ORIGINAL ARTICLE

A Review on the Role of Soft Robotics in Medical Assistive Devices

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Abstract: The development of soft robotics technology has enabled them to be used for healthcare devices. One of the areas where this technology can play a crucial role is the medical assistive devices for various purposes like rehabilitation. In contrast to commonly used technology utilizing rigid actuators with a limited range of motion simultaneously compromising the safety of their human counterparts, this technology suits well to be used in the same with an added advantage. These soft actuators address the issues like safety, compliance, freedom of motion, biocompatibility, and ease of use. Various technologies like Dielectric Elastomers Actuators (DEA), fluid-based soft actuators, Twisted String Actuators (TSA), Supercoiled Polymer Actuators (SCPA), etc., have been developed to mimic the motion of a living being. The focus of this write-up is concentrated on unconventional and recent approaches to the design and control of soft actuators. In the present study, each technology's working principle and application have been discussed, along with their limitations. Soft actuators with different technologies which can be used in assistive devices, their requirements, and limitations are discussed along with some recent devices and the importance of the material to develop soft robots.

Keywords: Artificial muscle; Assistive devices; rehabilitation; Soft actuators.

Nomenclature:
DEA: Dielectric Elastomers Actuators
TSA: Twisted String Actuators
SCPA: Supercoiled Polymer Actuators
DOF: Degree of Freedom
PAM: Pneumatically Actuated Muscles
FFMS: Fluidic Fabric Muscle Sheet
SMA: Shape Memory Alloy
TSA: Twisted String Actuator
SFM: Spring-based Fabric Muscle
TCP: Twisted and Coiled Polymers
PZT: Lead Zirconate Titanate
DEA: Dielectric Elastomer Actuators
CNT: Carbon Nano Tubes
CHAD: Compact Hand Assistive Device
POMA: Pneumatic Origami Muscle Actuator
BPAM: Bending Pneumatic Artificial Muscle
BRAG: Biomimetic Robotic Assistive Glove
SR-AFO: Soft Robotic Ankle Orthotics
TPU: Thermoplastic Polyurethane
ROM: Range of Motion
MCID: Minimal Clinically Important Difference
ILC: Iterative Learning Control
FPBA: Foldable Pneumatic Bending Actuator
UE: Upper Extremity

Introduction

In recent years, there has been a growing interest in developing soft actuators for medical assistive devices. Unlike traditional rigid actuators, soft actuators offer improved compliance and interaction safety when operating in close proximity to humans. Researchers have explored unconventional approaches to design and control soft actuators, leveraging materials and mechanisms that mimic natural movements [1]. By incorporating soft and flexible materials, such as elastomers or hydrogels, into actuator designs, the resulting devices can better adapt to complex anatomical structures and provide gentler interactions with the human body. Additionally, control strategies based on advanced sensing and feedback systems enable precise and coordinated movements of soft actuators, enhancing their performance and usability in medical applications. The acceptance of soft robotics technology in the medical field has gained momentum due to its potential to address limitations associated with conventional rigid actuators [2]. Soft robots offer unique advantages, such as improved safety, adaptability, and patient comfort. However, the widespread adoption of soft robotics in medical applications raises important ethical considerations. Designing soft robots that interact with humans necessitates careful consideration of patient autonomy, informed consent, privacy, and trust. As the integration of soft robots in healthcare settings progresses, it is crucial to address these socio-ethical ramifications and establish guidelines that ensure the responsible and beneficial use of the technology. Soft actuators have shown promise for use in assistive devices, catering to the needs of individuals with physical or neurological disabilities and the geriatric population. The requirements for assistive devices include high degrees of freedom (DOF) to enable natural movement, biocompatibility to ensure safe interaction with the user and ease of use for both patients and caregivers. Soft actuators, with their ability to mimic biological movements and provide compliant interactions, meet these requirements to a greater extent than their rigid counterparts. However, challenges such as power efficiency, size scalability, and long-term durability remain areas of focus for researchers in order to overcome limitations associated with current soft actuator technologies [3].

Recent advancements in soft robotics have led to the development of innovative devices for various medical applications. Soft robotic exoskeletons, prosthetic limbs, and assistive gloves are just a few examples of devices that leverage soft actuators to provide improved functionality and comfort. The choice of materials plays a crucial role in developing these devices, as they need to be both biocompatible and possess suitable mechanical properties. Elastomers, hydrogels, and smart materials, such as shape memory polymers, are commonly used to create soft actuators with tailored properties. The selection and characterization of materials are critical steps in optimizing the performance and effectiveness of soft robotic devices in healthcare settings [4]. Assistive devices incorporating soft actuators have demonstrated remarkable efficacy in delivering therapy and restoring motor functionality for individuals with physical or neurological disabilities. These devices can provide targeted assistance, promote rehabilitation, and enhance the quality of life for users. By offering a combination of support, control, and adaptability, soft actuators enable personalized rehabilitation programs tailored to the specific needs of patients. Moreover, the geriatric population, with reduced motor functionality, benefits from assistive devices that can assist with activities of daily living, thereby promoting independence and autonomy [5].

This research aims to provide comprehensive insights into actuation methods used in soft robotics for medical assistive devices. By examining various external assistive devices, their advantages, limitations, and future scopes, this research intends to contribute to the advancement of soft robotics in healthcare. By understanding the strengths and weaknesses of different actuation methods and assistive devices, researchers and practitioners can identify areas for improvement, optimize designs, and explore new possibilities for developing more effective and user-friendly medical assistive devices. The research seeks to foster innovation in soft robotics, addressing the specific needs of individuals with disabilities or age-related motor impairments while considering the ethical implications and societal impact of integrating soft robotics technology into healthcare settings.

Method of Study

A chronological review of several literature databases, i.e., Science Direct, PubMed, IEEE Explorer, and Google Scholar, was conducted to identify the trend of soft robotics in assistive medical devices from 2018 onward. The keywords used as the search entries to evaluate more categorical papers were 'assistive,' 'assistive medical devices, and 'soft robotic.' The search results were further narrowed down with keywords like 'rehabilitation,' 'lower body,' 'hand,' 'upper body,' 'spinal,' 'legs, and 'knee'. Given the upcoming actuation methods, this review focuses on not-so-commonly used assistive technologies. Also, the focus of assisted devices is more

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on the recent developments with special and miscellaneous purposes apart from rehabilitation.

Actuation Methods and Materials

The different actuation methods and their use have been discussed along with their working principle.

Actuation Methods

Fluid-based Soft Actuator

McKibben, also known as Pneumatically Actuated Muscles (PAM), common soft actuators which are made up of braided cylindrical bodies around a rubber tube and can be extended up to a certain threshold limit [6]. Compressed air is used to control the actuation of these actuators. They can be categorized into two types: pneumatic artificial muscles and hydraulic artificial muscles. In pneumatic type artificial muscles, compressed air is used for actuation, and in hydraulic, a liquid is used for actuation. The most used fluidic actuator is the McKibben muscle actuator [7]. This can be considered a rubber balloon with a mesh of flexible net tightly woven around the flexible balloon like a flexible tube [8]. The flexible mesh can expand radially but not in the axial direction. The tube will expand whenever the balloon-like rubber tube is filled with fluid. Due to the mesh net, the tube can only expand in the radial direction and will contract in the axial direction [9]. This contraction is utilized for actuation in various applications. Here in McKibben, compressed air inflates the tube and achieves actuation. But with little or no change, the same actuator can be actuated hydraulically in which pressurized liquid is used. These kinds of actuators can be used to achieve different kinds of actuations like linear, bending, twisting, etc. [10]. Levers and other mechanisms can be used to leverage the output of these actuators. For example, muscles used to move the arms use the lever type-3 mechanism for actuation. McKibben actuators. These actuators can produce large forces whose range can go up to 6 kilo Newton [11]. Hence, they can be used for heavy-load applications. The stroke achieved in the McKibben actuator can be around 25% [8]. The maximum strain and force values can be altered by using them in combinations like parallel and series arrangements. Whenever these actuators are connected in parallel, the maximum force can be increased, and the series arrangement can increase the maximum strain achieved from a single actuator. The operating bandwidth of hydraulically actuated artificial muscle can reach up to 100 Hz [11], which is significantly large for such force and strain obtained. These actuators are compliant and lightweight, but fluid pumps like air compressors and other supporting equipment give them a huge disadvantage. The whole system becomes bulky, leading to a decrease in its mobility and portability.

The decreased portability limits its use in numerous applications like mobile robots, as each muscle will require a pump to be controlled individually. Although these actuators can have a high-power density (up to 22 W/g) [12], the power to weight ratio is low due to the bulky pumping mechanism required for operation. The efficiency of fluid pressure conversion to mechanical force is nearly 30% [13]. Controlling these actuators is difficult. In addition, they give hysteresis. Its mathematical model becomes very complex despite the disadvantages mentioned before. This technology finds a good application in some specific designs and immobile platforms. A vacuum-powered PAM, having a bellow configuration with enclosed rings, was able to

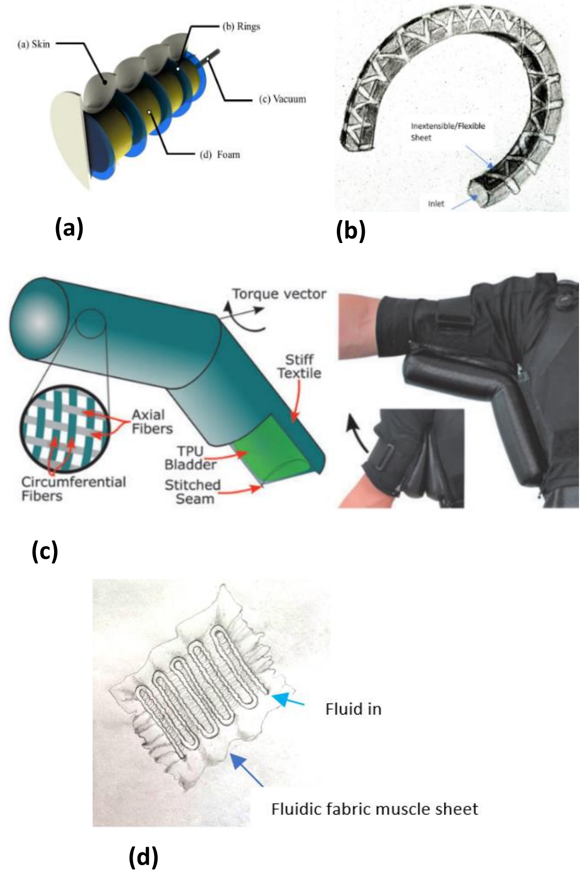


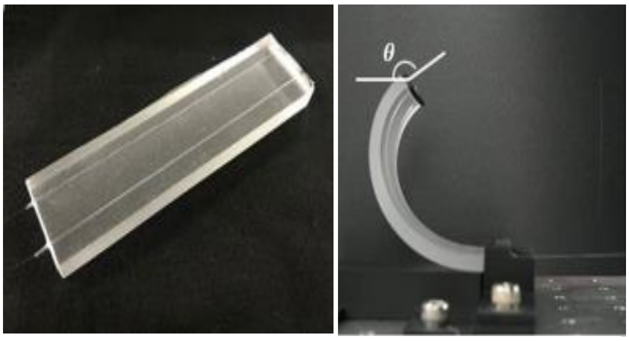
Figure 1. (a) Ring enclosed bellow actuator [7], (b) Fiber reinforced PAM [8], (c) Textile embedded PAM [15], (d) FFMS [10]

demonstrate higher buckling strengths and increased axial stiffness as compared to conventional PAM [14]. One other, fiber-reinforced Bending PAM was designed to be very thin (~2.5mm) in rest state when compared to regular PAMs and was also able to perform effective motion to counter the low-frequency tremors [15]. An origami-inspired PAM was also developed, with features of extreme compactness and relatively lighter weight [16]. A new class of pneumatic actuator Fluidic Fabric Muscle Sheets (FFMS) were developed, where the pneumatic lines are embedded as an array into the fabric, which when actuated, were able to strain, squeeze, bend, and conform to hard or soft objects of arbitrary shapes or sizes [17]. Due to the large area and soft fabric composite, FFMS showed potential to be used as integrated actuators. Elastomer-based Fluidic actuators proved to be effective and compliant when in a rest state, which helps in a free motion [18]. The intensity of force output is relatively low, hence confining it to hand wearable devices. With a combination of material properties and orientation, these actuators can generate different types of motions like bending and extension. PneuNet actuators are well suited for bend and curl operations [19]. The concept of 'Soft Continuum Actuation' can be used in conjugation with intrinsic shape memory alloy (SMA), and pneumatic actuation for improved DOF and compliance [20]. Inclusion of deformation-sensitive elements into the elastomeric base such as Carbon Fiber-based Piezoresistive led to self-sensing (With positional feedback) which can be used to make closed-loop feedback-controlled precise pneumatic actuated soft robotic finger [21]. Elastomer-based material provides a compliance and comfortability advantage.

Textile-based pneumatic actuators have a high strength-to-weight ratio and high area-to-volume ratio in the rest state. They can be modeled to attain various actuation motions and manufactured from commercially available materials. The relatively low thickness profile of the fabric makes it suitable to use in compact locations such as underarm, groin, and knee pit to attain desired assistance with minimal rest state displacement and increase the subtlety of the application in human social interaction [22].

Cable Tension Driven Transmission or Twisted String Actuator (TSA)

Since muscles work in tension and are connected at two ends, cables could mimic this as a simplified model [23]. These cables are fed through frictionless sheathed hinges [24], tubing, or roller pulley along the desired line of action. They are powered through a hydraulic actuator or motor, generating high torques [25]. The primary issue with cable-driven systems is the feedback lag at sharp turns. This can be avoided by using a two-way driven cable mechanism. When loaded axially and twisted with the help of a motor, a string changes length and undergoes secondary coiling. The stroke length is relatively high compared to SMA and pneumatic actuation methods. It can be used in a multi-string parallel combination to generate high-intensity forces. One such attempt was conducted using a hard exoskeleton with a guide rail, which ultimately increased the device's weight [26]. A new device with multi- parallel string combination in a soft glove used TSAs with a sorter adaptor mechanism to provide adjustable linear motion as on-demand [27]. The limitations due to friction of lines are one issue associated with this method. Another study on 'Rubber' as a suitable material for twisted actuation showed promising controlled actuation with custom set equilibrium positions, reduced average, and initial stiffness [28]. However, rubber showed limitations with energy storage.

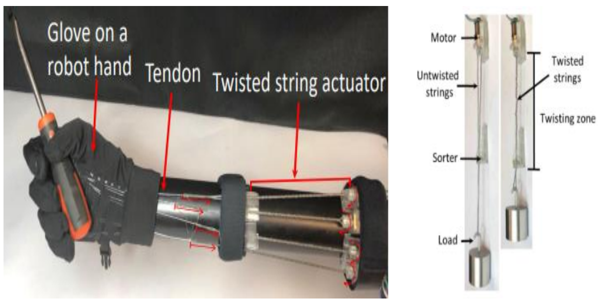


(a) **(b)**

Figure 2. (a) SMA embedded in silicon, (b) Actuated SMA showing curvature as deformation [23].

Shape Memory Alloy (SMA) based actuator

SMAs are silent, have a high power density, and require only an electric input for actuation compared to common fluidic actuators, which need bulky assembly, fluid lines, motors, etc. The major limitation of SMA as an actuating component is the low stroke length between two extreme states [29]. The system of embedded SMA fibers in the base matrix proved to be less effective. This was overcome by allowing the SMA wires to freely slide inside the tubing space of the matrix substance and using an external fixture remote to the matrix so that the SMA acted as a tendon actuating mechanism [30]. With this technique, the researchers were able to generate up to



(a) **(b)**

Figure 3. (a) TSA glove, (b) TSA lifting a test load. © [2020] IEEE. Reprinted, with permission, from [TSA-BRAG: A Twisted String Actuator-powered Biomimetic Robotic Assistive Glove] [20].

400 degrees of bending curvature and a force of 0.89N at the tip of the matrix. It was then used to model a two-fingered soft gripper that could perform both powers (~30N of pulling force) and fingertip grasping activities. Although the tendon model could generate satisfactory results, the model compliance is still an issue when intended to be used in geometrically complex areas. A study presented a spring-based fabric muscle (SFM), an SMA bundle covered in standard fabric [31]. SFM was contracted by heat and showed a contraction strain of 50% at a heating temperature of 70 degrees Celsius while generating 100 N force or higher. Due to its simple design, SFM can be included in soft robot suits. The bulk of the fabric material adds to the advantage of being light in weight compared to other skin bases. SFM can also be used in parallel combinations to attain higher tensile strength.

Electro and Other Modality Based thermally Activated TCP Muscles

Twisted and coiled polymers have shown high tensile force generation and displacement when actuated under the electro-thermal stimulus. During fabrication of the TCP, heat-sensitive polymers like nylon are wrapped around a mandrel without any external load to form a coiled structure capable of generating high tensile forces. When these coils are exposed to heat stimulus, they undergo uncoiling due to positive axial and negative radial thermal expansion coefficients leading to a change in length [32]. A qualitative study conducted on embedded TCP coils in a silicon-like skin layer could mimic certain realistic animal motions like a caterpillar, elephant trunk, etc [33]. The motion of the embedded skin was dependent on the skin thickness and placement of the TCPs in the silicon skin, giving rise to two major modes of motion, i.e., bending and Undulatory.

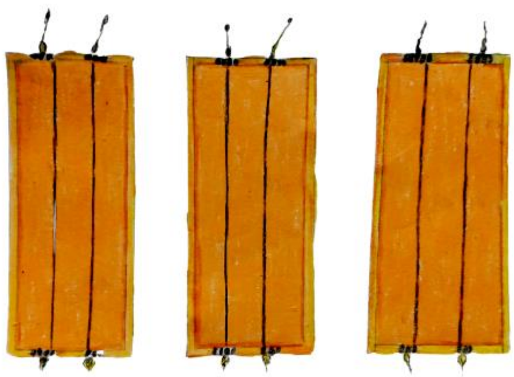


Figure 4. TCP embedded in silicon [26].

Further quantification of the parameters was analysed by using the Elastic Rod Theory model, which successfully predicted the relationship between tensile actuation and fabrication load and tensile stroke as a function of temperature. TCP muscles of 10.44 MPa fabrication load could demonstrate a maximum stroke of 52.6% with a specific work of 186.49 J/kg [32]. Another physics-based model study was conducted on one, and two-ply twisted TCP [33], where it was decided that thermal expansion rate is magnified significantly as the temperature grows beyond the polymer glass transition temperature, and materials with a more significant difference in anisotropic coefficient of thermal expansion would yield more displacement in TCP actuators. A slightly unconventional but interesting study was able to design and model TCP muscle made up of carbon nanotubes embedded in Nylon 6 polymer, activated thermally by the stimulus from microwaves [35]. Although the stimulus is not suitable for human application, it is significant to use this technology in remote autonomous robots.

(a) **(b)**

Figure 5. (a) Principle of layer jamming, (b) Actuator with layer jamming [30].

Jamming Mechanism-based Transmission

The study [36] states that focusing on harnessing the jamming mechanism is more of a transmission-based interest. Jamming is a phenomenon where a certain kind of substance transits from fluid to solid state under the influence of an activating stimulus.

Three types of jamming ((i) granular, (ii) layer, and (iii) fiber mechanisms are employed in soft robotics.

In [37], three variable friction joints were used to understand the scalability of layer jamming joints. Negative pressure was used as an activation mechanism to vary the friction between layers of Mylar film to achieve variable stiffness. These joints showed desirable features to be used as finger assistive devices.

The latest device consisting of a dual-chamber, interposed pressure-based activation mechanism also shown to have the potential to be used as an orthotic brace, providing support in a static position and being compliant in dynamic motion [38].

Piezoelectric Actuators

Piezoelectric actuators produce mechanical stress and strain under the influence of an external field or vice-versa. This mechanical strain and stress are further utilized for mechanical actuation in different areas [52]. These actuators work on the principle of the piezoelectric effect. The material primarily used for this actuator is Lead Zirconate Titanate (PZT) [53]. The material can be a polycrystalline or single crystal. Typical polycrystalline ceramics are PZT-5A and PZT-5H, whereas single crystals used are PZT-PT and PMN-PT [54]. These actuators can generate high stresses, whose range can go up to 110 Mpa [55]. Despite high-stress generation, these piezoelectric actuators produce very low strain (As low as 0.1%) [56].

The single piezoelectric crystal actuator can give high efficiency of up to 90% [57]. Looking for applications, main applications of these actuators are in places where ultra-high positioning precision is required which can be up to the sub-nanometre level [58], high-frequency generation is required like in electronic devices (Crystal oscillators for Microcontrollers and Microprocessors based electronic devices), autofocusing of a video camera like in phones, etc. Piezoelectric actuators can run for billions of cycles in their lifetime. Because no lubrication is required, these actuators do find applications in devices/machines operating in a vacuum and cryogenic environment. Comparing power density, the piezoelectric actuators have the advantage of having high power density compared to a biological muscle for cyclic operations up to hundreds of hertz. Despite having a lot of advantages, this technology suffers a lot of disadvantages as well. Even a single piezoelectric crystal requires high voltage to operate (Up to 100V is required for the thickness of 100um and the electric field strength up to 1MV/m). Piezoelectric actuators are brittle in nature; therefore, they suffer very low robustness. Their utility in the application, which is prone to high jerks and vibrations, is low. Due to their brittle nature, they may take high compressive loads but cannot sustain tensile, shear, or twisting loads. Therefore their robustness is low. The piezoelectric crystals can be used both as a sensor and an actuator. They have relatively low power densities where peak value can go up to 0.17 W/g [59,60].

Dielectric Elastomer Actuator

The dielectric elastomer actuator consists of two parallel conducting plates or flexible electrodes with dielectric elastomers filled in between them. Two electrodes are connected to a power supply via wires. In general, this can be thought of as a parallel plate capacitor with a flexible dielectric polymer filled in between the plates. Whenever a potential difference is applied between the electrodes, opposite charges of the same amount will accumulate on both plates. According to Coulomb's law of attraction, the electrodes will attract each other, and the thickness between electrodes will reduce. This Maxwell compressive stress will expand the dielectric polymer material [61,62]. This expansion and contraction are further utilized for actuation in different applications. This technology has multiple advantages as a strain value of 200% can be achieved [63], which makes it suitable for numerous applications. Because the potential difference between electrodes can be instantly changed, the operating bandwidth of this technology is very high. Typically, this can go from tens to hundreds of hertz [64]. Hence, making it suitable for fast cycling actuation applications. DEAs give an excellent efficiency of value as high as 80% - 90% and high-power density [65]. Despite having advantages, DEA technology suffers from various disadvantages. The most significant drawback is that DEA requires a very high voltage to operate (Up to 10 kV). Also, a high electric field is required of the order of 10-100 MV/m [66]. A separate circuitry is needed to generate this high voltage, which adds complexity and cost. This makes it impractical for use in daily used applications. An artificial muscle needs to be flexible to mimic a real biological muscle and be used as a soft actuator. During the operation, the reduction in thickness causes the expansion of dielectric polymer material. For both flexibility and stretchability, electrodes need to be compatible. The manufacturing and production of compatible electrodes (Stretchable and flexible) is a difficult task, adding to the actuator's cost and complexity. The expansion can cause strains up to 10%. FLEX 1 Robot was the first robot that utilized these kinds of actuators. This robot had bowtie actuators which were very slow with a speed of millimeters per second [61,63].

Super Coiled Polymer Actuator

This is a new class of actuators based on highly twisted fiber. The carbon nanotubes (CNT) were the first to be demonstrated to obtain torsional actuation with a rotation of 250° / mm at a rotational speed 590 rpm when it is electrochemically charged [72]. It was a highly twisted 12um diameter (CNT) yarn immersed in an electrolyte. The CNT was very expensive to fabricate and commercialize, limiting its applications [73]. In 2014, the use of polymer fibers for this class of actuators gave a boost to research and development. In contrast to CNT, much cheaper and widely available polymer strings like fishing lines and sewing threads could be used to fabricate artificial muscles [64]. The actuation mechanism is based on polymers that have fibers with some degree of internal alignment of macromolecules along the direction of the fiber. The critical property achieved from this kind of alignment is anisotropy. Polymer muscles can be fabricated from fishing string and sewing thread, which have high-strength fibers. The polymer material which can be used is Nylon. The Nylon fiber expands radially and contracts along its length as a thermally actuated polymer. Here, the entropic forces make the fiber structure contract in length while increasing overall volume when heat is applied [74]. The Nylon 6/6 a 4% decrease in fiber length can be observed when heated up to 240° C. The actuators are constructed by twisting anisotropic fiber (Fishing string) to a point where they will form coils. By inserting twists in an anisotropic material, the polymer chains, which are basic elements of that material, will form helices at an element level. The materials which expand more radially than along the axis are used for twisting actuation. These materials, when twisted, tend to untwist along with the increase in diameter whenever the temperature is increased [73]. This is the key property that is used for actuation in twisted-type actuators.

In the case of supercoiled actuators, a fiber representing a polymer chain is twisted to a point where it forms coils and takes a spring-like structure. This spring-like fiber/structure/polymer chain is then attached to a load and a fixed point with its ends, where one end is attached to load, and another end to a fixed point and are connected so that each end is prevented from twisting. It can be pre-assumed that the actuation is achieved due to fiber contraction, but this is not the case. Whenever the temperature is increased, the already twisted polymer will tend to untwist. This untwisting will generate a torsional force at every fiber's cross-section and force the coils to come closer. This torsional force at every cross-section will integrate to give a large actuation force. Because both ends of the fiber are prevented from twisting, the large force will be in one direction, and the spring-like structure will tend to contract [73]. This contracting force is enough to lift heavy loads. The SCPs can give a rotor a rotational speed of 10,000 rpm [75]. It can give 50 times more specific work during contraction (2.48 kJ/kg) than natural muscles. SCPs have a high-power density (27 W/g), and their power efficiency may vary from 0.71% to 1.32% [76].

The accuracy of the mathematical model of SCP is less due to inherent frictional hysteresis, and the error value can go up to 15% for a linear model. The actuation in these types of actuators made of polymers is achieved with a temperature change. The heat transfer rate is low because of material properties and dimensions, leading to a slow response. Hence, the operational frequency of these actuators is low (around 0.3 Hz in still air). Environmental conditions play a significant role as the actuation happens due to heat transfer. In many applications, the current is used to control the actuation. A high-resistance wire-like nichrome wire can be wound around the twisted polymer. The wire will heat up when the current is passed through the wire due to high resistance. Because the wire is in close contact with the twisted polymer string, the polymer string will heat up, and the actuator will contract.

Electro-Osmotic Actuator

In soft robotics for biomedical applications, electro-osmotic actuators can be crucial in achieving controlled and precise movements. Here are a few types of electro-osmotic actuators used in soft robotics for biomedical applications:

Ionic Polymer-Metal Composite (IPMC) Actuators: IPMC actuators are an electro-active polymer (EAP) that utilize ion migration within a polymer matrix in response to an applied electric field. They can produce bending or actuation movements when a voltage is applied. IPMC actuators find applications in soft robotic systems for tasks such as gripping, crawling, and manipulating objects in biomedical settings [77].

Electroactive Hydrogel Actuators: Electroactive hydrogel actuators utilize the swelling or deswelling behavior of hydrogels induced by an electric field. By applying an electric stimulus, the hydrogel can undergo shape changes, resulting in actuation. These actuators are used in soft robotics for biomedical applications, such as micro-robotic systems for targeted drug delivery or tissue manipulation [79].

Conductive Polymer-based Actuators: Conductive polymers, such as polypyrrole or polyaniline, can exhibit electro-osmotic behaviour in response to electric field. By incorporating conductive polymers into soft actuator structures, they can be utilized for controlled movements in soft robotics. These actuators can be used in biomedical applications such as haptic feedback systems, assistive devices, or wearable robotic systems [80].

Dielectric Elastomer Actuators (DEAs): Although DEAs were excluded from the initial list, they are worth mentioning in the context of soft robotics in biomedical applications. DEAs consist of a compliant elastomer film sandwiched between compliant electrodes. When an electric field is applied, the elastomer deforms, leading to actuation. DEAs find use in soft robotic devices such as robotic prosthetics, exoskeletons, or assistive wearable systems [66,78].

These electro-osmotic actuators in soft robotics for biomedical applications offer advantages such as compliance, flexibility, and controllable actuation. They enable the development of soft robotic systems that can interact with biological tissues or perform delicate tasks in healthcare settings. Ongoing research in this field continues to explore new materials and design approaches to enhance the capabilities and performance of these actuators.

Magnetostrictive Actuator

Magnetostrictive actuators utilize the magnetostrictive effect, where certain materials change shape in response to a magnetic field. There are several types of magnetostrictive actuators commonly used in various applications. Here are a few examples:

Terfenol-D Actuators: Terfenol-D is a magnetostrictive material composed of the alloy of terbium, dysprosium, and iron. Terfenol-D actuators exhibit significant magnetostrictive properties, allowing them to produce large deformations in response to magnetic fields. These actuators find applications in precision positioning systems, vibration control, and robotics [81].

Magnetostrictive Fluid Actuators: Magnetostrictive fluid actuators utilize magnetostrictive materials in a fluid form. The fluid contains magnetostrictive particles suspended in a liquid or gel matrix. By applying a magnetic field, the magnetostrictive particles align and induce shape changes in the fluid, resulting in actuation. Magnetostrictive fluid actuators have applications in haptic feedback devices, robotics, and microfluidics [82].

Magnetostrictive Stack Actuators: Magnetostrictive stack actuators comprise multiple layers of magnetostrictive material stacked together. Each layer is individually poled, and when a magnetic field is applied, the layers expand or contract, causing the actuator to elongate or shorten. Magnetostrictive stack actuators are used in precision positioning systems, micromanipulation devices, and adaptive structures [82].

These are common magnetostrictive actuators used in various fields, including robotics, precision engineering, and control systems. The specific choice of magnetostrictive actuator depends on factors such as desired strain or displacement, force, and time.

Material For Actuator and Sleeve Design

Silicone-based elastomer is the most commonly used material to design pneumatic actuators and enclose other mechanisms as skin. Elastomers provide a human-like touch and end grip [23]. Actuators embedded in silicon base composite are one common arrangement observed across various actuation techniques. This also makes sense due to the biocompatibility, and the soft end effect of silicone makes it best for contact with skin.

Soft Robotics Enabled Assistive Devices

Upper Body

Humans depend on their hands for doing Activities of Daily Living (ADL) like touching, holding, lifting, eating, etc. Impairment of hands due to stroke, spinal cord injury, and dementia make people highly dependent on others for ADL. Soft Robotics is an emerging field that can rehabilitate such patients and help them regain their functions. Compact Hand-Assistive Device (CHAD) for enhancement of function in hand impairments developed by Alnajjar F et al. is a compact multi-functional hand assistive single unit device which can be worn on forearm by the patient. This was designed to be light weight and compact with a total weight of 565g. The components included 4 LiPo cells. An actuator consisting of DC motor attached to a gear box, power screw, and cable locking mechanism. 3D printed structure comprises a base, a cover, and a hand support. Other components included rubber bands, Bowden tubes, and a circuit board. The device utilizes a unique cable driven mechanism which comprises linear actuators for flexion and uses removable rubbers on the dorsal side of the glove for a passive extension. CHAD glove is based on a three-jaw chuck model with five tendon cables connected to the index, middle finger, and palmar side of the thumb. During experiments, this device showed motions closer to the free hand movements without producing any abnormal muscle activities. CHAD provides numerous advantages as this has precise control for motor strokes and a self-locking mechanism for holding grasping force without draining the battery power. It showed a normal handgrip with a force of 20N to 30N sufficient to do normal ADL activities [18]. Another rehabilitation device used a sensory glove and a motor glove. The sensory glove measured bending angles of the non-affected hand accurately with the help of flexion sensors, the movements of the hand were sensed and classified using a machine learning algorithm. The hardware included sensor interface, a module for power supply, ARM Cotex M3 processor as a control module, and a Wi-Fi module for communication. Ten flexion sensors were placed on each joint of all the fingers and another ten force sensitive resistors were placed at the fingertips and the palm. The collaborative data collected at the sampling rate of 200Hz from flexion sensors and force sensitive resistors was used to recognize the gesture of grasping and touching while performing the task-oriented therapy. These movements were actuated using artificial tendons made of nylon strings wrapped around the finger to provide a two-way control which are connected to dc micromotors with maximum force generation capacity of 15N. This system has proposed up to 16 kinds of finger gestures with an accuracy of 93.32%. This system also uses an IoT-based platform to evaluate therapy progress [33]. Another device developed by Min Li et al., is a pneumatic driven hand rehabilitation soft robotics glove used to give rehabilitation therapies to stroke patients with hand malfunctioning. The device utilizes two gloves, one to take control inputs worn on the healthy hand, and the other to move the hemiplegic hand in coordination with the movements of the healthy hand. The actuations are achieved using pneumatic actuators controlled by a pressure regulator connected to a high-pressure source. The maximum force produced by the flexion actuator was 36.9 N, which is higher than the force produced by the previously mentioned device [33].

Table 1. Summary of actuation methods and the mechanisms

Serial No	*Actuation Methods*	*Types*	*Mechanism*
1	Fluid-based soft actuators	1. Mc Kibben PAM 2. A vacuum-powered PAM 3. Fiber-reinforced bending PAM 4. An origami-inspired PAM 5. FEMS	Pneumatic actuation
2	Cable tension-driven transmission	1. Single-way driven cable 2. Double-way driven cable	1. Sheathed hinges or roller pulleys. 2. Hydraulic actuator or motor
3	Twisted string actuators	1. Single string model 2. Multi-parallel string combination 3. Rubber-based twisted actuation	Twisted controlled actuation
4	Shape Memory Alloy (SMA) based actuators	1. Tendon model or tendon actuating mechanism. 2. Spring-based fabric muscle (SFM).	1. Single electric input for actuation 2. Free sliding of SMA wires inside the tubing space.
5	Electro and thermally activated TCP muscles	1.Elastic rod theory model 2.Carbon nanotubes 3.ply twisted TCP	1. Tensile actuation and fabrication. 2. Stimulus from microwaves. 3. Electro thermal stimulus. 4. Thermal expansion rate.
6	Jamming mechanism-based transmission	1. Granular mechanism 2. Fiber mechanism 3. Layer mechanism.	Negative pressure activation mechanism.
7	Electro-Osmotic Actuators	1. Ionic polymer-metal composite 2. Electroactive Hydrogel 3. Conductive Polymer-based	Application of electric field and potential.
8	Magnetostrictive Actuators	1. Terfenol-D 2. Magnetostrictive fluid 3. Magnetostrictive stack	Application of magnetostrictive effect

The total weight of the flexible gloves was 0.144kg. Instead of ML Algorithm this device used a C++ based tool to visualize the movement and gesture of the control hand. This device helped recover the hand functions by imitating the gestures of the control hand with a delay of 0.8 seconds [34]. In [35], a combination of cable mechanism and Mckibben pneumatic artificial muscle was used to control a compact, lightweight, and a flexible wearable glove for rehabilitation purpose. Two EMG sensors were placed on the forearm. To get the user's intent sEMG signals from digitorum superficialis (responsible for flexion) and extensor digitorum communis (responsible for extension) were obtained. The PAM was pressurized to achieve flexed, open, or hold the state of the hand. The maximum force generated at the fingertip was 12 N which is less than the force generated by the previously mentioned devices [33, 34]. Exo-Glove Poly II (EGP II) used a polymer-based glove for grasping. The device is made completely of polymer

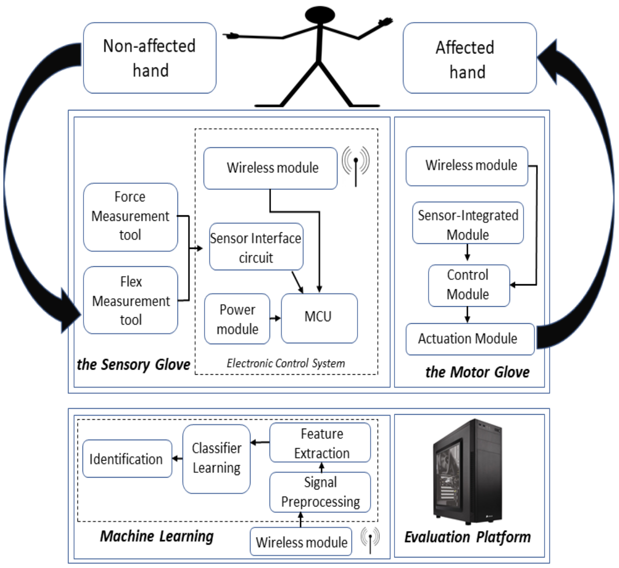


Figure 6. Architecture of Assistive devices using Machine Learning [34].

material with a tendon driven mechanism for actuation for use in spinal cord injury. It has been designed to have minimum number of components made of single material (KE1300T; Shin-Etsu Chemical Co., Ltd.). Its passive thumb structure helps in achieving better-grasping capabilities. EGP II has a glove with weight 104g and an actuation system that can be placed on a desk or a wheelchair with a weight of 1.14 Kg [36]. Another device used Pneumatic Origami Muscle Actuator (POMA) for grasping assistance. The origami-inspired soft actuator elongates in only one direction [37]. The actuator is encased in a non-stretchable casing which causes bending in one direction upon applying pressure. MRC-Glove uses a silicone elastomer-based glove to actuate finger motions using pneumatic actuators and take functional Magnetic

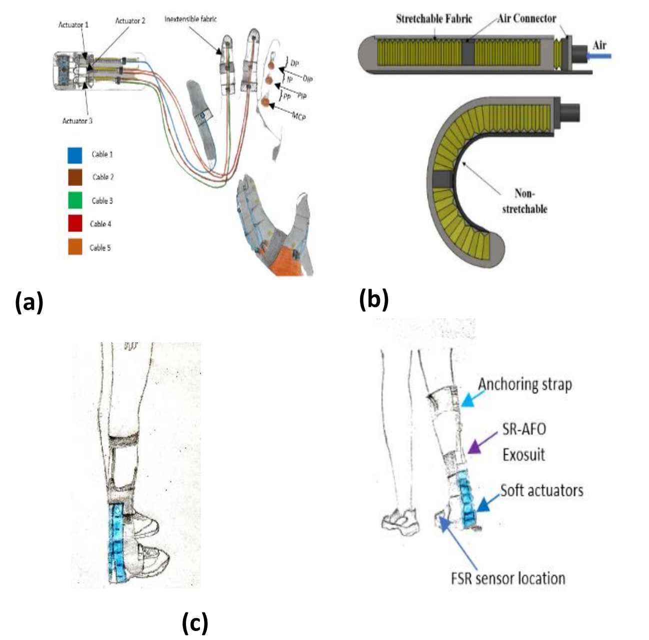


Figure 7. (a) Schematic of cable in CHAD [18], (b) Actuation strategy of POMA© [2020] IEEE. Reprinted, with permission, from [Design of Pneumatic Origami Muscle Actuators (POMAs) for A Soft Robotic Hand Orthosis for Grasping Assistance] [37]. (c) Illustration of SR-AFO [46].

Resonance Images simultaneously without introducing any artifacts [38]. This allows the doctors to understand the brain's response to specific movements. Another group developed a bellow-type soft pneumatic actuator for elbow flexion [39]. The soft actuator is sewn into the elbow of the fabric, and the device is worn on the dorsal side of the elbow. Pneumatic pressure inside the actuator causes the actuator to end, and movement of the elbow from 0-90 degrees is achieved. Another device designed by Hosseini M et al. used a sEMG driven soft exosuit for both single and dual-arm elbow assistance through Twisted String Actuators. TSA mounted on the back is used to actuate the arms through sEMG electrodes connected to the forearm [40]. This device helps in compensating the user's muscle activities while removing or applying loads. Soft gloves using pneumatic actuators have shown improvement in ADL with the help of novel eye-tracking for elbow rehabilitation. The pneumatic actuators are inflated or deflated based on the position of the eye on the graphic interface [41,42]. Hand tremors are commonly seen in people with essential tremors and Parkinson's Disease. These hand tremors can be actively suppressed by bending pneumatic artificial muscle (BPAM) [8]. An assistive device using BPAM decreases the frequency of tremors detected, and the tremor amplitude is converted into angular displacement. The tremor is not completely eliminated by using this device. A soft wrist industrial field from getting excessive fatigue, thereby increasing their efficiency [43].

A cable-driven device was seen to reduce fatigue and muscular effort for lifting or holding weights up to 3kgs. A robotic finger designed on the principle of triple-layer hybrid jamming (particle-layer-particle) could express variable stiffness when activated with pneumatics [44]. The layers acted as bones, and the particle chambers served as joints. This finger showed promising results with variable stiffness to perform adaptive grasping to high stiffness robust holding. An unconventional biomimetic Robotic Assistive Glove (BRAG) used TSA to eliminate rigid railing for non-rotating ends [20]. It showed good assistive capabilities, but the TSA is not back drivable, which makes it any unwanted movement can lead to over contraction, and the user may not be able to resist the motion. One such study implemented graphite-based flex sensors in a soft robotic glove for post-stroke rehabilitation [45].

Intent recognition mode and fixed interval assist modes were configured to feedback the pressure-based actuators against the metacarpophalangeal joint angle. The glove was able to regulate the amount of force applied to the user's finger.

Lower Body

The mobility of the human being is primarily dependent on the lower limbs. Soft Robotic Ankle Foot Orthosis (SR-AFO) aims to help patients with ankle plantarflexion [46]. It uses fabric-based pneumatic actuators, allowing dorsiflexion, inversion, and eversion (IE). Using two actuators increases the payload capacity by 45.3%. The thermoplastic polyurethane (TPU) coated nylon actuator provides an actuation force of 1.6N.m/kg sufficient for plantarflexion assistance. The actuator also allows dorsiflexion movement of the foot. The Range of Motion (ROM) for plantar flexion and dorsiflexion is 30 and 20 degrees, respectively. The actuator inflates from 40-60% of the gait, allowing the patient to move normally. Force Sensitive Resistor (FSR) sensor records the value when the patient is standing naturally with even weight distribution. 10% FSR value measured is set as a threshold to detect a shift in body weight during walking. The difference between muscle activity without SR-AFO exosuit and inactive exosuit was negligible. Active SR-AFO exosuit, gastrocnemius, and soleus muscle activity reduced by 13.4% and 16.6%, respectively. The activity of the Tibialis Anterior increased slightly due to system deflating during that window. This SR-AFO exosuit helps in reducing the muscle effort of the patient during plantar flexion.

Soft robotic exosuit used the textile-based anchor to deliver mechanical power generated by the actuator to the user's limb [47]. On their second visit, the patients showed acclimatization to walk with the exosuit unpowered. Still, they did not show any significant difference concerning the distance covered without the exosuit compared with the unpowered exosuit. In contrast, the patients showed a significant increase in the walking distance in their second visit with the powered exosuit. Three of the six patients in their second visit with powered exosuit crossed a Minimal clinically Important Difference (MCID) of 34 m by each increasing their distance covered by 29 m. Results showed no significant difference in walking speed in patients without the exosuit, and with an unpowered exosuit. However, patients with powered exosuit showed a significant change in speed with a median of 0.14±0.06 on the first day to 1.07±0.06m/s on the second day. 50% of the patients surpassed MCID of 0.14m/s. The patients were seen to walk faster and further with the help of an exosuit without spending any extra energy.

Another lower assistive device used soft exoskeleton Iterative Learning Control (ILC) was used for increase the capacity of wearers walking or loading. Using this device has shown a decrease in metabolic rate of 7.33%, 14.56%, and 10.45% with the walking speed of 3km/h, 5km/h, and 7km/h [48]. A novel Foldable Pneumatic Bending Actuator (FPBA) inspired by accordion bellows are used for knee assistive devices [49]. FPBA is fixed on one side and can rotate freely on another side. FPBA can produce torque and bending motion, just by inflation or compression of interconnected chambers without the help of any rigid mechanical conversion structure. The FPBA was embedded into a flexible knee exosuit consisting of all the onboard electronic system, sensing systems, and off-board pneumatic and control systems. The pressure sensor measures the air pressure inside the tube. An onboard microcontroller processes information from different sensors and sends it to the distant device through wireless communication modules. The off-board controller can control the valve after analyzing the received signal. Five healthy subjects were asked to perform five postures, i.e., forward lunge, barbell lunge, half squat, deep squat, and Bulgarian Deep Squat with and without exosuit, to verify the assisting effect of exosuit.

The output torque increased with increasing internal pressure but decreased the angle of the prototype. sEMG signals of all the muscles were reduced when measured with exosuit except for RF signal in deep squat posture, which increased for a negligible amount, showing wearable knee assistive devices can assist the human knee joint during rehabilitation training.

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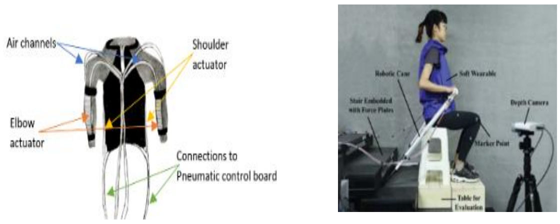
Miscellaneous Applications

Children with brain injury and developmental disabilities develop impaired upper extremity (UE). This also leads to other disabilities like loss of perception and cognition. As major UE motor changes and brain development occur in the first six months and two years, respectively, early intervention is required to gain early motor experiences. UE wearable device for infants focuses on children's tasks, performance, wearability, and safety [50]. This device was tested against an artificial child model and was seen to produce the necessary forces to lift small arms against gravity using pneumatic actuators. Super Limb is a soft robot that provides assistance to the elderly during the sit-to-stand transition [51]. It helps in reducing lower limb efforts and fall risk while getting up. It contains a wearable vest that supports the upper body and also forms a bridge between the robot and the user. The sit-to-stand mechanism is assisted by a robotic cane which is fluid-driven, it also uses a non-intrusive depth camera which is used as an ambient sensor. When the intention of the movement is detected, the wearable vest is inflated, providing force in the standup direction. Table 2. shows various assisted devices and mechanisms.



(a) **(b)**

Figure 8. (a) Thoracic wearable device [50], (b) Experimental setup of super limb © [2021] IEEE. Reprinted, with permission, from [Robotic Cane as a Soft SuperLimb for Elderly Sit-to-Stand Assistance] [51].

Future Ethical Implications

The attributes like softness, flexibility, and conformability make soft robots a desired choice of technology for assistive devices. Technically, a soft robotic device, specifically wearables, must be stable, comfortable, and biomechanically compatible while performing the intended function. Their successful translation relies on several social and non-therapeutic aspects too. Considering the role of soft robots as assistive devices, several concepts arise around their interaction environment, be it the user, other human beings, or any other surrounding objects. Apart from the ability to perform the intended functions, it is necessary to consider the long-term use, social acceptance, and emotional impact on the user. Although the illusionistic term "soft" is used to elude the understanding of soft robotics, one should comprehend the potential power packed in most cases. Like in any technology, the chance of misuse exists even here. These aspects affect not only the design safety of the equipment but also challenge the existing system of human responsibility and governing rules. To begin with, on a long journey of optimizing the social and scientific implications of soft robotics, the first step is to follow the guidelines quoted [5] for addressing the social interactions: " Soft robotics should look toward (1) developmentally oriented attachment (with information gathering kept separate from patiency), (2) primary fidelity to function, and (3) appropriately bounded social modeling", shall help in humanizing robots and reorienting the human minds [83].

Conclusion

The present study discusses various unconventional technologies' working principles, limitations, and advantages in medical assistive devices. In addition, the types of materials to be used in various devices have been discussed. From the study, it can be seen that soft robotics technology can play a crucial role in healthcare assistive devices due to multiple advantages like compactness, safety, compliance, high degree of freedom, inbuilt sensory system along with an actuator, biocompatibility, etc. Despite having numerous benefits, the inclusion of this technology in healthcare assistive devices has numerous roadblocks. Some of these technologies can produce high strain or stress but with low operating bandwidth. Whereas some technologies can produce high stress with descent strain, their compliance with the user's feedback is questioned. Despite the success achieved with initial prototyping, this technology still needs to be developed to be widely adopted. Especially in the healthcare industry, where ethical approval and undoubted acceptance by healthcare professionals are major concerns. One can take advantage of a hybrid combination of different technologies to overcome the limitation of one another. With the advancement in artificial intelligence, reinforcement learning can play an important role in controlling these non-rigid actuator-based devices.

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Table 2. Shows various assisted devices and mechanisms.

Body Parts	***Types of the rehabilitation device***	***Operation/Mechanism***	***Application***
Upper body	CHAD (Compact Hand Assisted Device)	1. Three-jaw chuck model 2. Cable-driven linear actuator & removable rubbers.	Enhanced function of hand impairments
	Device uses a sensory glove and motor glove	Flexion sensor & cable-driven linear actuator.	1. Machine Learning 2. C++
	Origami-inspired soft actuator	Pressure applied for stretchable	Finds application in elongation in one direction.
	POMA (Pneumatic Origami Muscle Actuator)	Non-stretchable	Grasping assistance
	MRC-glove	1. Silicone elastomer glove 2. Pneumatic Actuator	1. For actuating finger in MRI 2. It provides the brain response to certain organs.
	Bellow type SPA	Pressure causes the actuator to bend or actuation.	Elbow flexion.
	sEMG-driven soft exosuit	Use of TSA	1. For both single and dual arm elbow assistance. 2. Helped in compensating users muscle activities while removing.
	Bending Pneumatic Artificial Muscle (BPAM)	It decreases the frequency of tremor detected and the amplitude of tremor is converted into angular displacement.	It actively suppresses the hand tremors and Parkinson's disease.
	Robotic finger	Triple-layer hybrid jamming (particle-layer-particle)	It performs adaptive grasping to high stiffness robust holding.
	Biomimetic Robotic Assistance Glove (BRAG) Exo-glove poly-II	Use of TSA Polymer based glove.	It eliminates the use of rigid railing for non-rotating ends. For better-grasping capabilities.
Lower Body	Soft robotic ankle foot orthosis (SR-AFO)	Fabric-based pneumatic actuation.	It aims to help patients with ankle planter flexion.
	Force Sensitive Resistor (FSR)	Pressure Sensor (Bellow type) mechanism.	It records the value when the patient is standing naturally with an even distribution of weight.
	Soft robotic exosuit	It uses a textile-based anchor.	1. It delivers mechanical power generated by the actuator to the user's limb. 2. The patient showed acclimatization to walk with the exosuit unpowered on their second visit.
	Iterative Learning Control	It uses a soft exo skeleton mechanism.	It is used for increasing the capacity of wearers.

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