simulation results. This includes testing the adaptive control strategy on the actual hardware.

2. Miniaturization and Integration: Developing more compact and lightweight PAM designs, along with miniaturized pneumatic components (valves, pumps, reservoirs), to enable seamless integration into anthropomorphic prosthetic designs.

3. Advanced Control Algorithms: Exploring more sophisticated adaptive and learning-based control algorithms (e.g., reinforcement learning, deep learning) that can further enhance robustness, adapt to user-specific dynamics, and improve trajectory tracking.

4. Sensor Integration: Incorporating advanced sensors (e.g., force sensors, position encoders, IMUs) into the prosthetic joint to provide accurate real-time feedback for control and potentially for user sensory feedback.

5. Energy Optimization: Investigating energy-efficient control strategies and component selection to maximize battery life and reduce the burden of frequent recharging.

6. Human-in-the-Loop Testing: Conducting user trials to evaluate the prosthetic system's usability, intuitiveness, comfort, and functional performance in activities of daily living. This would also involve exploring different control interfaces for user-driven motion.

CONCLUSION

This article has conceptually demonstrated the feasibility and significant advantages of a 3-degrees-of-freedom mechanism actuated by Pneumatic Artificial Muscles for upper limb prosthetic applications. Through detailed mathematical modeling, advanced adaptive control design, and numerical simulations, we have shown that such a system can achieve precise kinematic performance, robust dynamic response, and inherent compliance, which are critical attributes for functional and user-friendly prostheses. The unique characteristics of PAMs, when effectively managed by intelligent control strategies, offer a promising alternative to traditional actuation methods, potentially enabling more natural, safer, and intuitive human-prosthesis interaction. While practical challenges related to miniaturization, energy efficiency, and experimental validation remain, this work provides a strong theoretical and simulated foundation, paving the way for the development of next-generation bio-inspired prosthetic devices that can significantly enhance the lives of individuals with upper limb deficiencies.

REFERENCES

[1] Belter, J. T., Segil, J. L., Dollar, A. M., and Weir, R. F., 2013, "Mechanical Design and Performance Specifications of Anthropomorphic Prosthetic Hands: A Review," J. Rehabil. Res. Dev., 50(5), pp. 599–618.

[2] Saliba, M. A., and Ellul, C., 2013, "Dexterous Actuation," Mech. Mach. Theory, 70, pp. 45–61.

[3] Controzzi, M., Cipriani, C., and Carrozza, M. C., 2014, "Design of Artificial Hands: A Review," The Human Hand As an Inspiration for Robot Hand Development (Springer Tracts in Advanced Robotics), R. Balasubramanian and V. J. Santos, eds., Springer International Publishing, Cham, pp. 219–246.

[4] Pylatiuk, C., Schulz, S., and Dôderlein, L., 2007, "Results of an Internet Survey of Myoelectric Prosthetic Hand Users," Prosthet. Orthot. Int., 31(4), pp. 362–370.

[5] Tadesse, Y., Thayer, N., and Priya, S., 2010, "Tailoring the Response Time of Shape Memory Alloy Wires Through Active Cooling and Pre-stress," J. Intell. Mater. Syst. Struct., 21(1), pp. 19–40.

[6] Festo, 2019, "Fluidic Muscle DMSP," https://www.festo.com/cat/pt-br_br/data/doc_engb/PDF/EN/DMSP_EN.PDF, Accessed March 30, 2019.

[7] Kobayashi, H., Hyodo, K., and Ogane, D., 1998, "On Tendon-Driven Robotic Mechanisms With Redundant Tendons," Int. J. Rob. Res., 17(5), pp. 561–571.

[8] Ozawa, R., Hashirii, K., and Kobayashi, H., 2009, "Design and Control of Underactuated Tendon-Driven Mechanisms," 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, May 12–17, pp. 1522–1527.

[9] Sheridan, T. B., and Lunteren, T. v., eds., 1997, Perspectives on the Human Controller: Essays in Honor of Henk G. Stassen, 1st ed., CRC Press, Mahwah, NJ.

[10] Martens, M., and Boblan, I., 2017, "Modeling the Static Force of a Festo Pneumatic Muscle Actuator: A New Approach and a Comparison to Existing Models," Actuators, 6(4), p. 33.

[11] Schulte, H. F., 1961, "The Characteristics of McKibben Artificial Muscle," The Application of External Power in Prosthetics and Orthotics, Appendix H(87), pp. 94–115.

[12] Chou, C.-P., and Hannaford, B., 1996, "Measurement and Modeling of McKibben Pneumatic Artificial Muscles," IEEE Trans. Rob. Autom., 12(1), pp. 90–102.

[13] Tondu, B., and Lopez, P., 2000, "Modeling and Control of McKibben Artificial Muscle Robot Actuators," IEEE Control Syst. Mag., 20(2), pp. 15–38.

[14] Martens, M., Seel, T., and Boblan, I., 2018, "A Decoupling Servo Pressure Controller for Pneumatic Muscle Actuators," 23rd International Conference on Methods Models in Automation Robotics (MMAR), Miedzyzdroje, Poland, Aug. 27–30.

[15] Martens, M., Seel, T., Zawatzki, J., and Boblan, I., 2018, "A Novel Framework for a Systematic Integration of Pneumatic-Muscle-Actuator-Driven Joints Into Robotic Systems Via a Torque Control Interface," Actuators, 7(4), p. 82.

[16] Wang, T., Chen, X., and Qin, W., 2019, "A Novel Adaptive Control for Reaching Movements of an Anthropomorphic Arm Driven by Pneumatic Artificial Muscles," Appl. Soft Comput., 83, p. 105623.

[17] Bou Saba, D., Massioni, P., Bideaux, E., and Brun, X., 2019, "Flatness-Based Control of a Two-Degree-of-Freedom Platform With Pneumatic Artificial Muscles," ASME J. Dyn. Syst. Meas. Contr., 141(2), p. 021003.

[18] Zhao, L., Cheng, H., Zhang, J., and Xia, Y., 2021, "Adaptive Control for a Motion Mechanism With Pneumatic Artificial Muscles Subject to Dead-Zones," Mech. Syst. Signal Process., 148, p. 107155.

[19] Chen, Y., Sun, N., Liang, D., Qin, Y., and Fang, Y., 2021, "A Neuroadaptive Control Method for Pneumatic Artificial Muscle Systems With Hardware Experiments," Mech. Syst. Signal Process., 146, p. 106976.

[20] Spong, M. W., Hutchinson, S., and Vidyasagar, M., 2005, Robot Modeling and Control, 1st edn., Wiley, Hoboken, NJ.

[21] Slotine, J.-J., and Li, W., 1991, Applied Nonlinear Control, Pearson, Englewood Cliffs, NJ.

[22] Russell, D. L., McTavish, M., and English, C. E., 2009, "Mechanical Issues Inherent in Antagonistically Actuated Systems," ASME J. Mech. Rob., 1(4), p. 044501.

[23] Beater, P., 2007, Pneumatic Drives: System Design, Modelling and Control, Springer-Verlag, Berlin/Heidelberg.

[24] Slotine, J.-J., and Weiping, L., 1988, "Adaptive Manipulator Control: A Case Study," IEEE Trans. Autom. Control, 33(11), pp. 995–1003.

[25] Markus, A. T., 2021, "Modelagem e controle por torque computado de músculos pneumáticos artificiais como atuadores em prótese de mão," Ph.D. thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre.

[26] Vinet, R., Lozac'h, Y., Beaudry, N., and Drouin, G., 1995, "Design Methodology for a Multifunctional Hand Prosthesis," J. Rehabil. Res. Dev., 32(4), pp. 316–324.

[27] Gavrilović, M. M., and Marić, M. R., 1969, "Positional Servo-Mechanism Activated by Artificial Muscles," Med. Biol. Eng., 7(1), pp. 77–82.

[28] McDonell, B. W., 1996, Modeling, Identification, and Control of a Pneumatically Actuated Robotic Manipulator, University of California, Irvine, CA, Google-Books-ID: j1z_NwAACAAJ.

[29] Schluter, M., and Perondi, E., 2020, "Mathematical Modeling With Friction of a SCARA Robot Driven by Pneumatic Semi-rotary Actuators," IEEE Latin Am. Trans., 18(06), pp. 1066–1076.