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The Role of Bio-Inspired Soft Robotic Gloves in Stroke Rehabilitation: A Comprehensive Analytical Review

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ABSTRACT

Stroke is a leading cause of long-term disability, with many survivors experiencing impaired motor function. Traditional rehabilitation methods often face limitations in achieving full functional recovery. In recent years, bio-inspired soft robotic gloves have emerged as a promising solution for enhancing stroke rehabilitation, mimicking the natural movement and adaptability of biological systems. This paper provides a comprehensive analytical review of bio-inspired soft robotic gloves designed for stroke rehabilitation, focusing on their development, fabrication methods and therapeutic applications. The primary objective of this review is to evaluate the role of bio-inspired designs in the creation of soft robotic gloves and assess their effectiveness in facilitating motor recovery post-stroke. A systematic analysis of existing literature is conducted, exploring various fabrication techniques, including soft material integration, actuators and sensors, as well as the application of these gloves in clinical and therapeutic settings. Findings from this review reveal that bio-inspired soft robotic gloves show significant potential in improving patient outcomes by enhancing finger and hand movement through assisted motor control. These devices offer advantages in terms of comfort, flexibility and adaptability, allowing for prolonged and intensive rehabilitation sessions. However, limitations remain, such as the high cost of fabrication, challenges in achieving precise motor control and the lack of large-scale clinical trials to validate long-term efficacy. The research has several implications: (1) Theoretical: advancing the understanding of bio-inspired design principles in soft robotics; (2) Methodological: highlighting fabrication techniques that enhance glove performance and user adaptability. This review offers original value by consolidating and analysing recent developments in bio-inspired soft robotic gloves, contributing to both the academic literature and practical applications in stroke rehabilitation. It emphasizes the necessity of future research to address current limitations, especially in optimizing performance and reducing production costs, while enhancing patient outcomes.

Keywords:
Bio-inspired robotics; stroke rehabilitation; soft robotic gloves; motor recovery; fabrication methods

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1. Introduction of the Soft Robotic Gloves

Soft robotics is a new way of thinking about how to make robots that are safe and flexible by nature. Soft robots are different from rigid robots because they are made to interact gently with their surroundings. This makes them perfect for jobs that need to be handled carefully or that need to be able to adapt to uneven surfaces. The word "soft" can mean both how flexible a building is and what kind of material it is. Softness can come from the materials used, like elastomers or hydrogels or it can come from outside the robot, like its mechanical design or software control methods. It depends on how they are organized or moved and even normally hard materials like metals can be made "soft" about the thing they touch. For example, rubber parts can be added to the drive chain of robotic systems to make them more flexible. This lets the system handle shocks or change forces. This flexibility is very important in situations like medical devices, which need to be able to gently mould human cells. So, soft robotics is a big step towards making robots that are more flexible and friendlier to people.

In addition to the well-known benefits of soft robotics, such as safe interaction and adaptability, these systems offer a range of other significant advantages. Soft robots are inherently safer to handle due to their flexibility, which minimizes the risk of injury or damage during human interaction. They are also highly adaptable and capable of functioning in both open and constrained environments by conforming to obstacles, making them versatile in diverse applications. This adaptability extends to their ability to manipulate and grasp objects using their entire structure, removing the need for specialized end-effectors. Moreover, soft robots exhibit non-linear elastic behaviour, enhancing their resilience and allowing for easier repairs when damaged. This characteristic contributes to their cost-effectiveness, as they are generally less expensive to produce compared to traditional discrete manipulators. Additionally, soft robots often feature a high power-to-weight ratio, particularly those with inflatable structures, which are advantageous for space applications due to their compact storage when not in use. Finally, their inherent shock-absorbing properties further enhance their utility, as they can significantly reduce collision forces compared to robots with stiff joints. Aside from the highlighted benefits described thus far, soft robots possess many other interesting benefits by their nature.

The goal of this analytical study is to investigate the most recent developments in soft robotics, with a special emphasis on bio-inspired designs and their incorporation into stroke rehabilitation technology. A comprehensive review of the most notable soft robotic gloves now in use or in development for stroke therapy. This includes an examination of their structural designs, the materials utilized and the main mechanical and electrical components that enable their operation. an examination of the fundamental design concepts that direct the creation of these devices. This includes talking about how the materials' softness, flexibility and adaptability—all of which are essential for imitating hand movements naturally and guaranteeing user comfort—are discussed. The integration of sensors, actuators and control systems—all necessary for accurate motion and force control—will also be covered in this section.

2. The Application of Soft Robotic Gloves in Stroke Patients

Stroke, also known as “angin ahmar” in Malay, is a serious illness with a high rate of death and disability. A stroke happens when a clot blocks or ruptures an artery responsible for transporting oxygen and essential nutrients to the brain. When this happens, certain areas of the brain die because they lose their supply of blood and oxygen [1]. The brain needs a steady flow of blood that contains essential nutrients and oxygen. Ischemic stroke and haemorrhagic stroke are the two primary causes of stroke. An ischemic stroke is defined as a blockage of the blood supply to the brain, accounting for about 87% of all stroke cases. and a haemorrhagic stroke happens when the blood vessels around the brain burst, resulting in bleeding [2]. Figure 1 shows the types of strokes.

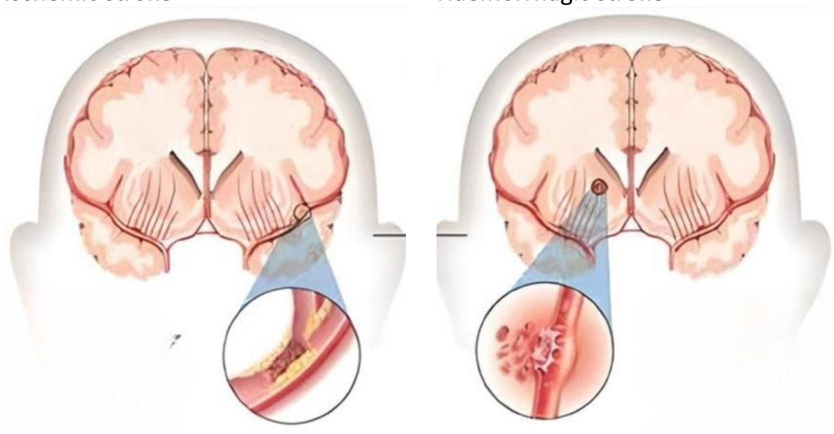


Fig. 1. Types of strokes

A stroke can affect many various body functions, including speech, vision and sensorimotor control of the limbs. In the early stages of a stroke, around 80% of people have impairment of their upper limbs, particularly in the hands [3]. Spasticity is a typical side effect of stroke that causes muscles to stiffen or tighten [4]. For many survivors, spasticity affects the arm and hand, resulting in a clenched hand or curled fingers after a stroke. The wrist, hand and fingers cannot move through their full range of motion due to reduced voluntary movement. When left untreated, spasticity can eventually result in contractures and cause fingers to curl. Contractures are defined by extreme stiffness in the muscles, joints and connective tissues. When contractures form, the range of motion of the fingers and wrist is limited, forcing the fingers to curl into the palm. Early spasticity management and rehabilitation are crucial to preventing the development of contractures.

To improve motor function after a stroke, the patient typically needs to undertake rehabilitation therapy for several months. Some types of techniques, such as specialized training, resistance training or other exercises focus on enhancing the flexibility and elasticity of soft tissues. or reducing tone may be used in rehabilitation. Conventional stroke rehabilitation, which includes daily one-on-one passive, active and assisted hand therapy, must be maintained to preserve range of motion, relax, stretch and strengthen the hand [5]. Patients must engage with a therapist in person as well as independently to achieve these goals. Conventional rehabilitation procedures are frequently used and they place a lot of pressure on physical therapists. Due to the need for specialized facilities and the involvement of qualified physiotherapists, these procedures are expensive.

Robotic devices have been presented as an alternative to the conventional rehabilitation approach for hand rehabilitation [6,60]. The scores of stroke patients who used a robotic glove device were also higher than those who did not have a device to help them, according to clinical research and the findings show that the device can assist individuals with weakened hands after a stroke in performing gripping, pinching and grasping movements [7]. A robotic exoskeleton, more specifically a soft robotic glove, is a technological solution for therapy that reduces the need for daily human contact and increases the amount of therapy that can be done. Commercially available rehabilitation and assistive devices today are based on rigid, standard robots and often have exoskeleton structures built in. But these devices can be hard to use, expensive, big, bulky and heavy and they need to be customized [8]. Even though there are a lot of ideas and experiments on pneumatic gloves already, they can still be made better by making them simpler, cheaper, easier to make, more mobile and easier for individuals to use.

The hand plays a key role in daily activities, but for individuals with stroke-related impairment, it can reduce the quality of life [9]. Stroke survivors often experience a common motor function disability, which is spasticity that can cause clenched hands or curled fingers [4]. Hand disability can result in both physical and emotional distress, restrict employment opportunities and lead to substantial financial strain due to increased healthcare expenses [10]. Hand rehabilitation therapy is particularly important to restore mobility in the hand and finger for improving daily activities and restoring the quality of life. Due to the high demand for qualified physiotherapists and special facilities, conventional rehabilitation therapy is costly [8]. Since that, it has been suggested that robotic exoskeleton devices may be used to assist in hand rehabilitation. Robotic exoskeleton actuators, on the other hand, are rigid and heavy, which makes the patients less comfortable, safe and able to mimic natural hand movements [11].

Improved soft robotic gloves and functions are regarded as key to addressing various problems with rigid and heavy hand robotic hand gloves. Currently, available soft robotic glove designs mostly use soft material actuation technologies, such as motor-driven cables and soft pneumatic elastomeric actuators. Examples of soft pneumatic actuators are PneuNets, fibre-reinforced modular elastomeric, fabric-based and variable stiffness actuators. However, most of these actuators can only actively control finger flexion when they supply air pressure and are only able to achieve finger extension passively, depending on the characteristics of the materials. As a result, they are unable to actively control their fingers' extensions. Most of the time, patients with impaired finger reflex function will experience involuntary muscle contractions that make the fingers initially positioned in a clenched position and unable to extend [12].

To address the issue of hand spasticity, it is necessary to create soft robotic actuators that can fit the shape and movements of the clenched fist. These actuators should allow for gentle and progressive finger extension, reducing the pain and resistance sometimes experienced with spasticity. By fitting the specific shape of the hand, such an actuator would provide a more natural and comfortable solution for patients affected by this condition, potentially increasing their quality of life.

3. Soft Gloves Analysis Review Based on Application

Soft robotic gloves focus on finger movement through an actuator and their main application is rehabilitation which involves exercises and assists disabled people in gripping and manipulating objects in daily activities [13]. The design requirements for these two classes of soft robotic gloves, particularly rehabilitation, are to provide a wide range of accurate hand motion movements. Although portability offers various advantages, it may not be essential for all users, particularly those who primarily get rehabilitation therapy in a clinical setting. Soft robotic gloves for assistance should be light and portable, meaning they should weigh as minimum as possible and have maximum mobility. Additionally, they should be comfortable, fit the hand’s anatomy and be easy to wear. Human-robot interface safety is also essential for designing robotic gloves. The flexibility of soft gloves makes them ideal for this safety.

Based on discussions with doctors, an analysis of the medical literature and experimental research, Polygerinos [14], one of the early researchers, offers a setting for the standard performance criteria and requirements of soft robotic gloves. The performance criteria and requirements fall into three main categories: practical considerations, motion and force and control requirements [14,58]. Practical considerations dictate that the integrated glove with the actuators should weigh less than

0.5kg, the total weight of the control system or actuation should not be more than 3kg, the profile of the actuator, which is width and height, should not exceed finger size by 2 cm and the actuator lengths should be customized to fit the hand, including the glove.

Next, in Polygerinos *et al.,* [14] for the motion requirement, each soft actuator must have three bending degrees of freedom (DOF) for each finger, with the thumb requiring at least two bending DOFs, one rotating DOF and a total joint angle of approximately 250° for the middle finger and 160° for the thumb. Prior research on hand grasping has documented that individuals of Malay ethnicity who are in good health can achieve a maximum grip strength of 223 and 387 N for females and males, respectively [15]. However, it is not required that the soft actuators produce the maximum grip strength of a healthy person, the authors estimated that to accomplish such a palmar grasp, each soft actuator would have to exert a distal tip force of about 7.3N. For the control requirements, according to the author's estimation, performing a maximum of 30 finger cycles per minute is enough for repetitive exercises. Similarly, a speed of actuation of 0.5 Hz is suitable for providing help during activities of daily living (ADL). On the other hand, a minimum controller bandwidth of 10 Hz should produce a smooth response [14].

3.1 Rehabilitation and Assistive Soft Glove

The functions that rehabilitative gloves and assistive gloves are supposed to do are quite different. However, the lines between the two fields are not clearly defined, so some researchers suggest that their gloves can be used for both rehabilitation and assistance [16-19]. These ideas find a middle ground between what a therapy glove should do and what an assistive glove should do. The following is a collection of interesting devices that are either rehabilitative, assistive or both and have unique features, either in terms of how they are built or how they are used. Another rehabilitation technology for stroke is rehabilitation using Brain-Computer Interfaces (BCIs) as done by Narudin, Mohamed Nasir and Fuad [20]. Rehabilitation using Brain-Computer Interfaces (BCIs) is a cutting-edge approach that focuses on leveraging the brain’s electrical activity to facilitate recovery, particularly in stroke rehabilitation. BCIs establish a direct communication pathway between the brain and external devices, enabling patients with motor impairments to control machines, such as robotic limbs or exoskeletons, through their thoughts or brain activity. Let’s break down how BCIs, combined with technologies like soft robotics, can revolutionize stroke rehabilitation.

Panagiotis Polygerinos is an established expert in the field of soft actuators and soft gloves, having made significant contributions via extensive study. The individual highlighted a soft robotic glove designed specifically for rehabilitation [6]. Additionally, they introduced a soft glove intended for assisting. Lastly, they introduced an invention that serves the dual purpose of rehabilitation and assistance [8,14]. Polygerinos [6] provides the initial findings of a study on a rehabilitation glove. The PneuNet concept is the basis for the glove's actuation design.

Figure 2 gathers some soft robotic gloves that have been proposed for both rehabilitation and assistance. The glove later improved [8,14], features moulded soft actuators based on multi-segment elastomeric that assist with both rehabilitation and daily tasks. The actuators' fibre reinforcement design allows for flexion, twisting (for thumb application) and extension motions.

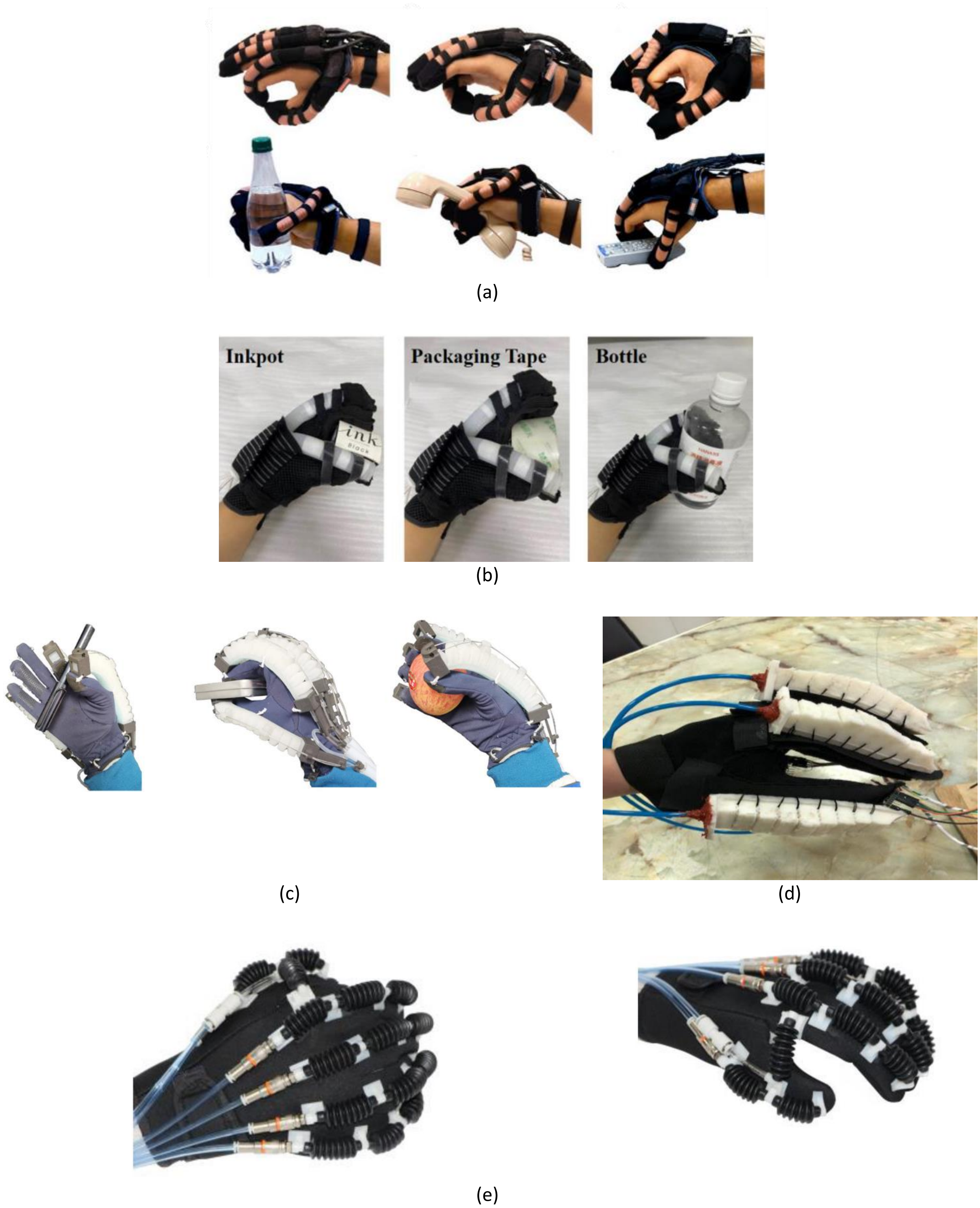


Fig. 2. Soft gloves for both rehabilitation and assistance (a) hydraulic soft robotic glove with soft fibre-reinforcement actuators [14] (b) pneumatic customized soft glove with bioinspired segmented hybrid bending actuators (SHBAs) [21] (c) bidirectional soft glove with a hybrid actuator that combines a silicone flexion actuator with an extension actuator made from shape memory alloy (SMA) springs [23] (d) KNTU-RoboGlove: The soft glove integrates with variable stiffness layer actuators, drawing inspiration from pangolins [24] (e) A novel soft robotic glove with positive-negative pneumatic actuator mode of bel

Figure 3(a) shows that the device, which has a standard open-palm glove and can produce forces of around 8 N at the fingertip with an input pressure of 345 kPa, is sufficient for ADLs. The glove weighs 285 g and the system can work continuously for about 3.8 hours at a speed of 0.25 Hz. Among all the devices analysed in the review, this one is the only one with hydraulic actuation.

Pneumatic bioinspired segmented hybrid bending actuators (SHBAs) Figure 3(b) for rehabilitation interactions are designed, modelled and tested in this work [21]. Compared to conventional continuous structures, the soft rigid architecture of the SHBAs more closely resembles the finger. A finite-element model was constructed to validate theoretical analysis and experimental results, while a static model was created to forecast motion trajectories and flexion angles. The efficacy of underactuated hand rehabilitation gloves with soft hybrid actuators (SHBAs) in assisting activities of daily living (ADLs) was proven. In a 370kPa test, the SHBAs caused fingers to bend to a maximum of 170.65 degrees for wearable rehabilitative procedures.

Hu *et al.,* [22] state that positive-negative pneumatic actuators made from bellows move the glove's six degrees of freedom, which include flexion, extension, abduction and adduction for the thumb (Figure 3(e)). The authors first consider the device's design to enable a person to independently conduct the typical activities of daily living (ADLs) and determine the essential ranges of motion required for this objective. The range of rotation for the (carpometacarpal) CMC joint in the thumb is limited, whereas the range of motion for swinging is large. On the other hand, the (metacarpophalangeal) MCP joint in the thumb has a wide range of rotation but a limited range of swinging motion. Therefore, their main accomplishment is the movement of the CMC joint and the rotation of the MCP and (interphalangeal) IP joints. For the remaining fingers, the mobility of the MCP is not essential due to its limited range of motion and insignificant impact on gripping. The author simplified the movement of the three thumb joints by assuming that they constantly move in a plane, with the CMC joint swinging to either adduct or abduct the thumb. This assumption is based on the small amplitude of the thumb's MCP swing. The researchers positioned the adduction/abduction actuator within the palm side and the thumb. The actuator increases or decreases length in response to positive or negative pressure, respectively, allowing the thumbs to move closer together or farther apart. The actuators' extension forces were tested at a maximum pressure of 90 kPa. The results were as follows: 4.6 N for extension, 1.9 N for flexion, 8.1 N for adduction and 5.7 N for abduction. The device's primary benefits include its lightweight design at 149 g, comfort, customization capabilities, ease of implementation, safety and affordability. Because each actuator is made up of separate parts, the glove can actively help the flexing and extending of 14 joints in five fingers, as well as the bringing in and pulling out of the thumb. This makes the thumb more opposable. The device can perform multiple gestures and facilitate object grasping.

Lai *et al.,* [23], create a bidirectional soft robotic glove for rehabilitation and assistance. The glove uses a hybrid actuator that includes a soft bending actuator and an extending actuator manufactured from shape memory alloy (Figure 3(c)). The author primarily focuses on the limitations of the current glove's extension force output. The actuator generated a tip force of 16.2 N and an extending force of 8.675 N at an applied pressure of 200 kPa. A refined finite element model was used to calculate the material and parameters for the actuator. The shape memory alloy spring actuator was equipped with a cooling water system to decrease temperature and improve reaction speed by 55.8%. When integrated into a soft glove, the range of motion of stroke patients' index fingers indicated a significant enhancement and the glove increased the maximum force required to slide against a 50mm cylinder between 8.4 ± 3.5 N and 21.34 ± 5.8 N.

In this research, Boka *et al.,* [24] introduce a soft glove specifically created to assist patients in their hand rehabilitation therapy and everyday activities. The glove provides both active finger flexion and passive extension, which helps support the hand during rehabilitative therapy. The system employs integrated soft actuators, such as a variable stiffness layer and a pneumatically driven layer, to control precise bending, extending and twisting motions by applying air pressure. The concept of the variable stiffness layer is derived from pangolins (Figure 3(d)), which feature scales that are flexible during normal activity but rigid when confronted with danger. A toothed pneumatic actuator has been specially designed to deliver greater force while maintaining improved stiffness. The glove is fabricated using a highly flexible material and produced using 3D printing technology. Empirical findings demonstrate that these actuators can produce significant force and torque, hence enabling finger bending even when subjected to reduced air pressure levels. A control unit for gripping has been created, which consists of sensors for the motion processing unit and a closed-loop system for precisely adjusting air pressure. This glove can improve users' self-sufficiency and independence. Figure 3 displays a selection of soft gloves that have been suggested for rehabilitation or assistance.

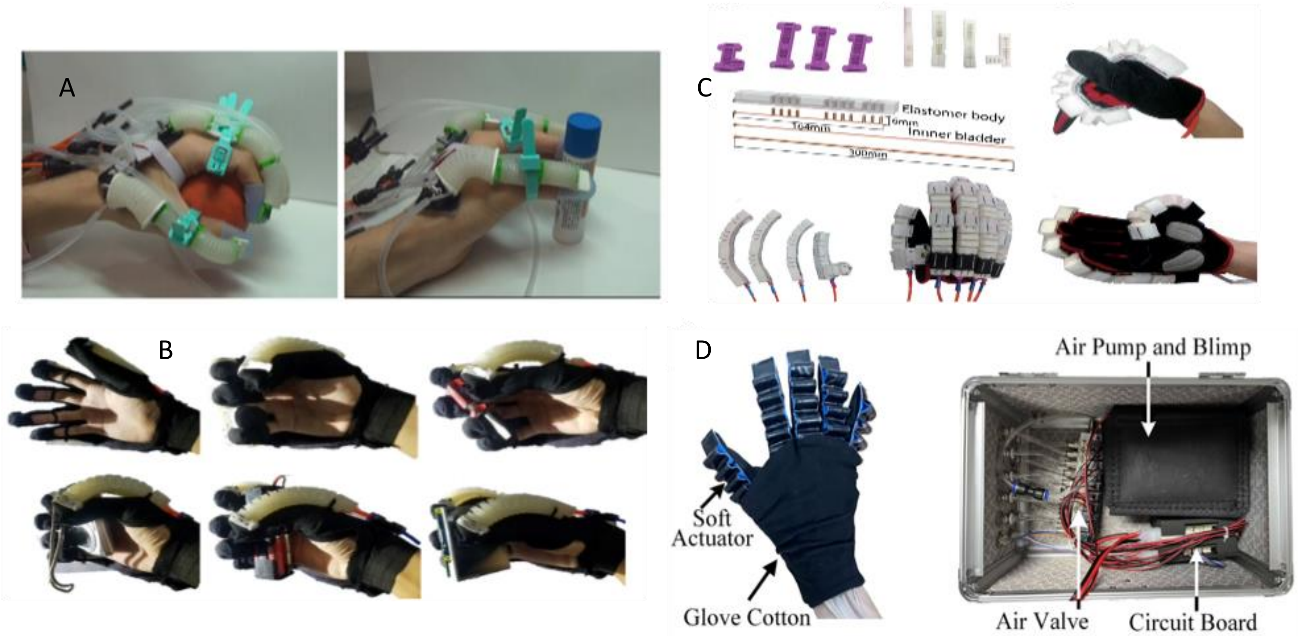


Fig. 3. Soft robotic gloves for rehabilitation and assistance (s) soft robotic glove with fibre-reinforced elastomer-based joint-modular soft actuators [25] (b) Do *et al.,* [26] developed soft glove with five PneuNets soft actuators (c) Wang *et al.,* [27] developed a soft pneumatic glove based on segmented PneuNets bending actuators (SPBAs) (d) The glove presented by Lai *et al.,* [28] with honeycomb pneumatic actuator

In their study, Kokubu *et al.,* [25] created soft actuators for hand rehabilitation. These are based on modularized soft actuators, which are fibre-reinforced elastomer-based joint-modular soft actuators (Figure 4(a)). Each finger joint has its actuator. Under pressure 200kPa, the banding angles for soft actuators alone are 131.9° and the maximal tip force is 13 N. The maximum range of motion (ROM) for soft actuators with a dummy finger for DIP, PIP and MCP is 75.7°, 99.0° and 86.9°. This indicates that soft rehabilitation provides motion support that is at least equivalent to 60% to 90% of a healthy person's range of motion.

Do *et al.,* [26] presented a glove with five PneuNets soft actuators (Figure 4(b)). To accomplish flexion motion, a 2/2-way pneumatic solenoid valve supplies pressurized air via an air pump motor, while another 2/2-way pneumatic solenoid valve connects the actuator's pump to reduce the time it takes for deflation. The five actuators, which share a common power supply, move the fingers simultaneously. A touch sensor commands the opening and closing of the glove. The glove performed well in a test to hold objects weighing 30–220 g, but it could only lift heavier objects for a few seconds. The lifting limit for the maximum weight was 500 g.

In Wang *et al.,* [27] created a soft robotic glove that uses segmented PneuNets bending actuators (SPBAs). The glove is designed to fit the shape of human fingers by adjusting the placement of air chambers at every finger's joint. This ensures that the glove bends in a way that matches the natural contour of the fingers (see Figure 4(c)). The soft robotic glove can close the hand up to an angle of 230° when tested with a pneumatic pressure of 150 kPa. A detailed analytical model and a series of tests were conducted to determine the fingertip forces. The difference between the obtained findings is 8.87%. At a pressure of 150 kPa, the modelled fingertip touch force for the soft actuator reaches a maximum of 1.55 N, but the measured value is 1.60 N. The maximum value of the force produced by the four fingers and the bottom part of the hand during grasping is about 6.4 N. A patient with an impaired hand may securely hold an item weighing about 582 g due to a contact friction coefficient of 0.46.

Lai *et al.,* [28] described an assistive glove with a new type of honeycomb pneumatic actuator (HPA) (Figure 4(d)), that is made by hot pressing to weld the flexible thermoplastic polyurethane (TPU) layers. The end output force of the HPAs is an amazing 862% higher than that of the double-layer fabric-based pneumatic actuators (DLFPAs) that were used before. Several activities of daily living can be made easier with the incorporation of HPAs into a soft glove. To evaluate the efficacy of the soft glove, nine patients participated in a series of trials. The experimental findings demonstrated that the patients' proximal interphalangeal (PIP) and metacarpophalangeal (MCP) finger joints obtained angles of 64.2 ± 30.66° and 87.67 ± 19.27°, respectively, with the use of the glove. The average grip force and fingertip force were 26.04 ± 15.08 N and 10.16 ± 4.24 N, respectively and the patient's daily function completion rate went from 39% to 76%. These results show how the soft glove improves the patients' everyday functioning and helps with finger movements efficiently. The HPA effectively increases the patient's hand strength at a pressure of 150 kPa by improving the pneumatic actuator's output performance without changing its volume or mass.

3.2 Pneumatic Glove Actuation

Over the years, researchers have invented, created and evaluated many types of soft pneumatic actuators. Pneumatic soft actuators encompass a wide range of constructive solutions and fall into four major groups. The first category includes pneumatic artificial muscles [29]. Next, we have soft elastomer actuators, which include PneuNets actuators [17,27,30] or soft bending actuators [31]. Afterward, we have fabric-based actuators [16,18,32] and finally, 3D-printed actuators [33,34]. Each category contains a variety of constructive solutions, some of which define subclasses.

Fiber-reinforcement soft pneumatic actuators are the majority often used among silicone-based pneumatic actuators, with PneuNets actuators being the next most popular choice [13]. The Others class mostly consists of pneumatic actuators, such as embedded inflatable actuators made by heat-bonding flexible plastic sheets [28] and variable stiffness soft pneumatic actuators [35,36]. Soft gloves can only act on the closed hand, the open hand or both, but typically the open hand is passive flexion and the closed hand is active extension [13].

This research by Wang, Fei and Pang [27], describes the invention, development and evaluation of a soft pneumatic glove equipped with five elastomers-based segmented PneuNets bending actuators.

Figure 4 of Discus Structure of the proposed soft glove equipped with five elastomers. The actuators are designed to mimic the structure of human fingers, consisting of three flexible parts for finger joints and four rigid sections for finger metacarpals and phalanges. The quantity of inflated chambers in the flexible part may be determined based on the range of motion of the matching joint. (Active flexion, passive extension actuation). Chambers include an inner bladder that is lodged inside them to improve air tightness. At full pressure of 150 kPa, the glove can flex the finger up to a maximum angle of 237.8°, this bending generates a grabbing force of 1.55 N for every fingertip. The model and test validate the design's sustainability and its promise in hand rehabilitation.

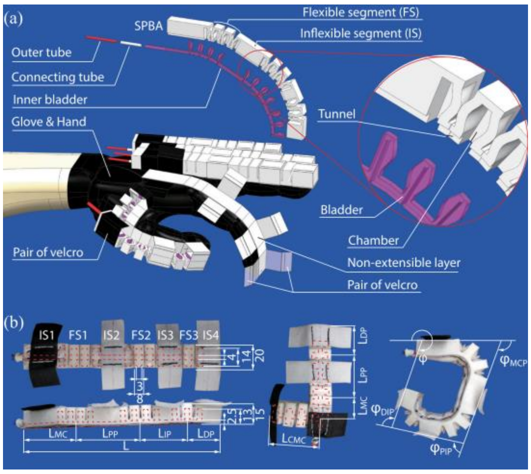


Fig. 1. Structure of the proposed soft glove equipped with five elastomers

The article by Wang *et al.,* [17], introduces an innovative soft glove specifically developed for rehabilitation and assisting in grasping objects. The soft actuator comprises five segmented pneumatic networks (PneuNets) that are capable of bidirectional bending (**Error! Reference source not found.**). These networks are designed using a framework that can be adjusted to different heights. The MCP joint chambers and DIP joint chambers are shaped like trapezoids on their sides, which improves their capacity to bend in the opposite direction. The reverse bending module chambers are constructed in the shape of a triangular prism chamber to prevent any obstruction to forward bending. This enables the actuator to actively flexion and actively extend. Experimental tests demonstrate that the soft actuator can generate a bend angle of 261º at a pressure of 100 kPa and a fingertip force of 1.59 N at a pressure of 130 kPa. The glove may be used to stretch fingers, ventilate various finger joints and assist the hand in forming four rehabilitation positions. In assisted grasping mode, it may enhance the hand's ability to hold cylindrical and big planar items, making it beneficial for those with partial loss of hand function.

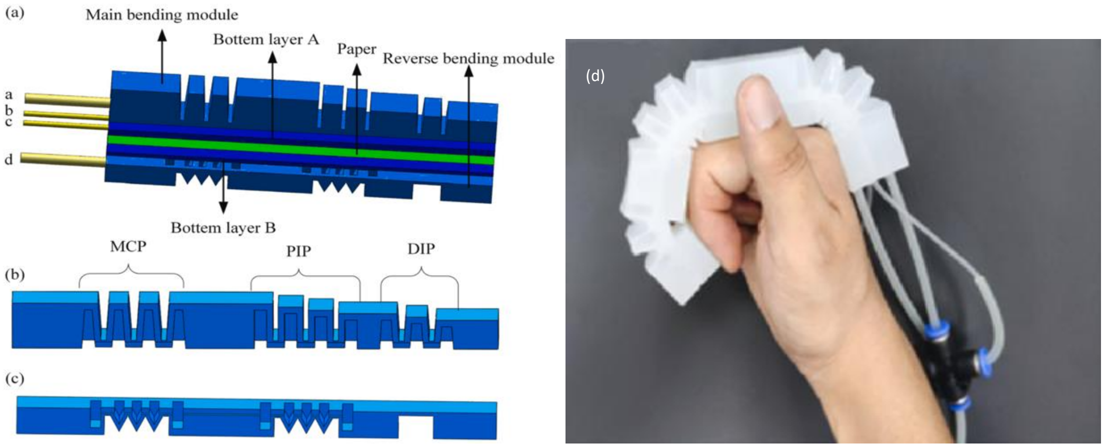
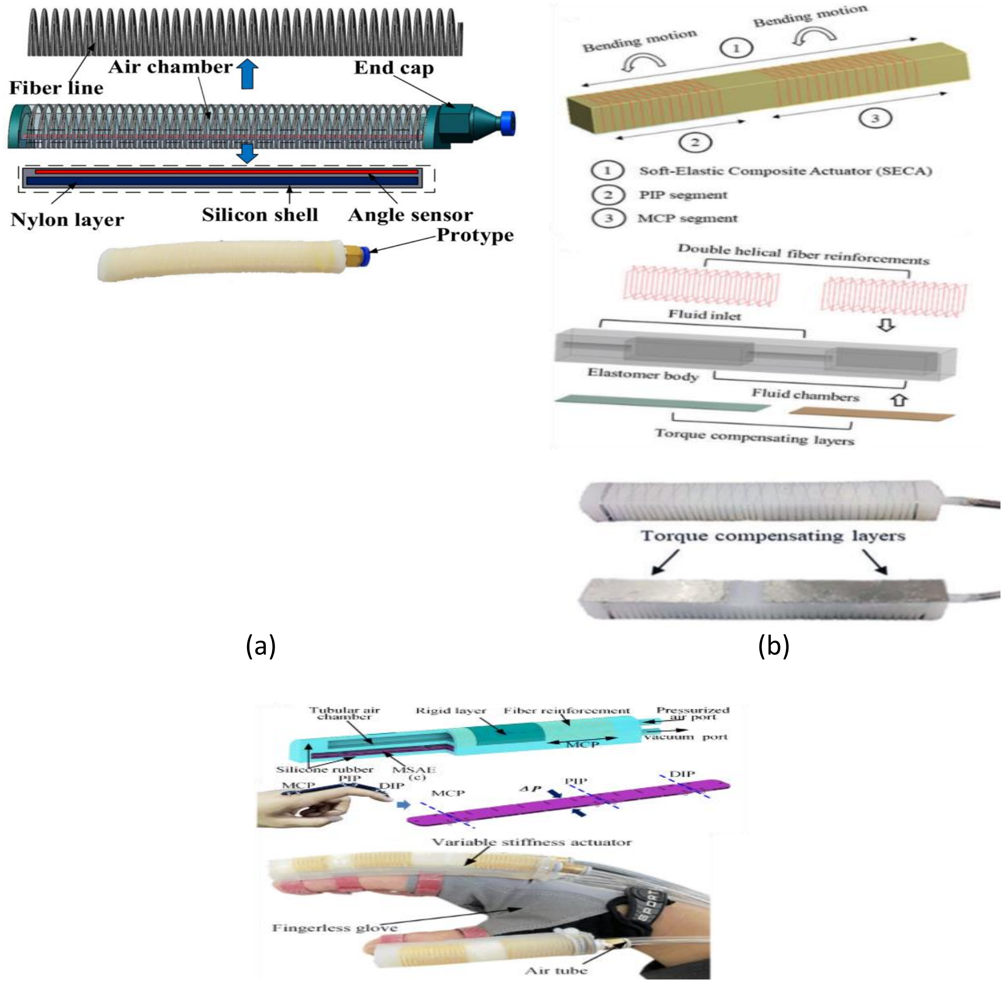


Fig. 5. The five segmented PneuNets bidirectional bending actuator (a) the structure of the actuator (b) the internal chamber structure of the main bending module (c) The internal chamber structure of the reverse bending module (d) the genuine soft actuator and human hand are fully actuated [17]

Due to its simple structure and ease of manufacturing, the fibre-reinforced actuator finds widespread use. Based on this paper by Han, Xu and Wu [37], research on human hand bone structure and finger joint characteristics led to the development of the soft pneumatic bionic actuator (SPBA) (Figure 6(a)). The actuators can be divided into PneuNets actuators and fibre-reinforced actuators based on their internal chamber structure. The range of motion of the SPBA can reach 260º and the output force can reach 5.1N with 0.25 MPa air pressure input. The glove's grasping experiments demonstrate its flexibility, large grip force and consistent grasping of objects. The SPBA meets rehabilitation training requirements and restores normal hand motion for stroke patients.

This work by Heung *et al.,* [38] presents the creation of a soft-elastic composite actuator (SECA) for fingers with gloves based on active flexion and passive extension. The SECA is a kind of actuator that is made up of two fibre-reinforced linked in series, with two torque compensating layers (thin A2 stainless steel) at the bottom (Figure 6). The SECA has a complex construction that includes a torque-compensating layer, enabling it to support both flexion and extension movements inside a single unit. The SECA regulates flexion and extension during pressurization and depressurization, respectively. The torque-compensating layer restricts axial elongation at the lower part of the actuator, allowing the top part to elongate and produce the flexion motion. The SECA design consists of two segments, the MCP and PIP segments, which enable a double-bending action over the length of actuators. The soft robotic glove applies the SECA design principle by placing a torque-compensating layer below each segment. This layer regulates the actuator's extension upon pressure release. The double-segmented SECA was constructed using flexible silicone rubber, which has both high elongation (364%) and hardness. When bent, this combination of properties allows the material to withstand significant deformations without failure or rupture. The formation of the silicone rubber and metal composite structure involves using a virtual lost-wax casting process, whereby the silicone rubber is wrapped with a double helical fibre and torque-limitation layers are attached to the lower sections of the MCP and PIP segments. Each SECA weighs 37g.



(c)

Fig. 6. Soft actuator based on fibre-reinforcement (a) Han *et al.,* bionic actuator (SPBA) (b) Heung *et al.,* designed a soft-elastic composite actuator (SECA) with double helical fibre reinforcements (c) Xiang Li *et al.,* proposed a variable stiffness pneumatic actuator with fibre-reinforced and multi-stage articulated elastomer

The authors Li *et al.,* [36], suggest a variable stiffness soft actuator for hand rehabilitation that enhances the elasticity of the soft actuator to promote more open hand motion. The soft actuator is composed of a multi-stage articulated elastomer that is pneumatically actuated to flex and extend the fingers and combined with a fibre-reinforcement technique. The three fibre reinforcements align with the three joints of the finger, namely the metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints. The two rigid layers correlate to the middle and proximal phalanx of the finger. The fibre-reinforced actuator receives a compressed air supply, which results in bending motion. The variable stiffness component consists of the multi-stage articulated elastomer (MSAE) that is embedded inside the variable stiffness chamber. This arrangement allows the actuator to extend when subjected to vacuum pressure, due to the elasticity provided by the MSAE. The MSAE is composed of three layers of spring steel sheets connected by rope, with the middle layer including three finger joints. The findings demonstrate that the actuator can generate a fingertip output force of 1.54 N and a stiffness change that is 2.4 times greater, therefore fulfilling the needs of stroke patients. The MSAE operates in a low stiffness mode, allowing the actuator to follow finger movement without limiting joint motion. The high stiffness mode enhances the actuator's durability by using vacuum pressure, enabling finger extension for patients with high muscle tension.

4. Fabrication

Many researchers used the soft lithography method to create soft robotic actuators, which involve moulding or stamping elastomers [25,26,36]. With this method, we use a soft material, which is liquid silicone Ecoflex 0030, then pour the material over 3D printed moulds and allow it to cure to carve out the mould's shape. This paper by Jiang *et al.,* [40], proposes a monolithic fabrication method that combines the advantages of the lost-wax and reverse flow injection (IFI) processes. The lost-wax approach allows for monolithic fabrication (cast as a single piece) and complex actuator chamber designs, while the IFI method reduces the occurrence of unwanted bubbles in actuators. Since the end caps at the actuator's end do not need to be glued, this method can withstand pressure 2.5 times before failing, compared to the traditional fabricated method.

The fabrication of soft robotics involves creating flexible, compliant structures using materials and methods that differ significantly from traditional rigid robotics. The goal is to develop devices that can interact safely with humans and adapt to unpredictable environments, mimicking the flexibility and resilience of biological systems. The fabrication process typically involves several key steps, including material selection, design considerations, moulding and casting techniques, integration of actuators and the application of additive manufacturing. Material selection is crucial, with elastomers such as silicone rubbers (e.g., Ecoflex, Dragon Skin) or thermoplastic elastomers (e.g., TPU) often chosen for their high elasticity, durability and biocompatibility, allowing the robots to stretch, bend and deform in response to external forces without breaking. For applications requiring operation in wet environments or interaction with delicate tissues, hydrogels—water-based materials with flexibility similar to biological tissues—are used. Additionally, smart materials like shape memory alloys (SMAs) and dielectric elastomers (DEs) are employed for actuation, with SMAs changing shape in response to temperature changes and DEs deforming when an electric field is applied.

Design considerations for soft robotics often draw inspiration from nature, replicating the complex movements and adaptive behaviours of biological organisms. For example, the structure of soft robotic gloves may mimic the anatomy of the human hand, using segmented chambers that replicate finger joints. Multi-material printing allows for the integration of materials with varying properties, achieving different functions within a single component, such as flexible and rigid areas for both adaptability and structural support. Finite Element Analysis (FEA) is commonly used to predict the mechanical behaviour of the soft robot under various loads and deformations, optimizing the design before fabrication to ensure desired performance. Fabrication techniques like soft lithography, which involves creating a mould of the desired soft robotic structure using photolithography, are widely used. The mould is filled with a liquid elastomer, which is then cured to form the soft structure—particularly useful for creating microfluidic channels and small-scale features. For larger and more complex structures, 3D-printed moulds can be used, with liquid elastomers poured into these moulds and cured to create the desired shapes. In some cases, different material layers are cast sequentially to achieve a multi-layered structure with specific mechanical properties.

Actuation in soft robotics is often achieved using pneumatic systems, where soft structures are embedded with small air chambers connected to an external air supply. When air is pumped into these chambers, they expand, causing the robot to bend, twist or contract in a controlled manner. Hydraulic actuators, which use fluids like water or oil instead of air, provide more force but are more complex to integrate. Flexible sensors, such as strain gauges, capacitive sensors or soft conductive materials, are integrated into the soft structures to provide feedback on the robot's position, force and interaction with the environment—crucial for precise control and adaptive behaviours. Additive manufacturing, particularly 3D printing, has become a cornerstone in soft robotics fabrication. Techniques like Fused Deposition Modelling (FDM), Stereolithography (SLA) and PolyJet printing allow precise control over geometry and material distribution. Direct Ink Writing (DIW), a method involving the extrusion of viscous inks or gels, is particularly useful for creating structures with complex internal architectures, such as lattice structures or graded material properties. Advanced 3D printers can print multiple materials simultaneously, integrating rigid components, flexible joints and even embedded sensors within a single build process.

After moulding or printing, the materials undergo post-processing steps such as curing and vulcanization to achieve the desired mechanical properties. Curing may involve heat or UV light exposure, while vulcanization—a chemical process involving sulphur—improves durability and elasticity. Parts are then bonded and sealed using adhesives or thermal techniques, ensuring structural integrity during operation, especially for pneumatic or hydraulic systems. The final step in fabrication involves testing the robot to ensure it meets performance criteria and calibrating sensors and actuators to fine-tune its behaviour under various conditions. The challenges in soft robotics fabrication include material fatigue due to repeated stretching and deformation, miniaturization and precision for medical devices and the development of enhanced actuation mechanisms such as electroactive polymers (EAPs) and magnetoactive elastomers (MAEs). Advanced fabrication techniques, like laser cutting, welding and electrospinning, are also employed to create intricate designs and unique surface properties.

By combining these diverse fabrication methods, researchers are developing soft robotic systems that are not only more flexible and adaptive but also more sophisticated, capable of a broader range of functions and suitable for various applications, especially in healthcare, where patient comfort, safety and personalized solutions are paramount. The integration of soft materials, bio-inspired designs and advanced manufacturing technologies continues to expand the potential applications of soft robotics, improving patient outcomes and pushing the boundaries of what robots can achieve in terms of adaptability and resilience.

4.1 Additive Manufacturing

In the twenty-first century, robotics has been transformed by a new perspective: robots constructed of soft materials that replicate nature have various benefits over their hard robot counterparts, resulting in the emergence and rapid expansion of a new scientific area known as soft robotics. Because of the unconventional materials used in soft robotics (including conductive, magnetic and other materials used for soft robot actuation), the manufacturing process is the foundation for obtaining soft structures that can meet specific requirements while saving time and money. The purpose of this study is to provide an overview of how additive manufacturing (AM) technologies are currently being used to manufacture soft robots. AM, commonly known as 3D printing, is distinguished by various characteristics, including the ability to readily manufacture extremely complex geometries that are ideally suited for soft robotic construction. After providing a summary of the most commonly used actuation systems in soft robots, the authors classify the use of AM technologies in soft robotics, investigating the most important and recent works in this field, based on how these technologies are used throughout the soft robot manufacturing cycle. With this in mind, the authors devised three strategies for using AM in soft robotics: quick mould fabrication (AM plays a passive function), hybrid (AM plays an active role but other manufacturing technologies are also utilized) and total additive manufacturing (only AM technologies are used). Only the latter strategy fully utilizes AM, however the other two still offer benefits. With new developments in commercial 3D printing systems (machines and materials) aimed at fabricating soft and unconventional parts, AM is poised to become the manufacturing technology of the future in the soft robotics field, displacing traditional manufacturing methods such as moulding and soft lithography.

The use of soft materials allows the creation of soft robots. Soft materials are necessary. They enable:

i. soft robot mobility in unpredictable environments because they can passively deform and adapt to the surrounding shape
ii. high impact resistance because they distribute stress over a large area
iii. complex geometries and shapes of soft robots [41].

Some commonly used words in the soft robotics sector are frequently misinterpreted due to a lack of specific literature and rapid advancements. Chubb *et al.,* [42] propose interesting terminology, referring to compliance as the inverse of stiffness and softness as the inverse of hardness. Even though Young's modulus (E) applies to prismatic and cylindrical samples exposed to axial stress, it is nevertheless helpful for categorizing materials as soft or hard. Soft materials (E < 109 Pa) are similar to natural biological materials like fat, cartilage and skin, with E values ranging from 104 to 109 Pa. [43-45]. It is vital to note that soft materials, both biological and commercial, display viscoelastic behaviour, dissipating energy when a load is applied; this material characteristic must be considered when designing soft robots based on their application [46,47]. Recent advancements in living materials may usher in a new era of soft hybrid robots capable of interacting with the human body [48]. Soft materials, combined with bio-inspired design, result in soft robots with unusual skills such as leaping, climbing, flexible grabbing, movement and growing [49]. Animals and plants can:

i. undertake complicated motions with soft structures
ii. adapt to new situations
iii. modify stiffness; based on all of these aspects, bio-inspired design is a critical necessity in soft robotics [50,51].

Soft robots inspired by the octopus [52,53], pangolin [54], fish [55], caterpillar [56] and flower [57] are just a few instances of how nature can be a tremendous source of inspiration in the field of soft robotics. Because of the complex geometries and movements of soft robots, the classical models widely used in hard robotics are useless; according to Das and Nabi [57] the approaches used to model robot kinematics and dynamics can be divided into three categories: black-box (based on neural networks), white-box (divided into geometry- and mechanics-based methods) and hybrid. Abdul Rahman *et al.,* [59] has designed the model of the robot on the other side which is designed using a simulation environment. Finally, the robot will be integrated with the real implementation, which benefits disabled people.

4. Discussion

The application of bio-inspired soft robotics in stroke rehabilitation, particularly through the use of soft robotic gloves, demonstrates considerable promise in enhancing motor recovery for stroke survivors. The reviewed literature indicates that these devices effectively assist in replicating natural hand movements, providing an intuitive, adaptive interface between human physiology and robotic assistance. Soft robotic gloves, inspired by biological systems such as tendons and muscle fibres, enable smooth, continuous motion control, facilitating repetitive task-specific exercises. This is critical for neuroplasticity, the brain’s ability to reorganize and form new neural connections during rehabilitation. Several studies confirm that patients using bio-inspired robotic gloves experience improved dexterity, strength and motor control compared to conventional therapy alone. However, challenges remain in optimizing the performance of these devices, including refining actuation control and ensuring the alignment of robotic assistance with the patient's voluntary movements. This underscores the necessity for further innovation in sensor integration and adaptive control systems to enhance the efficacy of robotic gloves in therapeutic settings.

In terms of fabrication methods, advancements in soft material engineering and actuation technologies have significantly influenced the design and functionality of bio-inspired robotic gloves. The integration of soft materials such as silicone and elastomers, combined with pneumatic or tendon-driven actuators, allows for flexibility, comfort and lightweight designs that are crucial for long-term use by stroke patients. The reviewed studies highlight that fabrication techniques like 3D printing and moulding are frequently employed to customize gloves to the specific anatomical and functional needs of the user, enhancing wearability and performance. However, limitations such as the durability of soft materials, the complexity of multi-material fabrication and the need for miniaturization of components to reduce bulk remain persistent challenges. These findings suggest that future research should focus on the development of more robust, scalable fabrication processes that maintain the flexibility and adaptability of soft robotics while ensuring cost-effectiveness and ease of use in clinical applications.

5. Conclusions

This review underscores the significant impact of soft robotics, especially soft robotic gloves, in enhancing stroke rehabilitation outcomes. Traditional rehabilitation methods often rely on rigid exoskeletons that can be uncomfortable, bulky and difficult to use, limiting their effectiveness and accessibility for patients. In contrast, soft robotic gloves, utilizing advanced materials like elastomers and pneumatic actuators, are designed to replicate the natural flexibility and agility of the human hand. These gloves offer targeted assistance for stroke survivors experiencing spasticity and limited motor control, gently guiding the hands through necessary movements and promoting muscle recovery.

The research reveals that the unique properties of soft robotics—such as their lightweight structure, inherent adaptability and the ability to conform to complex anatomical shapes—make them ideal for applications requiring safe, precise interaction with humans. This adaptability reduces the risk of injury and enhances user comfort, which is critical for patient compliance and the effectiveness of rehabilitation programs. Furthermore, soft robotic gloves provide a versatile platform for both active rehabilitation and assistance in daily activities, expanding their utility beyond clinical settings to home environments.

By integrating bio-inspired designs and leveraging additive manufacturing techniques, soft robotics can achieve unprecedented levels of customization and complexity, making it possible to develop devices that cater to the specific needs of individual patients. The use of additive manufacturing also facilitates the rapid production of prototypes and reduces costs, making these devices more accessible and scalable for widespread clinical use.

The review highlights several key challenges, such as the need for improved control mechanisms to enable more precise movements and the development of more durable materials to withstand repetitive use. Additionally, there is a need for further clinical studies to validate the long-term benefits and usability of these devices in diverse patient populations.

In conclusion, the development and application of soft robotic gloves represent a promising advancement in rehabilitation technology. They offer a more natural, comfortable and effective solution for restoring hand function in stroke survivors while also demonstrating the broader potential of soft robotics in healthcare and beyond. As the field evolves, continued innovation in materials science, design and manufacturing will be essential to overcoming current limitations and fully realizing the potential of soft robotic technologies to enhance patient care and quality of life.

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