Soft Robotics in Rehabilitation: Current Trends and Future Prospects for Hand Function Recovery

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ABSTRACT

Hand dysfunction, particularly after neurological events, such as stroke, presents a substantial challenge in rehabilitation. Traditional rehabilitation methods often lack the engagement and adaptability necessary to address the needs of individual patients effectively. This paper reviews the advances in soft robotic exoskeletons, which have emerged as a transformative solution in rehabilitation technology. Using compliant materials and innovative control mechanisms, these devices provide targeted assistance and promote recovery through enhanced user interaction. The study examines recent trends in the design and functionality of soft robotic gloves, highlighting their effectiveness for people with hand impairments. In addition, it identifies existing research gaps in terms of dexterity, precision control, and long-term efficacy, highlighting the need for further innovations. The findings suggest that while progress has been made, future advancements should focus on improving user experience, customization, and the integration of these technologies into therapeutic practices. Ultimately, soft robotic exoskeletons hold significant promise for enhancing rehabilitation outcomes for individuals with hand dysfunctions, paving the way for more effective and accessible rehabilitation solutions.

Keywords: Soft Robotics, Hand Rehabilitation, Exoskeletons

I. INTRODUCTION

The growing global population and aging demographics have led to an increase in neurological disorders such as strokes, resulting in hand dysfunction and long-term disability. Traditional rehabilitation methods, though beneficial, often require significant time, repetitive manual assistance, and continuous supervision by medical staff. These constraints limit scalability and may affect the consistency of patient outcomes. Robotic rehabilitation technologies have emerged as a solution, particularly for hand function recovery. While early rigid robotic systems provided accurate motion control, their bulkiness, limited flexibility, and discomfort hindered their clinical effectiveness. In response, soft robotics has emerged as a promising alternative, offering lightweight, compliant, and biomimetic systems that ensure safer and more natural interaction with the human body [1]. Soft robotic exoskeletons, especially those driven by pneumatic actuators, are capable of mimicking natural hand movements and providing adaptive support. Recent research has focused on enhancing actuator design, material durability, and control mechanisms. However, challenges remain. Many current systems still lack the dexterity and precision required for complex hand motions, and their long-term reliability and adaptability to user intent are limited. Effective control strategies and diverse training modes are essential to improving rehabilitation outcomes [2]. This paper reviews the current landscape of soft robotic hand exoskeletons, examining advances in design, materials, actuation, control strategies, and training methodologies. It also identifies existing research gaps, particularly in replicating natural hand motion and enabling personalized, feedback-driven therapy. Finally, the paper outlines a proposed system featuring a pneumatically actuated glove with real-time feedback and dual training modes—targeting individual and mirrored hand exercises—to address these limitations and enhance rehabilitation efficiency.

II. LITERATURE REVIEW

Rehabilitation robots gained prominence approximately two decades ago, particularly in patients with neurological disorders. Among the methods of hand function rehabilitation after a stroke, robot-assisted rehabilitation is the most widely used. Hand rehabilitation robots can provide functional training of the hand or assist the paralyzed hand in activities of daily living (ADL). These robots were not initially intended for full

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recovery but rather to assist people in recognizing objects through touch and aiding those with nervous system disorders. Rehabilitation robots fall into two main categories. The first category is Assistive Robots, which substitute for lost limb movements, and the second category is Therapy Aids, which are used mainly for therapeutic training rather than as assistive devices. However, patients with hand disorders reported that the needs of some users are not being met. It has been clinically proven that exoskeletons are effective self-training rehabilitation or daily living assistance devices for patients with hand dysfunctions. Exoskeletons or wearable robots are mechanical systems that humans can wear to complete certain tasks. However, exoskeleton-assisted hand exercises with high degrees of freedom are considered as challenging tasks. Initially, rigid hand rehabilitation robots were used, but they had limitations of flexibility, comfort, safety, etc. During the last decade, soft robotic systems, such as actuators and grippers, have been employed in various commercial applications [3].

III. SOFT ROBOTIC EXOSKELETON

Soft robotics utilizes compliant materials and flexible structures to mimic the natural properties of biological tissues, enabling gentle interaction with the human body and facilitating natural and intuitive movement. Compared with the rigid hand rehabilitation robot, the soft hand rehabilitation robot has the advantage of good flexibility, which is of great significance to its research. The development of wearable soft pneumatic finger gloves has gained significant attention in the field of rehabilitation robotics. These devices are designed to assist individuals with hand impairments, particularly those recovering from strokes or other conditions that affect hand functionality.

A. DESIGN AND FUNCTIONALITY

The primary focus of recent research has been on the design and functionality of soft robotic finger gloves. A notable study mentions the use of pneumatic actuators with variable stiffness to assist and rehabilitate hand movements. Fig.1 shows that the radius of curvature during bending for an actuator with variable stiffness is larger than for a conventional actuator. The actuators are customized for different hand dimensions and therapy exercises. The device's performance was evaluated through experiments measuring the range of motion and maximum force output. A 3D-printed reusable mold was used, and an actuator was made using casting, i.e., pouring liquid elastomer [4].

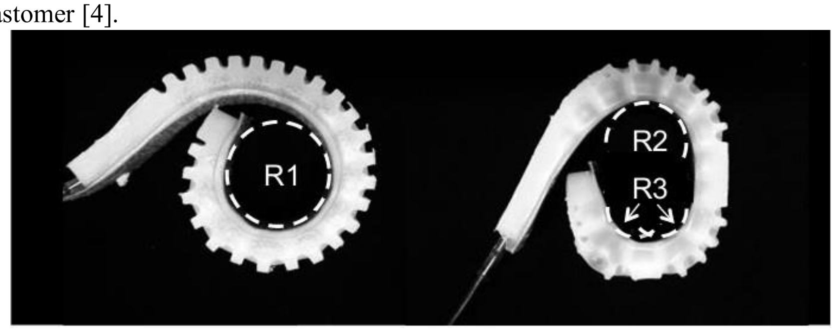

Fig. 1. Radius of curvature R1 during bending for an actuator designed with variable stiffness, was larger than R2 and R3 for a conventional actuator [4].

Towards this direction, another work developed a wearable soft pneumatic finger glove that employs antagonistic actuators, as shown in Fig.2, to facilitate finger rehabilitation. The performance of the glove was characterized by experiments that measured bending angles and force output under varying pressure conditions. The actuators were constructed from various materials and reinforced with Kevlar fibers to prevent excessive expansion, thereby improving durability and performance [5].

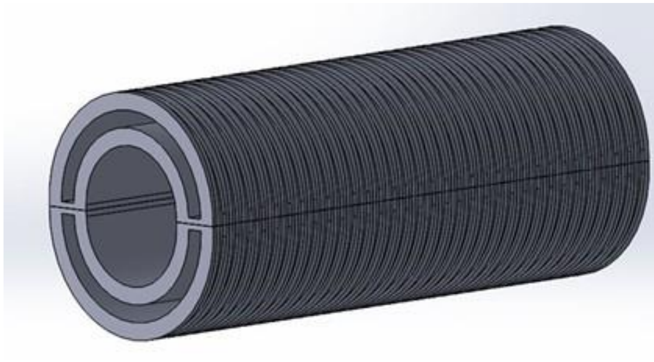

Fig. 2. CAD model of the glove-exploded view without end caps of antagonistic actuators [5].

B. MATERIALS AND FABRICATION

The choice of materials is critical in the development of effective rehabilitation gloves. Fig.3 shows the prototype for a study that developed a fabric-based soft exoskeleton glove using two mini linear actuators and a motor-tendon

actuation system. The control system is an on-off control system implemented to manage the motion of the actuators, with a joystick for user input. Cotton fabric, while comfortable, is prone to tearing. Denim is durable but can cause skin irritation. Initial designs were either too stiff or not secure enough, leading to potential usability issues. The glove was tested on a healthy hand to assist in grasping various objects [6].

Fig. 3. The prototype of a fabric-based soft glove [6].

The work AirExGlove utilizes a combination of nylon fabric and latex bladders, which not only ensures cost-effectiveness but also maintains ergonomic properties. This glove is designed to be lightweight and adaptable to different hand sizes, making it suitable for a diverse patient population. However, despite these advancements, the bulkiness of pneumatic actuators, as seen from Fig.4, remains a challenge, potentially limiting some hand movements [7]. By exploring more durable materials for long-term comfortable use, another work discusses about improved materials using a novel fabrication method that combines lost-wax and Inverse Flow Injection (IFI) processes are combined to create soft actuators with superior pressure bearing capability and fatigue endurance in another work. This was concluded by conducting pressure bearing and fatigue endurance tests on actuators fabricated with both the novel method and the traditional SDM method [8].

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Fig. 4. Nylon fabric and latex bladder-based AirExGlove (a) hand dorsal side (pneumatic chambers pressurized), (b) hand palm side (tendon channel seams visible in white) [7].

C. ACTUATION MECHANISM

Different methods of actuation mechanisms have been experimented to realize a proper lightweight exoskeleton. A few studies discussing the use of lightweight motor-driven actuation have also been analyzed. One such study uses bidirectional actuators for thumb and finger movements, with a soft, adjustable structure that allows free wrist motion. Cable guides are used to make the product lightweight. At the same time, the glove can support the flexion and extension of 4 fingers (excluding the little finger) while enabling the wrist to move freely. The use of a cable-driven soft structure, the direct placement of actuators on the back (dorsal) side of the hand, and the optimal cable routing, which mimicked real human hand anatomy, allowed the development of a compact, bidirectional, and powerful exoskeleton glove. Direct actuator placement allowed for the elimination of any additional friction originating from the transmission mechanism. As a result, the designed glove is compact and light and provides a maximum pinch force of 16 N [9].

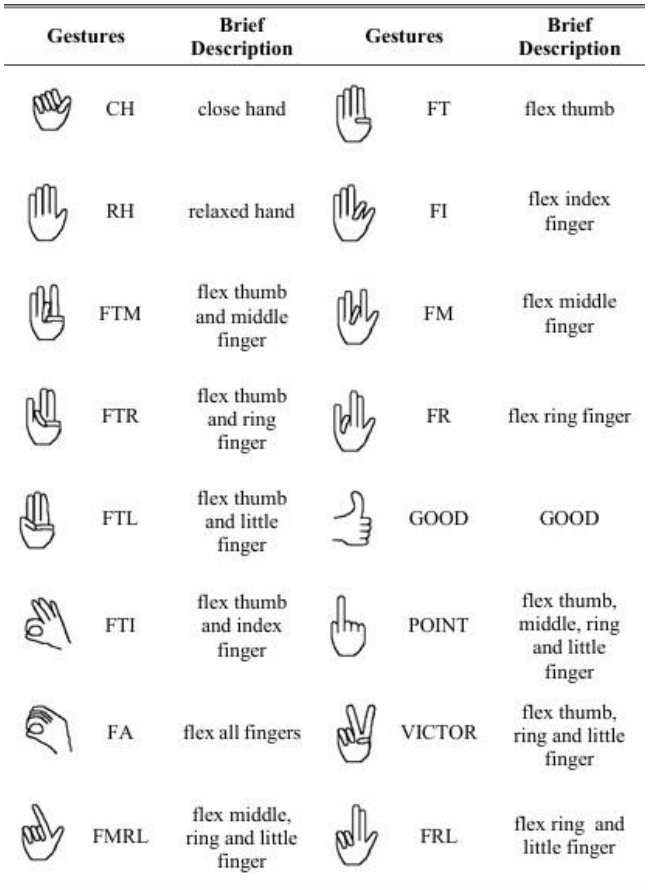
In contrast, another work utilized a bidirectional cable-driven spooling system with four micro-DC motors for finger movement and designed a glove using a parameterized CAD model and 3D printed with flexible Thermoplastic Polyurethane (TPU). It comprised of intention-sensing via wireless sEMG and externally directed via a smartphone app [10]. Recent studies have explored different types of actuators, including using a hybrid approach by combining tendon-driven and pneumatic systems. The system used EMG sensors to trigger motions based on muscle activity, and experiments were conducted for abduction/adduction tests, force exertion experiments, and grasp quality assessments [11].

D. CONTROL STRATEGY

Control mechanisms play a vital role in the effectiveness of rehabilitation gloves. Achieving stable intermediate hand positions requires precise control, which can be complex. The Iterative Learning Model Predictive Control (ILMPC) is used to manage the actuator's bending angles in a study made on a 3D-printed Soft Elastic Composite Actuator (SECA) that can fit different finger sizes, allowing for personalized rehabilitation. Experiments of rehabilitation were conducted on two stroke patients, and the results revealed that insufficient extension force limits their effectiveness [12]. Another research work uses a fuzzy PID controller for precise and stable control of the actuators. The paper presented the design, control, and testing of a soft pneumatic rehabilitation glove, which included fabric-based Double Chamber Actuators (DCAF) and Single Chamber Actuators (SCAF) with flex sensors. To verify the glove's performance, single actuator bending, passive rehabilitation motion, and grasping experiments were conducted [13].

E. TRAINING MODES

The rehabilitation exercises to be done to improve hand motion differ according to the medical conditions of different patients. Hence, a rehabilitation robot must be able to provide generalized and versatile training modes to accommodate the needs of most of the patients. For instance, some studies have proposed training modes that analyze natural finger movements, allowing for individualized rehabilitation exercises that target specific deficits. One such study involved 10 chronic stroke patients performing 10 Activities of Daily Living (ADLs) using an integrated system of a gravity compensating upper limb exosuit and a novel hand exoskeleton. The effects on muscular activity and coactivation patterns were measured using EMG data and kinematic data [14].



Gestures	Brief Description	Gestures	Brief Description
CH	close hand	FT	flex thumb
RH	relaxed hand	FI	flex index finger
FTM	flex thumb and middle finger	FM	flex middle finger
FTR	flex thumb and ring finger	FR	flex ring finger
FTL	flex thumb and little finger	GOOD	GOOD
FTI	flex thumb and index finger	POINT	flex thumb, middle, ring and little finger
FA	flex all fingers	VICTOR	flex thumb, ring and little finger
FMRL	flex middle, ring and little finger	FRL	flex ring and little finger

Fig. 5. 16 Fine Grained Gestures [15].

Different methods of rehabilitation training are also discussed in some of the papers, where some papers discuss rehabilitation training using fixed types of movements like pinching, grasping, etc., while many others use mirror training using sensors. A similar study developed a pair of soft gloves (sensory and motor) for hand rehabilitation. This study was used to recognize gestures from the sensory glove and facilitate rehabilitation tasks. It supported 16 fine-grained gestures for mirror therapy and six types of training tasks as shown in Fig.5 [15]. A recent study developed a 3D-printed pneumatic-driven soft robotic glove controlled by the movements of the healthy hand. A data glove collects motion data 7 from the healthy hand to control the robotic glove. Tests were conducted under the study to prove the feasibility of the glove, including ROM, output force, and system delay tests [16].

IV. RESEARCH GAP

The review on wearable soft pneumatic finger gloves highlights significant advancements in design, materials, and functionality aimed at improving rehabilitation outcomes for individuals with hand impairments. The results portrayed that the trends in recent years are more inclined to pursue new lightweight materials to improve hand adaptability. However, this review also identified certain shortcomings of Soft Rehabilitation robots like limited dexterity and lack of long-term efficiency. i.e. many existing devices do not replicate the full range of motion of a

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healthy hand and over a long time, these soft exoskeletons tend to lack precision. Effective control strategies are also essential for the successful implementation of soft exoskeleton gloves. The possibility of improving precision control mechanisms is much needed for better rehabilitation outcomes. Researchers can also to focus on developing adaptive control systems that can respond to the user's intentions and provide appropriate assistance. Moreover, the design of training modalities is critical for maximizing the rehabilitation potential of these devices. The ability to support multiple training modes, such as individual finger training and collaborative finger training, enhances the versatility of soft exoskeleton gloves in rehabilitation settings. Future research should focus on long-term efficacy, user experience, customization, integration with therapy, and cost-effectiveness to ensure these gloves meet the diverse needs of patients effectively. The integration of sensors, such as pressure sensors and flex sensors, is crucial for providing real-time feedback and enhancing the control of these devices. For example, the Flex sensor can be utilized in a feedback loop to regulate fingertip force, ensuring that the glove responds appropriately to the user's movements. This combination of advanced actuators and sensors contributes to the overall effectiveness of soft exoskeleton gloves in rehabilitation.

V. PROPOSED WORK

Pneumatic soft robots are lightweight but difficult to control with precision. Usually, the training mode of the pneumatic soft robot is relatively simple, which cannot give full play to the function of the hand rehabilitation robot. Therefore, this review aims to develop a Soft Hand Rehabilitation aimed at addressing the shortcomings of traditional hand rehabilitation techniques. By leveraging the principles of soft robotics, this innovative system seeks to provide an easy and independent rehabilitation experience to each patient.

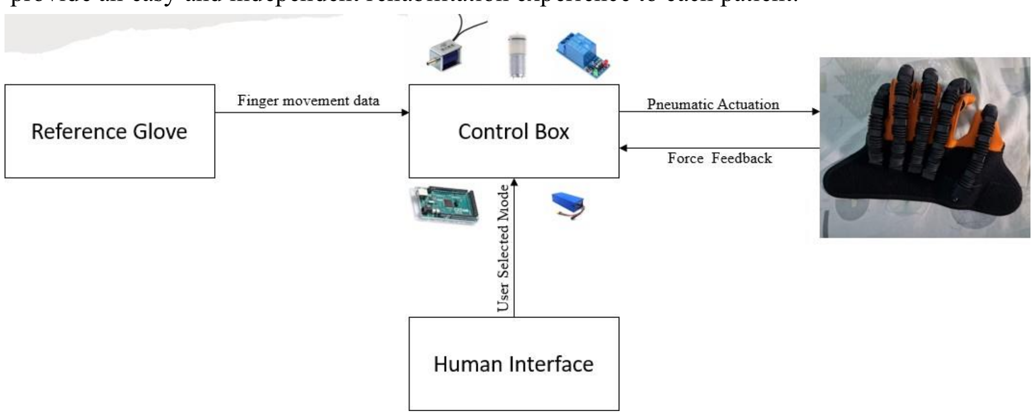

Fig. 6. Block diagram of the proposed system.

This project aims to make a fully functional soft robotic hand exoskeleton system utilizing air-pressurized soft actuators. The system consists of a Soft Exoskeleton Glove (SEG) controlled with the assistance of, micro-valves, and a controller. As shown in Fig. 6 the main components are a soft exoskeleton, made from flexible materials like silicone or elastomers, a pneumatic actuation system offering controllable force and lightweight design, and a control system to interpret data and control the actuation system. There will be two different training modes which are individual finger training and mirror training. In individual finger training each finger can be separately trained as necessary while under mirror training a reference glove will be made for the unaffected hand and the movements made on this hand can be copied to the exoskeleton. A real-time feedback mechanism using flex sensors to monitor and control the exoskeleton training as required to increase the precision of actuation after multiple rounds of training will also be implemented.

Fig. 7 shows the flow diagram of the proposed system that specifies the power, pneumatic, and control flow of the system for a single pneumatic actuator. The proposed project is expected to be able to perform daily life activities training such as grasping, pinching, etc., and also enable controlled movement of individual fingers(extension and retraction) targeting their range of motion needs. The main objective is to achieve the range of motions of an unaffected hand using the pneumatic exoskeleton (maximum, minimum, and intermediate positions) and precisely control the affected hand using the reference glove.

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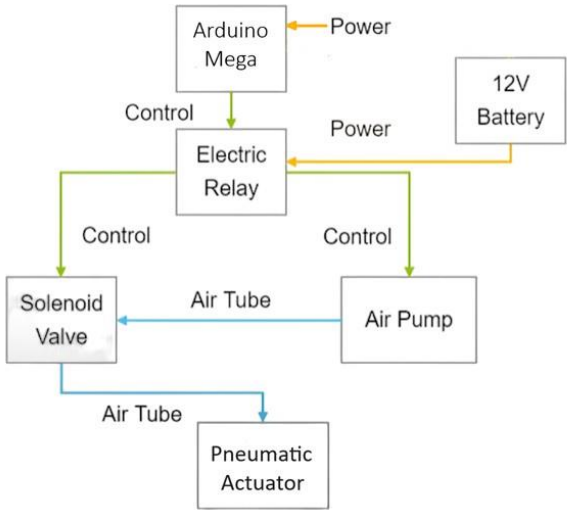

Fig. 7. Flow diagram of the proposed system

VI. RESULTS

The proposed soft pneumatic hand exoskeleton was developed to support rehabilitation through two primary modes: individual finger training and mirror training. Preliminary evaluations and basic functionality tests were performed on a healthy user. The system successfully demonstrated controlled flexion and extension of individual fingers, replicating a natural range of motion as shown in Fig. 8.

Fig. 8. Soft Exoskeleton Glove under actuation for all fingers

The pneumatic actuators enabled smooth and adaptive movement, with flex sensors providing real-time feedback for precise control adjustments over repeated training cycles. In mirror training mode, the exoskeleton effectively mirrored movements from a reference glove worn on the unaffected hand. This bilateral coordination allowed the affected hand to mimic healthy movements in real time, potentially enhancing neural recovery through increased sensory-motor engagement. These results highlight the potential of the proposed system to deliver targeted and versatile rehabilitation. The lightweight and compliant structure of the glove ensured comfort, while the integration of feedback mechanisms improved control accuracy. This user-centered approach may reduce the dependency on therapists and promote independent rehabilitation sessions. In general, the proposed glove shows promise as an assistive and therapeutic device, with the potential to improve engagement, precision, and functional recovery in hand rehabilitation.

VII. CONCLUSION

Soft robotic exoskeletons represent a significant advancement in the field of hand rehabilitation. Their ability to provide tailored support and facilitate recovery through innovative designs and control schemes offers new hope for individuals with hand dysfunction. However, continued research and development are essential to address existing gaps and enhance the effectiveness of these devices in clinical settings. The future of rehabilitation technology lies in the integration of advanced materials, intelligent control systems, and user-centered design principles, paving the way for more effective and accessible rehabilitation solutions.

CONFLICT OF INTEREST

The author do not have any conflict of interests.

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