


Rehabilitation Hand Exoskeleton Robot based on Soft Actuator and Adaptive Control

Zahraa Al-Faeq, Hassanin Al-Fahaam

Department of Computer Engineering, University of Basrah, Basrah, Iraq

Article Info	Abstract
<p>Article history: Received: 28 February 2026 Revised: 21 April 2026 Accepted: 4 May 2026</p> <hr/> <p>Keyword: Adaptive control ANFIS Hand rehabilitation robot Soft actuators Wearable robots</p>	<p><i>Every year, millions of people suffer from severe motor impairment in the hand as a result of strokes or spinal cord injuries, which hinders their ability to perform simple daily activities. However, conventional rigid robots still face significant challenges related to their heavy weight and anatomical incompatibility with human joints, limiting their effectiveness in home-based rehabilitation. This research proposes a solution based on soft pneumatic actuators, Expansive Bending pneumatic actuators muscle (EBPAM) characterized by light weight and high flexibility. The methodology involves designing an intelligent control system that begins with fuzzy logic to track the therapist's finger movements, and was subsequently developed using an Adaptive Fuzzy Neural Inference System (ANFIS) to compensate for the non-linearity of pneumatic systems. Experimental results demonstrated the system's ability to achieve accurate motion tracking, with ANFIS successfully reducing tracking error by up to 50% compared to conventional control, whilst maintaining a total glove weight of less than 100 grams, making it ideal for domestic and clinical use.</i></p>
<p>Corresponding author: Zahraa Al-Faeq, zahraa.mohamad@uobasrah.edu.iq</p>	<p>DOI: https://doi.org/10.54732/jeeecs.v11i1.8</p>
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1. Introduction

Stroke is a main cause of long-term disability, with more than 15 million cases recorded worldwide each year [1]. The most obvious result is loss of hand function, which prevents patients from performing activities of daily living (ADLs). Although physical therapy is crucial, the manual effort required of therapists is intense and often leads to career exhaustion. Robotic devices have appeared as a solution to provide intensive repetitive training, but traditional rigid exoskeletons are often huge, expensive and difficult to align with the human musculoskeletal system [2], [3].

Recent literature has shown a shift towards soft robotics to enhance the safety and comfort of devices for users. Alicea et al. (2021) presented a soft robotic glove based on myoelectric control to assist patients with spinal cord injuries [4]. Al-Ibadi et al. (2022) investigated the design and kinematics of biologically inspired robotic arms to enhance movement flexibility [5], while Secciani et al. (2021) developed a wearable exoskeleton designed for home assistance and remote rehabilitation. In the context of innovative actuators [6], Lee & Park (2024) presented a glove based on braided shape memory alloys (SMAs) to increase strength whilst maintaining lightness [7]. Gonçalves et al. (2025) reviewed various robotic interfaces designed for post-stroke rehabilitation [8]. Barria et al. (2023) researched the clinical outcomes of using the RobHand exoskeleton to improve muscle force [9]. Al-Mayahi (2024) developed soft actuators with changing stiffness (CEB-PAM) to overcome mechanical control issues [10], whilst Xie et al. (2023) focused on bionic upper limb designs using smart materials [11]. However, a large research gap remains in achieving accurate motion tracking and system stability under the non-linear operating conditions of pneumatic actuators, particularly in fine pinching and grasping movements.

The purpose of this project is to design and develop a hand rehabilitation glove based on new pneumatic actuators (EBPAM), which use a rubber bladder and a braided sleeve to generate force and precise motion curve. The proposed system is lightweight (approximately 100 grams) and highly flexible, allowing it to support daily activities naturally [12]. The research value of this work lies in the development

of an intelligent control strategy that integrates fuzzy logic with an Adaptive Fuzzy Inference System (ANFIS) [8], resulting in a reduction in tracking errors of up to 50% compared to conventional systems through the 'learning' of air dynamics and compensation for non-linearity [13]. Furthermore, the research includes a custom MATLAB application designed to enable patients to perform rehabilitation exercises independently in their own homes without the need for a physiotherapist to be present at all times.

2. Research Methodology

The research followed a systematic approach that began with the mechanical design of the EBPAM actuators, followed by the integration of flexible sensors into the glove, and concluded with the development of the ANFIS control algorithm and experimental testing.

The system is divided into three functional subsystems:

1. Sensing system: This uses flexible bending sensors placed under each actuator to provide immediate feedback on the angles of the finger joints (thumb, index, and middle fingers).
2. Processing system (controller): An Arduino Mega-based unit that implements the ANFIS algorithm. It processes the error and the change in error between the therapist's glove (reference point) and the patient's glove (feedback) to make control decisions.
3. Actuation system: This uses MATRIX 3/3 solenoid valves to regulate the flow of air from a portable compressor to the EBPAM actuators, converting pneumatic pressure into mechanical bending force.

2.1 Actuator Design and Fabrication

The actuators used in this design are based on lightweight pneumatic artificial muscles (PAMs), specifically the Extensor type, which expands longitudinally when compressed [8], [14]. As shown in Figure 1, The fabrication process begins with the construction of special end caps using 3D printing technology to provide air flow outlets and secure the internal components [2], [15], [16]. An 8 mm diameter internal rubber bladder is secured to these end caps using nylon and silicone threads to ensure a tight seal under high pressure, and then covered with a nylon braided sleeve with a flexible diameter ranging from 8 to 18 mm.

Physically, the initial braid angle is set to be greater than the minimum energy angle of 54.7 degrees as shown in Figure 2, which is a prerequisite for converting the bladder's radial expansion into longitudinal expansion rather than contraction. This process requires the woven cover to be manually compressed so that its edges match the stoppers, creating a length reserve that allows the actuator to achieve an expansion ratio of 56% of its original length when activated. The mechanical behavior is clearly evident with gradual pressure increase, as the actuator begins to elongate linearly as soon as the bladder comes into contact with the woven cover, providing the force necessary to move the joints of the human hand.



Figure 1 .The PMA Construction

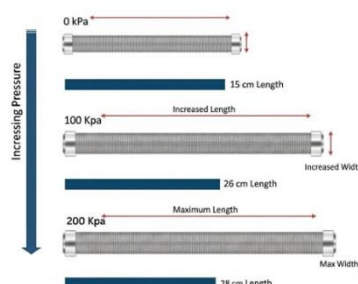


Figure 2. The Extensor artificial muscle with no-load at different pressures

2.2 Expansive Bending Pneumatic Actuator macule (EBPAM)

EBPAM actuators were developed by converting the linear motion of the actuator into rotational bending motion that mimics the movement of finger joints. This is achieved by longitudinally reinforcing one side of the actuator with a high-strength thread with a breaking strength of up to 500 N, which acts as a mechanical restraint preventing that side from expanding. When air pressure is applied, the unrestricted side expands freely while the reinforced side remains fixed, forcing the entire structure to bend at an angle proportional to the applied pressure.

This lateral restraint geometry demonstrates how the operator's movement path can be controlled to shift from longitudinal extension to a regular circular arc that mimics the natural flexion of a human finger. Mechanical tests have shown that movement only actually begins after a pressure threshold of 25 kPa is exceeded, which is the distance required for the internal bladder to expand until it contacts the woven shell and begins to transfer force to the structure, as shown in Figure 3.

This design allows the actuator to generate sufficient torque to overcome the resistance of stiff hand joints, while maintaining the flexibility of the materials to ensure user safety during intense exercises.

2.3 Proposed Glove Architecture

The final glove consists of five bending actuators (EBPAM) carefully attached to the back of a standard work glove using flexible fasteners that ensure effective motion transfer. The entire glove weighs approximately 100 grams, which is an ideal weight that reduces strain on an already weak hand, while airflow is controlled via advanced MATRIX 3/3 spiral valves. These valves are designed to regulate inflation and deflation with high precision, allowing the speed and force of each finger's flexion to be controlled independently or collectively. The prototype shows in Figure 4, the geometric distribution of the actuators, with the glove designed to be durable and capable of withstanding repeated cycles of operation in clinical environments. Flex sensors are integrated beneath the actuators to record actual movement angles and provide feedback to the control system, ensuring stable performance and force balance. This design is characterized by its ability to support complex hand functions such as grasping and pinching, while providing a comfortable interface for the patient that allows for prolonged use without the discomfort associated with rigid robotic structures.



Figure 3. EBPAM pressured by different amounts of pressure



Figure 4. Proposed soft glove; (a) The design. (b) and (c) The real prototype

2.4 Controller System

Design The control system is based on the concept of a ‘therapist glove’ as a set point and a ‘patient glove’ as feedback. The therapist wears a glove equipped with flexion sensors on the thumb, index finger, and middle finger, and these angles are sent as reference signals to the system. The ring and little fingers were excluded from independent sensing based on the assumption of human motor synergy, as these fingers move with the middle finger at approximately the same angle in most daily tasks, reducing the complexity of the system and the number of sensors required. The signals are processed through a closed-loop control loop that uses fuzzy logic algorithms to deal with the non-linear nature and complexity associated with air compressibility as Figure 5 and Figure 6. The ‘error’ between the processor angle and the patient angle is calculated, as well as the ‘change of error’ to generate valve control commands (fill or empty). This system was later developed into ANFIS to incorporate the learning capability of neural networks, allowing the system to automatically adjust inference rules and membership functions based on recorded data, which compensated for time delays resulting from valve response and complex air dynamics.

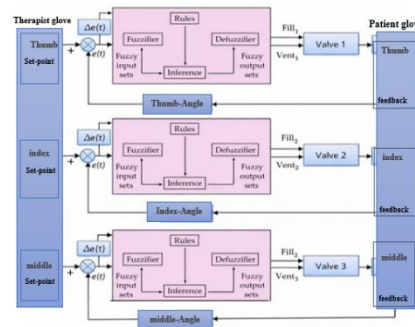


Figure 5. The fuzzy controller system diagram for each actuator

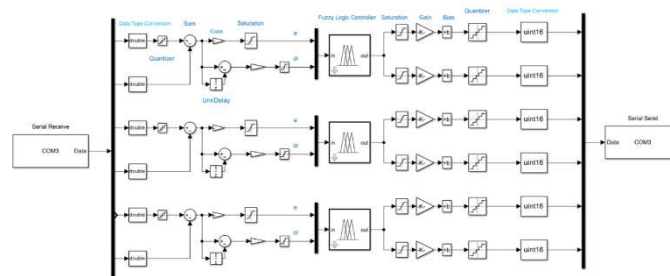


Figure 6. The fuzzy controller system for each actuator

3. Results and Discussions

3.1 Actuator Characterization

A thorough experimental analysis was conducted on the relationship between applied pressure and longitudinal displacement of the actuator in the absence of load. The results recorded a maximum length of 28.5 cm at a pressure of 350 kPa, which is equivalent to an expansion ratio of 56% of its original length, with some models reaching 68% when the length of the woven cover was improved. A ‘dead zone’ was observed under a pressure of 25 kPa, where no expansion occurred, which is the time required for the bladder to inflate internally to contact the cover, as shown in Figure 7.

The graphs show a clear linear zone in the range between 50 and 250 kPa, where the displacement is directly proportional to the increase in pressure. When the pressure exceeds 250 kPa, the response curve begins to flatten (saturation) as the materials that make up the actuator reach their maximum elasticity limits, reducing the effectiveness of additional pressure increases. This analysis provides safe and optimal operating limits for the control system, where it is recommended to operate within the linear range to ensure a quick response and facilitate the mathematical modelling of the actuator in rehabilitation applications, as shown in Figure 8.

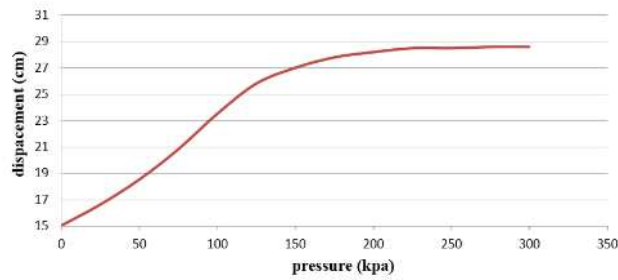


Figure 7. No-load displacement characteristic of the extensor muscle with increased applied pressure

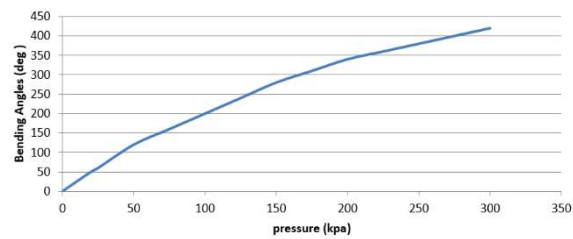


Figure 8. Extensor-Bending Pneumatic Artificial Muscles bending angle with the supplied pressure

These results show that the actuator depends on converting the bladder's radial expansion into elongation thanks to a coil angle exceeding 54.7 degrees. The stability of the displacement at high pressures (over 250 kPa) is explained by the rubber materials and the fabric cover reaching their maximum flexibility (saturation), meaning that any increase in pressure will result in an additional increase in the actuator's stiffness rather than an increase in its length.

3.2 Discussions of Fuzzy Logic Performance

Motion tracking experiments using fuzzy logic showed good ability to simulate the movements of the processor, but recorded varying errors between the fingers. The root mean square error (RMSE) values were 25.41 degrees for the thumb and 34.64 degrees for the index finger, while they rose to 38.29 degrees for the middle finger. The higher error in the middle finger is attributed to the air distribution system design, where the middle, ring, and little finger actuators share a single valve and a common flow path, resulting in air flow division and mechanical response time delay, as shown in Figure 9.

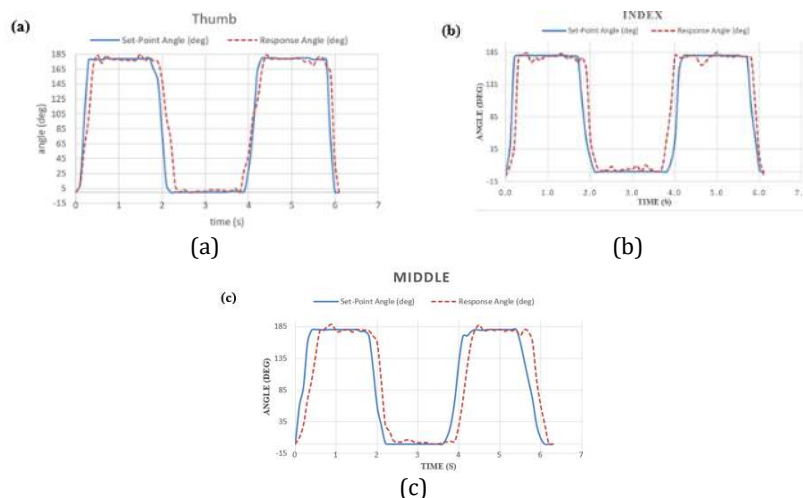


Figure 9. Hand rehabilitation controller results: (a) thumb; (b) index, and (c) middle

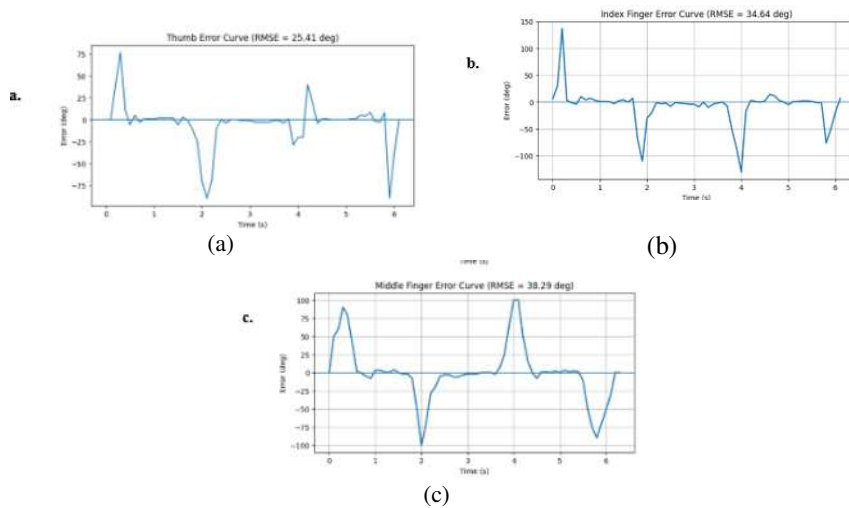


Figure 10. Error analysis: (a) thumb; (b) index; and (c) middle

Signal tracking analyses the temporal and spatial gap between the set point and the actual response of the soft actuators. It was observed that most errors occur during transitional periods (rapid rise and fall) as a result of the dynamic response deficiency of the valves and the hysteresis phenomenon inherent in rubber materials, as shown in Figure 10. Although the system stabilizes when it reaches a steady state, these overshoots in the dynamic phases necessitated the development of a control algorithm that is more adaptable to the instantaneous variables of the pneumatic system, paving the way for the use of ANFIS techniques.

The analysis shows that the middle finger recorded the highest error rate (38.29 degrees). Technically, this discrepancy is due to the airflow distribution design; the actuators for the middle, ring and little fingers share a single solenoid valve (MATRIX 3/3) and a common flow path. This division of the airflow leads to a reduction in pressure and an increase in mechanical response time compared to the thumb and index finger, creating a time lag between the processor signal and the patient's response.

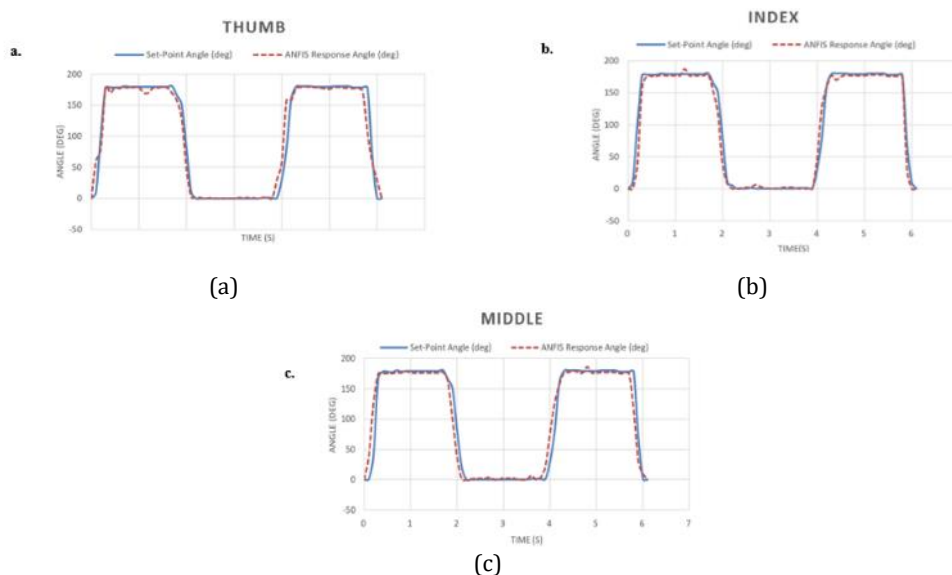


Figure 11. Hand rehabilitation controller results; (a) thumb; (b) index; and (c) middle (ANFIS)

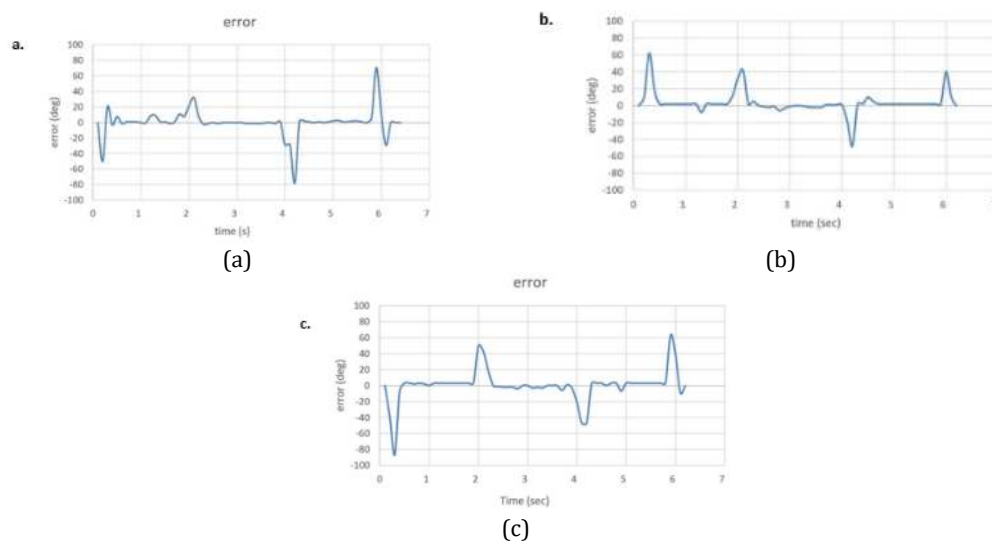


Figure 12. Error analysis: (a) thumb; (b) index; and (c) middle (ANFIS)

3.3 Improving results using ANFIS

To achieve higher accuracy, the ANFIS system was trained using input and output data recorded from the traditional fuzzy control system via the MATLAB ANFIS tool. This process allowed the system to learn the non-linear behavior of the actuators and adjust the membership functions to reduce deviations. This methodology led to a significant improvement in tracking accuracy, with a 50% reduction in error compared to previous results as shown in Figure 11, making the patient's glove movement appear smoother and more consistent with the original therapist's movement as shown in Figure 12.

A comparison of the results before and after the improvement shows how the ANFIS system succeeded in reducing the delay time and compensating for air compression inside the long tubes. By adaptively adjusting the inference criteria, the system was able to significantly reduce the RMSE in all fingers, especially the middle finger, which suffered from poor flow. This improvement proves that combining machine learning techniques with fuzzy logic is the optimal solution for controlling soft actuators that are difficult to model mathematically with precision, providing a safer and more effective rehabilitation experience for patients who require precise and controlled movements.

The results clearly show that the ANFIS controller significantly performs better than the traditional fuzzy logic-based controller, achieving a consistent 50% decrease in the root mean square error (RMSE) across all fingers, indicating excellent tracking accuracy and high robustness in non-linear hand rehabilitation systems. Table 1 shows the results of tracking accuracy using the root mean square error (RMSE) and a comparison of the systems used.

The success of the ANFIS system in reducing error by 50% is attributed to the ability of neural networks to 'learn' the non-linear dynamics of air, such as compressibility and the hysteresis inherent in pneumatic actuators. Through adaptive tuning of the membership functions, the system was able to compensate for the time delay caused by the length of the air tubes, providing smoother and safer movement for the patient. This proves that the integration of machine learning with fuzzy logic is the optimal solution for controlling soft actuators for which it is difficult to formulate an accurate mathematical model.

3.4. MATLAB application for home use

A graphical user interface (GUI) was developed in the MATLAB environment to enable patients to perform their exercises independently in offline mode, as shown in Figure 13. This application allows the selection of predefined exercises (such as hand grip or individual finger movement exercises) where the control points recorded from the movements of an expert therapist are sent directly to the glove. The system is set to operate at 6-second intervals between each movement, giving the patient sufficient time to react to the pneumatic pressure and comfortably complete the flexion and extension cycle.

Table 1. Experimental Tracking Accuracy (RMSE) for Hand Fingers

Finger Type	Fuzzy RMSE (deg)	ANFIS RMSE (deg)	Error Reduction (%)
Thumb	25.41	12.70	50
Index Finger	34.64	17.32	50
Middle Finger	38.29	19.14	50

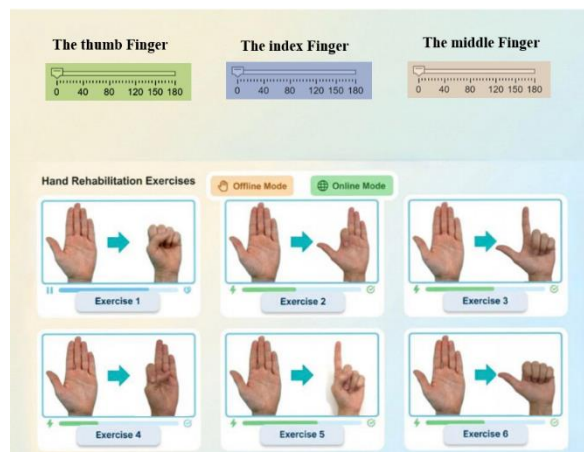


Figure 13. The MATLAB application foreground

The application interface displays visual indicators to track the patient's progress and allows the activation of triggers for each finger individually or collectively to enhance motor coordination exercises. This technical solution aims to eliminate the need for patients to be constantly present at the health center, providing a safe way to repeat exercises at home while ensuring that the movements are performed at the correct angles specified by the therapist. This approach contributes to increased adherence to rehabilitation programs, which is a critical factor in restoring motor abilities after severe neurological injuries.

4. Conclusion

This research has succeeded in developing an integrated robotic system for hand rehabilitation that is lightweight (100 grams) and highly flexible. Key contributions include the invention of soft curved pneumatic actuators (EBPAM) capable of generating sufficient driving forces, and proving the effectiveness of adaptive control (ANFIS) in reducing tracking errors by 50% compared to conventional systems. The 'zero mode' problem of stiff fingers has been solved by designing actuators that provide controllable stiffness. The proposed system balances engineering performance and human comfort, with the possibility of home operation via a MATLAB application. Future challenges remain related to the integration of additional actuators for the wrist joint and the development of more complex control algorithms to support delicate daily tasks such as handling fragile objects.

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