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Review

Soft Hand Exoskeletons for Rehabilitation: Approaches to Design, Manufacturing Methods, and Future Prospects

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Abstract: Stroke, the third leading cause of global disability, poses significant challenges to healthcare systems worldwide. Addressing the restoration of impaired hand functions is crucial, especially amid healthcare workforce shortages. While robotic-assisted therapy shows promise, cost and healthcare community concerns hinder the adoption of hand exoskeletons. However, recent advancements in soft robotics and digital fabrication, particularly 3D printing, have sparked renewed interest in this area. This review article offers a thorough exploration of the current landscape of soft hand exoskeletons, emphasizing recent advancements and alternative designs. It surveys previous reviews in the field and examines relevant aspects of hand anatomy pertinent to wearable rehabilitation devices. Furthermore, the article investigates the design requirements for soft hand exoskeletons and provides a detailed review of various soft exoskeleton gloves, categorized based on their design principles. The discussion encompasses simulation-supported methods, affordability considerations, and future research directions. This review aims to benefit researchers, clinicians, and stakeholders by disseminating the latest advances in soft hand exoskeleton technology, ultimately enhancing stroke rehabilitation outcomes and patient care.

Keywords: stroke; disability; soft robotics; hand exoskeletons; robotic-assisted therapy; bioengineering

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1. Introduction

Strokes are the second leading cause of death worldwide [1–3]. These events, which consist of the sudden death of some brain cells due to lack of oxygen when blood flow is lost due to blockage or rupture of an artery [4,5], are also the third cause of permanent disability and one of the main causes of dementia and depression [6,7]. The occurrence of strokes is subject to different risk factors [8,9]. Diseases such as hypertension and diabetes, along with habits such as smoking, are considered modifiable risk factors, that is, factors susceptible to prevention. Other risk factors are not preventable, such as atrial fibrillation and transient ischemic attacks, which are presumed to be of genetic origin [10].

Globally, 70% of strokes and 87% of deaths related to these events occur in low- and middle-income countries [11]. Over the past four decades, the incidence of stroke in low- and middle-income countries has increased by more than 100%. During these decades, its incidence has decreased by 42% in high-income countries. On average, this event occurs 15 years earlier and causes more deaths for people living in low- and middle-income countries when compared to those in high-income countries. Strokes mainly affect people at the peak of their productive lives [12], and despite its enormous impact on the socio-economic development of countries, this growing crisis has received very little attention to date.

Recent neurological research indicates that impaired motor skills of stroke patients can be improved and possibly restored through repetitive, task-oriented training [13–17]. This is due to a property of the human brain known as neuroplasticity or the ability of the brain to reorganize itself by establishing new neural connections [18,19]. On this basis, the use of automatic devices has been implemented to help therapists increase the intensity of treatments, produce multisensory stimulation, and reduce costs during their work [20–25]. This new concept dates to the early 1990s with a new family of robotic machines called "haptic interfaces". These mechanical devices were designed to interact with the human being, guiding the upper limb towards passive and active assisted mobilization, assisting in some movement tasks through biofeedback systems, and measuring kinematic changes and dynamics in motion. However, there is no consensus on the metrics or devices used to treat motor function deficiencies through neuroplasticity [26,27]. Additionally, recovery success relies heavily on a patient's ability to attend therapy, which can be deterred by the frequency, duration, or cost of the therapy [28]. In this way, robotic therapy could represent a standard and successful complement to rehabilitation programs, improve patient access, and increase compliance and subsequent outcomes of rehabilitation efforts.

Despite the multiple designs reviewed in the last decade [29], there is no clinical evidence of the superiority of robotic training over traditional therapy. However, this procedure can complement traditional therapy processes [30]. In contrast, soft robots have the potential to overcome the limitations that are present in rigid robots. This design paradigm, inspired by the behavior and structure of living things, seems to be more compatible with rehabilitation activities due to increased versatility and compliance [31,32].

In addition, the solutions proposed, under the appropriate portability parameters, would have the potential to support the patient in the execution of activities of daily living, increasing their level of independence, mental health, and the well-being of their family nucleus.

The purpose of this work is to present a comparative review of the most recent rehabilitation hand exoskeletons based on soft actuators. This comparison is based on two main criteria: (i) the complexity of the manufacturing process and (ii) the resulting adaptability to the patient's anatomy in rehabilitation environments.

This review also wants to motivate future designers to work in interdisciplinary solutions, taking into consideration multiple initiatives related to the implementation of makerspaces within the facilities of healthcare institutions, enabling the high reception and adoption of digital fabrication methods in society, and specifically, in healthcare [33–38].

2. Review Methodology

This study used a narrative review methodology involving the use of several search terms in multiple online databases. These databases included IEEE Xplore (Institute of Electrical and Electronics Engineers), Science Direct, Scopus, and MDPI, as well as complementary databases such as Google Scholar and Semantic Scholar. Searches were meticulously crafted by combining several relevant keywords. These included terms such as "soft actuator", which denotes flexible mechanisms that facilitate movement; "hand exoskeleton", which refers to external support structures for hand movements; "hand rehabilitation", which encompasses techniques and technologies aimed at restoring hand function; and "assistive device", which highlights tools designed to improve mobility and independence. The incorporation of these various terms was intended to comprehensively capture the literature relevant to the topic of this review.

2.1. Inclusion Criteria

In research studies, inclusion criteria are essential to delimit the boundaries of the research and to ensure the accuracy and relevance of the selection process. This section clarifies the precise inclusion criteria adopted in this review. Each of the criteria that guided the selection of the articles under review is detailed below. The hierarchical classification employed to establish inclusion and exclusion criteria is shown in Figure 1, where the elements highlighted in green indicate the aspects to be considered in this review.

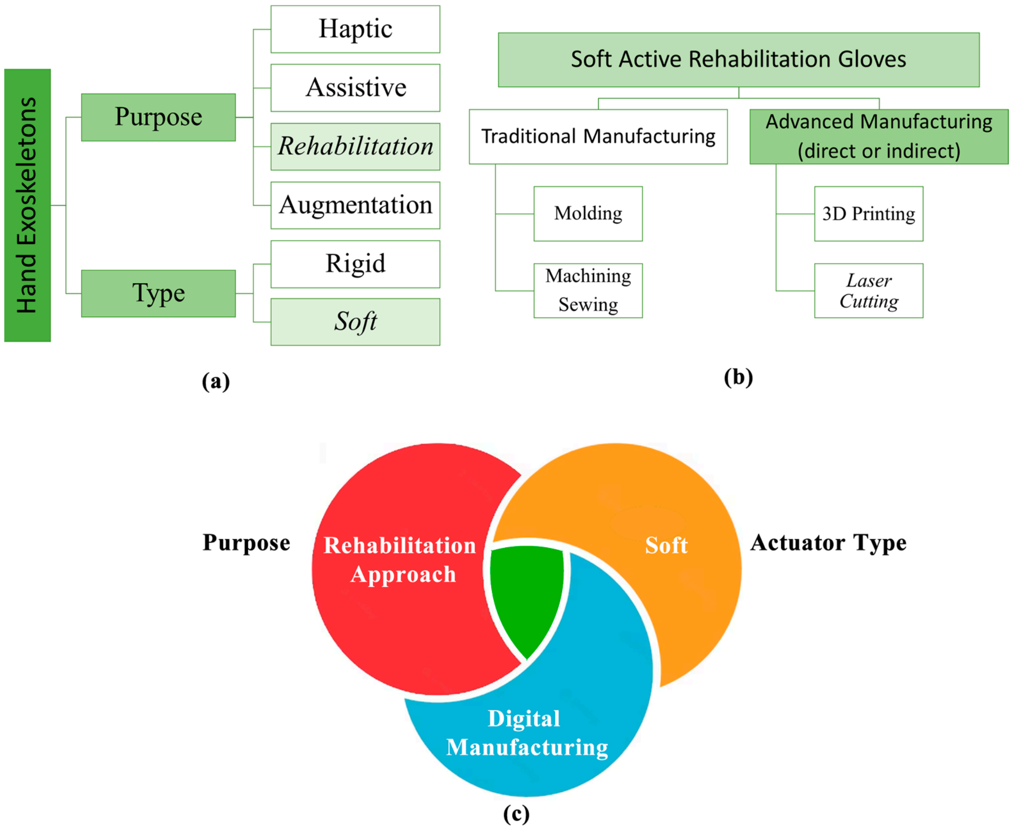

Figure 1. Hierarchical structure for defining inclusion and exclusion criteria. (**a**) Categorization of hand exoskeleton types according to function. (**b**) Classification of soft actuator manufacturing methods. (**c**) Illustration of inclusion criteria scope in a Venn diagram.

2.1.1. Active Exoskeletons

Devices in this category are equipped with components called actuators, responsible for converting energy into motion. The resulting motion is transmitted to the fingers to facilitate task-oriented training. This group includes devices with independent motion. However, those combining passive and active mechanisms [39] are not included in this paper, mainly because of their rigid design. The same principle is applied to passive hand rehabilitation devices [40–44]. The actuator type is focused on electric and pneumatic mechanisms, excluding shape memory alloys (SMAs) and electroactive polymer actuators. The complex design of SMA actuators made them difficult to use for rehabilitation purposes and activities of daily life (ADL) [45–48].

2.1.2. Softness and Compliance

Unlike hard devices with levers, pins, or pulleys, soft devices interact with the patient's hand more flexibly. Softness encompasses both structural flexibility and inherent material compliance [49,50]. The terms "soft actuators" and "soft robotics" describe systems that interact with their environment due to their flexible nature. Soft robotics, as defined by Rossiter et al. [51], is a broad term that encompasses all compliant systems, whether active or reactive. Additional thoughts on soft robotics can be found in works such as Albu-Schaeffer et al. [52], among others [53–56].

2.1.3. Wearable Configuration

Devices in this category can be worn by the patient, often as gloves [57]. This distinguishes them from end-effector exoskeletons [58,59].

2.1.4. Rehabilitation Approach

This study exclusively includes devices designed for clinical rehabilitation settings. It encompasses devices used for both rehabilitation and home care. Other types of gloves, such as haptic or force augmentation devices, are outside the scope of this review.

2.1.5. Digital Fabrication Process

Device components are materialized using digital fabrication techniques, a subset of advanced manufacturing methods [60], namely additive manufacturing or 3D printing [61–63]. In 3D printing, materials are added to form volumetric parts, as opposed to traditional milling, where the material is subtracted, a technology available for all kinds of materials and shapes [64–66]. Digital fabrication can involve direct or indirect approaches. Three-dimensional printing effectively realizes soft actuators and glove components [67–69].

2.2. Exclusion Criteria

The inclusion of specific criteria in the selection process is essential to delimit the scope of this study. To ensure clarity and focus, certain categories have been deliberately excluded. The exclusion criteria guide the identification and evaluation of relevant devices as presented below.

2.2.1. Prosthetic Devices for Limb Replacement

This study focuses on the rehabilitation setting and excludes prosthetic devices designed for complete limb replacement. The focus here is on devices that help restore hand function and not those intended to replace lost limbs.

2.2.2. Hard Mechanical Devices

The study gives priority to soft robotics and compatible systems, thus excluding devices with hard mechanical components such as levers, pins, and pulleys. Emphasis is placed on devices characterized by structural flexibility and flexible interaction.

2.2.3. Passive Hand Rehabilitation Devices

Devices that rely solely on passive mechanisms are excluded. The intention is to delve into active solutions that enhance rehabilitation through independent movements and interactions.

2.2.4. Traditionally Manufactured Devices

Exoskeletons, gloves, or active hand rehabilitation orthoses manufactured primarily by conventional methods, such as machining or sewing, are excluded from the study. The focus is on innovations derived from digital manufacturing technologies.

2.3. Article Selection Process

The article selection process involved categorizing published articles and filtering out irrelevant data. Titles, abstracts, and full articles were scrutinized to ensure relevance. Only publications and data from 2010 to 2023 were included in the study. Figure 2 illustrates the flow of information through the various phases of this systematic review.

2.4. Framework for Comparison

A framework is established to analyze the research articles identified during the search. The objective is to extract the merits and demerits of each solution, considering the complexity and volume of fabrication activities, especially digital fabrication. Before delving into the individual devices, the following section outlines the biomechanical principles essential for evaluating design features, particularly those of the soft actuators responsible for transmitting motion. An additional evaluation tool is presented in the “design requirements” section to help place each design within the established frame of reference.

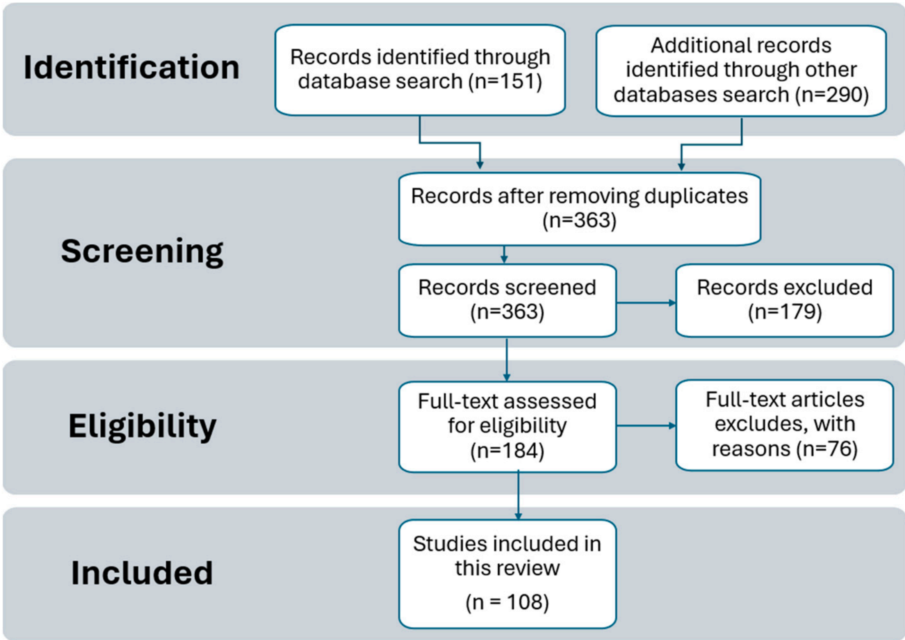

Figure 2. Phases of information processing in the systematic review.

3. Past Reviews of Soft Hand Exoskeletons

Wearable exoskeletons have become indispensable tools in the field of rehabilitation and assistance, especially for people recovering from stroke or wishing to improve hand function. Notable studies have contributed significantly to understanding the landscape of these devices. Gu et al. [70] provided valuable information on advances in hardware and software components of hand function rehabilitation systems, integrating gesture recognition devices and artificial intelligence modules. Similarly, Birouaș et al. [71] performed a statistical analysis of trends in hand exoskeleton technology, shedding light on current applications and technological advances. In addition, Shahid et al. [54] explored the evolution of handheld exoskeleton design, with a specific focus on the incorporation of soft robotics technology in mechanical design, actuation units, and sensory feedback control. These studies demonstrate various methodologies employed in the development of handheld exoskeletons, addressing a myriad of challenges and opportunities in the field. In addition, recent reviews by Pacchierotti et al. [72] and Varghese et al. [73] provide insight into wearable haptic systems and wearable robotics for upper extremity rehabilitation and assistance, respectively, elucidating emerging technologies and future research directions. In addition, Chu and Patterson [28] provided a comprehensive review of the design and development of soft robotic devices tailored for hand rehabilitation and assistance, analyzing 44 devices within a structured framework. Their review highlighted crucial aspects such as portability, safety features, user intent detection methods, actuation systems, total degrees of freedom, device weight, and rehabilitation modes while addressing current challenges and proposing future directions for advancing soft robotics in hand rehabilitation and assistance. This review, focusing on active exoskeletons characterized by softness, compliance, and portable configuration, identifies significant advances in wearable robotics specifically designed for rehabilitation purposes. The emphasis on digital fabrication processes underscores a shift toward innovative manufacturing techniques, enabling the development of customized and adaptable exoskeletons. Furthermore, the exclusion criteria applied in this review, which eliminates limb replacement prostheses, hard mechanical devices, passive hand rehabilitation devices, and traditionally manufactured devices, underscores its focus on cutting-edge soft robotics technologies aimed at improving rehabilitation outcomes. This approach provides valuable insight into the evolving landscape of hand exoskeletons, emphasizing the importance of softness, compliance, and portable design to promote effective rehabilitation.

4. Hand Anatomy for Rehabilitation Wearable Devices

To ensure the effectiveness and safety of portable rehabilitation devices, it is critical to understand the principles governing the anatomy and biomechanics of the hand. Factors such as degrees of freedom (DOF) and range of motion (ROM) play a critical role in the mechanical design of rehabilitation gloves [74,75]. Understanding the anatomy of the hand is essential for designing soft exoskeletons. The human hand encompasses various biological structures, such as muscles, bones, tendons, ligaments, nerves, and veins. In general, the hand consists of 5 fingers, 27 bones, 36 joints, 39 active muscles, and 21 DOF. [76,77]. A fundamental overview of hand anatomy is provided, focusing on the fingers, thumb, joints, and muscles. An anatomical and biomechanical representation of the human hand is depicted in Figure 3, while Table 1 illustrates the ROM and DOFs in the biomechanical model of the hand.

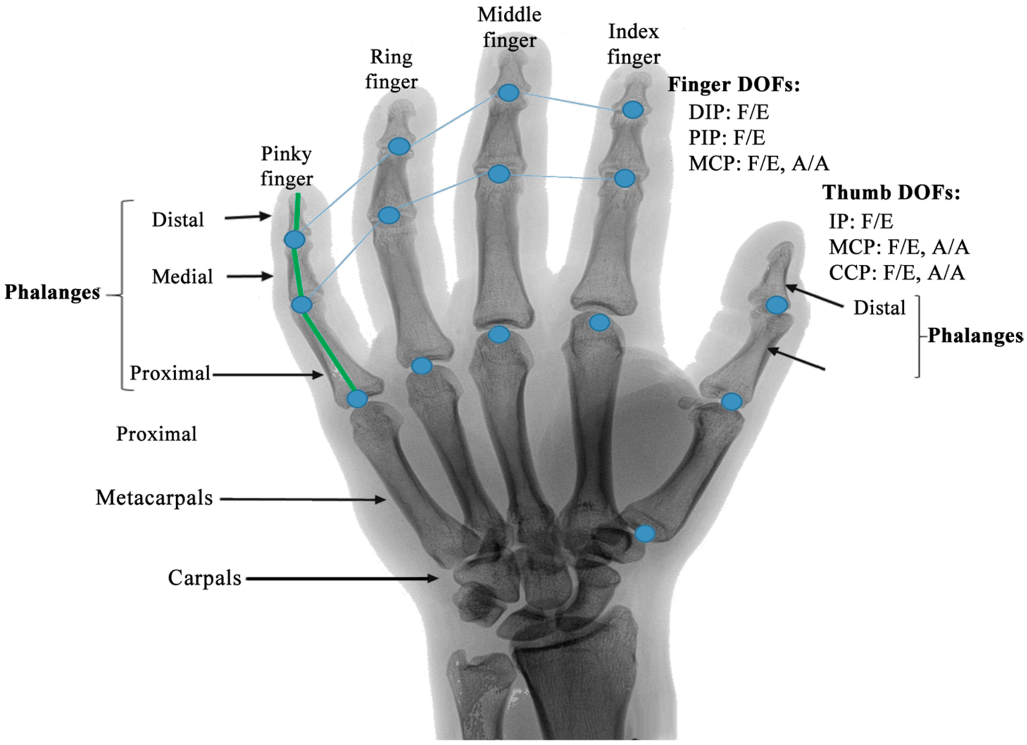

Figure 3. Anatomic and biomechanical representation of the human hand.

Table 1. Biomechanical model of the hand: range of motion and degrees of freedom.

Joint Name	Acronym	ROM	DOF
Carpometacarpal	CMC	1.5°	F/E (Flexion/Extension), A/A (Abduction/Adduction)
Metacarpophalangeal	MCP	90°	F/E, A/A
Proximal interphalangeal	PIP	[30–45°]	F/E
Distal interphalangeal	DIP	[10–20°]	F/E

4.1. Grip Movements

The human hand can execute a diverse range of grasping movements essential for ADL. These grips are classified into three main categories: power grips, intermediate grips, and precision grips. Dollar et al. [78] and Feix et al. [79] offer comprehensive classifications of grips suited for various purposes.

4.2. Variants of Power Grip

The power grip, also known as coarse function, is used for force tasks that do not require precision, such as grasping, squeezing, or pulling objects. It consists of performing a pincer grip with the fingers partially flexed while applying pressure with the thumb in the plane of the palm. Three types of power grip are characterized: the hook grip, the cylindrical grip, and the spherical grip.

4.3. Precision Grip

Precision grasping is used when manipulating small objects, which are grasped between the distal phalanx of the thumb and the terminal volar pads of one or more fingers [80]. It can be classified as pad-to-pad prehension or thumb pinch, tip-to-tip prehension or tip pinch, or pad-to-side prehension or key pinch.

5. Design Requirements for Soft Hand Exoskeletons

Exoskeletons for rehabilitation are mainly designed for the treatment of patients within institutions dedicated to health care. These devices focus on the performance of repetitive activities that seek training for the execution of ADL. In general terms, rehabilitation exoskeletons should be easy to wear and should not cause discomfort. They should also allow interaction with real objects, exert considerable force, and, preferably, monitor finger movement for subsequent evaluation or follow-up on treatment progress. The portability specification is not mandatory but is desirable, as it would allow the patient to perform therapy at home. A description of the design features found in the available literature is given in the following paragraphs. Table 2 presents the design requirements for soft exoskeletons employed in hand rehabilitation.

Table 2. Requirements for the design of soft exoskeletons for hand rehabilitation.

Design Requirement	Description
Security	Ensuring patient safety is paramount for both actuators and their motion control systems. This involves aligning with the anatomical movements of the fingers and their respective joints. It is crucial to confirm that the actuators exert force within the natural limits of the joints.
Bidirectionality	The actuators of the device should apply force to the patient's fingers in a natural manner, avoiding any discomfort.
Effective force transmission	The actuators of the device should apply force to the patient's fingers naturally, ensuring comfort and avoiding discomfort.
High power-to-weight ratio	The system needs to be both lightweight and compact, all while maintaining the capacity to generate the necessary force and speed typical of gripping motions.
Affordability	Soft robotic rehabilitation gloves, in general, should be the outcome of a relatively uncomplicated manufacturing process. Additionally, they ought to be user-friendly, easy to maintain, and operable by individuals lacking technical expertise.

6. Review of Soft Exoskeleton Gloves

Soft exoskeleton gloves have emerged as promising devices for rehabilitation and assistance in activities of daily living. This section provides a comprehensive review of various design alternatives within the realm of soft exoskeleton gloves, highlighting recent advancements and alternative manufacturing methods.

6.1. Based on Fluidic Bladders

This type of soft exoskeleton glove incorporates inflatable bladders in its actuators to transform energy into motion. When fluid, gas, or liquid enters the bladder, it changes the actuator's shape, creating a trajectory and transmitting force to the fingers. Among the various design principles identified, those incorporating inflatable fluidic bladders emerged as a prominent approach for creating soft exoskeleton gloves. Indirect digital manufacturing techniques, such as the use of reusable 3D-printed molds, were found to be used in creating these actuators. However, the results presented lack specific details regarding the effectiveness, range of motion, and potential limitations of these devices. The role of digital manufacturing in the fabrication process can be defined as direct or indirect. In the direct approach, the actuator is made directly in the 3D printer. On the other hand, the indirect method is carried out with the help of a driven mechanism (powered by a single linear electric actuator). The common element in the solutions described in this section is the tendon-driven mechanism. According to Zanotto et al. [81] cable-driven systems provide many advantages compared to their rigid link counterparts. The cables allow the offboarding of motors, which allows less weight to be added to the user and less inertia reflected on the user during movement. Although there is no risk of fluid leakage in a cable-driven mechanism, the risk of overpassing the natural ROM in MCP, PIP, and DIP joints is still present. The risk of failure after a considerable number of cycles is low; however, attention should be paid to the performance of the 3D-printed parts over time. Material selection is a key issue in this device because of the direct contact of the glove parts with the human hand molds made with 3D printing techniques, for example, fused deposition modeling (FDM) and selective laser sintering (SLS) [82–84].

6.2. Indirect Digital Manufacturing

In the soft rehabilitation devices developed by Polygerinos et al. [82,84], hydraulic actuators were fabricated with the aid of a reusable 3D-printed mold. The focus of this specific research is on the innovative capabilities of the corresponding finger actuator. To achieve the research goals, the developers used a multistage manufacturing process to make a fiber-reinforced hydraulic actuator. ExoGlove at Seoul National University [85] is another hand exoskeleton designed for both rehabilitation and at-home assistance. In this device, the finger's actuator exhibits variable stiffness, which implies that specifically compliant zones will be activated upon pressurization trying to mimic the hand biomechanics. This feature adds adaptability to the device, and the shape in the flexion position resembles the shape of the human finger. Jiang et al. [86] present a solution that involves a multicomponent actuator for each finger. This design incorporates a fishbone-like structure covering an inflatable bladder and two nylon string reinforcements. The mentioned fishbone structures were fabricated with a method called lost-wax inverse-flow injection.

6.3. Direct Digital Manufacturing

Direct manufacturing methods are also present, as demonstrated by the POMA muscle solution (pneumatic muscle actuator), for instance [87]. In this scenario, the inflatable bladder is manufactured from fabric that has been CNC machined, employing the traditional Japanese paper-cutting technique known as kirigami. A 2D gantry CNC cutting machine uses a laser to make specific cuts on a fabric that is then folded in a tubular shape to form an air chamber. Another solution in this category is the PIY (Print It Yourself) glove [88], where an accordion-shaped actuator is entirely fabricated using additive manufacturing with the aid of a low-cost FDM 3D printer. The main component of the "PIY" glove is the pleated bellows-type actuator. The bending movement is achieved during pneumatic pressurization of the actuator's chamber. Pressurization causes the crests to unfold, which in turn causes an asymmetric bending motion due to a stress-limiting layer being printed on only one side of the actuator.

Li et al. [89] developed and tested a prototype with pneumatic actuators to assist flexion and abduction movements. These actuators were entirely 3D printed with an FDM 3D printer. The resulting air chamber, made of thermal polyurethane (TPU), is attached to the glove using a hook-and-loop fastener, and the air tubes are glued with silicone sealant. In the soft glove developed by Heung et al. [90], the direct 3D-printed actuators, thoroughly described in [91], present a soft elastic composite actuator with both extension and flexion capabilities. The scientific contribution of this author lies in the ability of the actuator to perform flexion movement in a controlled manner and not just by passive behavior during depressurization.

Nevertheless, several disadvantages should be highlighted, including the risk of leakage and the cleaning difficulty of the textile component of the system that is the glove itself. Fatigue strength is also a vulnerability of the material used in the fabrication of the soft actuators, especially the more compliant sections. Patients and clinicians should be aware of the appearance of cracks after a considerable number of cycles or working hours.

6.4. Based on Polymer Structural Components

This type of active soft glove corresponds to those devices in which the structural hand support is fabricated using a polymer, and the fabrication process is carried out via direct or indirect additive manufacturing. In the case of the indirect additive manufacturing process, the most common alternative in recent developments is the use of rubber silicone. Another design category involved the use of polymer-based structural components for soft exoskeleton gloves. The resulting parts provide the patient's hand with a compliant structure with proper anchor points and the necessary routing for a cable-driven system. While the potential advantages of these designs, including customizability and portability, were mentioned, there was a lack of in-depth analysis of their performance and user experience. This is the case with Exoglove Poly [92,93] and Exoglove Poly II [94], where the multistep fabrication process was aided by an SLA 3D printer, employed to make a reusable mold from a 3D digitally parametrized CAD design. Several attributes, such as digital control performance and actuator design optimization, are studied by authors like Setiawan et al. [95], but the stages of fabricating the structural components are quite similar.

On the other hand, direct manufacturing methods were applied to create the components needed for the soft rehabilitation glove presented by Yoo et al. [96], who designed and developed a myoelectric hand orthosis for patients with spinal cord injury. The design developed by Mohammadi et al. [97] (FlexoGlove) used a flexible TPU to 3D print the structural compliant components for the tendon-driven actuators in each finger. The actuation control unit case seems to be also 3D printed in PLA filament. Guo et al. [98] decided to use some mechanical elements to integrate a Bowden system into a set of compliant 3D-printed finger supports. A hard part is strapped in the dorsal region with a mechanical guiding system. Three-dimensional printing is also a resource to fabricate testing materials. Last is the case of the soft exoskeleton presented by Yi et al. [99], where a PLA dummy finger was designed and 3D printed based on anthropomorphic measurements. The articulated finger is used to test the usability of the new device before testing on real patients.

6.5. Fabric or Textile Based

This section is intended to describe the soft rehabilitation exoskeletons developed from commercially available work gloves. For example, Rudd et al. [100], present a low-cost design (less than USD 200), where some 3D-printed parts are attached to a flexible fabric glove to provide routing and anchor points for a tendon-driven system. The design presented here uses a jointless structure that relies on natural movement and joint constraints imposed by the patient's bone structure. The same design approach, in terms of digital manufacturing, is taken by other devices [101–104], where some 3D-printed elements needed to make the fingers move are sewed or glued to a commercially available work glove. This alternative design allows for grasping movements, keeping the carpometacarpal joint in a natural range of motion for such tasks.

Another design category involved the use of fabric-based soft exoskeletons, where 3D-printed elements were integrated with commercially available work gloves, showcasing a low-cost and accessible solution. However, the specific benefits, challenges, and usability aspects of these devices were not discussed comprehensively in the text. A different use of fabric in the development of the soft robotic glove is addressed by Araujo et al. [105]. In this device, called HERO, the designers take advantage of the capacity of a low-cost FDM 3D printer to pause the controlled filament extrusion and add a fabric layer while the process is halted. Then, after resuming, the molten plastic is deposited on the textile material to create a fabric sandwich.

The fabric-based soft exoskeletons cited so far in this section are activated by tendon-driven mechanisms. This movement system, as mentioned before, has advantages and disadvantages from a biomechanical point of view.

Other devices, like the one published by Nguyen et al. [106], present a particular design where the resulting active element is a flexible fluidic actuator. The innovation in this approach comes precisely from the manufacturing method, which includes the use of a 2D CNC heat-seal machine to form patterns in a fabric that will be later folded to give shape to the inflatable bladder, creating a bending actuator.

Figure 4 shows various types of soft gloves used in the categories described above.

Figure 4. Variations in soft glove designs: (**a**) fluidic bladder-based, (**b**) digital manufacturing-derived, and (**c**) polymer structural component-based models.

Actuators are pivotal components within these gloves, facilitating user hand movement, replicating natural gestures, and supporting rehabilitation routines. The array of actuator varieties underscores the dynamic innovation within the realm of soft robotics, catering to diverse requirements and applications. Table 3 describes a spectrum of soft gloves documented in the literature, detailing the actuators employed in designs tailored for rehabilitation or assistance, along with their operational attributes.

Table 3. Overview of soft actuators used in hand rehabilitation gloves.

Description	Type of Actuator	Ref.
Fiber-reinforced soft actuators composed of elastomer and featuring bendable structures inflated by air pressure. Modular and adaptable to various finger sizes and joint stiffness.	Pneumatic	[107]
Flexible thermoplastic polyurethane actuators with a honeycomb-like structure enabling bending and folding movements.	Pneumatic	[108]
Bi-directional bending actuators made of soft elastomer with embedded air chambers for lightweight, flexible, and anthropomorphic design.	Pneumatic	[109]
Combination of bending and rotating actuators made of soft materials like silicone and fabric, with embedded strain and force sensors.	Pneumatic	[110]
Actuators fabricated by heat bonding flexible plastic sheets, inflating upon pressurization to extend fingers, embedded in glove pockets.	Pneumatic	[111]
Soft pneumatic bending actuators made of molded elastomeric bladders with fiber reinforcements provide finger and wrist motion assistance.	Pneumatic	[112]
Hybrid actuators combining silicone flexion actuators and shape memory alloy extension actuators for flexion and extension assistance.	Hybrid pneumatic-magnetic	[113]
Modular glove utilizing twisted string actuators (TSAs) for lightweight, flexible motion generation through twisting tendons.	Twisted string	[114]
Soft segmented fiber-reinforced actuators with anisotropic fiber reinforcements enable specific bending, twisting, and extending trajectories.	Segmented fiber-reinforced	[115]
Soft-elastic composite actuators (SECAs) combine elastomer bladder, fiber wrapping, and torque-compensating layer for finger flexion and extension.	Elastic composite	[90]

7. FEM-Based Topology Optimization in Shaping Soft Robotic Structures

The field of soft robotics has experienced remarkable advances in recent years, driven by innovative methodologies aimed at designing and optimizing complex robotic structures. Among these methodologies, topological optimization based on the finite element method (FEM) stands out as a powerful tool for shaping the future of soft robotics. In their quest to improve robotic capabilities, researchers are increasingly turning to FEM-based approaches to tailor soft robotics designs to specific tasks and environments. This brief review serves as a gateway to explore the intersection between soft robotics and FEM-based topological optimization, focusing on recent research by Sun et al. [107]. This review aims to shed light on the role of FEM-based topological optimization in shaping the soft robotics landscape and pave the way for future advances in this field.

In their recent research paper, Sun et al. [107] delve into the realm of soft robotics with a focus on FEM-based topology optimization techniques for designing sophisticated robotic structures. Their study introduces a novel lightweight robotic gripper featuring 3D topology-optimized adaptive fingers, showcasing the potential of FEM-based methodologies in this domain. Through meticulous exploration in Part II of their paper, the authors elucidate the application of FEM-based topology optimization in designing a continuum-structure-based double-finger gripper. This section offers detailed insights into problem formulation, boundary conditions, design domain, and objective function considerations. Their research presents experimental findings, highlighting the performance metrics of the developed gripper, including grasping capabilities, load capacity, and comparisons with existing grippers. Moreover, the authors critically discuss both the advantages and limitations of employing FEM-based topology optimization methods in the design of soft robotic structures.

The study aligns with broader discussions in the literature concerning numerical methods for simulating soft robot dynamics. Kumar and Chhabra [116] underscore the capabilities of FEM-based topology optimization methods in optimizing the shape, size, material distribution, and actuation of soft robots while highlighting challenges such as computational complexity and simulation accuracy. Although Bianchi et al. [117] touch upon FEM for simulating soft robotic designs, Sun et al.'s research offers a more comprehensive examination, particularly focusing on the application of FEM-based topology optimization.

Furthermore, the study presented by Faller et al. [118] contributes to ongoing discussions on multiscale topology optimization and functionalization in soft robotics. It emphasizes the importance of incorporating FEM-based topology optimization methods into the design process to address challenges such as incorporating dynamic effects, multiphysics coupling, and multimaterial design considerations [119].

8. Discussion and Future Work

New approaches in design and materials for soft robotics applications are constantly emerging. This section summarizes the areas with the greatest prospects for future development in the authors' opinion, looking for attributes such as portability, accessibility to manufacturing technology, customization, and affordability.

8.1. Simulation-Supported Methods

Given that additive manufacturing technology allows for the realization of designs that in many cases are impossible to manufacture by other methods, the field of design has been and will continue to be a work area with a considerable number of study variables. In this sense, the processing of design inputs (needs) and its consequent iterative process (of a dynamic nature) justifies the competition of the largest number of available techniques. On the other hand, the task of imitating attributes of nature to integrate them into robotics solutions is not simple.

Given this general panorama, the implementation of design techniques based on metamaterials constitutes a viable path for the development of integrated dynamic structures that are related to the final functional requirements of soft robotic gloves. Some of these can be evolutionary algorithms, shape optimization, finite element simulation, and algorithm-assisted design, among others, all of which require great processing capabilities and methods for their maximum use.

8.2. Affordability

The development of new intelligent materials, from the point of view of their chemical composition and not their architecture, is of vital importance for the advancement of intelligent and low-cost robotic actuators. Materials with mechanical properties compatible with the requirements of soft gloves for rehabilitation should be complemented with electrical, magnetic, and thermal properties that promote the expansion of the spectrum of solutions. Therefore, the raw materials developed must be consistent to raise awareness of the potential present in robot-mediated rehabilitation technologies and allow them to reach more patients and rehabilitation professionals around the world.

9. Conclusions

This comprehensive review article has examined various solution principles within the realm of soft hand exoskeletons, particularly those designed for rehabilitation purposes. Throughout this exploration, a clear demand for solutions that are more accessible and scalable has emerged. This necessity stems from the exorbitant costs associated with the functional recovery of stroke survivors, the high demand for specialized healthcare personnel, and the intricate nature of rigid robotic systems. Despite the advancements these systems have made in improving therapeutic processes, their reception among patients and healthcare professionals has been less than ideal.

From the findings of our extensive literature search, it is evident that digital manufacturing plays a pivotal role in the fabrication of soft robotic devices. The synergistic integration of innovative design approaches and advanced manufacturing techniques holds promise for generating alternative solutions that could address the widespread need for rehabilitation robots.

Furthermore, the research underscores the potential of diverse digital fabrication technologies in significantly advancing the development of soft-bending actuators tailored for hand rehabilitation. Techniques such as 2D CNC laser cutting and heat-sealing CNC machines exhibit considerable potential, as they enable the processing of textiles or fabrics to create functional soft wearable rehabilitation devices. This underscores the transformative impact that digital fabrication can have on the evolution of rehabilitation technology.

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