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A Brief Review of Rehabilitation Wearable Robots for the Upper and Lower Limbs

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ABSTRACT

Many diseases, such as stroke, physical disability in the elderly, work injuries, and sports injuries can lead to weak limbs. Stroke is one of the main reasons for long-range disability, especially upper limb disability, that affects the activities of daily living (ADL) of individuals. Rehabilitation, such as manually assisted training or physical therapy that involves repeatedly moving the affected limb, is one of the most successful ways to reduce the effects of stroke. However, patients may be prevented from attending a clinic for rehabilitation for many different reasons, so researchers have developed robotic devices that can help in rehabilitation, enabling patients to perform repetitive movements at home with appropriate accuracy. These wearable robots (WR) must be smart, reliable, compatible, light, and functional for the safety of the user and must provide the appropriate support. This paper describes wearable devices, including rigid wearable devices and soft wearable devices, and some of their uses, especially in rehabilitation. It presents a summary of the designs used for the rehabilitation of the lower and upper limbs, especially the hand, which is the organ that is used most often in daily activities. The materials used in the manufacture of gloves that are used to rehabilitate the hand must be taken into account, and the size and weight of the glove must be suitable so that the user can wear and remove it easily.

Key words : Rehabilitation, wearable robot, upper and lower limbs, soft robot, Exoskeleton

1. INTRODUCTION

With 15 million people suffering stroke annually around the world, stroke is the third most common reason for death after heart disease and cancer. It is also one of the main causes of substantial long-rate disability, with most stroke survivors experiencing various disabilities. For instance, 25% of survivors have minor disabilities, 40% have moderate to severe disabilities that require special care, and 85% of survivors suffer from upper extremity disability in the early stages. Three to six months following a stroke, 55–75% of survivors still have significant upper extremity dysfunction.

Four years after their stroke, approximately two-thirds of patients still consider the loss of upper extremity function to be a primary problem, while five years after experiencing a stroke, 25% of survivors still suffer acute upper extremity inflammation, making it the most prevalent type of disability. Neurological damage leads to the loss or impairment of the ability to control the limbs. As well as stroke, spinal cord injuries, trauma, job injuries, and sports injuries can all result in limb weakness [1]–[5]. In addition, physical deficits in the elderly are prevalent, including whole or partial loss of wrist, elbow, or shoulder function [6].

A stroke is an ischemic or hemorrhagic disruption in blood flow to brain tissue. In an ischemic stroke, blood flow to the brain is disrupted due to a blood clot, while in a hemorrhagic stroke, blood flow to the brain is disrupted due to an internal hemorrhage that is a consequence of the significant destruction of cortical tissue. During both kinds of stroke, neural commands from sensory areas in the cortex are disrupted, and as a consequence, a stroke patient loses physical strength on one side of the body [7], [8] resulting in paralysis or hemiplegia, and hence, decreased or complete absence of the ability to selectively activate muscles. This in turn impacts motion task performance, resulting in compromised arm and hand motion activity [9], [10].

Rehabilitation, such as manually assisted training or physiotherapy, can be used to reduce the effects of a stroke. Therapists need to repeatedly move the injured limb as part of rehabilitation; this is considered one of the most successful treatments for recovering arm and hand function. In the course of rehabilitation, some motion abilities that were lost following a stroke may be relearned. It has been claimed that the brain may heal itself due to its neuroplasticity, which refers to the capacity of the brain to form new neural connections [11], [12]. Recent studies have confirmed that intense and early therapy allows people to regain function within a few weeks of having a stroke, while patients who do not receive therapy during this early window will gradually lose the ability to move their limbs. Because these exercises seem mundane, patients may become bored and demotivated in their rehabilitation, which could have significant impacts on their progress and commitment [13], [14]. Generally, only 35.5% of stroke survivors access rehabilitation services. Factors that prevent patients from accessing treatment include the lack of availability of therapists, the length of the treatment sessions, and the cost of rehabilitation devices and transportation. Additionally, training sessions are often shorter than is necessary to achieve an appropriate treatment result, and treatments differ from one therapist to another and from one clinic to another, depending on the therapists' views and expertise. Also, manually assisted training lacks sufficient repetition as well as objective evaluations of patient performance and development. These factors led the researchers to develop rehabilitation robots that enable patients to perform many more repeated limb movements with the proper precision [15], allowing for intensive and successful rehabilitation with an increased number and duration of training sessions, a reduced need for therapists, and lower costs for patients. Rehabilitation robots provide additional motion forces that allow patients to practice real-world tasks, which the patients would otherwise be unable to practice without a therapist present [16]–[19].

Robotic limb devices are classified into two types. The first type is artificial limbs that are part of the body, such as a hand or a leg, which a disabled one can wear to displace a missing part of the body and that assist the person in daily activities. The second type is an orthosis, which is an orthotic device that can be used to improve alignment, support people with disabilities, or improve the function of a limb that still exists but has been injured in some way. Orthotics offer adequate external force to support the assisted movement of the person's limb. With the development of WR, the orthotics industry has grown. WR has been the subject of extensive research in the areas of rehabilitative devices, assistive robotics, human strength augmentation, vulnerability assessment, and strengthening exercises [20], [21]. To improve the freedom and quality of life of elderly people who have physical disabilities and persons with disabilities who have neurological issues, assistive and rehabilitation robots have evolved [22]. These devices are created to be worn by people and to work closely with the body [23], [24].

Although rigid traditional robotic systems offer high accuracy and repeatability, their large mass and weight make them unsuitable for close human interaction. Several strategies have been developed to overcome this problem and make interactions between humans and robots safer. The simplest method is to cover the robot with a soft, compliant material that would prevent the impacts of rigid materials on the human body, but this approach hasn't always worked. Soft robots have been proposed as a substitute approach for safer robot-human interactions. To create robots without rigid connections, soft robotics study takes inspiration from the biological of soft creatures without rigid skeletons, such as worms, octopuses, caterpillars, and others [25], [26].

2. RELATED WORK

Numerous research and review papers on rehabilitation robots have been published. Interest in this field has clearly increased, especially in recent years. Many of these articles focused on rehabilitation robots for the upper limbs compared to the lower limb robots. Narayan et al.[2] presented a tabulated comparison of upper limb robots with respect to design, control, and training modes. Li et al. [4] published a summary of the design requirements for in-home rehabilitation robots. Babaiasl et al. [9] introduced a review that included the classification of robots, their advantages, and disadvantages, as well as robot design, simulation, and control. Bardi et al. [27] presented a scheduling of numerous types of upper limb robots that included degrees of freedom (DOF) and type of control. The research also included experiments that were conducted to evaluate the device. Stephens-Fripp et al. [28] suggested an overview study of the experiences and desires of upper limb prosthesis users in Australia. Khalid et al. [29] conducted a review of various rehabilitation robots for stroke survivors, patients with spinal cord injuries, and other diseases, as well as for various ages. Assistive devices were also included in the study. The research presented findings, limitations, and outcome measures used to assess improvements and recovery to various upper limb parts. The review introduced by Varghese et al. [30] included the classification of robots based on design, operation principle, control… etc. In addition to their advantages and disadvantages. Demofonti et al. [31] reviewed low-cost robots focusing on the various techniques used to reduce production costs. Gull et al. [32] discussed upper-limb anatomy and the design challenges involved in developing an exoskeleton robot, the mechanical design of upper-limb exoskeletons, control strategies, actuation, power transfer, and exoskeleton design modeling. Additionally, they described the future prospects and potential difficulties for these robots. The intrinsic mechanical components that should be taken into account during the manufacturing process and the extrinsic biological components, which include the machine-human interface, physical performance, and user compliance, were categorized and examined as the factors and barriers affecting the adoption of soft wearables [33]. Significant obstacles to wider dissemination include the high cost and complexity of implementation, as well as the limited incremental clinical benefit [34]. Hays et al. [35] identified gaps and inconsistencies in assistive and rehabilitation devices in terms of strength, responsiveness, complexity, DOF, cost, …. etc. Islam et al. [6] presented the main drawbacks and limitations in the device design in addition to the development of the algorithm for controlling the exoskeleton to close the gap between the prototype research model and the commercial type.

Torre et al. [36] performed a review to evaluate upper limb spasticity using robotic-based methods. The review by Ochieze et al. [37] presented rigid and soft upper limb robots, their designs, and applications in various healthcare settings and discussed the technical requirements for these robots. Vatan et al. [15] specified a comprehensive review of wearable rigid and soft robotic devices for shoulder rehabilitation with their benefits and drawbacks. Peng and

Huang [38] assessed the typical mechanical structures, modeling methods, and control strategies of soft robots and classified them based on their operating technique. Chen et al. [39] classified Soft Wearable Robots (SWR) for the upper limb, lower limb, and back based on the different joints, and summarized the application of key technologies in terms of structure, actuator, and control.

Several reviews of hand rehabilitation robots have been presented, including a comparison of various design aspects as well as the advantages and disadvantages of each of them, and provided evidence for the effect and effectiveness of wearing soft robotics gloves for rehabilitation [40]. Cardoso et al. [41] conducted a review of WR that assist in hand rehabilitation following spinal cord injuries. The study included technical advancements such as user intention detection, portability, calibration, and consistent evaluation of functional outcomes for such injuries and functional electrical stimulation (FES) wearable devices. Shahid et al. [42] presented a summary of several exoskeletons for the soft robotic hand, with electroencephalography (EEG) and electromyography (EMG) based devices and controls, for rehabilitation and assistance in ADL.

3. WEARABLE ROBOTS

The usage of WR has quickly expanded in the last few years. Previously, they were kept in isolation in factories, because robots may seriously harm or injure people if they came into contact with them. However, robots can now integrate themselves into human bodies and directly assist humans because of the rapid advancement in technology. Application fields now comprise healthcare, medical, warehouse, construction, sports, material handling, industrial, and military. Because the robots may reduce human physical workload while boosting mobility and speed of movement, the economic and ergonomic potential of this sort of robot is immense [43], [44].

Wearable assistive robots have developed as a promising technology for assisting humans to improve, supplement, or displace limb movement functions, which are typically damaged after an injury, stroke, or natural aging. It also helps individuals with disabilities to be more independent in their daily activities. This robotic help is critical in enabling individuals to execute physical and social ADL freely, contributing to dignity and a higher standard of life. WR are available as exoskeletons, orthotics, and prosthetics, and can increase the strength of human limbs, recovering impaired limb functions, and substituting amputated limbs [45], [46] These assistive devices are intended to be worn by humans and interact closely with the human body. WR must, thus, be safe, dependable, intelligent, compatible, lightweight, and comfortable to ensure proper support, user safety, and device efficiency [47], [48].

WR are generally classified into two types according to the system materials: architecture, and operation [15]. The first type is wearable Rigid Robot (WRR) which has the advantage to be placed on the external human body to support the weight, but it is large and heavy in comparison to the human body, making the robot unwieldy and difficult to handle. The high inertia also increases the power demand of the robot, making power consumption a major issue and necessitating regular battery replacement. The second type is WSR, which is lightweight and considerably more comfortable to wear because the structure is made of fabric, soft plastics, and wiring. But, there is a problem in that the power that the system can create is significantly low, resulting in a low power transmission efficiency. This implies that the wearer will not be able to obtain a suitable degree of power from the robot [43].

There are three types of exoskeleton systems: full body, upper limbs, and lower limbs. It can also be classified based on its uses as rehabilitation, touch, assistive device, teleoperation, and energy increasing. Exoskeletons employ one or more devices that give the energy required to complete the task. Exoskeletons are categorized as active or passive based on the source of the mechanical force delivered to the body as illustrated in Figure 1. Passive devices have no external source of energy and depend on human movement or gravity to store energy and selectively release it at various stages of movement. A passive exoskeleton cannot assist or control motion; it uses mechanical elements such as springs and dampers that store and release energy when needed, enhancing the wearer's strength without adding inertia. A passive-adaptive exoskeleton requires an external power source to supply and control the actuator, a device that provides power, i.e. an electric, hydraulic, or pneumatic motor [49]–[52]. Exoskeletons can have varying DOF based on the design and desired performance. The proposed designs range from designs with one DOF to designs with 12 DOFs. The complexity of the system increases as the number of DOFs increases, while in the case of whole-body rehabilitation systems, the number of DOFs can be about 9, 10, or more [15].

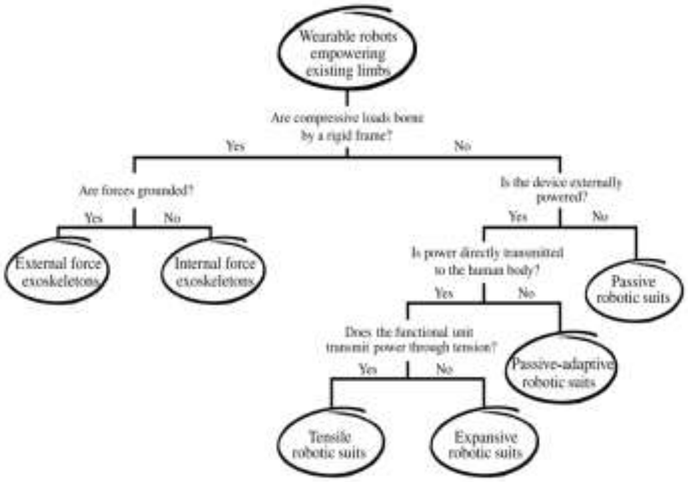


Figure 1: The two main types of WR: exoskeletons and soft robotic suits. Soft robotic suits are further subdivided into categories based on the way they are powered. Robotic suits that get their power from an external source can be classified as either using a tensile element or an expansion functional unit [52].

4. WEARABLE RIGID ROBOT

It is utilized to support movement activities, keep a person's balance when walking and replace a missing limb by attaching it to the patient's body and performing all of the tasks of the missing limb. their functions are managed and controlled by patients via muscle or brain impulses. Robotic prosthetics work directly with the human body. The essential parts in the design of robotic prostheses are stereoscopic appearance, physical requirements, simulation of movements, force application, and grip patterns in the actual human body [39],[46]. The exoskeleton WRR is also used to enhance muscle strength by using high output from a system constructed of a rigid material such as aluminum and plastic composite, as aluminum is a low-density material with appropriate strength qualities. Carbon fiber is also an excellent choice for exoskeleton body material [11] which also makes it suitable for employment in military and industrial applications. It was designed for military usage to transport heavyweight artillery projectiles or heavy-caliber machine guns as well as to move big loads for industrial purposes. It is also utilized in rehabilitation for patients with fewer joint spasms or who require higher power and torque [30] because it provides support and protection for the patient's limb and has fine movement control. However, human joints have a relatively complex anatomical structure in which the center of rotation shifts throughout the range of motion. This feature makes recreating the natural route of limb movement harder for exoskeletons that simulate human joints with rotating pairs. The imbalance between the exoskeleton joints and the wearer causes a reduction in cooperation. On the other hand, it eventually adds resistance to the overall system and adds another weight to bear, resulting in decreased wearing comfort [52],[53]. Additionally, the absence of flexibility in external structures causes secondary damage and injury as a result of the impact force generated by the quick motion of rigid constructions. Furthermore, it is heavy (the lower limbs of the robot weigh 15 kg to 25 kg) This necessitates more force and torque to move and, subsequently, the provision of more power sources [15]. Interestingly, this robot has complex structures and limited agility because uncomfortable rigid constructions prevent human limbs from moving normally in some directions. Finally, this robot is expensive. [23], [43], [44], [54], [55]. This results in poor human-machine matching, resulting in low energy efficiency and deviation from typical human movement [56]. Examples of rigid and semi-rigid robots are shown in Figures 2 and 3.

5. WEARABLE SOFT ROBOT

Various terms have been used to describe this new category of devices such as exomuscles [57], soft exoskeletons [58], and exosuits [59]. The term exoskeleton is derived from the Greek words έξω, outer and σκελετός skeleton the final portion of the word was changed to suit to refer to the device's soft frame. It indicates the similarity of WSR to clothing. The word exomuscles better expresses their working principles [52]. In contrast to the WRR, WSR is made of soft material which makes it highly safe for human-robot interaction, in addition to being inexpensive to construct and maintain, lightweight, and flexible (does not limit upper and lower limb movement). Rehabilitation training can be carried out anytime and wherever it is needed by patients, implying that the robot is highly portable for independent use. Significant material elements that have been utilized in a variety of WSR include shape-memory alloys, fabrics, Boden cables, pneumatic artificial muscles, and textiles. The most essential area of study is the creation of a lightweight power source capable of replacing electric or hydraulic actuators. Figure 4 shows examples of soft robots [43], [55], [60].

Figure 2: Examples of rigid and semi-rigid robots [43]

Figure 3: Rigid Exoskeletons of the Upper limb [32]

Electric actuators provide high controllability; however, their drawbacks include it is big size and heavy weight , and their temperature might rise in addition to being costly [61]. Hydraulic actuators have a high power-to-weight ratio, while hydraulic fluid leakage is a major concern in medically sterile environments. Additionally, it suffers from high friction. Pneumatic actuators provide a high power-to-weight ratio and have no risk of medical contamination. Pneumatic muscle actuators (PMA) are lightweight and generally compliant. Compliance softens the force generated by the PMA when its motion is impeded, making PMAs ideal for rehabilitation applications. but, it also suffers from high friction [62].

Figure 4: Examples of soft robots [43].

5.1 Wearable Soft Robot for The Lower Limb

This kind of robot is designed to help those who walk abnormally and to aid in the recovery of those who have undergone surgery or neurological conditions that may partially affect their ability to walk. Additionally, they are beneficial for those whose limb motor deficits prevent them from doing their daily tasks, as well as for the rehabilitation of patients with stroke and spinal cord injury [63] to support the ankles, knees, or hips. Figure 5 shows several examples of exosuits of the lower limb [53].

The human hip can move in several axes, including internal and external rotation, flexion and extension, and adduction and abduction [53]. Several studies have been conducted to design a robot that can be worn on the hip joint to reduce the load on the wearer, flex the hip, help extend the joint, help walk or run, and to strengthen the multiple movements of the hip [64]–[68].

The primary motor functions of the knee are flexion and extension. Many studies have been performed to improve knee flexion and extension [69],[70]. Sridar et al. [71] provided a flexible, lightweight, low-cost knee external prosthesis that incorporates a novel type of inflatable actuator to help knee extension during rehabilitation. Two soft inflatable actuators with various cross-sectional forms are used to compare the output performance. Sridar et al. [72] introduced a soft-inflatable exosuit for stroke rehabilitation that aids knee extension during walking training. The soft exosuit is intended to provide 25% of the required knee moment during the swing phase of the gait cycle, and it is coupled with inertial measurement units and smart shoe insole sensors to improve gait phase recognition and controller design as shown in Figure 6.

Figure 5: Example of lower limb exosuits [53]

Figure 6: The soft-inflatable exosuit's design [72]

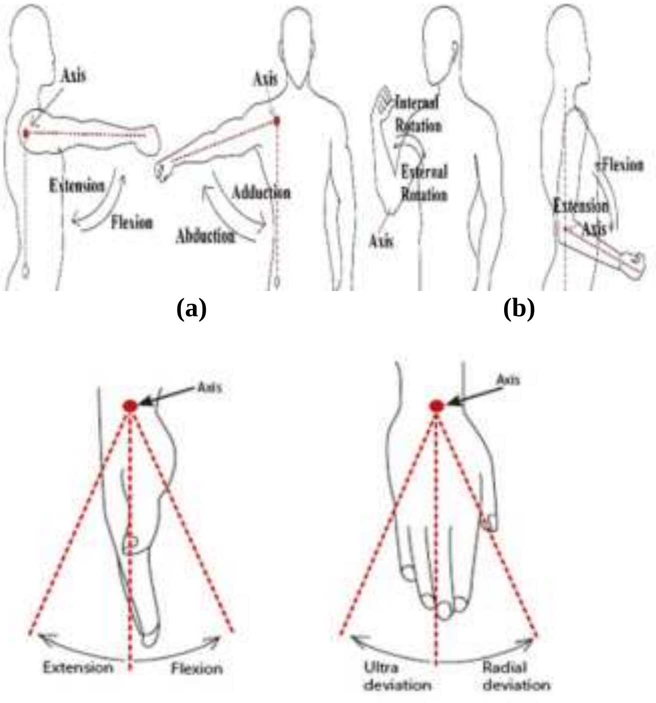
The essential ankle movements include internal and external rotation, plantar flexion, and dorsiflexion. The first usage of a soft exosuit as aid in walking after a stroke was presented by Bae et al. [73]. Textile clothing and cable-driven actuators are combined. It provides more comfort, makes donning and doffing easier, and does not limit the wearer's kinematics while maintaining the potential to produce significant moments at target joints during walking. The stroke-specific exosuit gives the paretic limb unilateral aid when walking. Thalman et al. [74] presented the design of a soft ankle-foot orthosis (AFO) exosuit to aid natural gait restoration for individuals suffering from foot drop. Exosuit is pneumatically powered and consists of soft actuators made of a thermally bonded, sock-like nylon fabric that is worn over the users' shoes. The system helps dorsiflexion in the swing phase of the gait cycle, using a soft contractile actuator and provides internal reception to the ankle joint while standing, using a stiffness variable soft actuator.

5.2 Wearable Soft Robot for The Upper Limb

The function of upper limb robot devices is to provide rehabilitation or assistance to any part of the upper limb, including the shoulder, elbow, forearm, wrist, and hand [15].

5.2.1 Shoulder Wearable Robot

The human shoulder represents one of the most complicated joints in the human body. Because of their wide range of motions, shoulder flexion/extension (f/e), abduction/adduction (a/a), internal/external rotation (r/t), and circumduction are fundamental shoulder motions as shown in Figure 7 (a) [2]. Exoskeletons must be able to fit the capabilities of the shoulder to be effective. Shoulder exoskeleton actuators must be fitted to each user's specific stereoscopic measurements. Each patient requires a specific actuator. This was overcome by developing an exoskeleton with the ability to make structural changes in order to vary and alter its mechanical performance based on the needs of a specific user. The actuator is made up of an inflating and changeable fabric bladder system and a flexible fabric spine [75]. O'Neill et al. [76] developed a soft fabric-based armpit pneumatic actuator that combines two types of pneumatic actuators to push the arm upward while two smaller actuators rotate the abduction actuator to allow horizontal expansion and bending. When not in use, the actuator's ability to unfold flat is invisible. It's nearly simple to put on and take off as normal clothes. Due to the difficulty of predicting the smooth and reliable behavior of textiles, textile-based design is frequently an iterative process. The tapered, multi-component pneumatic actuator is made of a high-strength textile with a polyurethane membrane inner bladder. The influence of the operator's geometric parameters was studied to obtain multiple designs. Figure 8 shows the model integrated into a WR to assist the shoulder in abduction and placed under the armpit [77].



(a) **(b)**

(c)

Figure 7: Schematic diagram of (a) shoulder flexion/extension, abduction/adduction, and internal/external rotation, (b) elbow flexion/extension, and (c) wrist flexion/extension and ulnar/radial deviation [2].

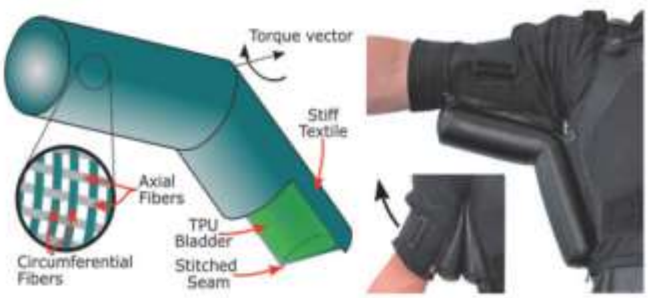


Figure 8: Textile-based pneumatic actuator worn under the armpit to assist in the abduction [77].

Thompson et al. [78] proposed the basic design concept of a cable-driven exosuit with soft pneumatic actuators that provide shoulder flexion. They used fiber-reinforced elastomeric enclosures to develop two actuator designs, the nested linear and pennate forms and then compared their output properties. The driving power was transmitted to the relevant joint via a Bowden cable.

5.2.2 Elbow WR

The most popular movements for the elbow joint are flexion/extension (f/e) and supination/pronation (s/p), as shown in Figure 7 (b) [2]. Chen et al. [55] propose a reinforced soft pneumatic actuator with flexible support and two TPU composite bladders to provide patient-specific rehabilitation training for human wrist and elbow joints. Carvalho et al. [62] produced a pneumatic muscle actuator constructed to move the elbow's exoskeleton. It displayed the construction and evaluation of 12 pneumatic muscles of different sizes and materials to determine the most effective combination for the intended purpose. The experiments revealed that muscles with higher tensile moduli had better load-bearing capacity, lower hysteresis, and lower contraction and force characteristics. Irshaidat et al. [79] proposed a soft robot for the elbow joint that allows patients to perform repetitive movements for rehabilitation. It consists of two pneumatic extensor muscles that can flex on the remote side and a pneumatic flexor contractor muscle on the opposite side, this increases the force generated when bending and extending the arm and is suitable for a wide range of people. Figures 9 and 10 show examples of elbow WR.

Figure 9: Elbow and wrist rehabilitation training [55].

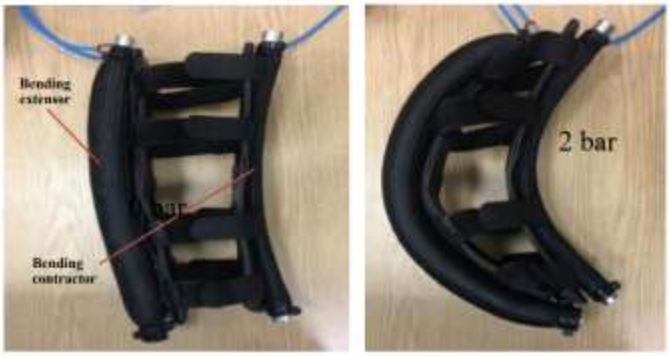


Figure 10: A soft robotic arm for elbow rehabilitation is consisting of soft and bendable parts without separate joints to minimize external structural alignment with the user's arm [79].

The exoskeleton, Carry, was designed by Nassour et al. [80] to reduce stress and workload and to reduce the risk of injury. Carry uses a soft human-machine interface and a soft pneumatic actuation to assist the elbow with strength and weight bearing. Carry's assistance reduces muscle activity, net metabolism, and fatigue. They found up to 50% reductions in muscle activity and 61% in net metabolism. Ang and Yeow [81] explained the attempt to develop a 3D printable soft exoskeleton with high force to assist the user in flexing the elbow. The soft actuator has a peak force of up to 100 N. They also present a force model that allows the dimensions of the bellow-based actuator to be adapted to different payloads when the actuator is used in other applications.

5.2.3 Wrist WR

Wrist exoskeletons are often designed for rehabilitation or general haptics, and each exploits a unique kinematic property. Portable wrist exoskeletons are classified as rigid (A–C), compliant (D), or soft (E–J) in Figure 11 [82]. Flexion and extension of the wrist and ulnar and radial deviation are the basic movements of the wrist, as shown in Figure 7 (c) [2]. A soft exoskeleton robot was developed by Hassanin [20] to increase energy and rehabilitate the wrist. It can perform extension movements in flexion, abduction, and adduction. Its external structure adapts to the size of an adult's hand without requiring mechanical modifications, i.e. it can be easily interchanged between users.

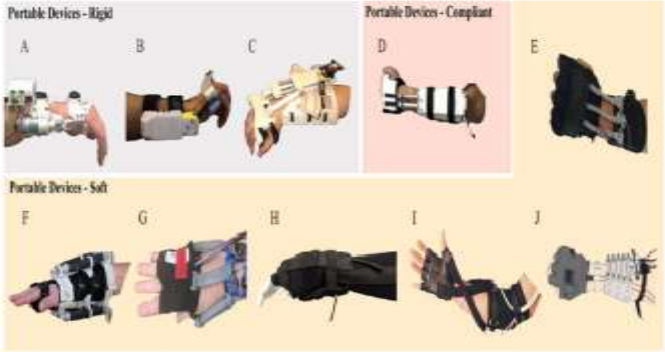


Figure 11: Wrist exoskeletons in the state of the art can be classified as rigid (A-C), compliant (D), or constructed of soft materials (E–J) [82]

Andrikopoulos et al. [83] designed a robotic Exoskeletal WRIST (EXOWRIST) working model for wrist rehabilitation purposes which is considered the required infrastructure for enabling future therapeutic applications. They are distinguished by adjustable performance to meet the needs of individualized configuration, assisted movement ability, high reliability in different treatment environments and conditions for safe human-robot interactions, and low or no need for maintenance. The EXOWRIST employs PMAs to perform two DOFs (extension-flexion, ulnar-radial deviation) movements made by the human wrist as in Figure 12.

Figure 12: The four design stages for the EXOWRIST device development: (a) An arm and hand replica is used, with a spherical joint acting as a passive wrist. (b) A wearable neoprene-based glove covers the forearm and hand, providing the required orthopedically support and protection to the wrist. (c) For PMA support, plastic equipment is placed on the glove. (d) For further support, thermoplastic coverings are properly positioned. (e) Four PMAs are connected to the support equipment and wrapped around the forearm symmetrically [83].

A wrist-soft exosuit prototype that aiding healthy participants in working contexts was presented by Chiaradia et al. [82]. It consists of a glove that was reinforced using flexible 3D-printed plastic parts. Due to their ergonomic shape, these flexible elements were made to be as stiff as was required for effective force transmission while maintaining comfort. The created exosuit was light, safe, and efficient in aiding users in both isometric and dynamic duties using an admittance controller because of the sewed reinforcement. The significant reduction in users' muscle activity and stress justify the relevance usage of flexible structures in conjunction with fabric gloves for the proper delivery of exosuit assistance.

5.2.4 Wearable Soft Robotic Glove for Hand

As ADL performance is heavily relying on hand function, human with hand impairments are less able to carry out ADLs, which leads to reduced quality of life. Neurological and musculoskeletal conditions that can cause hand impairments include arthritis, cerebral palsy, Parkinson's disease, and stroke [40]. Rehabilitation of hand functions requires physical treatment, which involves carrying out repetitive actions that are frequently separated into specific tasks similar to those performed in daily life, such as gripping and pinching, to improve hand functions in terms of power and range of motion [84]. A new method includes the use of technology innovations to provide effective, intense, and task-specific hand training for direct hand support while providing ADL based on the concept of a wearable robotic glove. People with impaired hand function can also use their hands for a variety of daily tasks with the aid of such a glove. This is believed to enhance patient independence in carrying out ADL and hand function [48]. The glove's design must consider the size of the hand so that a user with limited hand function can easily put on and remove the device. The weight of the glove must also be considered and must not exceed 0.5 kg [85]. Additional components of the system necessary for power, operation, or control can be placed around the waist or back and must weigh less than 3 kg, which is the normal weight of portable consumer electronics. Furthermore, the materials from which the glove is constructed must be considered, so that it is soft, suitable, and does not impede finger movement when unpowered [86][87].

Hand exoskeleton control strategies can be classified into two types: low-level control techniques and high-level control techniques. In low-level control techniques, the controller addresses the physical properties of the device, such as force, torque, and position. Based on the design specifications, it employs simple control loops for positioning or controlling force/torque. A high-level control approach, which measures the exoskeleton and the surroundings, is also known as an impedance or admittance control strategy. In executing positioning and force-related activities [42], [88]. This utilizes information from low-level controllers to measure multiple factors at once, such as gripping force, finger location, and bending angle. It also enables more accurate calculation of values such as the shape of an object, the gripping power required to hold an object, the stroke speed, and many other variables. This benefit allows for better control of position based on the shape of the object and applies the necessary forces for a near-perfect grasp [89]. Three different kinds of actuators are employed: hydraulic, pneumatic, and cable systems. Cable systems are those that attached at the distal phalanges with cables. When tension applied, it could direct finger flexion or extension. It was made to look like the muscle tendon systems of the hand's bending and extensor. Pneumatic systems use pressurized air to bend and/or extend fingers through an actuator in contact with the hand. On the other hand, hydraulic systems pressurize the actuator with some kind of fluid rather than air [40].

The majority of hand exoskeletons made for clinical research are pneumatically powered. These robotic gloves are powered by air pressure that flows via air tubes and is controlled by particular pressure valves; the air compressor is the source of pressure. To open and close the fingers, pneumatic actuators are tied to the gloves. A glove can be made to accommodate a patient's fingers of any size. To evaluate the grip strength, pressure sensors are used with the glove [8],[90]. Examples of these devices are MRC gloves [84], rheumatoid arthritis rehabilitative devices (RARD) [91], and rheumatoid arthritis (RA) gloves [92]. The MRC glove was made to assess neurological progress during a physiotherapy session. In this kind of glove, closing and opening the fingers are done by increasing and decreasing the actuator pressure, respectively. To determine the bending value and the patient's stage of recovery, the bending angles of the affected fingers can be measured [93],[94].

Polygerinos et al. [86] introduced a glove with soft actuators made of molded rubber chambers enhanced with fibrous reinforcements that produce bending, torsion, and trajectory under fluid pressure. A cheap soft hydraulic actuator is composed of flexible materials with fiber reinforcements for finger control. It is used to support comfortable flexion and extension of the hand and it has low resistance when it is not active. The thumb soft actuators have at least two DOF, one for flexion and one for rotary movement (flexion and abduction). For other fingers, the actuator has three DOF as shown in Figure 13.

Figure 13: soft robotic glove in which the soft actuators are attached to the dorsal side of the hand providing an open interface to the palm that does not impede the motion [86].

Polygerinos et al. [95] designed the EMG-controlled soft robotic glove made up of soft actuators that mold to the user's hand using a mix of elastomeric and inextensible materials. Electromyography electrodes placed on the user's forearm are utilized to identify his/her purpose, whether closing or opening the hand, by monitoring gross muscle activation signals with the surface. It has an open-loop surface electromyography (sEMG) that sensitizes muscle contractions and sends the information to a low-level fluidic pressure controller that adjusts pressure in pre-selected groups of the glove actuators as in Figure 14.

Figure 14: Illustrated the separate textile layers of the glove and the prototype glove [95].

The exoskeleton of the glove is designed by Al-Fahaam et al. [22],[96] to enhance energy and rehabilitate the hand by using soft pneumatic actuators with variable stiffness, bendable artificial extensor and contractile muscles. The exoskeleton is proportionate to the size of any adult hand requiring no mechanical alteration from one hand size to another. EMG signals from the hand are used to test the suggested prototype assistive force. The extensor artificial muscle is bent by strengthening one side with a strong thread while the other side is still free. when more pressure is applied to the artificial bending muscle, a greater twisting or bending angle can form. And by putting another contraction muscle on the terminal part of the bending muscle, the partially variable stiffness soft actuator is transformed into a fully variable stiffness soft actuator [22]. The second contraction muscle is responsible for controlling the stiffness of the bending of the muscle's second portion (Figure 15). The amount of stiffness is dependent on the level of pressure inside the contraction muscles. Heung et al. [94] introduced a soft-elastic composite actuator consisting of fiber-reinforced actuators and a bottom torque-compensating layer to assist stroke patients with finger bending and extension to enable ADL. The bending and stretching capabilities of the model were tested. The constructed glove made it easier for the patient to open, close the hand, and grip things.

Figure 15: The exoskeleton glove is made by sewing four variable stiffness actuators onto the dorsal side of a traditional worker glove. A solenoid valve controls the muscle filling and venting separately [22].

A soft assistance exoskeleton glove is intended to aid post-stroke rehabilitation as in Figure 16. The soft bending actuator used in the glove has a rubber-like flexible feature. Thus, flexing of the finger is easily accomplished with air pressure. Nylon gloves are employed because of their elastic properties, which allow for more flexible finger movement when the actuators are triggered. RTV silicone was employed as an adhesive agent. The surface of the glove does not harden, which is advantageous to the user since it does not impede the movement of the actuator. The rubber actuator remains flexible and tightly affixed to the glove surface. RTV silicone is also utilized as a sealant at the entry of the rubber actuator to ensure that the pneumatic tubing remains inside the rubber actuator regardless of air pressure. It also keeps air from leaking through the entrance [97].

Wang et al. [98] developed the Stretchy Rehabilitation Glove, which is made of a soft, bi-directional pneumatic bending actuator. The design aims to optimize the rate of motion and actuation force to satisfy the demands of ADL while decreasing weight and volume to provide comfort while training. The design enables both stretching and gripping. Biggar and Yao [99] introduced a wearable and adaptive glove design. Motion analysis was performed on the prototype to measure how well it performed in comparison to the hand when a variety of blocks and spheres were being grasped.

Figure 16: Illustrates the rubber actuators mounted to a nylon glove. The rubber actuator attaches to the top of the nylon glove, and the entrance to the pneumatic tube is entirely closed. RTV silicone was employed as the adhesive agent [97].

GRIPIT was designed by Kim et al. [100] to assist users in grasping tools with their hands by utilizing a light compact assistive device that is manually actuated by a single wire. GRIPIT is made up of merely a glove, a wire, and a small structure that keeps tendon tension constant to allow for a solid grasp. The tendon routing points are intended to exert force on the thumb, index finger, and middle finger to establish a tripod grip. A tension-maintenance structure maintains proper tension in the clutching posture. GRIPIT could be developed to assist the majority of daily hand functions by inventing additional forms of its glove for various grip postures and enhancing its wearability and ease of usage. Yao et al. [101] produced a soft glove construction with strings, bands, and shape-memory alloy (SMA) spring actuators to mimic the functions of the ten tendons of the human hand. The gripping performance of the muscle glove with coupled and uncoupled flexion of the finger joints was compared to attain the functional range of motion of the human hand. The uncoupled control achieves a better fit between the grip position and the form of the object, resulting in more effective force transfer.

A soft, wearable functional Magnetic Resonance Imaging (fMRI) compliant glove was introduced to study brain activity and motor performance during hand rehabilitation and training for a specific task as shown in Figure 17 [84]. It consists of a glove and a set of soft pneumatic actuators made of silicone rubber that generate bending motion and stimulate finger joints when pressure is applied. The significant delay and narrow bandwidth of the glove make it unsuitable for applications that require high kinetic control and dynamic interactions with the hand and fingers, but it is appropriate for simpler activities like pressing hard, grasping, and opening.

An easy-to-use soft mechanical glove that supports grip strength and hand training exercises at home has been developed; The participants are instructed to perform hand exercises (games) with the ironHand system for, at least, 180 minutes each week to provide additional strength for the grip of the thumb, middle, and ring fingers. The first support is provided by artificial tendons in the soft robotic glove as in Figure 18. This randomly controlled experiment is one of the first of its sort, looking into the impact of using a WSR for hand assistance at home for several weeks. The results of this study revealed that participants could utilize both modalities (assistive and therapeutic) of the ironHand device on their own for an extended period at home. Participants in the therapy group improved their unsupported handgrip strength and pinch strength after 4 weeks of using ironHand [48].

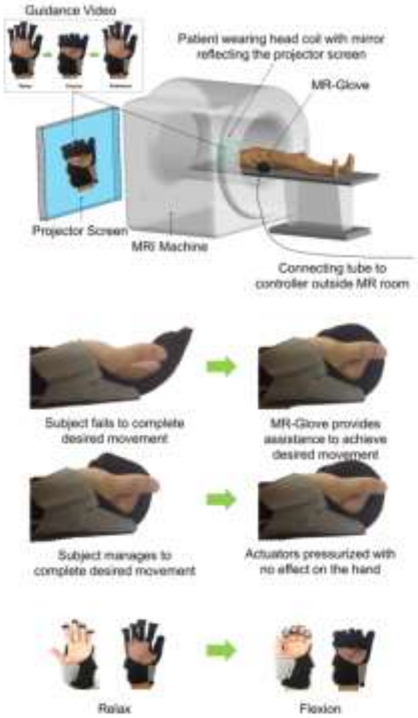


Figure 17: Magnetic Resonance-Glove combined with fMRI [84].

Figure 18: The ironHand system [48]

6. CONCLUSION

WSRs are preferred to WRR when it tends to be used in human-robot interaction such as rehabilitation. Even though rigid robots have high accuracy and repeatability, their mass and weight render them unsuitable for close human interaction. In contrast, soft robots are more lightweight and comfortable to wear since the system is made of soft materials like fabrics, textiles, and artificial pneumatic muscles, making them extremely safe for human-robot interaction and relatively cheap to build. This paper provided several references for WR for the upper limbs, including the shoulder, elbow, wrist, and hand, in addition to the lower limbs, including the hip, knee, and ankle.

This study focused on upper-limb robots, particularly the hand. Future work will include a greater focus on lower-limb robots and an expansion of the topic of assistive prostheses, whether soft or hard robots.

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