


Review

Soft Rehabilitation and Nursing-Care Robots: A Review and Future Outlook

Zengqi Peng and Jian Huang * 

School of Artificial Intelligence and Automation, Huazhong University of Science and Technology, and also with the Key Laboratory for Image Processing and Intelligent Control of Education Ministry of China, Wuhan 430074, China

* Correspondence: huang_jan@mail.hust.edu.cn; Tel.: +86-27-8755-8472

Received: 17 June 2019; Accepted: 24 July 2019; Published: 31 July 2019



Abstract: Rehabilitation and nursing-care robots have become one of the prevalent methods for assistant treatment of motor disorder patients in the field of medical rehabilitation. Traditional rehabilitation robots are mostly made of rigid materials, which significantly limits their application for medical rehabilitation and nursing-care. Soft robots show great potential in the field of rehabilitation robots because of their inherent compliance and safety when they interact with humans. In this paper, we conduct a systematic summary and discussion on the soft rehabilitation and nursing-care robots. This study reviews typical mechanical structures, modeling methods, and control strategies of soft rehabilitation and nursing-care robots in recent years. We classify soft rehabilitation and nursing-care robots into two categories according to their actuation technology, one is based on tendon-driven actuation and the other is based on soft intelligent material actuation. Finally, we analyze and discuss the future directions and work about soft rehabilitation and nursing-care robots, which can provide useful guidance and help on the development of advanced soft rehabilitation and nursing-care robots.

Keywords: soft robot; rehabilitation and nursing-care; tendon-driven; soft intelligent material

1. Introduction

In many cases, population aging increases the probability of disability and the number of disabled people in, and the age structure of disabled people is becoming an inverted pyramid [1]. Due to the degeneration of physiological function, the incidence of cardiovascular diseases, osteoarthritis, hemiplegia, and other related diseases increased in the elderly. According to the statistic data from World Health Organization (WHO), stroke kills 6.2 million patients every year, which is more than the combined total of AIDS, tuberculosis, and malaria [2]. Therefore, the treatment and rehabilitation of stroke, hemiplegia, and other related diseases have become a particular concern of the medical community. However, the recovery of these diseases requires long-term treatment. Besides, nursing for the elderly and the disabled is also a topic of high social concern. As a result, the demand for medical resources is high, which leads to a shortage of professional labor-force. Rehabilitation robots, which is able to provide assistant treatment instead of professional labor-force and alleviate the problem, has become a popular research area. Traditional rehabilitation robots typically consist of rigid parts such as rigid drives, actuators and so on [3,4]. They can help patients accomplish rehabilitation training, daily activities, and even restore some loss abilities. The emergence of such robots has created a new collaborative relationship between robots, patients and therapists. This new collaborative relationship has improved the effectiveness of the patient's rehabilitation training and the efficiency of the rehabilitation worker, providing an effective way to address the challenges posed by the trend of an ageing community. Therefore, this kind of robots has a huge potential market in the field of medical rehabilitation. However, the rigid structure of conventional rehabilitation robots makes it difficult for

patients to obtain a good experience when using them, and if the machine malfunctions, it will most likely cause great damages to the patient, which greatly limits the application of the rehabilitation robots. Human beings or animals usually have elaborate structures and unique movement mechanism to achieve varieties of complex behavioral patterns. Inspired by nature, researchers began to study biomimetic robots and soft robots, such as multijoint robotic rat, snake robot, and so on [5–7], and these new robots have become research hotspots in the field of robotics nowadays [8]. The flexible of soft robots make this type of robot have higher safety than the rigid robot when interacting with humans. Therefore, soft robots have great advantages in the field of medical robots, and existing research results show that soft robots have great potential in the field of medical rehabilitation and nursing-care due to their inherent compliance and safety. In a narrow sense, Soft Rehabilitation and Nursing-Care Robots (SRNCRs) refer to robots which are designed to provide therapy and assistance for specified persons and are entirely composed of flexible materials. However, due to current technical limitations, it is difficult to obtain an entirely flexible robot. In a broadly sense, SRNCRs are those that include flexible drives and some other rigid components, which are currently the most studied type of soft robots for providing therapy and assistance to persons. Admittedly, the SRNCR in a narrow sense is our ultimate goal, while the research of those in a broad sense will lay a solid technical foundation for us to achieve complete flexibility. The rehabilitation robot based on artificial pneumatic muscles is a typical example, such as [9–11]. Compared to some rigid rehabilitation robots that have been widely used, such as Lokomat [12,13] and Welwalk [14], it is hard to find the mature SRNCR products on the market. Furthermore, in the study of SRNCRs, the highly nonlinear and time-varying properties of soft materials cause difficulties for control, which is also a hard problem that must be solved. This paper aims to review and summarize the structural design, modeling methods and control strategies of some existing SRNCRs, and provide some useful references and reliable guidance for researchers in this field for future research.

According to the actuation technologies, soft robots can be divided into two categories, one is based on the tendon-driven actuation, and the other one is based on the soft intelligent material actuation [15]. The former is also termed as continuum robots. However, the continuum robots are not real soft robots in the past because they still utilize the traditional mechanical components. One can learn about this kind of “soft robot” by referring to [16]. Now there are real SRNCRs based on tendon-driven actuation, and this kind of robot is always driven by cables. The latter is made of soft intelligent materials, which is radically different from the former. Soft intelligent materials mainly include pneumatic fiber braids, elastomeric polymers, shape memory alloys (SMAs), shape memory polymers (SMPs), hydrogels, electroactive polymers (EAPs) and so on. These soft intelligent materials are suitable for the research and development of rehabilitation robots. Pneumatic fiber braids and elastomeric polymers have been studied for a long time, and there are already a lot of research results. Several other kinds of materials also have certain research results in the fields of rehabilitation. The paper will review them later.

In recent years, the application of soft robots in rehabilitation robotics has experienced rapid development. As far as the authors know, although the review of SRNCRs driven by pneumatic muscle can be found, there are few reviews focusing on the whole SRNCRs. Therefore, based on the existing research, this paper summarizes the achievements of soft robots in the field of rehabilitation from a broader and more comprehensive perspective. Based on the completed work of SRNCR, the paper also discusses the current research gaps in this field and prospects the future development direction to promote the emergence of better and more mature SRNCRs, in order to alleviate the growing demand for rehabilitation. The rest of the paper is as follows: Section 2 introduces the structure and design of rehabilitation robot made of various soft and intelligent materials. In Section 3, the modeling methods and control strategies are discussed. Section 4 discusses the current limitations of this field and looks forward to the future development direction. Finally, the conclusion is drawn in Section 5.

2. Mechanical Design

2.1. Soft Rehabilitation and Nursing-Care Robots Based on Tendon-Driven Actuation

Soft rehabilitation and nursing-care robots based on tendon-driven actuation are usually driven by cables [17,18], such as Bowden cable. Cables in robotic structures are used to simulate tendons of human. This kind of SRNCR guides patients to perform rehabilitation exercises by simulating the biomechanical properties of ligaments and tendons. Therefore, SRNCRs based on tendon-driven are usually used for the rehabilitation of upper and lower limbs. Since such robots are driven by cables, this kind of robots has the characteristic of routing diversity, and the payload of such robots is determined by the quality of the cables, which also determines the assistant capability of robots.

The application of robotic technology in therapy has been continually explored for decades. Meanwhile, the conventional rehabilitation devices still remain inaccessible outside of a clinical setting because they are cumbersome and expensive. In order to expand the accessibility of rehabilitation robot to those who need it, Delph et al. proposed a design concept of glove for hand rehabilitation in 2013. Then they designed a robotic glove to assist the movement and coordination of grip exercises (Figure 1a) [19]. This glove produces maximum grip strength of 15N. Based on the initial concept and previous work, Nycz et al. explored a lightweight, soft, cable-driven design, and fabricated an upper limb rehabilitation exoskeleton with 6 actuated degrees of freedom by adding actuation of the elbow joint and constructing a better new system (Figure 1b) [20]. In the same year, In et al. developed a soft wearable rehabilitation robot called Exo-Glove with a soft tendon routing system and an underactuation adaptive mechanism (Figure 1c) [21]. Fabric tapes and Teflon tubes were used in the Exo-Glove instead of mechanical pulley used in the traditional tendon routing system. Exo gloves use Bolton wires to control fingers. In order to improve the energy efficiency of the whole system, a passive brake mechanism was added to the drive units [22,23]. The Exo-Glove is compact in structure and weighs 194 g. It has 20 N grip force, 40 N package grip force, and 76 mm maximum grip size. The test results show that patients can grasp objects of various shapes without active control by using the under-actuated mechanism to control the Exo-Glove. Subsequently, the team proposed a slack enabling mechanism [24]. They built a prototype and tested it on the Exo-Glove to prove the advantages of the proposed mechanism. The prototype can eliminate tendon pre-tension and minimize friction caused by pre-tension, which improves the efficiency of the system and ensures the safety of the soft tendon routing system. Then, in 2016, Vikas et al. proposed a design method of a 3D-printed flexible and high-deformable flexible robot driven by motor-tendon [25]. This modular design approach facilitates rapid fabrication, deployment, and maintenance, and Xiloyannis et al. developed an 8-DOF tendon-driven mechanical glove (Figure 1d) [26]. The glove is actuated by a Bowden cable transmission and a brushless motor actuator. For portability, only one motor is used to control the 8-DOF hand. Recently, in 2018, Stilli et al. proposed a new lightweight inflatable soft exoskeleton glove called AirexGlove (Figure 1e) [27], which is based on the antagonistic driving principle [28–30]. The system is based on the previous work done by the group of Stilli in [31–33]. At the same time, Guo et al. proposed a soft hand sheath combined with electromyography (EMG) sensor (Figure 1f) [34]. The soft gloves are optimized based on a tendon-driven glove. The tendon routings of the glove are typically parallel to single fingers, respectively. Compared with the soft gloves driven by tendon, the singularity of motion is avoided. The design adopts the optimized bionic fin-ray structure to enhance the proprioception of the hand because the palm is not covered by the wearable structure. The gloves are designed with a novel self-tightening finger button. The wearer can open or close the exoskeleton device by himself and simplify the ADL assistance.

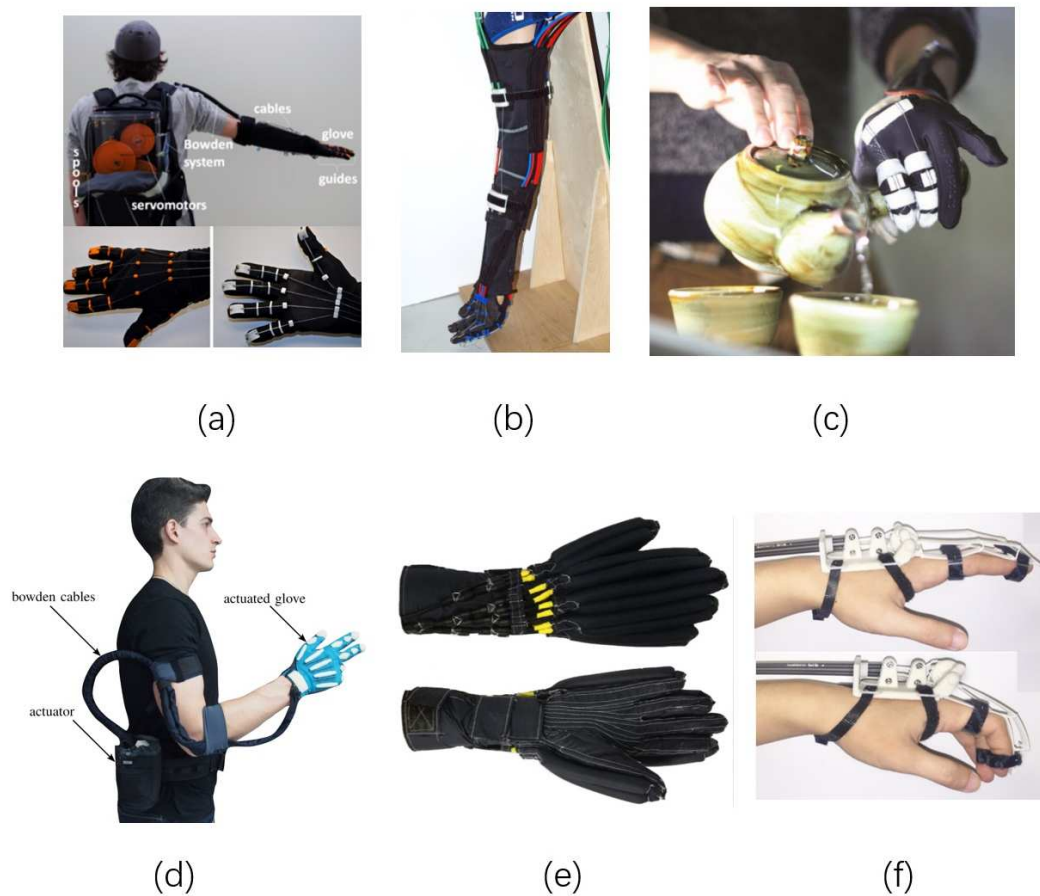


Figure 1. Soft rehabilitation and nursing-care robots based on tendon-driven in upper limb. (a–c) is reprinted from [19–21], respectively. (d–f) is reprinted from [26,27,34], respectively.

For the lower limb rehabilitation, rehabilitation robots can be divided into two categories by the training mode, including over ground exoskeletons and orthoses based on a treadmill. Both of them can help patients regain walking ability to varying degrees. In 2014, Park et al. imitated the shape and function of the biological muscle-tendon-ligament structure and proposed an ankle-foot rehabilitation robot driven by a pneumatic artificial muscle actuator (Figure 2a) [35]. The robot contains four pneumatic artificial muscles, which helps patients with dorsiflexion and plantarflexion as well as inversion and eversion. One of the main features of the device is a flexible structure, which provides active assistance without restricting the natural degree of freedom of the ankle joint. This ankle-foot rehabilitation device can produce a motion range of ankle of 27° . At the same time, Park et al. proposed a soft, wearable knee extensor to help weak people stretch their knees when climbing stairs [36]. Recently, Kwon et al. proposed a prototype of robotic ankle-foot orthosis (Figure 2b) [37]. The device includes a 3D-printed flexible support and ankle support. The orthosis allows ankle natural flow and extension but provides support in the vertical direction to prevent structural bending. Bi-directional tendon-driven actuators are used to assist dorsiflexion and plantarflexion. The device also includes a wearable gait sensing module for real-time measurement of leg trajectory and foot pressure. The Exosuit is also a feasible means of lower limb rehabilitation. Refs. [38,39] proposes a reconfigurable multi-joint driving platform to explore the interaction of human and exosuit in an effective and controllable way. Then, in 2015, Bae et al. designed a soft exosuit (Figure 2c) to assist stroke patients in walking [40]. They proposed a new soft exosuit module, a mobile non-vehicle driving device, and a new control algorithm, which enables human subjects to test stroke patients on treadmills and the ground. Compared with their previous designs [41–45], the exosuit provides only one-sided assistance for ankle paralysis during the push process, and a new textile module

provides back-bending assistance during the swing phase. Also, the Exosuit optimizes the design of textile components to enable them to exert greater force and improves the controller to provide greater adjustment assistance for wearers.

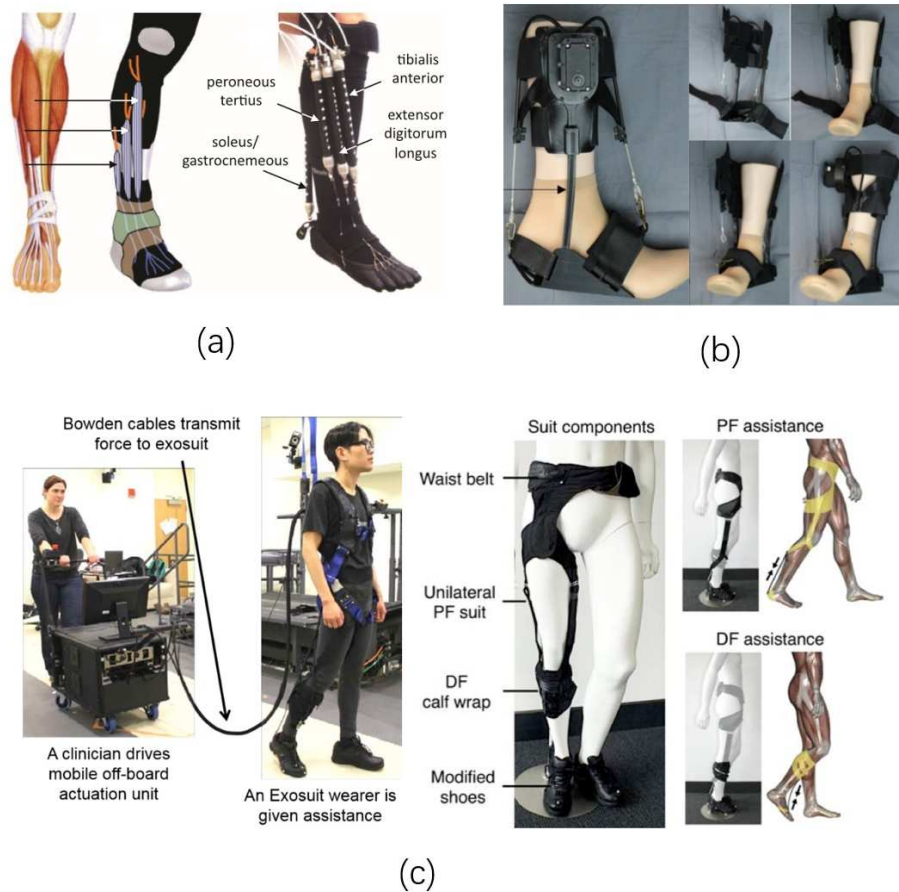


Figure 2. Soft rehabilitation and nursing-care robots based on tendon-driven in lower limb. (a) is reprinted from [35]. (b) is reprinted from [37]. (c) is reprinted from [40].

An overview of above and some other tendon-driven SRNCRs is shown in Table 1. Tendon-driven SRNCRs have been studied for a long time, and many achievements have been made. However, tendon-based driving has many limitations, such as rigid components in the structure that have a negative impact on the treatment process, and some types of rehabilitation robots cannot be manufactured by utilizing this actuation technology. Soft intelligent materials may fundamentally enable rehabilitation robots to enter the door of “soft” and design more kinds of rehabilitation and nursing-care devices.

Table 1. Overview of soft rehabilitation and nursing-care robots based on tendon-driven actuation.

Robots	Aims	Assistance Capacity
Soft robotic exomusculature glove [19]	Providing help for the movement and coordination of gripping exercises	A maximum 15N grip assistive force in one DOF
Tendon actuated soft robotic exoskeleton for hemiparetic upper limb rehabilitation [20]	Providing assistance for patients in finger and elbow movements	
Exo-glove [21]	Providing rehabilitate for patients who cannot open or close hands but can use other joints of the upper limb	46°/48° for MCP/PIP ROM; 20N of pinch force; 76mm diameter of maximum gripping object
AirExGlove [27]	Suitable to provide rehabilitation to stroke patients affected scoring up to 3 in the MAS	Maximum diameter of graspable objects: 140 mm(100 Kpa), 190 mm (200 Kpa), 230 mm(200 Kpa)
Soft robotic exo-sheath for hand rehabilitation [34]	Providing rehabilitation and activities of daily living assistance for stroke and spinal cord injury patients	30.71° / 75.64° / 109.11° for MCP / PIP / DIP(palmar)
Bio-inspired soft wearable robotic device for ankle-foot rehabilitation [35]	Designed for ankle-foot rehabilitation and sagittal ankle motions	A range of 27° for test subject's ankle
Soft wearable knee extensor [36]	Helping the physically weak people to walk	
Soft wearable robotic ankle-foot orthosis [37]	Providing assistance for ankle-foot-rehabilitation	A 70N assistive force in the test
Soft exosuit [40]	Provideing unilateral assistance during walking and improving patients' gait symmetry and paretic limb progression	A positive effect on temporal symmetry and paretic limb propulsion
Hybrid rigid-soft hand exoskeleton [46]	Providing assistance and rehabilitation for patients with with neuromuscular impairment	72° /66° for MCP/PIP ROM

DOF = degree of freedom, MCP = metacarpophalangeal, PIP = proximal interphalangeal, ROM = range of motion, DIP = distal interphalangeal.

2.2. Soft Rehabilitation and Nursing-Care Robots Based on the Soft Intelligent Materials Actuation

Soft intelligent materials usually have excellent flexibility and can directly convert physical stimuli such as force, electrical, heat, and so on into physical displacement. Soft actuators of various shapes and types can be made by using soft intelligent materials. Therefore, the SRNCR based on soft intelligent materials can be applied not only to the rehabilitation of upper limbs and lower limbs but also to the rehabilitation of some other parts, such as facial rehabilitation and oral rehabilitation. This is undoubtedly a significant progress in the field of rehabilitation. Therefore, the SRNCR based on soft intelligent materials has a broader development prospect. However, the material characteristics of intelligent materials make it very difficult to control. As far as the authors know, the SRNCR based on intelligent materials is still at the early stage of development.

2.2.1. Pneumatic Fiber Braids and Elastomeric Polymers

The application of pneumatic fiber braided fabrics and elastic polymers in the field of SRNCRs has been studied for many years. The most typical soft actuator is the pneumatic artificial muscles actuator [47]. The main body of the pneumatic muscles is usually a rubber tube covered with braided fabrics. One end is connected with proportional electromagnetic valves to regulate the internal air

pressure, and the other end is closed. Pneumatic muscles usually have much greater elasticity on one side than on the other to form a difference in axial contraction force and bend them. Pneumatic muscle can only be contracted by tension, which is a kind of unidirectional action element. In order to achieve complete rehabilitation exercise, pneumatic muscles are usually designed for configuration. McKibben muscle is a typical representative, which was invented by physician McKibben in the 1950s [48]. It is a bladder tube actuator packaged in a braided sleeve wrapped in a braided sheath.

In 2013, Polygerinos et al. proposed a new silicon soft actuator and integrated it into a wearable rehabilitation glove (Figure 3a) [49]. The main material of the glove is an elastic fabric (neoprene) that fits the fingers to the maximum extent at all bending angles of the joint. Performance test results of actuators show that they can bend more than 320° and provide enough force to help patients to close fingers passively. Shortly afterwards, they also proposed multi-segment soft actuators [50,51]. Based on this, an integrated hydraulically actuated soft rehabilitation glove was designed (Figure 3b) [52]. The same research group optimized the semi-circular fiber reinforced actuator in [50], and improved the rehabilitation gloves by using a better rectangular actuator design. In the preliminary clinical evaluation, patients showed a 40 percents increase in picking blocks by using soft robotic gloves, and the accuracy and precision of the participant's grasp are significantly improved. In 2015, Zhang et al. proposed a method for rapid design of soft fingers made of light hyperelastic material (Figure 3c) [53]. This method is suitable for various sizes and lengths of fingers. The part is designed by SolidWorks, and the mould is printed by 3D laser rapid prototyping. However, this work only made a single soft finger, which needs further study if it is to be applied to rehabilitation robots. In the same year, Guo et al. proposed a new actuator made of liquid silicone (Ecoflex 30) and carried out the simulation and bending characteristic curve test of the actuator [54]. They found that the silicone-only structure was prone to be excessively deformed, and then solved the problem by utilizing fiber reinforced structures. They tested five actuators tied to the back of their hands but did not integrate them into a whole rehabilitation glove. In this system, five actuators were actuated by only one pump at the same time, which reduces the flexibility of each actuator. Multy-pump system can solve this problem, but the system would become heavier and more complex either. In 2016, Al-Fahaam et al. proposed a linearly extending artificial muscle with fixed unilateral sleeve length. Based on this pneumatic muscle, a soft wearable rehabilitation glove which can be grasped and pinched repeatedly and a rehabilitation wrist exoskeleton were designed (Figure 3d,e) [55,56]. Gloves solve the challenge of releasing motion under electric assistance by not setting assistive muscles at the little finger, which is the main achievement of this work. In the same year, Huang et al. proposed a low-cost and easy-to-use upper extremity exoskeleton robot, RUPERT (Figure 3f), which has 5 degrees of freedom [57]. RUPERT is driven by compliant and safe pneumatic muscles. Compared with their previous work, this manipulator has been expanded and improved in safety and feasibility. In the clinical trials of patients with chronic stroke, it was proved that RUPERT exoskeleton robot was safe, and Rupert could enhance the motor function of the palsy arm of moderate or severe stroke patients for six months or more. Besides, Zhao et al. proposed a flexible orthosis with integrated curvature sensor (Figure 3g) [58]. The rehabilitation is purely polymeric and highly compliant. The main body of the composite glove is made of silicone elastomer. Gloves provide little resistance to natural movement without pressure. When inflated, the fingers of gloves bend and harden. The force test of the actuator shows that the output tip force ranges from 0 to 5 N, and the applied pressure ranges from 0 to 270 kPa [59,60]. The output force is not large enough to carry out many daily activities and needs to be improved. In 2017, Yap et al. proposed flexion and extension actuators that could be inserted into actuator bags separately, which alleviates the problem of slow dynamics in previous work on soft mechanical gloves [50,61]. Based on this, a bidirectional soft mechanical glove, which is completely based on fabric, was designed (Figure 3h) [62]. Compared with the previously developed soft actuator, the fabric-based flexible actuator can achieve smaller bending radius and higher force output under lower pressure. The motion range and grip force of gloves were tested and evaluated. The results showed that the actuator could generate 11.3 ± 2.5 N (tested with a cylinder with a diameter of 75 mm) and 7.9 ± 3.0 N

(tested with a cylinder with a diameter of 50 mm) friction. The glove-assisted finger motion range was larger than the average functional range of motion of the hand. Gloves are based entirely on fabric actuators, so they are lighter and cheaper than gloves in previous studies. In 2018, Rosalia et al. proposed a new type of 3D-printed soft-pneumatic actuator [63]. This is a new soft pneumatic actuator's design scheme that allows customization of geometry-based bending modes. Inspired by the biological structure of fish bones, Jiang et al. proposed a novel fish-bone soft actuator with multi-degrees-of-freedom and designed a preliminary soft glove (Figure 3i) [64]. Fishbone actuators are manufactured by a method called lost-wax-inverse-flow-injection [65]. The actuator can execute three motion modes with only one chamber. Each finger of the fishbone-inspired soft robotic glove can achieve two degrees of freedom through a single chamber, and the glove can achieve multi-DoFs movement. Compared with the traditional fiber reinforced actuator, the fishbone-inspired actuator can exert 11.27 N force at 250 kPa, while the fiber reinforced actuator can exert 11.38 N force at the same pressure. The results show that besides realizing multi-DoFs motion, the actuator has similar force output characteristics as the fiber reinforced actuator. Ru et al. proposed a new kind of fiber-reinforced pneumatic muscle and established a dynamic model of pneumatic muscle by using second-order differential equation [66]. The parameters in the model are identified by visual recognition experiments with a high-speed camera. The final results of simulation verified the reliability of this model. The results show that the pneumatic muscle can be used to make soft rehabilitation mechanical gloves. In 2017, O'Neill et al. proposed a soft wearable shoulder joint robot consisting of a vest (Figure 3j) [67]. The vest is made of neoprene and is fitted with two fabric-based actuators. This robot is lightweight, low-profile, comfortable, and does not affect the patient's wearing other clothes, nor does it affect the patient's actions. Recently, Irshaidat et al. proposed a novel type of pneumatic muscle actuator, and based on this, they designed a soft robotic arm that can be used by individuals who suffer from lack of mobility due to stroke or other similar disabling illness (Figure 3k) [68]. This robotic arm is a portable rehabilitation device that is wear resistant and lightweight. Experimental results have shown that this portable exoskeleton can provide more effective intensive rehabilitation therapy at home without the need for a therapist and at a lower cost. In addition, Zhang et al. developed a soft elbow rehabilitation robot based on pneumatic muscles (Figure 3l) [69], which has two degrees of freedom. This soft robot is relatively simple to manufacture and its operation is easy and flexible. The experimental results show that the device can complete the rehabilitation process of the elbow joint under appropriate control.

As for the rehabilitation robots designed for helping other body parts, including lower limbs, facial, and so on, there are some existing studies based on pneumatic fiber braids and elastomeric polymers actuation. In 2013, David Baiden et al. proposed a concept of human-robot-interaction (HRI) control for orthosis and applied it to a pneumatic soft-actuators robot for lower limb rehabilitation [70]. The robot consists of two orthoses with two DOFs per orthosis (Figure 4a). A single actuator can provide movements from 0° (extension) to 45° (bending). In 2017, Wei et al. proposed and evaluated a rehabilitation robot for soft ankle joint (Figure 4b) [71]. The rehabilitation device is driven by four parallel pneumatic muscles and enables three rotational degrees of freedom. In 2019, Huang et al. proposed a lower-limb exoskeleton actuated by pneumatic muscle actuators (Figure 4c) [72]. The exoskeleton system consists of mechanical structure, a treadmill, and a weight support system. The mechanical mechanism of the exoskeleton system is optimized to achieve the wearing comfort for patients. In 2015, Yi et al. proposed a new oral rehabilitation robot driven by a new soft pneumatic actuator (SPA) for oral rehabilitation (Figure 3d) [73]. The oral cavity is a very sensitive and fragile part of the human body. The requirement of comfort and safety for oral rehabilitation is very stringent. They utilized the technology of soft robot based on silicone-based to solve this problem. This is an emerging topic, which has become the mainstream because of its inherent flexibility and high customizability for various applications [74–76]. But unfortunately, no actual rehabilitation effect test was presented.



Figure 3. Soft rehabilitation and nursing-care robots based on pneumatic fiber braided fabrics and elastic polymers in upper limb. (a–d) is reprinted from [49,52,53,55], respectively. (e–h) is reprinted from [56–58,62], respectively. (i–l) is reprinted from [64,67–69], respectively.

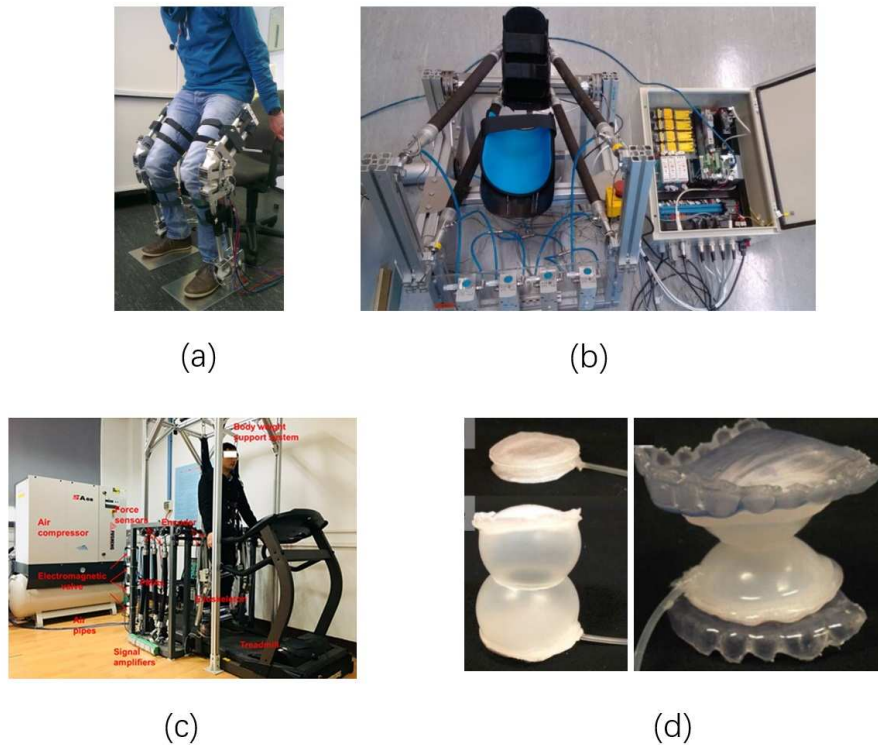


Figure 4. Soft rehabilitation and nursing-care robots based on pneumatic fiber braided fabrics and elastic polymers in other parts of body. (a) is reprinted from [70]. (b) is reprinted from [71]. (c) is reprinted from [72]. (d) is reprinted from [73].

2.2.2. Other Soft Intelligent Materials

Other soft and intelligent materials also have some good properties. However, their complex dynamics make these materials difficult to control and slow their progress. But these materials still show great potential for development. The SMAS and SMPs can withstand large strain when heated [18]. However, the temperature dependence of SMA and SMP makes precise control very difficult. The EAP is a kind of soft material which can change its shape according to electrical stimulation. Because of its ability to imitate the characteristics of natural muscles, the EAP is a new soft driving technology in the field of soft robots. The dielectric elastomer, as an electronic EAP, has good prospects in the emerging field of soft robot science due to its light weight, inherent compliance and large deformation [77,78]. As a kind of biomaterial, the hydrogel has soft properties and can keep a certain shape. It is also a kind of soft and intelligent materials with development prospects.

The SMA is a metal alloy that can withstand considerable strain when heated. When the temperature is higher than the transition temperature between the martensite phase (low temperature) and the austenite phase (high temperature), the SMA has the characteristic of restoring its original shape after deformation. Copaci et al. proposed the first wearable rehabilitation exoskeleton for elbow joint driven by the SMA [79]. This wrist rehabilitation exoskeleton is designed as a simple structure with two degrees of freedom. Then Villoslada et al. proposed a flexible SMA actuator [80] and built a simple wrist exoskeleton (Figure 5a) [81] driven by the designed actuator, which can extend the wearers' wrist to 45°. Inspired by them, David Serrano et al. proposed a wearable repair exoskeleton for wrist joint driven by a SMA actuator with two DoFs. Due to the memory characteristics of SMA, the total length of the wire which is used can be reduced by 3 % to 5 %. The exoskeleton actuation system is based on the flexible SMA actuator described in [80]. Due to the characteristics of SMA materials, the SRNCR equipment has a very light weight. The total weight of the device is less than 1 kg, which reduces many hassles for patients when they wear this device and perform rehabilitation exercises. It also has the characteristics of noise-free operation. The design of exoskeleton is based on the simulation of Bob's inverse dynamic version [82], which helps to select the appropriate actuator for the rehabilitation device. The flexible design of the actuator [80] can adjust its shape according to the human body or roll up without affecting the performance of the equipment [82]. In addition, the exoskeleton is made with a 3D printer, so that its cost is low, and its configuration can also be personalized depending on the patient. In the future, they will study the possibility of combining the wrist exoskeleton with the elbow exoskeleton [83] to form a complete upper limb exoskeleton.

In 2017, Firouzeh et al. designed a facial rehabilitation robot based on the shape memory polymers (SMP)—Robogami (Figure 5b) [84]. The temperature-controlled adjustable stiffness joint with SMP layer is used in the tendon-driven robot platform. The same ASL design, as previously confirmed, was used to provide more than 40 times the stiffness change between 30 °C and 110 °C [85]. The retractable heater embedded in the SMP allows us to control the temperature of the SMP layer, thereby controlling the stiffness of the joint. Facial rehabilitation robot uses a new type of telescopic thin sensor, which is based on strain-induced resistance change of telescopic grid structure. The novel thin sensor is made by laser ablation and chemical etching technology [86]. It is light and thin and is very suitable for facial rehabilitation.

In 2018, Amin et al. proposed a design method of actuator of hand rehabilitation system based on spring roll dielectric elastomer (DE) [87]. They made a sample of the driving mechanism based on the calculated design parameters. In the same year, Lidka et al. developed a dielectric elastomer actuator (DEA) for wrist-assisted wearing device [88]. A dielectric elastomer actuator has a mass of 20.9 g and the parts connected to the base account for most of the weight. 12 DEAs were constructed, and a test was conducted to evaluate their potential as an actuation of wrist rehabilitation devices. According to the experimental results, a single DEA cannot fully drive the assistant wearable device of the wrist and the Muti-DEAs system maybe a possible solution.

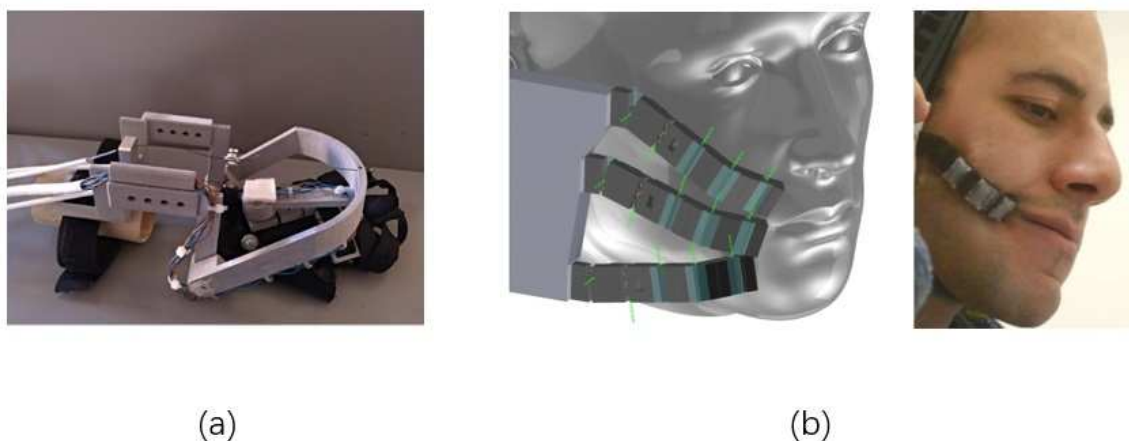


Figure 5. Soft rehabilitation and nursing-care robots based on other soft intelligent materials. (a) is reprinted from [81]. (b) is reprinted from [84].

To the best of our knowledge, there are very few applications of SRNCR based on hydrogel. The author collected some information about hydrogels for researchers who might be interested in this field in the future. In 2015, Runge et al. proposed a spine-like manipulator with a bio-probe—SpineMan [89]. The SpineMan consists of rigid components made of polypropylene and soft components made of polyvinyl alcohol (PVA) borax hydrogel wrapped in the silicone skin. The manipulator follows the unique structure of the mammalian spine and has a high level of flexibility and softness as well as adequate load-bearing capacity. Banerjee et al. demonstrated a highly flexible hydrogel in [90] and used it to make a soft actuator. Its excellent biological characteristics make it have great potential in the medical field. Yuk et al. proposed a hydraulic hydrogel actuators made of polyacrylamide (PAAm)-alginate hydrogels and designed a simple robot based on it [91]. These actuators have a short response time and a large driving force. PAAm-alginate hydrogels has excellent fatigue resistance under moderate stress. The actuator made of it can maintain its robustness and functionality in multiple driving cycles. The above literature shows that hydrogels have extraordinary potential in the field of SRNCRs.

The mechanical structure of the SRNCR based on soft intelligent materials mentioned above is summarized as shown in Table 2.

Table 2. Overview of soft rehabilitation and nursing-care robots based on soft intelligent materials.

Robots	Aims	Assistance Capacity/Experimental Result
Soft pneumatic rehabilitation glove except thumb [49]	Designed for hand rehabilitation	1.21/ 1.09/ 1.21/ 0.91N for PFA/ MFA/ RFA/ SFA (@43kPa); curling more than 320°
Soft robotic rehabilitation glove [52]	Providing assistance for individuals with functional grasp pathologies	a notable increase in the speed, precision and accuracy of the grasp for Box-and-Block test
Soft actuator [54]	Soft actuator for hand rehabilitation robots	About 15°-150° bending angle
Soft pneumatic finger [53]	Helping patients bend and extend the disable hand in a large range of safety	Soft pneumatic finger can drive index finger to maximum bend angles
Power assistive and rehabilitation glove [55]	providing assistive force for gripping and pinching movements	Maximum force up to 17N (@4bar); amplifying patient’s force up to 40% and 45%

Table 2. Cont.

Robots	Aims	Assistance Capacity/Experimental Result
Wrist rehabilitation exoskeleton [56]	Assisting patients with all wrist rehabilitation movements	37N for wrist flexion movement, 55N for all other movements.
Soft orthosis with integrated optical strain sensors [58]	Developing a low-cost soft orthotic for hand rehabilitation	
Fully fabric-based bidirectional soft glove [62]	providing rehabilitation for hand impaired patients	$46.9 \pm 15.7^\circ$ (DIP), $73.4 \pm 11.1^\circ$ (PIP), $61.7 \pm 8.6^\circ$ (MCP) for index finger; $62.4 \pm 17.4^\circ$ (IP), $63.7 \pm 11.0^\circ$ (MCP), $36.7 \pm 11.7^\circ$ (CMC) for thumb
Fishbone-inspired soft robotic glove [64]	Providing assistance for the Metacarpophalangeal (MCP) and the proximal interphalangeal (PIP) joints of human fingers to bend or extend independently	100% of ROHM
Soft ankle rehabilitation robot [71]	Providing ankle rehabilitation for patients	PMA's peak pulling force is up to 1000N
Low-profile soft pneumatic actuator [73]	Providing the treatments for for patients with mandibular mobility dysfunctions	A 40mm of elongation and around 20N force output
SMA based wrist exoskeleton [81]	Providing wrist rehabilitation therapies for patients	
Soft facial rehabilitation robots [84]	Helping patients to finish facial rehabilitation exercises	

PFA=pointer finger actuator, MFA = middle finger actuator, RFA = ring finger actuator, SFA = small finger actuator, DIP = distal interphalangeal, PIP = proximal interphalangeal, MCP=metacarpophalangeal, IP = interphalangeal, CMC = carpometacarpal, ROHM = range of human motion.

3. Modeling Methods and Control Strategies

3.1. Soft Rehabilitation and Nursing-Care Robots Based on Tendon-Driven Actuation

In [27,34,40,46], traditional position control is used to achieve the control of rehabilitation robot. Admittance control is used to ensure the safety of rehabilitation gloves in [21]. Considering that the expected user is a person with a certain type of disability, wrist movement, which is easy to control intuitively is used as a control input command. Ref. [25] proposes a model-free control framework for soft robots with discrete contact points. Under some assumptions, the finger is modeled as a planar three-link kinematic chain [20]. According to the single factor equation, a complete hand motion model is established by utilizing MATLAB 2013b. The model has a cable-guided position and applied palm force and lays a foundation for the control of the upper extremity exoskeleton. Ref. [46] uses embedded sensors for pose estimation and intent detection to intuitively control gloves. Ref. [37] uses feedback control. The controller in [35] uses the system identified LTI model and model-based classical control design techniques. For those patients who have good movement from shoulder to wrist while their hands cannot be moved at all, Ref. [92] proposed a MCP joint flexion model. Based on this model, the force and direction of the metacarpophalangeal joint can be predicted by the length and tension of the wire actuation, and they showed the experimental results and calculated the difference between actual wire length and the values calculated by the model when the MCP joint angle is 17° , and the result indicates that the model is valid. Asbeck et al. proposed several control methods for overalls. Previous exosuits generated assistive force by contracting Bolton cables and changed the position of linear actuators [42,43,45] according to the instructions of position controllers. Considering the gait changes after stroke, Bae et al. developed a new control strategy to provide personalized supplementary information for each patient [40]. They designed an adaptive real-time gait event detection algorithm,

which divides the gait cycle into four stages. Thus each session in different walking experiments of each patient can adjust the actuator position command trajectory. The algorithm uses gyroscope sensor signals from both feet [93]. Exosuit uses a PID feedback controller with a closed-loop frequency of 1KHz to enable the actuator to accurately track the given instruction trajectory.

It should be noted that the control of tendon driven robots has been studied for a long time and plentiful results can be found so far. In fact, the choice of control strategy usually depends on the structure of rehabilitation robots and the requirements of rehabilitation movement.

3.2. *Soft Rehabilitation and Nursing-Care Robots Based on the Soft Intelligent Materials Actuation*

3.2.1. Pneumatic Fiber Braids and Elastomeric Polymers

Both model-free and model-based control methods have been proved to be effective in the control of SRNCRs made of these materials, and some classical control methods have already been successfully applied, such as the PID, sliding mode control (SMC), and proxy-based sliding mode control (PSMC).

In [62,70], a PID controller is used to control the soft actuator. The master-slave position control is used. Two bang-bang closed-loop controllers are used to complete the control in [55]. Ref. [56] uses direct control algorithm to control the exoskeleton. In [66], Ru et al. utilized the PID and proxy-based sliding mode control (PSMC) to control the soft bending actuator based on visual feedback system, and compared the control effect of the two methods. Huang et al. utilized a safe and model-free control strategy, PSMC, to ensure proper control of the exoskeleton [72]. In order to obtain the appropriate control parameters to achieve favorable performances, they proposed a global parameters optimization algorithm named switch-mode firefly algorithm. This algorithm can automatically calculate the pre-defined object function and obtain the most applicable parameters and the experimental results showed that it is effective. In [94], Xing et al. studied the dynamic model of pneumatic muscle, and applied the sliding mode approach to track a planar arm manipulator system. The sliding mode controller is designed based on dynamic model to ensure the joint angle track a reference trajectory. They also proposed a selection method to obtain a suitable spring coefficient and confirmed the effectiveness of it by simulation results. In [95], Ding et al. proposed a position-based SMC method to reduce the vibration at the end of deformable linear object (DLO) based on the decoupled dynamic model of a DLO system. The proposed control method is verified by simulation experiment. Besides, Huang et al. proposed a high-order disturbance observer and designed a sliding mode control method based on it for underactuated robotic systems [96,97].

A novel control strategy based on impedance control model is introduced in [71], and the amount of assistance is changed by modifying the parameters of the impedance model. The proposed scheme improves the flexibility control scheme of the flexible actuator by adjusting the stiffness of the actuator. The control system in [58] uses a state machine controller for closed-loop control. A static model of SPA was established to predict the behavior of oral interventional rehabilitation robot based on low-profile soft pneumatic actuator [73]. Ref. [98] proposes a force estimation algorithm based on the masseter muscle EMG signal and applies it to the control of a soft mouth rehabilitation robot system. Refs. [49,53,54,63,99] all established finite element models (FEM) and analyzed their mechanical behavior and the models were verified by the experimental results. The quasi-static analysis method is also used in [99]. In [100], Huang et al. utilized the FEM to realize a systematic modeling for deformable linear objects (DLOs). The simulation results showed that proposed modeling method based on Lagrange motion equations has a fast computation speed. Besides, predictive control scheme is recognized as a powerful control method for nonlinear dynamic systems because of its strong adaptive ability, robustness and on-line optimization. Ref. [101] proposed a model predictive control method based on particle swarm optimization (PSO) integrated single layer neural network (SNN) and echo state neural network (ESN). The method is verified by simulations and experiments. The experiments were carried out on a real PMA system connected with an XPC target system. According to the experimental results, the sum of absolute error between predicted value and true value are

respectively 0.0382 (SNN), 0.0223 (PSO-SNN), 0.0141 (SNN-ESN), 0.0114 (PSO-SNN-ESN). The results show that the control algorithm is effective, and [102] proposed an ESGP-NMPC strategy for stabilizing the tracking error dynamics model of PMA devices. The gradient descent algorithm is used to minimize the cost function. Compared with other control strategies, this method has the maximum absolute error and can achieve better model setting and better control performance of high precision tracking tasks for PMA, and the corresponding integral of absolute error is 6.8894×10^{-4} .

One of the main limitations of the model-based approach is the strictness for the accuracy of the model. Due to the high nonlinearity and time-varying characteristics of soft intelligent materials, it is difficult to obtain an accurate rehabilitation robot model in practical application. Even if an accurate model can be obtained, the order of the controller is usually too high, and the performance in practical application is not excellent. Iterative learning control (ILC) is a very appropriate control technology because of the repeatability of rehabilitation training, which can achieve up to 92% better performance compared to the conventional tuned controllers. Wei et al. proposed an IFT (NIFT) method based on normalization criterion in [103] and applied it to the repetitive training control of a flexible ankle rehabilitation robot driven by pneumatic muscle actuators (PMAs). As a model-free data-driven learning method [104], the IFT can learn from historical test data and adjust the controller to optimize its performance. Compared with traditional control systems, IFT-based systems have strong robustness to uncertainties [105]. Therefore, this ankle rehabilitation robot can provide better help in different rehabilitation stages of patients and promote patients to participate in rehabilitation training better. In the performance tests, Wei et al. obtained the initial PID gains by using Ziegler–Nichols tuning rules. Experimental results show that the IFT method always performs better than the initial Ziegler–Nichols tuned method, and the performance of peak amplitude can reach up to 95.6% better than the Ziegler–Nichols sets. Therefore, the proposed NIFT method provides robustness for the control system through continuous adaptation and adjustment in different situations to improve the effectiveness of robot rehabilitation.

3.2.2. Other Soft Intelligent Materials

These new soft intelligent materials have not been studied for a long time, and their respective characteristics hinder the progress of research. Thus the corresponding modeling methods and control strategies are relatively few.

Due to the thermal hysteresis non-linearity of SMA actuators, the non-linear control technology is usually utilized to control them. The bilinear controller is a subset of nonlinear controllers, which is relatively simple and feasible, so it may be a promising control method to control the position of SMA actuators. Villoslada et al. proposed a bilinear controller in [106]. It consists of a traditional PID controller and a bilinear compensator, called BPID, and has been successfully applied to control a single SMA line. Villoslada et al. compared the performance of the BPID controller with that of traditional PID controller and improved feed-forward PIPD controller to the control effect of the actual SMA actuator. In most experiments, BPID has better performance, especially tracking step reference. When BPID controller is tracking the step references, the response is very smooth when reaching the reference without any overshoot and the steady-state error is about 0.1% of the displacement, and the steady-state error is about 0.2% of the displacement when BPID controller tracking incremental step reference. On this basis, a simple Quadrinomial bilinear PID controller is proposed [81] and successfully applied to control SMA actuators in [79]. The simulation software used to design the wrist exoskeleton based on SMA is based on Bob simulator. Besides, Copaci introduced a simulation tool for SMA-based non-linear actuation in [82], which can provide help for researchers in the future. For shape memory polymer (SMPS), adjustable stiffness layer (ASLS) with variable stiffness can be used to effectively control the flexibility of the robot and its interaction mode with the environment [107–109]. The retractable heater embedded in SMP in Robogami [84] allows us to control joint stiffness by controlling the temperature of the SMP layer. In addition, by controlling the strain sensitivity [86], we can use instruments with opposite sensitivity to measure displacement and compensate for resistance

changes caused by changes in environmental conditions. Radan Pathan et al. proposed a new design scheme of the soft heater based on carbon fiber [110]. The heater adopts Joule heating mode and has the characteristics of light, thin and soft. It is very suitable for temperature control of a soft actuator in SMP manufacturing. The electromechanical modeling and parameter recognition of EAPs are studied in [111], and the three-tier EAP actuator is modeled as a soft robot actuator consisting of many rigid links.

3.3. Summary of Modeling Methods and Control Strategies for Soft Rehabilitation and Nursing-Care Robots

In this review, we roughly divide the control methods of SRNCRs into three categories, including model-based control methods, PID or extended PID methods, and other model-free control methods (Figure 6). To provide a foundation for model-based control methods, various SRNCR models are achieved by using the FEM, Lagrangian methods and so on [20,49,53,54,63,92,94,99,111]. Figure 7 shows the proportion of different control methods used by the SRNCRs involved in this review. From the Figure 7 we can know that the SRNCRs based on tendon-driven mainly use the first two kinds of control methods. Meanwhile the SRNCRs based on soft intelligent materials utilize all the three methods, in which the proportion of other model-free methods increased significantly. At present, the first two kinds of control methods have been extensively studied, while the latter is still in the process of development. Rehabilitation robots based on soft intelligent materials can achieve complete flexibility. Thus, the study of their modeling and control methods will be a research focus in the future. At the same time, due to the non-linearity and time-delay characteristics of flexible materials, it is difficult to establish an accurate model of such soft rehabilitation robot. Even if the corresponding model of system can be established, it will be very complicated and difficult to use for actual process control. Besides, for complex robotic systems, the parameter tuning process of PID or extended PID method is very troublesome and difficult, and it is hard to achieve ideal results. Therefore, the other model-free control methods, such as machine learning based methods, may become a very important direction in the future research of SRNCRs. This will greatly help to realize the application of soft rehabilitation robots with complete flexibility.

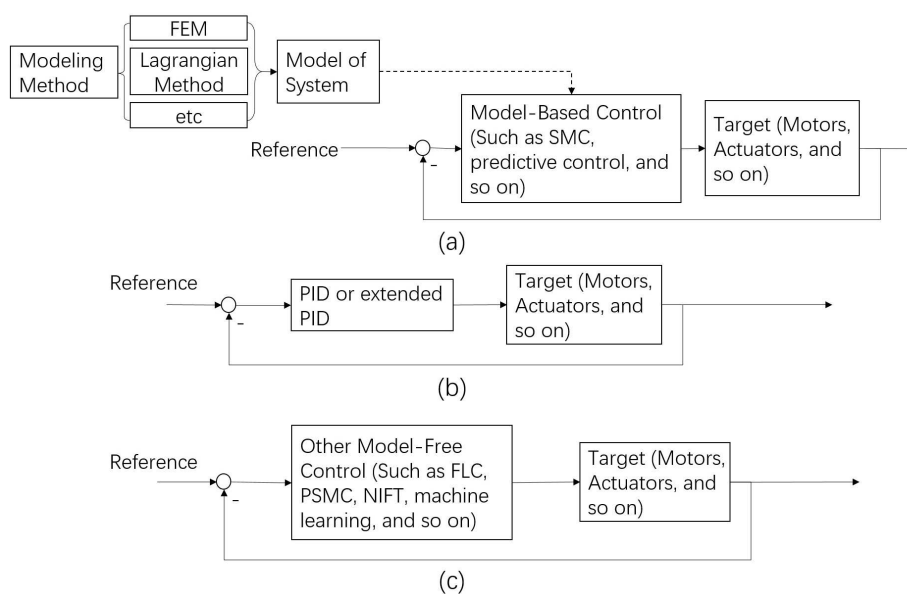


Figure 6. Three control strategies of SRNCRs. (a) Model-based control method; (b) PID or extended PID method; (c) Other model-free control method.

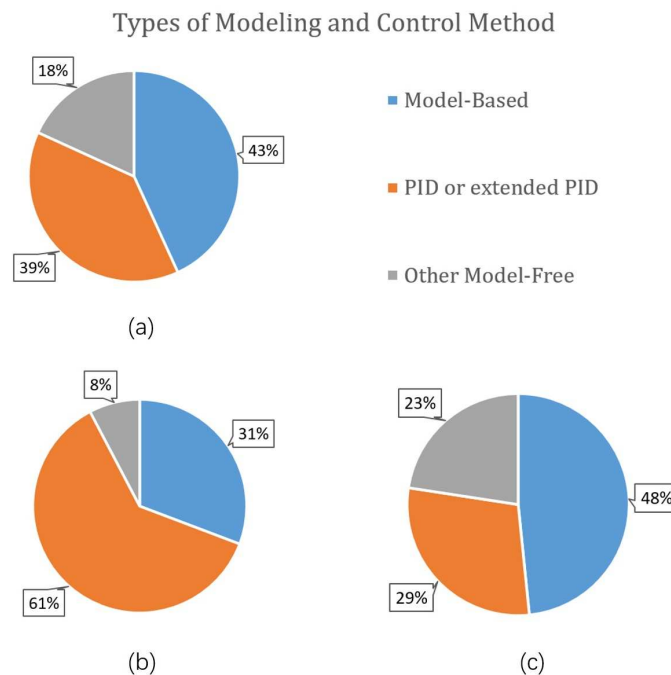


Figure 7. Types of control strategies and their percentage in this review. (a) Overall proportion of SRNCRs; (b) Proportion of SRNCRs based on tendon-driven; (c) Proportion of SRNCRs based on soft intelligent materials.

SRNCRs based on tendon-driven actuation and pneumatic fiber braids or elastomeric polymers actuation have a relatively complete theory in the production and control methods. But this doesn't mean that there is little development space of them; on the contrary, these two SRNCRs still have a great potential to be developed. SRNCRs based on other soft intelligent materials have just begun to be studied and their respective characteristics hinder the progress of research, which means that these kinds of rehabilitation robots still have a long way to go. But in the future, these SRNCRs will inevitably play an unparalleled role in the field of rehabilitation.

4. Discussion and Outlook

Due to the inherent compliance and safety, soft robots shows a great potential in rehabilitation and nursing-care and has broad application prospects. Although many SRNCRs have initially demonstrated their assistant rehabilitation ability, there are still many problems to be solved. Firstly, as a rehabilitation robot, its rehabilitation effect is the most important standard of measure. Although there are many kinds of rehabilitation robots and exoskeletons, most of them were only experimented in the laboratory, not put into the rehabilitation clinic and real life to get more validation. Especially for the SRNCR, there is no mature product on the market so far. Secondly, for rehabilitation equipment, the original intention of the design is to help more patients, so the production cost of the SRNCR must be considered. Some existing rehabilitation robots such as HAL and ReWalk are still expensive, which hinders their wide use.

SRNCRs are complex systems with multiple degrees of freedom. Traditional rehabilitation robots are often complex and cumbersome. For wearable rehabilitation robots, patients are generally required to carry the weight of the equipment for rehabilitation training. So it will be inconvenient for the patient to wear and use due to the complexity and the heavy weight of the devices. Therefore, an ideal SRNCR needs to have a lighter mechanical body, which requires researchers to optimize the

mechanical structure of rehabilitation robots to reduce the weight of SRNCR. The development of new soft-smart materials is a viable option, such as full fabric material, carbon fiber and titanium alloy, which is a common method of weight reduction. However, flexible materials are often less durable than rigid materials, which hinders the practical application of SRNCRs [112,113]. So the durability of soft materials is also a practical problem need to be solved. The development of new sensing devices and sensing technologies to reduce the number of sensors in robots is another viable option, and some new measurement techniques may be used. As a robot that needs to assist the patients with dyskinesia, from the current research results, the response speed and motion accuracy of SRNCRs still need to be improved to achieve better therapeutic effects and comfort of human–robot interaction. In addition, some rehabilitation robots still contain a few rigid components, which may affect patient comfort, and researchers need to explore more softer components. For example, soft heater based on carbon fiber contributes [110] to development of lighter and thinner sensors. Furthermore, most SRNCRs have a limited range of assistance output and motion angles. This problem may not have a obvious impact in the early stages of rehabilitation. However, when the rehabilitation treatment enters the later stage, further rehabilitation of the patient with certain abilities will be precluded. All in all, the structural design of SRNCRs should be flexible and comfortable.

As far as the modeling methods and control strategies of rehabilitation robots are concerned, most of the current SRNCRs use relatively simple control methods and rough models with numerous assumptions. Modeling and control work of soft materials is difficult due to the high nonlinearity, time-varying characteristics and response delay characteristics. Because the traditional theories are mostly not applicable to soft materials, researchers need to make a series of assumptions when modeling. These factors bring uncertainties and disturbances to the control system. The patient's feeling during the training process is also an important factor that needs to be considered. Designing more advanced sensors and combining appropriate control strategies may be a viable direction. The compliance of the rehabilitation robot should be adjusted according to the patient's wishes. How to change the auxiliary control strategy according to the patient's immediate thought is a problem that researchers need to think about, which allows the patient to participate in the rehabilitation process to the greatest extent possible. The brain-computer interfaces and visual feedback may be good solutions. For example, Refs. [114,115] propose some innovative control strategies. Furthermore, patients in different age groups, different disability levels and different rehabilitation stages need different control strategies and individualized training modes, which puts requirements of intelligence on SRNCRs. In addition, the specific control strategies and training modes should be set up after communication with the rehabilitation experts, which allows the patient to get the best, most timely and most suitable rehabilitation treatment. Besides, machine learning is a way to make computers intelligent, and it is a hot topic of research at this stage. As the core of artificial intelligence, the application of machine learning extends to many fields of artificial intelligence, which has a great impact on various fields. Similarly, machine learning has a very broad application prospect in the modeling and control strategies of soft robots. It can build a more accurate model of SRNCR and optimize the control strategy. For example, both [116,117] use machine learning methods to control and model SRNCRs. Therefore, it is foreseeable that in the future machine learning will become an important method for modeling and controlling SRNCRs.

In the process of rehabilitation and nursing-care, the human–robot interaction has a great influence on the medical effect of rehabilitation equipment. Effective human–computer interaction design can accurately translate the user's intention into the behavior of the rehabilitation robot, which allows patients to participate actively in the rehabilitation process to the greatest extent. In 2017, Noronha et al. proposed an interactive strategy to control the behavior of rehabilitation gloves by using binocular vision tracking technology to detect commands of “winking” [114]. This control method controls gloves by detecting a pre-defined “wink” signal. In their study, the eye tracking methods were compared with speech recognition and EMG gesture based methods in controlling the soft glove. The experimental results show that the average error rate of “wink” control is the lowest, followed by the speech

recognition and the EMG gesture based control. At the same time, Nithya et al. designed a new wearable brain-controlled mechanical glove (Figure 8a) [115]. The gloves use an emotive insight headset to receive signals from the brain, which is an electroencephalogram sensor (Figure 8b). The signals from the sensor are processed by a pic microcontroller. The processed signal is transmitted into the servo motor to control the movement of fingers and hands. Besides, in the field of SRNCR based on pneumatic fiber braids and elastomeric polymers, Ref. [118] proposed two assistant controllers of pneumatic direct driven SRNCR based on an inverse model of human limbs. Based on the adaptive feedforward model, the device can provide enough support for the patient's movement and maintain the high flexibility of the soft actuator. The first controller is based on prior information of model parameter estimation (MPE). When patients are active, the controller allows patients to find their personal trajectories without forcing them to use predetermined trajectories. The second controller is based on the function approximation technique using radial basis function (RBF), which does not require prior information. This controller only allows the patients to produce small deviations from the desired trajectory. When the wearer actively participates in the motion process, the overall torque will be reduced, and the dynamic model of human limbs suitable for patient behavior will be estimated until the torque that was calculated to compensate the weight of the device. These two controllers can be adjusted online, so that they can maximize the initiative of patients to participate in rehabilitation training, and achieve better rehabilitation effect.

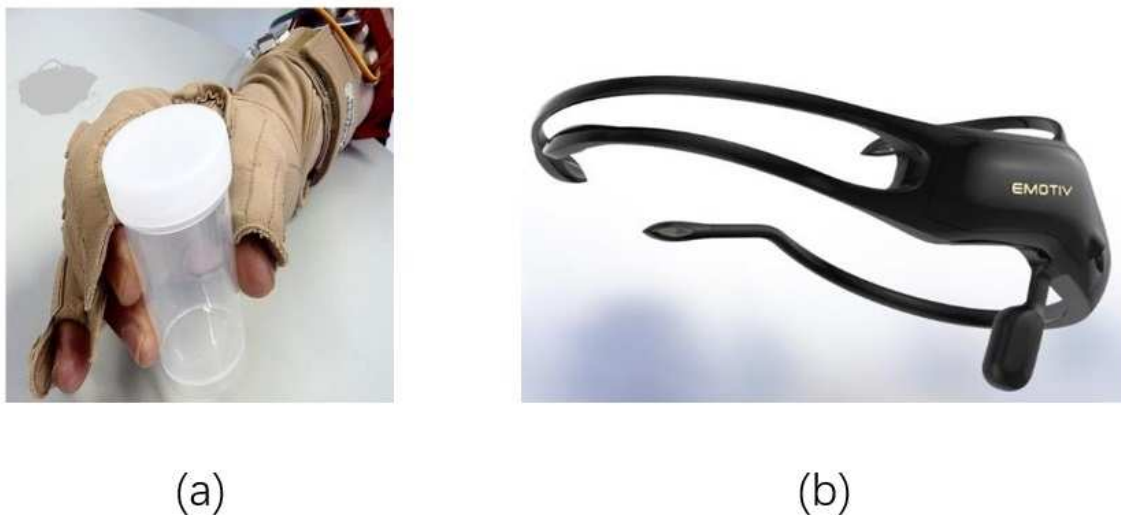


Figure 8. A brain controlled robotic glove. (a,b) is reprinted from [115].

In the actual rehabilitation process, the training often lasts for several hours. Therefore, the energy support of the rehabilitation robot is also a problem that needs to be explored. In existing related work, many rehabilitation robots in the laboratory have encountered difficulties in being put into clinical treatment due to factors such as the heavy weight and the large occupied space of the power source. Thus, researchers need to develop a power source that is lightweight and has a high energy density.

Finally, the clinical validation is a vital step in the development of SRNCRs. Although there are a number of SRNCRs, most current studies have only been tested and experimented in the laboratory and have not been put into rehabilitation clinics to verify their feasibility in application through long-term experiments on a large number of patients. Admittedly, this is a very long-term and patient work, while this work is very significant, the specific level of rehabilitation of patients needs to be evaluated according to professional assessment criteria. Furthermore, it is important to have comprehensive communication with rehabilitation specialists and patients, which helps the researchers to understand the patient's rehabilitation demands. This will help researchers find better ways to improve the devices and develop more practical and humanized soft rehabilitation medical robots. In [119], Patoglu et al. conducted a survey with engineers and health professionals, and through the

analysis of the results of the investigation, they improved the rehabilitation exoskeleton accordingly. Professional demand analysis and advanced application technology will probably bring a bright future for SRNCRs.

5. Conclusions

This paper conducts a review on soft rehabilitation and nursing-care robots in design, modeling methods and control strategies. There are many soft rehabilitation and nursing-care robots based on tendon-driven and elastomeric polymers but the development of rehabilitation robots based on other soft intelligent materials is just getting started. We discuss and summarize various soft rehabilitation and nursing-care robots with different actuation technologies, and their characteristics are described. This paper also discusses the possible future directions based on the current development situation and rehabilitation demands. The information of soft rehabilitation and nursing-care robots presented in this paper will probably provide knowledge and enlightenment for development of soft rehabilitation and nursing-care robots in the future. This study may provide assistance and comprehensive literature for researchers in the future.

Funding: This work was supported by the International Science and Technology Cooperation Program of China under Grant No. 2017YFE0128300 and the Fundamental Research Funds for the Central Universities (HUST: 2019kfyRCPY, 2019kfyXKJC019).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. World Health Organization. Available online: <https://www.who.int/disabilities> (accessed on 19 April 2019).
2. World Stroke Campaign. Available online: <https://www.worldstrokecampaign.org> (accessed on 19 April 2019).
3. Díaz, I.; Gil, J.J.; Sánchez, E. Lower-limb robotic rehabilitation: Literature review and challenges. *J. Robot.* **2011**, *2011*, 1–11. [[CrossRef](#)]
4. Lo, H.S.; Xie, S.Q. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects. *Med. Eng. Phys.* **2012**, *34*, 261–268. [[CrossRef](#)] [[PubMed](#)]
5. Gao, Z.; Shi, Q.; Fukuda, T.; Li, C.; Huang, Q. An overview of biomimetic robots with animal behaviors. *Neurocomputing* **2019**, *332*, 339–350. [[CrossRef](#)]
6. Rus, D.; Tolley, M.T. Design, fabrication and control of soft robots. *Nature*. **2015**, *521*, 467–475. [[CrossRef](#)] [[PubMed](#)]
7. Shi, Q.; Li, C.; Li, K.; Huang, Q.; Ishii, H.; Takanishi, A.; Fukuda, T. A Modified Robotic Rat to Study Rat-Like Pitch and Yaw Movements. *IEEE/ASME Trans. Mechatron.* **2018**, *23*, 2448–2458. [[CrossRef](#)]
8. Majidi, C. Soft robotics: A perspective—Current trends and prospects for the future. *Soft Robot.* **2014**, *1*, 5–11. [[CrossRef](#)]
9. Costa, N.; Caldwell, D.G. Control of a biomimetic “soft-actuated” 10dof lower body exoskeleton. In Proceedings of the First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, Pisa, Italy, 20–22 February 2006; pp. 495–501.
10. Hussain, S.; Xie, S.Q.; Jamwal, P.K. Adaptive impedance control of a robotic orthosis for gait rehabilitation. *IEEE Trans. Cybern.* **2013**, *43*, 1025–1034. [[CrossRef](#)]
11. Cao, J.; Xie, S.Q.; Das, R. MIMO sliding mode controller for gait exoskeleton driven by pneumatic muscles. *IEEE Trans. Control Syst. Technol.* **2017**, *26*, 274–281. [[CrossRef](#)]
12. Neckel, N.; Wisman, W.; Hidler, J. Limb alignment and kinematics inside a Lokomat robotic orthosis. In Proceedings of the 2006 International Conference of the IEEE Engineering in Medicine and Biology Society, New York, NY, USA, 30 August–3 September 2006; pp. 2698–2701.
13. Munera, M.; Marroquin, A.; Jimenez, L.; Lara, J.S.; Gomez, C.; Rodriguez, S.; Rodriguez, L.E.; Cifuentes, C.A. Lokomat therapy in Colombia: Current state and cognitive aspects. In Proceedings of the International Conference on Rehabilitation Robotics, QEII Centre, London, UK, 17–20 July 2017; pp. 394–399.

14. Holanda, L.J.; Silva, P.M.; Amorim, T.C.; Lacerda, M.O.; Simão, C.R.; Morya, E. Robotic assisted gait as a tool for rehabilitation of individuals with spinal cord injury: A systematic review. *J. Neuroeng. Rehabil.* **2017**, *14*, 126. [[CrossRef](#)]
15. Gu, G.Y.; Zhu, J.; Zhu, L.M.; Zhu, X. A survey on dielectric elastomer actuators for soft robots. *Bioinspir. Biomim.* **2017**, *12*, 1–22. [[CrossRef](#)]
16. Trivedi, D.; Rahn, C.D.; Kier, W.M.; Walker, I.D. Soft robotics: Biological inspiration, state of the art, and future research. *Appl. Bionics Biomech.* **2008**, *5*, 99–117. [[CrossRef](#)]
17. Laschi, C.; Mazzolai, B.; Cianchetti, M. Soft robotics: Technologies and systems pushing the boundaries of robot abilities. *Sci. Robot.* **2016**, *1*, 1–11. [[CrossRef](#)]
18. Laschi, C.; Cianchetti, M. Soft robotics: New perspectives for robot bodyware and control. *Front. Bioeng. Biotechnol.* **2014**, *2*, 1–5. [[CrossRef](#)] [[PubMed](#)]
19. Nd, D.M.; Fischer, S.A.; Gauthier, P.W.; Luna, C.H.; Clancy, E.A.; Fischer, G.S. A soft robotic exomusculature glove with integrated sEMG sensing for hand rehabilitation. In Proceedings of the 2013 IEEE International Conference on Rehabilitation Robotics, Seattle, WA, USA, 24–26 June 2013; pp. 1–7.
20. Nycz, C.J.; Delph, M.A.; Fischer, G.S. Modeling and design of a tendon actuated soft robotic exoskeleton for hemiparetic upper limb rehabilitation. In Proceedings of the 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Milan, Italy, 25–29 August 2015; pp. 3889–3892.
21. In, H.; Kang, B.B.; Sin, M.; Cho, K.J. Exo-glove: A wearable robot for the hand with a soft tendon routing system. *IEEE Robot. Autom. Mag.* **2015**, *22*, 97–105. [[CrossRef](#)]
22. Kang, S.; In, H.; Cho, K.J. Design of a passive brake mechanism for tendon driven devices. *Int. J. Precis. Eng. Manuf.* **2012**, *13*, 1487–1490. [[CrossRef](#)]
23. In, H.; Kang, S.; Cho, K.J. Capstan brake: Passive brake for tendondriven mechanism. In Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vilamoura, Portugal, 7–12 October 2012; pp. 2301–2306.
24. In, H.; Lee, H.; Jeong, U.; Kang, B.B.; Cho, K.J. Feasibility study of a slack enabling actuator for actuating tendon-driven soft wearable robot without pretension. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation, Seattle, WA, USA, 26–30 May 2015; pp. 1229–1234.
25. Vikas, V.; Cohen, E.; Grassi, R.; Sözer, C.; Trimmer, B. Design and locomotion control of a soft robot using friction manipulation and motor–tendon actuation. *IEEE Trans. Robot.* **2016**, *32*, 949–959. [[CrossRef](#)]
26. Xiloyannis, M.; Cappello, L.; Khanh, D.B.; Yen, S.C.; Masia, L. Modelling and design of a synergy-based actuator for a tendon-driven soft robotic glove. In Proceedings of the 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics, Singapore, 26–29 June 2016; pp. 1213–1219.
27. Stilli, A.; Cremoni, A.; Bianchi, M.; Ridolfi, A.; Gerii, F.; Vannetti, F.; Wurdemann H.A., Allotta, B.; Althoefer, K. AirExGlove—A novel pneumatic exoskeleton glove for adaptive hand rehabilitation in post-stroke patients. In Proceedings of the 2018 IEEE International Conference on Soft Robotics, Livorno, Italy, 24–28 April 2018; pp. 579–584.
28. Maghooa, F.; Stilli, A.; Noh, Y.; Althoefer, K.; Wurdemann, H.A. Tendon and pressure actuation for a bio-inspired manipulator based on an antagonistic principle. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation, Seattle, WA, USA, 26–30 May 2015; pp. 2556–2561.
29. Wurdemann, H.A.; Stilli, A.; Althoefer, K. Lecture notes in computer science: An antagonistic actuation technique for simultaneous stiffness and position control. In Proceedings of the International Conference on Intelligent Robotics and Applications, Portsmouth, UK, 24–27 August 2015; pp. 164–174.
30. Shiva, A.; Stilli, A.; Noh, Y.; Faragasso, A.; De Falco, I.; Gerboni, G.; Cianchetti, M.; Menciassi, A.; Althoefer, K.; Wurdemann, H.A. Tendon-based stiffening for a pneumatically actuated soft manipulator. *IEEE Robot. Autom. Lett.* **2016**, *1*, 632–637. [[CrossRef](#)]
31. Stilli, A.; Wurdemann, H.A.; Althoefer, K. Shrinkable, stiffness-controllable soft manipulator based on a bio-inspired antagonistic actuation principle. In Proceedings of the 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, USA, 14–18 September 2014; pp. 2476–2481.
32. Stilli, A.; Wurdemann, H.A.; Althoefer, K. A novel concept for safe, stiffness-controllable robot links. *Soft Robot.* **2017**, *4*, 16–22. [[CrossRef](#)]
33. Stilli, A.; Grattarola, L.; Feldmann, H.; Wurdemann, H.A.; Althoefer, K. Variable Stiffness Link (VSL): Toward inherently safe robotic manipulators. In Proceedings of the IEEE International Conference on Robotics and Automation, Singapore, 29 May–3 June 2017; pp. 4971–4976.

34. Guo, J.; Yu, S.; Li, Y.; Huang, T.H.; Wang, J.; Lynn, B.; Fidock, J.; Shen, C.L.; Edwards, D.; Su, H. A soft robotic exo-sheath using fabric EMG sensing for hand rehabilitation and assistance. In Proceedings of the 2018 IEEE International Conference on Soft Robotics, Livorno, Italy, 24–28 April 2018; pp. 497–503.
35. Park, Y.L.; Chen, B.R.; Pérez-Arancibia, N.O.; Young, D.; Stirling, L.; Wood, R.J.; Goldfield, E.C.; Nagpal, R. Design and control of a bio-inspired soft wearable robotic device for ankle-foot rehabilitation. *Bioinspir. Biomim.* **2014**, *9*, 016007. [[CrossRef](#)]
36. Park, D.; In, H.; Lee, H.; Lee, S.; Koo, I.; Kang, B.B.; Park, K.; Chang, W.S.; Cho, K.J. Preliminary study for a soft wearable knee extensor to assist physically weak people. In Proceedings of the 11th International Conference on Ubiquitous Robots and Ambient Intelligence, Kuala Lumpur, Malaysia, 2–15 November 2014; pp. 136–137.
37. Kwon, J.; Park, J.H.; Ku1, S.; Jeong, Y.H.; Paik, N.J.; Park, Y.L. A soft wearable robotic ankle-foot-orthosis for post-stroke patients. *IEEE Robot. Autom. Lett.* **2019**, *4*, 2547–2552. [[CrossRef](#)]
38. Ding, Y.; Galiana, I.; Asbeck, A.; Quinlivan, B.; De Rossi, S.M.M.; Walsh, C. Multi-joint actuation platform for lower extremity soft exosuits. In Proceedings of the 2014 IEEE International Conference on Robotics and Automation, Hong Kong, China, 31 May–7 June 2014; pp. 1327–1334.
39. Ding, Y.; Galiana, I.; Asbeck, A.T.; De Rossi, S.M.M.; Bae, J.; Santos, T.R.T.; de Araujo, V.L.; Lee, S.; Holt, K.G.; Walsh, C. Biomechanical and physiological evaluation of multi-joint assistance with soft exosuits. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2016**, *25*, 119–130. [[CrossRef](#)] [[PubMed](#)]
40. Bae, J.; De Rossi, S.M.M.; O'Donnell, K.; Hendron, K.L.; Awad, L.N.; Dos Santos, T.R.T.; De Araujo, V.L.; Ding, Y.; Holt, K.G.; Ellis, T.D.; et al. A soft exosuit for patients with stroke: Feasibility study with a mobile off-board actuation unit. In Proceedings of the 2015 IEEE International Conference on Rehabilitation Robotics, Singapore, 11–14 August 2015; pp. 131–138.
41. Wehner, M.; Quinlivan, B.; Aubin, P.M.; Martinezvillalp, E.; Stirling, L.; Holt, K.; Wood, R.; Walsh, C. A Lightweight Soft Exosuit for Gait Assistance. In Proceedings of the IEEE International Conference on Robotics and Automation, Karlsruhe, Germany, 6–10 May 2013; pp. 3362–3369.
42. Asbeck, A.T.; Dyer, R.J.; Larusson, A.F.; Walsh, C.J. Biologically-inspired soft exosuit. In Proceedings of the IEEE International Conference on Rehabilitation Robotics, Seattle, WA, USA, 24–26 June 2013; pp. 1–8.
43. Asbeck, A.T.; Rossi, S.M.M.D.; Galiana, I.; Ding, Y.; Walsh, C. J. Stronger, smarter, softer: Next-generation wearable robots. *IEEE Robot. Autom. Mag.* **2014**, *21*, 22–33. [[CrossRef](#)]
44. Asbeck, A.T.; Schmidt, K.; Galiana, I.; Wagner, D. Multi-joint soft exosuit for gait assistance. In Proceedings of the IEEE International Conference on Robotics and Automation, Seattle, WA, USA, 26–30 May 2015.
45. Asbeck, A.T.; Rossi, S.M.M.D.; Holt, K.G.; Walsh, C.J. A biologically inspired soft exosuit for walking assistance. *Int. J. Robot. Res.* **2015**, *34*, 744–762. [[CrossRef](#)]
46. Rose, C.G.; O'Malley, M.K. Hybrid Rigid-Soft Hand Exoskeleton to Assist Functional Dexterity. *IEEE Robot. Autom. Lett.* **2019**, *4*, 73–80. [[CrossRef](#)]
47. Caldwell, D.G.; Medrano-Cerda, G.A.; Goodwin, M. Control of pneumatic muscle actuators. *IEEE Control Syst.* **2002**, *15*, 40–48.
48. Wakimoto, S.; Suzumori, K.; Kanda, T. Development of intelligent McKibben actuator. In Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, AB, Canada, 2–6 August 2005.
49. Polygerinos, P.; Lyne, S.; Wang, Z.; Nicolini, L.F.; Mosadegh, B.; Whitesides, G.M.; Walsh, C.J. Towards a soft pneumatic glove for hand rehabilitation. In Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 3–7 November 2013; pp. 1512–1517.
50. Polygerinos, P.; Wang, Z.; Galloway, K.C.; Wood, R.J.; Walsh, C.J. Soft robotic glove for combined assistance and at-home rehabilitation. *Robot. Auton. Syst.* **2015**, *73*, 135–143. [[CrossRef](#)]
51. Maeder-York, P.; Clites, T.; Boggs, E.; Neff, R.; Polygerinos, P.; Holland, D.; Stirling, L.; Galloway K.; Wee, C.; Walsh, C. Biologically inspired soft robot for thumb rehabilitation. *J. Med. Devices* **2014**, *8*, 20933. [[CrossRef](#)]
52. Polygerinos, P.; Galloway, K.C.; Savage, E.; Herman, M.; O'Donnell, K.; Walsh, C.J. Soft robotic glove for hand rehabilitation and task specific training. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation, Seattle, WA, USA, 26–30 May 2015; pp. 2913–2919.
53. Zhang, J.; Wang, H.; Tang, J.; Guo, H.; Hong, J. Modeling and design of a soft pneumatic finger for hand rehabilitation. In Proceedings of the 2015 IEEE International Conference on Information and Automation, Lijiang, China, 8–10 August 2015; pp. 2460–2465.

54. Guo, S.; Zhao, F.; Wei, W.; Guo, J.; Zhao, X.; Zhang, W. Soft actuator for hand rehabilitation. In Proceedings of the IEEE International Conference on Mechatronics and Automation, Beijing, China, 2–5 August 2015; pp. 2197–2202.
55. Al-Fahaam, H.; Davis, S.; Nefti-Meziani, S. Power assistive and rehabilitation wearable robot based on pneumatic soft actuators. In Proceedings of the 2016 21st international conference on methods and models in automation and robotics, Miedzyzdroje, Poland, 29 August–1 September 2016; pp. 472–477.
56. Al-Fahaam, H.; Davis, S.; Nefti-Meziani, S. Wrist rehabilitation exoskeleton robot based on pneumatic soft actuators. In Proceedings of the 2016 International Conference for Students on Applied Engineering, Newcastle upon Tyne, UK, 20–21 October 2016; pp. 472–477.
57. Huang, J.; Tu, X.; He, J. Design and evaluation of the RUPERT wearable upper extremity exoskeleton robot for clinical and in-home therapies. *IEEE Trans. Syst. Man Cybern. Syst.* **2015**, *46*, 926–935. [[CrossRef](#)]
58. Zhao, H.; Jalving, J.; Huang, R.; Knepper, R.; Ruina, A.; Shepherd, R. A helping hand: Soft orthosis with integrated optical strain sensors and emg control. *IEEE Robot. Autom. Mag.* **2016**, *23*, 55–64. [[CrossRef](#)]
59. Zhao, H.; Li, Y.; Elsamadisi, A.; Shepherd, R.F. Scalable manufacturing of high force wearable soft actuators, *Extreme Mech. Lett.* **2015**, *3*, 89–104.
60. Zhao, H.; Huang, R.; Shepherd, R.F. Curvature control of soft orthotics via low cost solid-state optics. In Proceedings of the 2016 IEEE International Conference on Robotics and Automation, Stockholm, Sweden, 16–21 May 2016; pp. 4008–4013.
61. Yap, H.; Kamaldin, N.; Lim, J.; Nasrallah, F.; Goh, J.C.H.; Yeow, C.H. A magnetic resonance compatible soft wearable robotic glove for hand rehabilitation and brain imaging. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2016**, *25*, 782–793. [[CrossRef](#)] [[PubMed](#)]
62. Yap, H.K.; Khin, P.M.; Koh, T.H.; Sun, Y.; Liang, X.; Lim, J.H.; Yeow, C.H. A fully fabric-based bidirectional soft robotic glove for assistance and rehabilitation of hand impaired patients. *IEEE Robot. Autom. Lett.* **2017**, *2*, 1383–1390. [[CrossRef](#)]
63. Luca, R.; Keong, A.B.W.; Chen-Hua, Y. Geometry-based customization of bending modalities for 3d-printed soft pneumatic actuators. *IEEE Robot. Autom. Lett.* **2017**, *3*, 3489–3496.
64. Jiang, Y.; Chen, D.; Liu, P.; Jiao, X.; Ping, Z.; Xu, Z.; Li, J.; Xu, Y. Fishbone-inspired soft robotic glove for hand rehabilitation with multi-degrees-of-freedom. In Proceedings of the 2018 IEEE International Conference on Soft Robotics, Livorno, Italy, 24–28 April 2018; pp. 394–399.
65. Jiang, Y.; Chen, D.; Que, J.; Liu, Z.; Wang, Z.; Xu, Y. Soft robotic glove for hand rehabilitation based on a novel fabrication method. In Proceedings of the 2017 IEEE International Conference on Robotics and Biomimetics, Macau, China, 5–8 December 2017; pp. 817–822.
66. Ru, H.; Huang, J.; Chen, W.; Xiong, C.; Wang, J.; Huo, J. Design, modelling and identification of a fiber-reinforced bending pneumatic muscle. *Sci. China Inf. Sci.* **2019**, *62*, 50213. [[CrossRef](#)]
67. O’Neill, C.T.; Phipps, N.S.; Cappello, L.; Paganoni, S.; Walsh, C.J. A soft wearable robot for the shoulder: Design, characterization, and preliminary testing. In Proceedings of the International Conference on Rehabilitation Robotics, London, UK, 17–20 July 2017; pp. 1672–1678.
68. Irshaidat, M.A.E.; Soufian, M.; Al-Ibadi, A.; Nefti-Meziani, S. A novel elbow pneumatic muscle actuator for exoskeleton arm in post-stroke rehabilitation. In Proceedings of the 2nd IEEE International Conference on Soft Robotics, Seoul, Korea, 14–18 April 2019; pp. 630–635.
69. Zhang, G.; Lin, M. Design of a Soft Robot Using Pneumatic Muscles for Elbow Rehabilitation. In Proceedings of the 3rd International Conference on Robotics and Automation Engineering, Guangzhou, China, 17–19 November 2018; pp. 14–18.
70. Baiden, D.; Ivlev, O. Human-robot-interaction control for orthoses with pneumatic soft-actuators—Concept and initial trials. In Proceedings of the IEEE International Conference on Rehabilitation Robotics, Seattle, WA, USA, 24–26 June 2013.
71. Meng, W.; Liu, Q.; Zhang, M.; Ai, Q.; Xie, S. Compliance adaptation of an intrinsically soft ankle rehabilitation robot driven by pneumatic muscles. In Proceedings of the IEEE International Conference on Advanced Intelligent Mechatronics, Munich, Germany, 3–7 July 2017; pp. 82–87.
72. Cao, Y.; Huang, J.; Huang, Z.; Tu, X.; Mohammed, S. Optimizing Control of Passive Gait Training Exoskeleton Driven by Pneumatic Muscles Using Switch-Mode Firefly Algorithm. *Robotica* **2019**. [[CrossRef](#)]

73. Sun, Y.; Lim, C.M.; Tan, H.H.; Ren, H. Soft oral interventional rehabilitation robot based on low-profile soft pneumatic actuator. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation, Seattle, WA, USA, 26–30 May 2015; pp. 2907–2912.
74. Sun, Y.; Song, Y.S.; Paik, J. Characterization of silicone rubber based soft pneumatic actuators. In Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 3–7 November 2013; pp. 4446–4453.
75. Song, Y.S.; Sun, Y.; Van Den Brand, R.; Von Zitzewitz, J.; Micera, S.; Courtine, G.; Paik, J. Soft robot for gait rehabilitation of spinalized rodents. In Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 3–7 November 2013; pp. 971–976.
76. Shepherd, R.F.; Ilievski, F.; Choi, W.; Morin, S.A.; Stokes, A.A.; Mazzeo, A.D.; Chen, X.; Wang, M.; Whitesides, G.M. Multigait soft robot. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 20400–20403. [[CrossRef](#)] [[PubMed](#)]
77. Brochu, P.; Pei, Q. Advances in dielectric elastomers for actuators and artificial muscles. *Macromol. Rapid Commun.* **2010**, *31*, 10–36. [[CrossRef](#)] [[PubMed](#)]
78. Kim, S.; Laschi, C.; Trimmer, B. Soft robotics: A bioinspired evolution in robotics. *Trends Biotechnol.* **2013**, *31*, 287–294. [[CrossRef](#)]
79. Copaci, D.; Blanco, D.; Moreno, L. Wearable elbow exoskeleton actuated with Shape Memory Alloy in antagonist movement. In Proceedings of the Joint Workshop on Wearable Robotics and Assistive Devices, International Conference on Intelligent Robots and Systems, Daejeon, Korea, 9–14 October 2016; pp. 9–14.
80. Villoslada, A.; Flores, A.; Copaci, D.; Blanco, D.; Moreno, L. High-displacement flexible shape memory alloy actuator for soft wearable robots. *Robot. Auton. Syst.* **2015**, *73*, 91–101. [[CrossRef](#)]
81. Serrano, D.; Copaci, D.S.; Moreno, L.; Blanco, D. SMA based wrist exoskeleton for rehabilitation therapy. In Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, Madrid, Spain, 1–5 October 2018; pp. 2318–2323.
82. Copaci, D. Non-Linear Actuators and Simulation Tools for Rehabilitation Devices. Ph.D. Dissertation, Department Systems Engineering and Automation, Carlos III University, Madrid, Spain, 2017.
83. Copaci, D.; Flores, A.; Rueda, F.; Alguacil, I.; Blanco, D.; Moreno, L. Wearable Elbow Exoskeleton Actuated with Shape Memory Alloy. In *Converging Clinical and Engineering Research on Neurorehabilitation II*; Springer: Cham, The Netherlands, 2017; pp. 477–481.
84. Firouzeh, A.; Paik, J. Soft actuation and sensing towards robot-assisted facial rehabilitation. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Vancouver, BC, Canada, 24–28 September 2017; pp. 306–313.
85. Firouzeh, A.; Salerno, M.; Paik, J. Stiffness control with shape memory polymer in underactuated robotic origamis. *IEEE Trans. Robot.* **2017**, *33*, 765–777. [[CrossRef](#)]
86. Firouzeh, A.; Paik, J. The design and modeling of a novel resistive stretch sensor with tunable sensitivity. *IEEE Sens. J.* **2015**, *15*, 6390–6398. [[CrossRef](#)]
87. Amin, H.; Assal, S.F. Design Methodology of a Spring Roll Dielectric Elastomer-Based Actuator for a Hand Rehabilitation System. In Proceedings of the 2018 IEEE International Conference on Mechatronics and Automation, Changchun, China, 5–8 August 2018; pp. 997–1002.
88. Lidka, M.; Price, A.D.; Trejos, A.L. Development and Evaluation of Dielectric Elastomer Actuators for Assistive Wearable Devices. In Proceedings of the IEEE Canadian Conference on Electrical and Computer Engineering, Quebec City, QC, Canada, 13–16 May 2018.
89. Runge, G.; Preller, T.; Zellmer, S.; Blankemeyer, S.; Kreuz, M.; Garnweitner, G.; Ratz, A. SpineMan: Design of a soft robotic spine-like manipulator for safe human–robot interaction. In Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems, Hamburg, Germany, 28 September–2 October 2015; pp. 1103–1110.
90. Banerjee, H.; Ren, H. Optimizing double-network hydrogel for biomedical soft robots. *Soft Robot.* **2017**, *4*, 191–201. [[CrossRef](#)] [[PubMed](#)]
91. Yuk, H.; Lin, S.; Ma, C.; Takaffoli, M.; Fang, N.X.; Zhao, X. Hydraulic hydrogel actuators and robots optically and sonically camouflaged in water. *Nat. Commun.* **2017**, *8*, 1–12. [[CrossRef](#)] [[PubMed](#)]
92. Kang, B.B.; In, H.; Cho, K.J. Modeling of tendon driven soft wearable robot for the finger. In Proceedings of the 2013 10th International Conference on Ubiquitous Robots and Ambient Intelligence, Jeju, Korea, 30 October–2 November 2013; pp. 459–460.

93. Lau, H.; Tong, K. The reliability of using accelerometer and gyroscope for gait event identification on persons with dropped foot. *Gait Posture* **2008**, *27*, 248–257. [[CrossRef](#)] [[PubMed](#)]
94. Xing, K.; Huang, J.; He, J.; Wang, Y.; Wu, J.; Xu, Q. Sliding mode tracking for actuators comprising pneumatic muscle and torsion spring. *Trans. Inst. Meas. Control* **2012**, *34*, 255–277. [[CrossRef](#)]
95. Ding, F.; Huang, J.; Wang, Y.; Matsuno, T.; Fukuda, T. Vibration damping in manipulation of deformable linear objects using sliding mode control. *Adv. Robot.* **2014**, *28*, 157–172. [[CrossRef](#)]
96. Huang, J.; Ri, S.; Fukuda, T.; Wang, Y. A disturbance observer based sliding mode control for a class of underactuated robotic system with mismatched uncertainties. *IEEE Trans. Autom. Control* **2019**, *64*, 2480–2487. [[CrossRef](#)]
97. Huang, J.; Zhang, M.; Ri, S.; Xiong, C.; Li, Z.; Kang, Y. High-Order Disturbance Observer Based Sliding Mode Control for Mobile Wheeled Inverted Pendulum Systems. *IEEE Trans. Ind. Electron.* **2019**. [[CrossRef](#)]
98. Yu, H.; Sun, Y.; Bai, F.; Ren, H. A preliminary study of force estimation based on surface EMG: Towards neuromechanically guided soft oral rehabilitation robot. In Proceedings of the 2015 IEEE International Conference on Rehabilitation Robotics, Singapore, 11–14 August 2015; pp. 991–996.
99. Polygerinos, P.; Wang, Z.; Overvelde, J.T.; Galloway, K.C.; Wood, R.J.; Bertoldi, K.; Walsh, C.J. Modeling of soft fiber-reinforced bending actuators. *IEEE Trans. Robot.* **2015**, *31*, 778–789. [[CrossRef](#)]
100. Huang, J.; Di, P.; Fukuda, T.; Matsuno, T. Dynamic modeling and simulation of manipulating deformable linear objects. In Proceedings of the 2008 IEEE International Conference on Mechatronics and Automation, Takamatsu, Japan, 5–8 August 2008; pp. 858–863.
101. Huang, J.; Qian, J.; Liu, L.; Wang, Y.; Xiong, C.; Ri, S. Echo state network based predictive control with particle swarm optimization for pneumatic muscle actuator. *J. Frankl. Inst.* **2016**, *353*, 2761–2782. [[CrossRef](#)]
102. Huang, J.; Cao, Y.; Xiong, C.; Zhang, H.T. An Echo State Gaussian Process-Based Nonlinear Model Predictive Control for Pneumatic Muscle Actuators. *IEEE Trans. Autom. Sci. Eng.* **2019**, *16*, 1071–1084. [[CrossRef](#)]
103. Meng, W.; Xie, S.Q.; Liu, Q.; Lu, C.Z.; Ai, Q. Robust iterative feedback tuning control of a compliant rehabilitation robot for repetitive ankle training. *IEEE/ASME Trans. Mechatron.* **2017**, *22*, 173–184. [[CrossRef](#)]
104. Chi, R.; Hou, Z.; Jin, S.; Wang, D.; Hao, J. A data-driven iterative feedback tuning approach of ALINEA for freeway traffic ramp metering with PARAMICS simulations. *IEEE Trans. Ind. Inform.* **2013**, *9*, 2310–2317. [[CrossRef](#)]
105. Hjalmarsson, H. Iterative feedback tuning—An overview. *Int. J. Adapt. Control Signal Process.* **2002**, *16*, 373–395. [[CrossRef](#)]
106. Villoslada, Á.; Escudero, N.; Martín, F.; Flores, A.; Rivera, C.; Collado, M.; Moreno, L. Position control of a shape memory alloy actuator using a four-term bilinear PID controller. *Sens. Actuators A Phys.* **2015**, *236*, 257–272. [[CrossRef](#)]
107. Firouzeh, A.; Salehian, S.S.M.; Billard, A.; Paik, J. An under actuated robotic arm with adjustable stiffness shape memory polymer joints. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation, Seattle, WA, USA, 26–30 May 2015; pp. 2536–2543.
108. Firouzeh, A.; Salerno, M.; Paik, J. Soft pneumatic actuator with adjustable stiffness layers for multi-dof actuation. In Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems, Hamburg, Germany, 28 September–2 October 2015; pp. 1117–1124.
109. Firouzeh, A.; Paik, J. An under-actuated origami gripper with adjustable stiffness joints for multiple grasp modes. *Smart Mater. Struct.* **2017**, *26*, 055035. [[CrossRef](#)]
110. Pathan, R.; Wang, H.; Rehman, H.U.; Butt, J.M.; Chen, Y. Design of Carbon Fiber Based Flexible Soft Heater for SMP Embedded Soft Actuators: A Step Towards Artificial Joints. In Proceedings of the 2018 IEEE International Conference on Robotics and Biomimetics, Kuala Lumpur, Malaysia, 12–15 December 2018; pp. 1208–1213.
111. Mutlu, R.; Alici, G.; Li, W. Electroactive polymers as soft robotic actuators: Electromechanical modeling and identification. In Proceedings of the 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Wollongong, NSW, Australia, 9–12 July 2013; pp. 1096–1101.
112. Case, J.C.; White, E.L.; Kramer, R.K. Soft material characterization for robotic applications. *Soft Robot.* **2015**, *2*, 80–87. [[CrossRef](#)]
113. Yap, H.K.; Ng, H.Y.; Yeow, C.H. High-force soft printable pneumatics for soft robotic applications. *Soft Robot.* **2016**, *3*, 144–158. [[CrossRef](#)]

114. Noronha, B.; Dziemian, S.; Zito, G.A.; Konnaris, C.; Faisal, A.A. “Wink to grasp”—Comparing eye, voice & EMG gesture control of grasp with soft-robotic gloves. In Proceedings of the 2017 International Conference on Rehabilitation Robotics, London, UK, 17–20 July 2017; pp. 1043–1048.
115. Nithya, V.S.; Arun, C.S. Brain controlled wearable robotic glove for cerebral palsy patients. In Proceedings of the 2017 International Conference on Circuit Power and Computing Technologies, Kollam, India, 20–21 April 2017; pp. 1–4.
116. Runge, G.; Wiese, M.; Raatz, A. FEM-based training of artificial neural networks for modular soft robots. In Proceedings of the IEEE International Conference on Robotics and Biomimetics, Macau, China, 5–8 December 2017; pp. 385–392.
117. Yang, G.; Deng, J.; Pang, G.; Zhang, H.; Li, J.; Deng, B.; Xie, H.; Yang, H. An IoT-enabled stroke rehabilitation system based on smart wearable armband and machine learning. *IEEE J. Transl. Eng. Health Med.* **2018**, *6*, 1–10. [[CrossRef](#)]
118. Wilkening, A.; Ivlev, O. Adaptive model-based assistive control for pneumatic direct driven soft rehabilitation robots. In Proceedings of the 2013 IEEE 13th International Conference on Rehabilitation Robotics, Seattle, WA, USA, 24–26 June 2013; pp. 1–6.
119. Patoglu, V.; Ertek, G.; Oz, O.; Zoroglu, D.; Kremer, G. Design requirements for a tendon rehabilitation robot: Results from a survey of engineers and health professionals. *Soc. Sci. Electronic Publ.* **2010**, *307*, 75–88.



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).