

# Wearable Soft Actuator for Restoring Finger Adduction–Abduction

Yazan KANJO

Department of Biomedical Engineering  
Istanbul Medipol University  
Istanbul, Türkiye

Abed Alrahman AL SAYYED

Department of Biomedical Engineering  
Istanbul Medipol University  
Istanbul, Türkiye

Elif HOCAOGLU

School of Engineering and Natural Sciences  
Istanbul Medipol University, Istanbul, Türkiye  
Research Institute of Health Sciences and Technologies (SABITA)  
E-mail: ehocaoglu@medipol.edu.tr

**Abstract**—Finger adduction and abduction are essential for daily activities such as typing, grasping, and manipulating small objects, yet these movements are often impaired by neuromuscular disorders or injuries, significantly reducing quality of life. Conventional rehabilitation strategies frequently overlook lateral finger motions or lack the adaptability to accommodate the full range of movement. To address this limitation, we present a portable, low-cost, and user-friendly soft pneumatic rehabilitation device specifically designed to restore finger adduction and abduction. The elastomer-based actuator, dorsally mounted across the phalanges, enables controlled MCP joint rotation through regulated inflation–deflation cycles while ensuring natural alignment and automatic return to the neutral position. In contrast to existing systems that restrict movement by positioning actuators between fingers, the proposed design prioritizes comfort and physiological motion. Experimental validation with ten healthy participants demonstrates an average angular displacement of 36°, reliable inflate–hold–deflate cycle completion within 5 seconds, and peak lateral force generation of 8 N at a stable operating pressure of 80 kPa, sufficient to induce finger motion without discomfort. With position feedback integrated into an on–off control scheme, the device achieves consistent and repeatable motion patterns suitable for unsupervised rehabilitation. By targeting lateral finger motion recovery, the proposed system fills a critical gap in hand therapy and represents a practical alternative to rigid exoskeletons, advancing wearable rehabilitation technology.

**Keywords**—Soft robotics, hand rehabilitation, soft actuators, spasticity

## I. INTRODUCTION

Hand spasticity and impaired motor control are highly prevalent among patients with neuromuscular disorders and stroke survivors, with studies reporting occurrence rates exceeding 70% of post-stroke patients [1], [2]. Such impairments significantly reduce hand functionality and independence in daily life. Even though lateral movements, more especially, adduction and abduction, are essential for coordinated hand function, they are frequently disregarded in traditional rehabilitation techniques. The majority of the repeated manual

exercises used in current therapies tend to be time-consuming, physically taxing for physiotherapists, and challenging to perform consistently over extended periods of time [3]. These drawbacks highlight the necessity of an easily accessible, reproducible, and successful rehabilitation program that focuses on finger adduction and abduction in particular.

The coordinated activity of muscles, tendons, and nerves creates the intricacy of finger motion, and injury or a lack of neural function can result in stiffness or improper movements [4], [5]. Finger adduction and abduction are frequently affected by neurological conditions, including stroke, spinal cord injury, or multiple sclerosis, as well as traumatic injuries, such as tendon or nerve damage [6]. Stroke alone affects over 65% of patients with upper extremity disabilities [7]. In addition, injuries such as tendon laceration, nerve damage, or bone fractures can limit natural motion [8]. Physical and occupational therapy are examples of traditional rehabilitation techniques that involve repetitive manual exercises that can be time-consuming, reliant on the availability of therapists, and sensitive to patient variability [7]. Robotic rehabilitation systems, especially rigid ones such as Hand Mentor, Amadeo, and HEXORR, have been introduced to address these challenges but come with drawbacks such as high cost, limited mobility, and potential discomfort [9], [10], [11], [12], [13]. Soft robotic systems have become a viable substitute in recent years because of their safety, lightweight design, and ability to adjust to human biomechanics [14]. Soft pneumatic actuators have been shown to increase grip strength and range of motion in devices like the Harvard Soft Exosuit [15]. Because of their flexibility and durability, elastomeric materials such as Dragon Skin, Mold Max, and Elastosil have been widely used in actuator types [16], [17]. These actuators' morphology and structure, whether pleated, ribbed, or cylindrical, have an impact on their bending capabilities and tip force [18]. Rapid and personalized prototyping is made possible by the frequent use of 3D-printed molds or directly printed soft materials in the fabrication of soft robotic systems [19], [20]. Although open-

loop control techniques are basic [21], closed-loop control approaches that use sensors like rotary potentiometers or IMUs offer more dependable and flexible performance, particularly when it comes to accurately simulating MCP joint movements [22], [23]. The abduction and adduction motion at the MCP joints, which is frequently underrepresented in conventional rehabilitation technologies, must be addressed by these systems.

Despite significant advances in soft robotics, there remains a notable scarcity of finger rehabilitation systems specifically designed to address adduction and abduction movements. Most existing solutions reported in the literature are limited either to isolated thumb motion or primarily focus on flexion–extension, leaving critical lateral finger movements underrepresented in current therapeutic approaches. Actuators positioned between the fingers in many current designs limit the full range of motion and the ability to return to the neutral hand position. Furthermore, soft actuators that have been produced thus far either have complicated fabrication and integration issues or require high inflation pressures. These drawbacks highlight the need for a novel approach that restores the fingers' natural lateral mobility by combining flexible movement, enough force production, and an ideal positioning plan.

This work suggests a soft pneumatic actuator-based rehabilitation device for regaining finger adduction and abduction movements in order to solve these issues. By positioning the actuator directly above the phalanges, regulated air inflation and deflation allow the MCP joints to rotate naturally. The suggested placement approach enables the fingers to be restored to their neutral position, guaranteeing full mobility in treatment, in contrast to traditional designs that insert actuators between fingers and limit the entire range of motion.

## II. MATERIALS AND METHODS

### A. System Overview

The soft robotic finger rehabilitation system is designed to meet specific functional requirements based on typical human hand kinematics and therapeutic needs estimated from literature and experimental measurements. The actuator must achieve a minimum range of motion of  $0^{\circ}$ – $25^{\circ}$  for finger abduction and adduction[24], with a speed of 10-30 degrees per second[25]. The average required force to manipulate the index and middle fingers is 5-7 N [26]. The actuator is simulated on ANSYS to verify the meeting of the desired performance, as shown in Fig. 1(a,b).

The kinematic and dynamic analyses are performed to establish the relationships among joint motion, fingertip position, orientation, and required torque. The index finger is modelled as a single rigid link with a revolute joint at the MCP, representing adduction–abduction movement. Based on the dynamic analysis, a second-order transfer function of the finger is derived. Similarly, the actuator model is evaluated and simulated in ANSYS to characterize the relationship between input pressure, angular deflection, and output force. The resulting step responses, presented in Fig.1 (c,d), are

used to approximate the actuator behavior with a second-order transfer function.

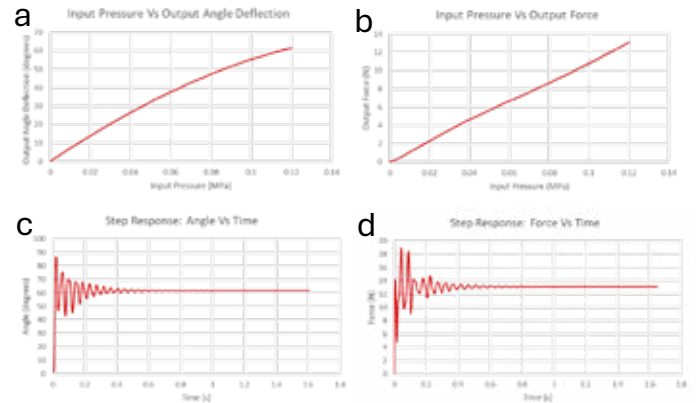


Fig. 1: ANSYS simulation results for the soft actuator: (a) Output angle deflection vs. input pressure, (b) Output force vs. input pressure, (c) Step response of angular deflection over time, and (d) Step response of force over time. The linear relationships in (a) and (b) validate the actuator's quasi-static performance, while the transient responses (c) and (d) were used to derive the actuator's second-order transfer function for dynamic modelling.

A specially made soft pneumatic actuator that produces finger adduction and abduction forms the basis of the rehabilitation system. SolidWorks is used to model the actuator, taking into account the typical human hand geometry, namely the separation between the index and middle fingers' MCP and PIP joints (see Fig. 2). Its form is designed to accommodate the fingers' natural curvature while allowing for controlled lateral movement. Natural finger motion during inflation and an unhindered return to the neutral position during deflation are made possible by the actuator's placement on the dorsal side of the phalanges. This arrangement facilitates full-range adduction and abduction workouts without limiting other finger movements.

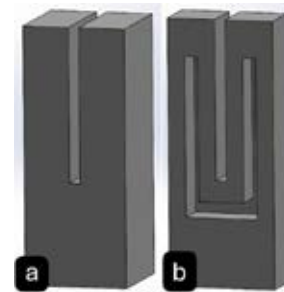


Fig. 2: Solid design of the soft actuator unit showing (a) an isometric perspective and (b) a cross-sectional view highlighting the internal channels.

The actuator is fabricated using two-part molds (upper and lower sections) coated on the inner surfaces with a thin layer of grease to facilitate demolding. A total of 20 mL of

SILASTOSIL A/B (10 mL of component A and 10 mL of component B) is mixed in a test tube using a vortex mixer for 3–4 min, followed by degassing in a vacuum chamber for 4 min to eliminate entrapped air bubbles. The degassed silicone is poured into the prepared molds, with any residual surface bubbles removed using a fine needle. The molds are cured at ambient conditions for 24 h, after which the two parts are demolded, joined with an additional layer of mixed and degassed silicone, and gently pressed together. A secondary curing period of 24 h yields the final assembled actuator.

The system integrates pneumatic and electrical components. Airflow is regulated by a 5/2 solenoid valve and a 12 V DC mini pump, each powered by separate 12 V DC sources. Pump and valve actuation are controlled via two 5 V relay modules. Force sensors are positioned between the actuator wall and the finger connectors for real-time force measurement, while two rotary potentiometers are attached to the index and middle fingers to provide continuous angular displacement monitoring. The assembled solid model of the system, positioned above the hand, is shown in Fig. 3.

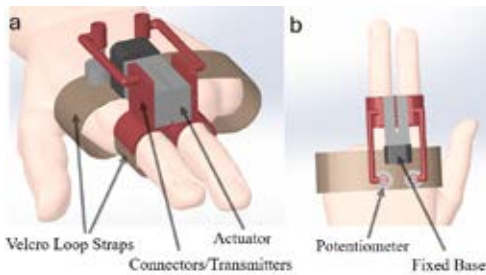


Fig. 3: Three-dimensional model illustrating the system implementation, from (a) an isometric view and (b) a top view

### B. Experimental Evaluation

The control cycle consists of four sequential states: inflation, hold, deflation, and wait. During the inflation phase, both the pump and 3-way valve are activated until the target angle (35°) is reached, as determined by the differential measurement of the finger potentiometers. In the hold phase, the pump is switched off via relay control while the valve remains closed, maintaining internal actuator pressure for a preset duration. Upon completion of the hold interval, the system transitions to the deflation phase, in which both pump and valve are deactivated and the stored air is released through the valve exhaust. A short wait phase is introduced before the cycle restarts, triggered when the measured finger angle returns to a predefined threshold. The control loop is illustrated in Fig. 4

## III. RESULTS

The connectors connect the fingers to the potentiometers that are fixed on the dorsal side of the hand. The fixed base stabilizes the actuator on the hand, preventing disturbing movements throughout the exercises. The connectors are attached to Velcro bands, which are fixed around the hand and fingers, ensuring controlled motion by the actuator. Force

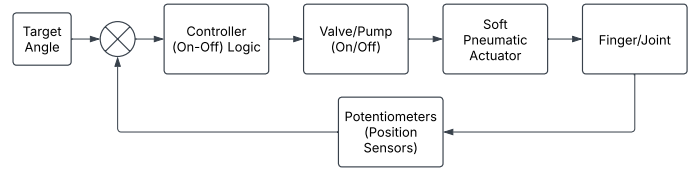


Fig. 4: Closed loop control block diagram of the soft pneumatic actuator unit

sensors are attached to the sides of the attachments where the actuator's surface pushes the connectors. The entire prototype is shown in Fig. 5.

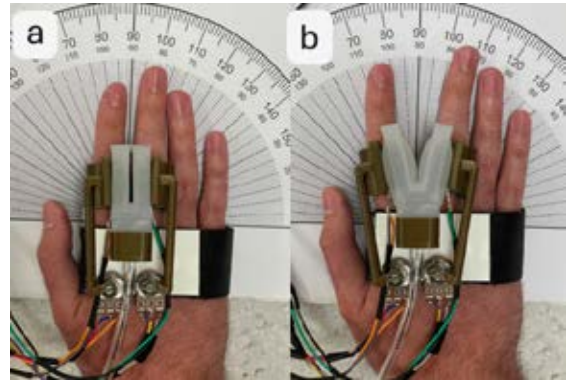


Fig. 5: Physical prototype of the soft rehabilitation system, showing the overall assembly in (a) deflation state and (b) inflation state

The calibrated potentiometers record the angle for each finger and send the data to the Arduino, where it subtracts the angles from each other to obtain the angle between both fingers, the abduction angle. The force sensors on each finger record the resistance difference due to the applied force and convert the resistance to output force through calibration. The results provide the behavior of the system's response to being cycled on and off 80 kPa of pressurized air.

The system is tested on ten people, and data for angle and force are recorded. These results demonstrate the average system's behavior applied to ten different persons. Hand stiffness differs among different individuals. The maximum angle is recorded as 38 degrees for the person with the least hand stiffness, and the minimum angle is recorded as 35 degrees, as this angle is set as the threshold for phase switching. The average angle is measured as 36 degrees, as demonstrated in Fig. 6(a). For the force recordings, the maximum force recorded is 11 N for the highest hand stiffness, and the minimum force value is recorded as 5 N for the lowest hand stiffness, averaging at 7.5-8 N, as shown in Fig. 6(b).

## IV. DISCUSSION

This study presents the development of a soft pneumatic actuation system designed to facilitate the rehabilitation of finger adduction and abduction. Following a review of prior designs in the literature, elastomeric actuators are selected

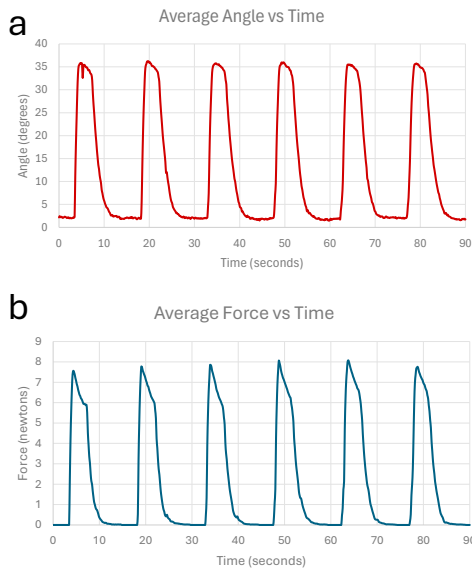


Fig. 6: Average system performance provided from cyclic actuation across ten participants: (a) Angle vs. time, showing a mean angle of  $36^\circ$  (b) Force vs. time, with an average output of 7.5–8 N reflecting variations in hand stiffness.

owing to their repeatability, flexibility, and capacity to deliver controlled motion. To guide the design process, both kinematic and dynamic analyses are performed, establishing the relationships between MCP joint rotation, fingertip displacement, and the torque required for functional movement. These analyses inform the geometric and mechanical design of the actuator, which is tailored to average human finger dimensions, with particular attention to the MCP–PIP joint spacing.

Experimental evaluation demonstrates that the actuator generates sufficient force to induce finger movement and achieves the desired angular displacement. These findings confirm the feasibility of the proposed actuator as a safe and efficient means of assisting finger rehabilitation. The integration of soft pneumatic actuation with real-time feedback control highlights the potential of this approach to provide cost-effective and adaptable rehabilitation solutions.

## V. CONCLUSION

In this study, a soft pneumatic actuator mechanism is designed and implemented to assist in the rehabilitation of finger adduction and abduction. The proposed design shows consistent behavior concerning repeatability, angular motion, and force generation. Effective cyclic actuation is made possible by the system's on-off control, guaranteeing controlled and secure rehabilitative movements. The efficacy of the strategy is validated by the implementation of the prototype, which verified that each of the design and performance requirements is satisfied.

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