




Review

Soft Exoskeletons: Development, Requirements, and Challenges of the Last Decade

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Abstract: In this article, various investigations on soft exoskeletons are presented and their functional and structural characteristics are analyzed. The present work is oriented to the studies of the last decade and covers the upper and lower joints, specifically the shoulder, elbow, wrist, hand, hip, knee, and ankle. Its functionality, applicability, and main characteristics are exposed, such as degrees of freedom, force, actuators, power transmission methods, control systems, and sensors. The purpose of this work is to show the current trend in the development of soft exoskeletons, in addition to specifying the essential characteristics that must be considered in its design and the challenges that its construction implies.

Keywords: soft exoskeleton; rehabilitation therapy; robotic enhancer; daily assistance; human-machine interface



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1. Introduction

Exoskeletons have been extensively researched and developed to aid the movement of various joints in the body. These devices can involve a single degree of freedom (DOF), for example, flexion and extension of the forearm, or multiple DOF, like hand movements. The complexity and physical capabilities of the exoskeleton depend on various factors, including the force/torque transmission medium, the range of motion, and the method of control.

One way to classify exoskeletons is according to their actuation devices, which can be electric, pneumatic, hydraulic, and hybrid. Electric actuators have the advantage of being fast and precise, but they are less resistant to sudden power changes. Alternatively, pneumatic and hydraulic actuators can perform various rotational changes and support heavier loads without overheating, but their power supply is weighty, complicating their portability. On the other hand, various power transmission methods have been used, for example, cables, rods, gears, elastomers, hydraulic and pneumatic hoses. The choice of these elements gives attributes to the exoskeleton that must be evaluated from the design. An incorrect configuration would negatively affect the user, not allowing continuous and prolonged use of the device.

Motor-driven metallic devices offer several advantages, including rigid and robust structures, as well as precise transmission of forces. However, these devices have certain disadvantages, such as being heavy and uncomfortable for the user. Additionally, due to their weight and complexity, most are not portable, and their installation requires

trained personnel. For this reason, the development of soft robotic devices is a trend that has been increasing, and various research groups are working on their construction and innovation [1,2].

Soft exoskeletons replace many or all of the hard, big and rigid elements with soft, light, thin and flexible ones. Further, some components that must remain rigid, such as batteries and controllers, are often placed in a backpack or separately to reduce weight. These devices are lighter, more flexible, and offer greater user comfort. Additionally, due to their characteristics, they are easier to transport and install, allowing the patient to use these devices alone and in multiple locations. Soft exoskeletons have been made to aid the movement of the fingers [3,4], wrist [5,6], elbow [7,8], shoulder [9,10], hip [11,12], knee [13,14], and ankle [15,16].

In this article, we carry out an analysis of the development of soft exoskeletons focused on the last decade. The study was conducted for different areas of the body, covering the upper and lower joints. We describe the current features, applications, and trends in the development of these devices. In Section 2, the general applications used for soft exoskeletons are mentioned. Section 3 sets out the main requirements to consider when designing a soft exoskeleton, as well as the challenges to overcome to build an efficient and safe device. In Section 4, soft exoskeletons are analyzed in different works, and their main characteristics are exposed. Additionally, a general explanation of human joints is provided, mentioning its structure and the types of movements it performs. The analysis is divided into two main groups: upper and lower joints. The first group includes the shoulder, elbow, wrist, and hand. Further, the second group focuses on the hip, knee, and ankle. In Section 5, the discussion and conclusions are presented.

2. General Applications

Soft exoskeletons are developed for different purposes. One of them is as an enhancer that increases the physical abilities or capacities of the individual [17,18]. Another use is to assist the patient with daily activities, supporting a weakened or disabled joint with a lack of strength or movement [19,20]. They are also used as rehabilitation devices, performing therapeutic movements on disabled joints [4,21].

The exoskeleton as an enhancer is used in people who do not have any motor disabilities. Further, its uses are intended to improve the skills and increase the individual's strength. They are used for work, military, and even space purposes [22–25]. On the other hand, assistive exoskeletons help the individual through auxiliary forces to perform adequate and precise movements in daily life tasks. It is useful for the elderly who have atrophied joints, and some of their daily activities cannot be fully or partially performed. They are also used in people with motor disabilities caused by illness or accidents. Various devices have been developed to provide the power required for standing [26], walking [27], or lifting [28,29].

Another important use is rehabilitation, which presents complex structural design and control challenges. For example, forces must be imparted safely to patients with limited physical and cognitive abilities. It is well known that it is possible to improve motor skills through rehabilitation therapy like passive movement exercises, which involve repetitive movements in the affected joint. Some studies have shown that patients who use soft robotic devices in rehabilitation therapy improve the recovery of motor skills, both in the short and long term [30–33]. Including robotic exoskeletons in the rehabilitation process allows prolonged, controlled, and precise therapies, with quantitative and measurable results. Additionally, if the system is inherently safe and portable can be used outside the clinic. Increasing the safety, comfort, and quality of therapies and reducing the workload of doctors and therapists.

Various actuation methods of actuation have been implemented in soft robots, such as electroactive polymers [34,35], shape memory alloy [36,37], and fluidic actuators [38–40]. Electroactive polymers change shape or size when stimulated by an electric field and are widely used in robotics as actuators or sensors. Shape memory alloys are materials

that change shape when subjected to thermomechanical or magnetic variations and can return to their previous form at the end of the stimulus. Fluidic actuators are commonly comprised of a chamber inflated with a pressurized fluid. They are widely used in soft robotics due to their high energy density and simple manufacturing.

On the other hand, the development of submersible technology is a growing trend in various fields such as telecommunications, sensors, and robots. Currently, several soft robotic devices have already been developed in underwater applications [41]. In order to provide precision and adaptability to the user in an environment that presents instability due to various disturbances.

3. Requirements and Challenges in the Development of Soft Exoskeletons

Different structural and functional properties must be considered in the development of soft exoskeletons. The mechanical design is a crucial element, and it is essential to define the characteristics that optimize the design and benefit the user. Some significant properties are weight, safety, portability, softness, comfort, to name a few. Each of the properties that should be considered in exoskeleton design is explained in more detail below.

Power to weight ratio: The energy demand necessary to assist any joint in the body is usually high. Therefore, it is essential to use actuators with a high power-to-weight ratio to create lightweight exoskeletons with sufficient force and speed to move the joints correctly. Due to the limited space in an exoskeleton and the high torques required for its operation, actuators usually must be modified to maximize the power-to-weight ratio. The weight must be reduced as much as possible to avoid uncomfortable loads for the user. The lower the weight of the device, the lower the inertia in operation. The actuators are components that substantially increase the weight of the exoskeleton. For this reason, it is essential to reduce the number of actuators by adding passive and quasi-passive elements to the design. For example, it is significant to include brakes or clutches to maintain a fixed position at specific times. Further, shock absorbers reduce the impact of the forces inherent to the system. Springs add some momentum to the initial phase of the movement.

Safety: It is an elementary point to consider for exoskeleton users who have motor disabilities or muscle weakness. A small error in the structure or operation of the device could cause serious injury to the user. For this reason, it is essential to include security and control elements that stop or correct the device in case of unforeseen events. Device variables must be continuously monitored. If any reading is outside the safe range, the actuators should stop or display a warning. Mechanical stops should also be included at the various joints to prevent the device from exceeding the intended ranges of motion. Additionally, sharp edges should be excluded.

Control: The control system must continuously monitor device variables such as position/angle, speed, temperature, current, and force/torque. Further, if any measure is outside the reliable ranges, corrective actions must be applied. Although soft structures are usually less dangerous than rigid ones, soft exoskeletons must be rigorously monitored as they present greater ruptures and deformations. It is crucial to include fault-tolerant control strategies that mitigate user misoperation and unforeseen structural errors. Therefore, feedback elements such as force, position, impedance, admittance, pressure, or displacement sensors are used. Likewise, electromyography and electroencephalography signals are used in motion detection for activation or deactivation of control elements. However, non-biological signals are mostly used as they are easier to identify. Some exoskeletons use impedance as the basis of control [42,43]. On some occasions, the patient has a partial motor disability and only needs to receive a specific force to complete the activity. This is a big challenge as the movement intent and power of the user must be detected correctly. Further, according to that detection, it is necessary to establish a suitable control system for the exoskeleton.

Portability: It is directly related to the weight of the device. The lower the weight of the exoskeleton, the greater the portability. Further, this benefits the patient by moving facilely without excessively fatigued. Furthermore, for portability, the device must be

compact, easy to equip and remove, and maneuverable so that the user can move freely. Additionally, the system complexity should be reduced and only include the degrees of freedom that allow the desired mobility. The power supply and some actuators should be located away from the affected joint or separate from the body. Some systems are accompanied by walkers with automatic wheels, which carry heavier components, such as motors, controllers, electronic boards, and batteries [44]. Another significant point to achieve portability is to unite the device's components in a garment that is easy to put on and take off, for example, an exoskeleton of the hand attached to a glove.

Softness: Moving from hard to soft mechanical systems has spread across many fields of robotics. This is mostly due to the desire to replicate biological models [45]. For this reason, elements such as elastomers, flexible cables, pneumatic and hydraulic pipes are incorporated for the transmission of forces and torques. The advantage of these elements is that they are easily adapted to the characteristics of the user. Additionally, they resist vibrations better and are lighter. Another advantage is that there are no maximum contact forces, as soft devices deform and distribute forces more facilely.

Comfort: Generally speaking, an exoskeleton should mimic the movement of biological joints and provide comfort to the user. The exoskeleton must include various features to provide comfort. Such as maneuverability, breathability, adaptability, softness, lightness, and simplicity to equip and remove. The more comfortable the user feels, the longer they can use the device. One way to provide user comfort is to integrate robotic devices into soft material garments that are easy to put on and take off. These are known as soft exosuits [27,46].

Durability: In soft robotic construction, the metallic and rigid elements are replaced by soft and flexible materials. These structures have greater fragility and lower durability. Additionally, other phenomena that elastic materials possess must be considered. Such as hysteresis, which becomes significant after several repetitions or cycles of action. Further, it increases the chances of failure. Therefore, to increase the device's durability, it is necessary to add control elements that carry out the relevant measurement and correction.

Accessibility: Many of today's exoskeletons are inaccessible outside of a clinical or specialized setting due to factors such as cost, weight, and safety. Additionally, the installation and handling of the device are often complex and require constant attention from trained personnel. Therefore, some features such as portability, simplicity, and low cost need to be implemented in the exoskeleton to increase accessibility. The accessibility of exoskeletons is improved by avoiding heavy, sharp, and complex components as much as possible and also reducing costs through the use of locally available materials.

Bidirectionality: Forces/torques must be produced in opposite directions to generate bidirectional movement in the joints. In specific cases, a unidirectional action can be used, such as for shoulder abduction and adduction, where it is possible to apply a single direction force for the abduction and separate the arm from the torso. Then, we eliminate or reduce the power to produce the adduction allowing the arm to return to its position by means of its own weight.

Transmission: Power transmission methods are highly dependent on the actuation method. For example, electric motors often include gears, cables, and pulleys. On the other hand, pneumatic and hydraulic actuators use cylinders, pistons, and flexible tubes. The pneumatic and hydraulic transmission are easier because the flexible tubes maintain uniform pressure in most of their structure, which facilitates their measurement and control. One of the advantages of the transmission system is the distal positioning of the actuators. It allows not to overload the affected joints. There are common errors in the transmission system, such as being bulky, heavy and misaligned. Furthermore, it presents undesirable deformations and disturbances, which could cause damage to the user. For this reason, the transmission must be efficient, mechanically simple, and without misalignment.

Stability: It is essential to efficiently perform any task of daily life. For example, in gait, hip abduction/adduction controls the width of the stride and thus the stability of the subject. A small disturbance implies losing control of the movement and even causing a

fall. For this reason, exoskeletons must include systems for acquiring information about the state of motion to correct them with additional forces to provide greater stability.

Maneuverability: The flexibility of the mechanism plays a key role in the ergonomics and comfort of exoskeletons. The range of motion can be limited based on its material, geometry, and flexibility. Exoskeletons must be designed to preserve maneuverability by allowing a full range of motion in biological joints.

Adaptability: The dimensions of the device must be adapted to the anthropometric measurements of the patients. It should be easily adjusted for use by different users. Or also in the same patient who requires slight modifications due to morphological changes.

Modularity: Making a modular device allows changing the behavior of the system. Further, we adapt it to the evolution and abilities of the patient. This with the facility of implementing and removing modules according to the needs that are required.

Actuators: They are devices with the ability to convert energy into movement. Pneumatic, hydraulic, electric and hybrid actuators are used in robotic applications. Hydraulic and pneumatic actuators have a high power density, and their power transmission is simple. However, they require demanding maintenance to prevent leaking and corrosion. Furthermore, the power supply is usually bulky and heavy, preventing it from being compact and portable. So, it is usually placed externally to the device. On the other hand, electric actuators have higher speed and more control and precision in force, torque, displacement, rotation, etc. Additionally, batteries are more portable due to their compactness. However, its transmission method has low energy efficiency, higher complexity (gears, cables) and misalignments.

Fixation: The design of exoskeletons often includes fixators that maintain the position of the device despite the transmission of forces. The fixators must resist the pushing force of the actuators. Further, they should not put pressure on the body for a long time because it causes medical problems due to prolonged stress. Therefore, it is advisable to use a controlled fixator, applying compressive forces only when is needed.

Alignment: It is of great importance to achieve efficient mobility. However, misalignment is normal due to substantial movement of the skin with the bone or unexpected forces. Therefore, it is essential to guarantee the device alignment through correct fixation or adding a control system that corrects misalignment.

Costs: The exoskeleton must be affordable for patients or health institutions. For this, in the design of the exoskeleton, it is essential to include components of easy acquisition in the marking and simplify the manufacturing process.

4. Development of Soft Exoskeletons

A prosthesis is used to replace a joint in the body. Further, the exoskeleton is designed to fit around a joint according to the physiological characteristics of the user. It is often used to activate a paralyzed or semi-paralyzed joint. It is divided into two main parts, the mechanics and the control system. Aspects such as DOF, support structure, actuators, and transmission components must be analyzed in the mechanical system. Further, the sensors, encoders, and control signals must be considered in the control system. Wearable devices are rapidly evolving to meet the mobility and autonomy needs of people with motor disabilities. Soft and portable exoskeletons are a trend that seeks to replace rigid materials that are heavy and uncomfortable with lightweight materials such as fabric, elastomer, plastic, cable or silicone-based elements. To better understand the development of these devices, it is essential to know some important concepts. For example, the planes and axes of motion, shown in Figure 1. Three planes divide the body, one is the sagittal plane that is divided into right and left. Another is the frontal plane that divides into anterior and posterior, and finally, the transverse plane that divides into superior and inferior. Likewise, there are three axes of a movement known as the medial–lateral axis (sagittal plane), anteroposterior axis (frontal plane), and longitudinal axis (transverse plane). A degree of freedom is the change in position that occurs in a plane. Further, the human

body has different joints that vary in the number of degrees of freedom to complete their movements (uniaxial, biaxial, and triaxial).

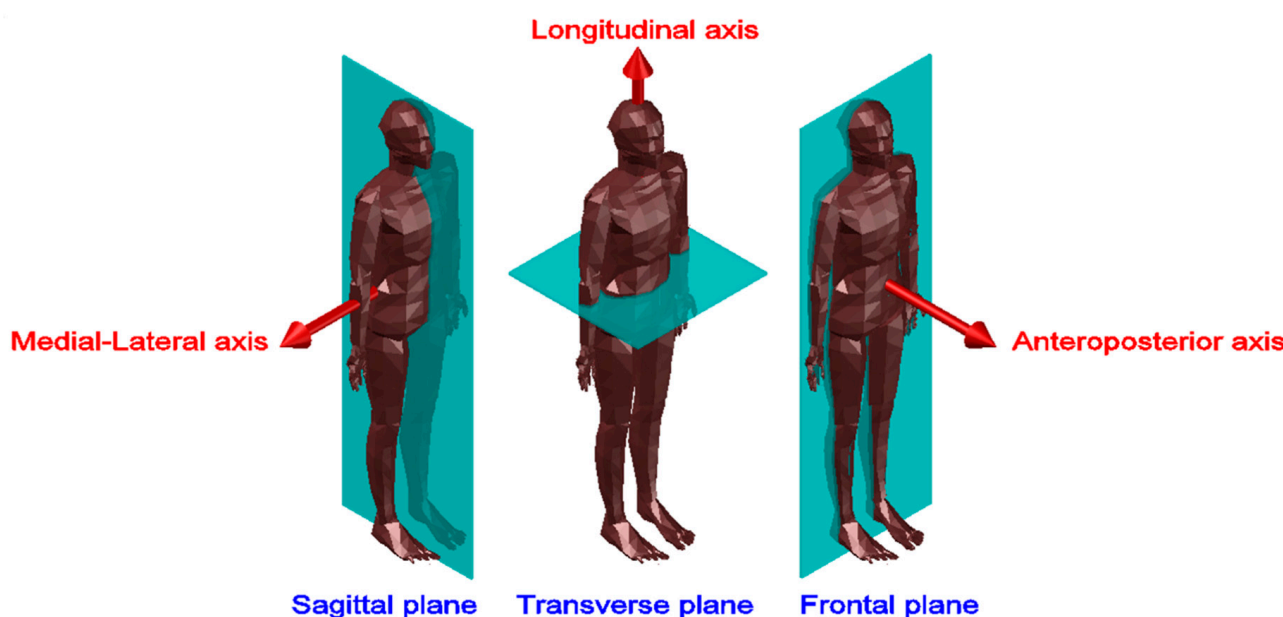


Figure 1. Planes and axes of movement of the human body.

The movements related to the sagittal plane are flexion and extension, such as bending the trunk back and forth, or raising and lowering the leg. Changes in position in the frontal plane are related to abduction and adduction movements, lateral flexion of the trunk and head, or inversion and eversion of the foot. The transverse plane corresponds to the rotation of the hip, shoulder or spine, as well as the pronation and supination of the forearm.

Some works on soft exoskeletons are detailed below. Its main features and functionality are mentioned. In Section 4.1, the soft devices created for the upper limb are explained. Specifically, the shoulder, elbow, wrist, and hand are addressed. Section 4.2 details lower extremity soft devices, specifically about the hip, knee, and ankle.

4.1. Upper Limb Exoskeletons

Upper limb anatomy consists of the shoulder complex, elbow complex, wrist joint, and fingers [47]. In general, after a stroke, most survivors have disabilities that prevent them from performing ordinary activities. Further, the upper extremities are the most common disability among stroke patients [5]. Therefore, prolonged and intense robotic assistance in rehabilitation therapy has been shown to reduce motor deficits and increase recovery speed in the upper extremities [48].

4.1.1. Shoulder

The shoulder complex is modeled as a ball-and-socket joint. It has three DOFs and corresponds to flexion/extension, abduction/adduction, and internal/external rotation movements [47]. Table 1 details the main characteristics of soft exoskeletons based on the shoulder complex.

The shoulder joint is very important because it is the first in the upper limb kinematic chain. Further, its deterioration drastically limits the function of the entire arm. A common disease is cerebral palsy that damages the motor system. There is evidence to suggest that performing repetitive tasks can reduce this disease. Natividad et al. [49] developed a soft and portable shoulder exosuit for use in repetitive task rehabilitation. It uses an inflatable fabric beam that facilitates the abduction of the shoulder joint.

The great flexibility and low cost of pneumatic devices give them ideal qualities for use in exoskeletons. O'Neill et al. [9] made an auxiliary exoskeleton using textile pneumatic actuators. This device allows flexion/extension and abduction/adduction movement of the shoulder. It can fold when not in use, making it almost invisible under clothing, enhancing its use in public. It consists of three actuators to perform its movements, one for the abduction and two for the bidirectional control of flexion and extension. The results showed a considerable reduction in muscle effort when using the exoskeleton. It is a lightweight, portable device that has the potential to help people with neuromuscular disorders perform the activities of daily living.

Park et al. [50] developed a soft device that reduces muscle fatigue of the shoulder. This device supports the gravitational force of the shoulder for any posture of the arm using an actuation tendon that constantly pulls the upper arm upwards. This device is helpful to reduce the muscular fatigue of the user, minimizing the possibility of injury. The components of the device are shown in Figure 2.

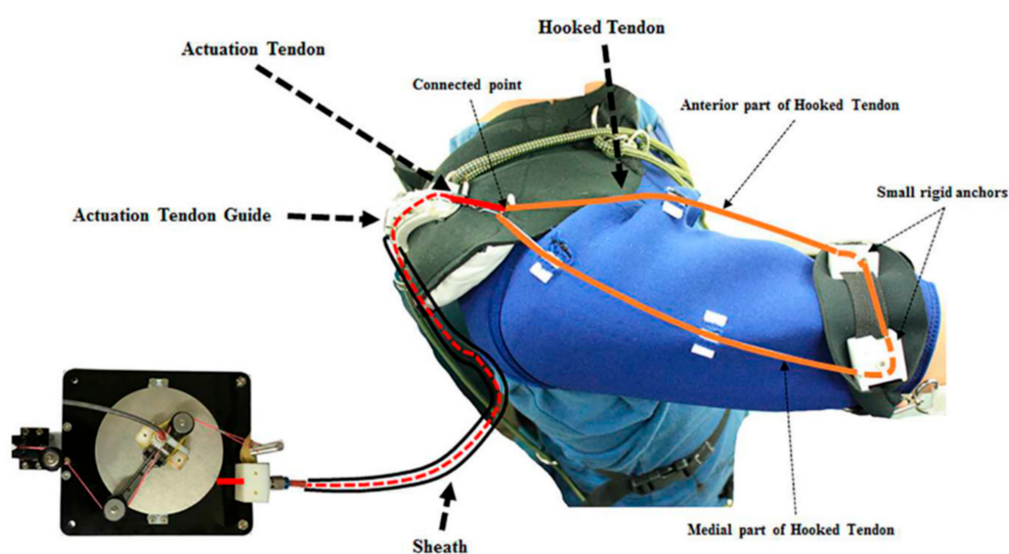


Figure 2. Soft device for shoulder and its tendon-driven mechanism [50] (Open access).

Bowden cables are widely used in force transmission, as they allow the actuators to be located away from the actuated joint. In Thompson et al. [51], a cable-driven exoskeleton was made to enhance shoulder flexion. Soft pneumatic actuators were attached, and networks of inextensible fibers were wrapped around the elastomer tubing. To control the deformation in pressurization and thereby produce a specific movement. This device reduces the risk of muscle and skeletal disorders by reducing joint and muscle loads.

Strokes affect millions of people around the world, causing paralysis of the upper or lower extremities. That should be treated with regular sessions with a specialist to regain motor function. In Galiana et al. [52], an orthopedic shoulder brace was made that is soft, cable-driven, and resistant to misalignment. The methodology to identify misalignments is based on the cable lengths and arm position. Misalignments were compensated with two actuation cables, thus avoiding off-axis pairs. Exoskeletons must adapt to the capabilities of the shoulder to be effective.

In Natividad et al. [53], a modular, soft, and pneumatic exoskeleton was developed to assist in activities of daily living. Studies showed a reduction in muscle activation during abduction and adduction.

4.1.2. Elbow

In general, the movements of the elbow complex are flexion/extension and supination/pronation [47]. Table 2 shows different investigations on soft exoskeletons focused on the elbow complex.

Table 1. Development of soft exoskeletons of the shoulder.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensor
2016 [49]	Pneumatic	1	Rehabilitation	Pressure-based position control	-	Inflatable beam made of thermoplastic polyurethane fiber	Abduction/adduction	-	Accelerometer, piezoresistive pressure sensor
2017 [50]	-	2	Assistance/enhancer	-	-	Cam-rod structure, tendon-driven mechanism, rubber band	Flexion/extension, adduction/abduction	-	Electromyography
2017 [9]	Pneumatic	2	Assistance for daily living	-	-	Neoprene vest, soft cross-link, pneumatic tube	Adduction/abduction and flexion/extension	0.48 kg	-
2019 [51]	Pneumatic	1	Enhancer	PID controller	-	Fiber-reinforced elastomer cylinder, Bowden cable, neoprene strap	Flexion/extension	-	Load cell, pressure sensors
2019 [52]	Electric	1	Rehabilitation	Digital positioning control	100 N	Clamp, Bowden cable, reel, gear	Abduction/adduction	Less than 300 g (without activation pack)	Electromagnetic tracker, encoder, inertial measurement unit, flexible piezoresistive sensor
2019 [53]	Pneumatic	1	Assistance for daily living	-	-	Fabric, air chamber	Abduction/adduction	-	Electromyography

Table 2. Development of soft exoskeletons for the elbow.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensors
2017 [54]	Electric	4	Rehabilitation	Slider mode controller	-	Bowden cable, gearbox, elastic actuator series	Flexion/extension, pronation/supination of the elbow and wrist	<750 g	Encoder
2018 [25]	Pneumatic	1	Enhancer	Single input single-output (SISO)	27.6 Nm	Air chamber, non-stretch fabric, thermoplastic polyurethane	Flexión/extensión	-	Load cell, electromyography
2018 [55]	Electric	1	Enhancer	Low-level closed-loop, high-level estimator	-	Fabric frame, Bowden cables, planetary gearhead, spool, silicone	Flexion/extension	-	Silicone stretch sensor, load cell, quadrature encoder
2019 [56]	Electric	-	Assistance for daily living	Neural network, PID	-	Cable, gear, pulley, spring	Flexión/extensión	-	Force sensor, encoder, electromyography, inertial measurement unit
2019 [57]	Electric	1	Assistance/enhancer	Admittance and PID controller	8.5 Nm	Bowden cable, fabric strap, webbing band, gearhead, pulley	Flexion/extension	170 g (wearable part)	Load cell, encoder
2019 [7]	Electric	2	Assistance	PI control		Fabric, lead screw, motor dc, Bowden cable	Flexion/extension, pronation/supination	358 g	Infrared sensor
2020 [58]	Pneumatic	1	Assistance for daily living	-	98.65 N	Bellows, fabric sleeve, elastomer	Flexión/extensión	230 g	Force sensor

In Jarrett et al. [54], a smooth and compact device for the elbow was made using Bowden cables with electric actuators. An elastomer was used in the joint's core, and its dynamic characteristics were modeled to implement a sliding mode controller. The device was tested with six healthy subjects who performed activities of daily living. Further, it was also tested in a patient with spastic cerebral palsy to experience the potential of physical therapy. An important feature of this device is the inclusion of passive joints. It includes one active and three passive degrees of freedom. The only active degree of freedom is the extension and flexion of the elbow. The weight of the device is less than 750 g, and the actuators are located remotely.

Some exoskeletons are constructed of fabric and are commonly called exosuits. They allow easy installation and eliminates the inconvenience of aligning a rigid frame to the joints.

Cargo workers must perform strenuous and repetitive activities that cause muscle fatigue and injury. Thalman et al. [25] investigated the design of a soft exosuit for the elbow that assists in lifting by reducing biceps muscle activity. Its goal is to improve efficiency and endurance in workers who repeatedly lift loads. The study showed a 43% and 63% reduction in biceps muscle activity for a weight of 1.5 kg and 2.5 kg, respectively.

Also, they have less inertia due to their lightweight, allowing a more efficient user's movement. Chiaradia et al. [55] present a device that reduces on average 77% of the total moment required to support and move a lightweight object. The exosuit on average decreases the effort of the biceps by 64.5%. A low-level closed-loop velocity control and a high-level assistance estimator are implemented in this article. The high-level controller evaluates the torque applied by the exosuit to the wearer and the torque due to gravity. Further, through closed-loop velocity control, the torque is delivered to the exosuit–human system.

In Wu et al. [56], a torque estimation controller through a neural network is proposed for a portable elbow assist exoskeleton. This device assists flexion and extension movements employing an adaptive tendon-sheath type actuator.

Xiloyannis et al. [57] feature an assist/augmentation elbow exosuit that reduces movement effort, making it a good candidate for industrial and clinical applications. Figure 3 shows the components of the device.

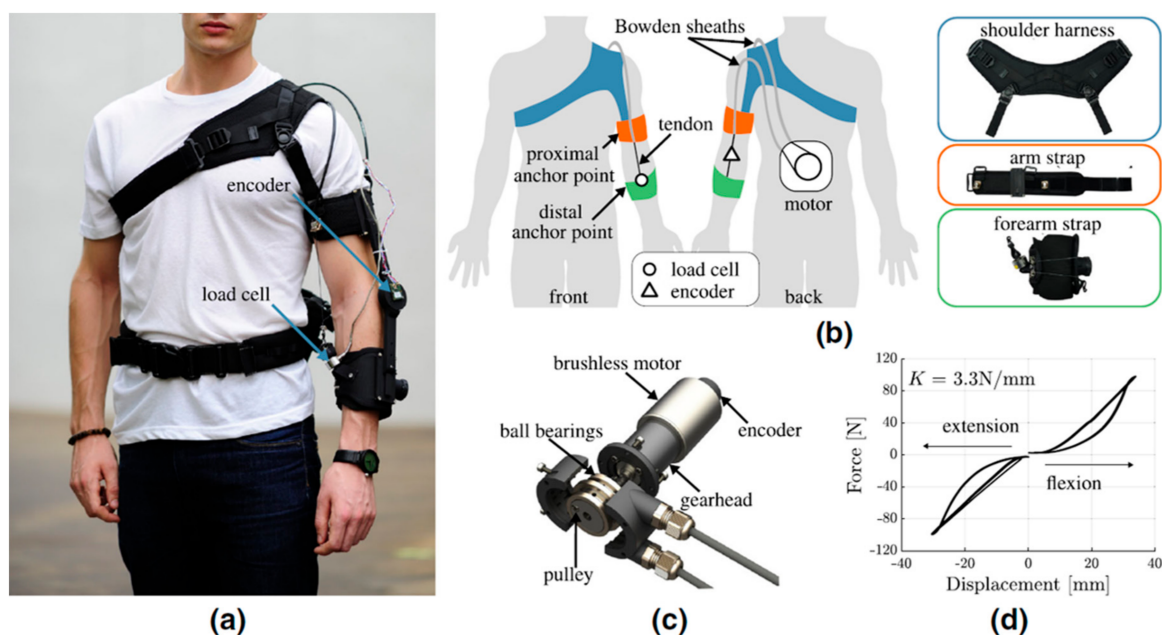


Figure 3. Components of the exosuit used to reduce elbow effort. (a) The exosuit consists of three straps that wrap around the shoulder and has an encoder and a load cell. (b) It also has a motor, anchor points, and Bowden cables. (c) In the transmission of force, the brushless motor is used together with gearhead, pulley, ball bearings. (d) Stiffness of the exosuit [57] (Open access).

Ismail et al. [7] made an exoskeleton with two degrees of freedom for the elbow. It allows a flexion/extension range of motion of 90° to 157° , while the maximum range of motion for pronation and supination are 19° and 18° , respectively. The portable soft device is shown in Figure 4.

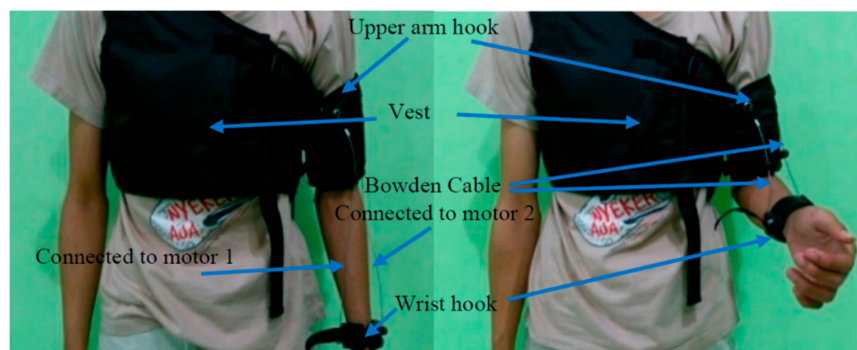


Figure 4. Portable soft exoskeleton for elbow assistance [7] (Open access).

Ang et al. [58] developed a pneumatic device, with 3D printable bellows and high force output, capable of assisting in elbow flexion. The actuator in this work demonstrates high force and torque output with a lightweight design.

4.1.3. Wrist

The wrist connects the hand with the forearm and has two degrees of freedom: flexion/extension and ulnar/radial deviation [47]. By adding the supination and pronation movement of the forearm, the hand can be oriented at different angles for collecting objects. The estimated ranges of motion of the wrist for extension are 0° to 70° , flexion 0° to 90° , radial deviation 0° to 20° , and ulnar deviation 0° to 50° [5].

In many designs, wrist flexion and extension occur through one axis, while radial and ulnar deviation through another axis. Some works on soft exoskeletons of the wrist are specified in Table 3.

Bartlett et al. [59] developed a lightweight and portable wrist device for the rehabilitation of patients with hemiparesis. This device supports flexion/extension and radial/ulnar deviation of the wrist and includes supination and pronation of the forearm, which are critical for many tasks. It is a lightweight, portable and pneumatic device that can be used outside the clinic.

Al-Fahaam et al. [5] developed a rehabilitation exoskeleton for the wrist. They used pneumatic actuators capable of flexion/extension, radial/ulnar and circular movements. The pneumatic muscle actuator is a cylinder-shaped device that decreases or increases its length when pressurized. Its manufacture is normally with latex or rubber tube and is surrounded by a braided sleeve. They can convert their pneumatic power into pulling and pushing force. Additionally, they have a high force-to-weight ratio, and their transmission does not require mechanical parts.

In Ang et al. [60], a soft robotic wrist brace is presented, capable of providing mobility in two degrees of freedom: flexion/extension and radial/ulnar. The device can help stroke patients achieve at least 71.1% of the range of motion on a healthy wrist.

Hemiparesis patients undergo various rehabilitation interventions. Such as restriction-induced therapy, considered one of the most effective rehabilitation protocols for the treatment of hemiparesis. The goal of this therapy is to restrict the healthy side and force the disabled side into rehabilitation. In Choi et al. [61], a cable-driven soft wrist robot was proposed. This device is developed for restriction-induced therapy in stroke patients with wrist movement difficulties.

Xu [62] designed a portable soft rehabilitation device for the wrist. This device uses soft actuators with elastomer chambers and casing plates. Its operation is through pneumatic pressurizations that induce flexion and extension trajectories.

Chiaradia et al. [63] developed a cable-based soft wrist exosuit. The device reduces muscle fatigue and allows it to lift small weights of up to 3 kg. Figure 5 shows the device and its components.

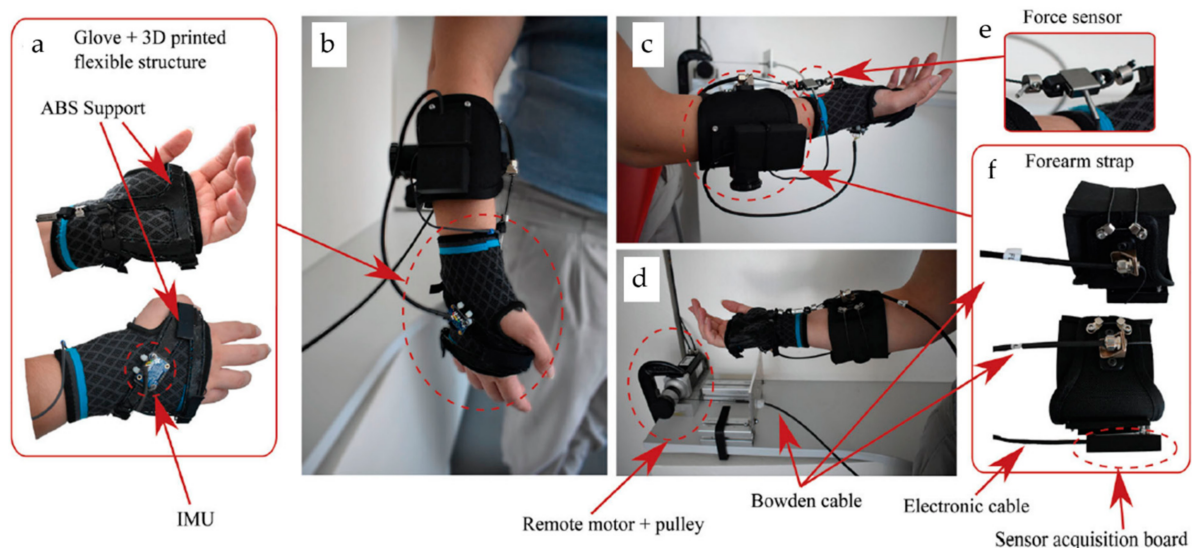


Figure 5. Cable-based soft exoskeleton for the wrist. (a) The glove together with the 3D printed flexible structure. (b–d) Bowden cables are driven by a remote motor and pulley. (e) A load cell was used to measure the force. (f) A strap wrapped around the forearm was employed to hold the Bowden cables and the sensor acquisition board [63] (Open access).

4.1.4. Hand

The hand is a complex system that allows the human to interact with the environment. Provides tactile and sensory feedback that facilitates the manipulation of objects. The hand is twenty DOF [64], consisting of carpometacarpal, metacarpophalangeal, and proximal and distal interphalangeal joints movements. It requires great precision even to perform daily tasks. For example, grasping an object requires applying forces to the index, middle, ring, and little fingers in opposition to the thumb's force.

There are millions of people around the world who suffer some impairment in manual functions, and this number is continually growing [65]. The functioning and coordination of the hand can deteriorate for various reasons. It is most commonly from degenerative diseases, trauma, or injuries involving the spinal cord or muscle tissues. It can also be due to a stroke or muscle weakness due to aging. The deterioration of the hand, even slightly, limits or prevents various activities of the individual. Particularly those that involve high dexterity such as writing, painting or manipulating a musical instrument. To improve hand mobility, disabled patients must undergo continuous passive movement exercises, which involve repetitive tasks such as grasping and opposition movements [66,67].

Designing a soft exoskeleton for the hand is challenging due to the various requirements to simulate its movement and precision. The structure of the index, middle, ring, and little fingers consists of three interphalangeal joints: distal (DIP), proximal (PIP), and metacarpal (MCP) [1]. There are only two interphalangeal joints of the thumb: metacarpal (MCP) and interphalangeal (IP). Table 4 describes some studies carried out on soft exoskeletons of the hand.

Nycz et al. [68] developed a lightweight and smooth cable-driven exoskeleton. The device has six DOF, one for each finger and one for the elbow. The wrist maintained a fixed neutral position to allow acceptance of the weight. The flexion and extension of the joints are achieved by connecting the DC motors to cables and pulleys.

Table 3. Development of soft exoskeletons for the wrist.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensors
2015 [59]	Pneumatic	3	Rehabilitation	-	-	Pneumatic tube, textile sleeve, glove, tensioning mechanism (ratchet, cable, eyelet)	Flexion/extension, and radial/ulnar deviation, supination/pronation	2.26 kg (complete), 0.22 kg (Portable part), 0.09 kg (distal)	Pressure sensor
2016 [5]	Pneumatic	2	Rehabilitation and assistance for daily living	Direct control	Flexion (37 N), another move (55 N)	McKibben, pipe	Flexion/extension, radial/ulnar and circular	150 g	Pressure sensor
2019 [60]	Pneumatic	2	Rehabilitation	-	-	Pneumatic chamber, thermoplastic polyurethane	Flexion/extension and radial/ulnar	-	Torque sensor
2019 [61]	Electric	2	Rehabilitation	-	50 N (tension), Torque > 0.35 Nm	Pulley, silicone rubber, Teflon tubes, cable (Dyneema), spring	Flexion/extension, abduction/adduction	1003 g (total weight), 233 g (portable part)	EMG, load cell
2020 [62]	Pneumatic	1	Rehabilitation	-	-	Siloxane elastomer, polyethylene terephthalate shell	Flexion/extension	-	-
2021 [63]	Electric	1	Assistance/enhancer	Admittance controller	3 Nm	Bowden cable, elastic fabric, ABS support, pulley, strap, motor	Flexion/extension	0.3 kg	Inertial measurement unit, force sensor, load cell, gyroscope

Table 4. Development of soft exoskeletons for the hand.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensors
2015 [68]	Electric	6	Rehabilitation	-	-	Cable, gear, pulley	Flexion/extension	-	-
2015 [69]	Pneumatic	-	Rehabilitation and assistance for daily living	-	3.59 N (grip), 2.72 N (pinch)	Platinum Liquid Silicone	Flexion/extension	200 g (glove only)	-
2015 [70]	Hydraulic	-	Rehabilitation and assistance for daily living	Controller closed circuit, sliding mode controller	8 N (distal end)	Fiber-reinforced actuator, hydraulic tubing	Four finger and thumb flexion/extension, thumb twist	285 g (glove), belt pack assembly (3.3 kg)	Hydraulic pressure sensor, led sensor, electromagnetic tracking sensor
2016 [65]	Electric	4	Assistance for daily living	-	16 N (pinch)	Cable (Dyneema), gear, pulley	Flexion/extension	250 g (wearable glove), 340 g (complete)	Resistive flexor, infrared sensor
2019 [71]	Electric	-	Rehabilitation	Joint position control	9 N	Spur gear, spool, DC motor, elastic material, cable	Grasp	<400 g	Position sensor
2020 [72]	Electric	3	Assistance for daily living	Direct force-based control	6.4 N (little finger), 5.2 N (middle finger), 5.4 N (thumb)	Bowden cable, rack and pinion, winch	Four finger and thumb flexion/extension, thumb abduction/adduction	148 g (hand module), 720 g backpack	Bending angle sensor
2020 [73]	Electric	-	Enhancer	Dual-threshold and Morse-code control	-	Bowden cable, gear, clutch, spool	Grasp	450 g	Electromyography

Yap et al. [69] made a portable exoskeleton for the assistance and rehabilitation of the hand. It is a lightweight device, easy to install, and works with pneumatic actuators. Additionally, different flex profiles of varying stiffness can be assigned to suit finger dimensions. Further, it can be used in various rehabilitation therapies. Two aspects were characterized to evaluate the prototype: the range of motion and the maximum output force. Further, the experiments were conducted examining the differences between passive and active tasks. This device obtained an acceptable range of motion and sufficient force to perform gripping and pinching tasks.

Polygerinos et al. [70] present a soft robotic glove that uses actuators consisting of elastomer chambers molded with fiber reinforcements. These actuators induce specific flexion, extension, and torsion paths under the pressurization of a fluid. The operating pressure was regulated by implementing a sliding mode controller in conjunction with fluidic pressure sensors in line with the hydraulic actuators.

Popov et al. [65] developed a glove exoskeleton for daily life assistance. It is a device with a soft and adjustable structure, which has no movement restrictions on the wrist and keeps the palm free to manipulate objects. The device flexes and extends the ring, middle, index, and thumb fingers (excludes little finger) through bidirectional actuation. The weight of the portable part is 250 g, and the complete system is 340 g, the maximum pinch force is 16 N. The glove can hold objects up to 300 g and uses a 3000 mAh battery that allows continuous operation for four hours.

It is important to reduce any user discomfort, such as unwanted residual forces. For this reason, a light rigid plate (fiberglass) with the anatomical shape of the hand is usually equipped. Further, it is placed in an internal layer to the actuators and transmission elements to reduce compressions and rotational forces to the hand. Placing a guide in the dorsal distal phalanx causes an uncomfortable sensation during the extension of the fingers [65]. This discomfort could be because the biological distal phalanx cannot extend independently of the middle phalanx. This differs from the palmar area of the fingers because the middle and distal phalanges flex independently.

Rudd et al. [71] designed a hand rehabilitation skeleton for remotely applied physiotherapy. It is built with widely available components and 3D printable parts. Its installation is visualized in Figure 6.

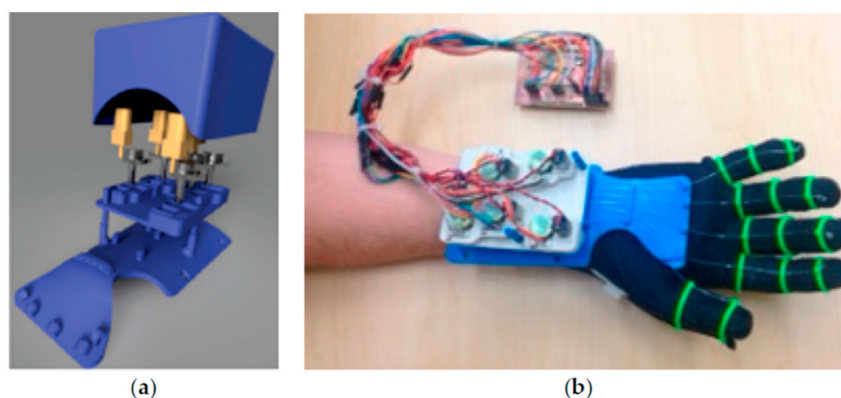


Figure 6. A soft robotic glove designed for remote application. (a) Mechanical design and (b) fully assembled exoskeleton connected to the microcontroller [71] (Open access).

Bützer et al. [72] present a soft device for hand assistance, completely portable for daily activities. It has three DOF that allow a manual grip. It can perform flexion and extension of the fingers and individual opposition of the thumb.

Cheon et al. [73] used an electromyography interface to control a robotic glove that provides grip strength. The anatomical characteristics of the musculotendinous junctions were used to identify the intention of force. Figure 7 shows the structure of the device.

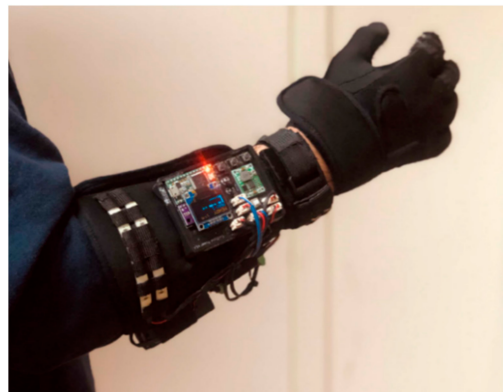


Figure 7. Portable exoskeleton glove with soft structure [73] (Open access).

Rose et al. [74] designed a hybrid exoskeleton, using soft and rigid elements, to assist patients with hand disabilities in activities of daily living. This device includes innovative ergonomic elements for power transmission and allows seven hand positions compatible with most activities of daily living.

4.2. Lower Extremity Exoskeletons

Human gait is defined as a series of alternating rhythmic movements of the limbs and trunk that determine a forward displacement of the center of gravity [75]. It consists of a cycle in which there are three phases for each leg. A stance phase in which one foot makes contact with the ground, a swing phase when the foot is off the ground, and a double stance phase in which both feet are in contact with the surface.

Gait disorders are due to different health conditions, such as spinal cord injuries, paresis caused by strokes, or age-related frailty. In Ortiz et al. [76], it is mentioned that patients with unilateral mobility disabilities can restore normal gait by applying an assist torque to the affected leg, which is equal to the difference between the torque of the disabled leg and the healthy leg.

Patients with mild and moderate disabilities participate together with the exoskeleton in locomotion, balance control, and decision-making processes. Therefore, inappropriate torque of the device can cause discomfort, overexertion or even a fall of the patient. Users with voluntary motor control inadvertently modulate their joints in the event of a disturbance or when they are losing their balance. Establishing the necessary assistance force is a complicated task since it varies between users and even varies in the same user for different circumstances. So, an ideal controller must continuously adapt quickly and precisely to the user's intentions and movements. However, appropriately delimiting mechanical assistance for gait balance recovery is a problem that is currently under development. The robotic design for gait is not limited to the implementation of forces but also to reduce metabolic expenditure. For this reason, passive elements are commonly included in exoskeletons to reduce weight.

4.2.1. Hip

The hip has three degrees of freedom and performs flexion/extension movements in the sagittal plane, abduction/adduction in the frontal plane, and rotation in the transverse plane [77].

There are two main issues in gait. One is the forward stride length, which is regulated by hip extension/flexion, and the other is stride width, which is crucial for stability and is controlled by hip abduction/adduction.

Hip exoskeletons can help a wide range of people. For example, patients with moderate disabilities and the elderly who have muscle weakness but still maintain some voluntary control over their joints. Table 5 shows works related to soft devices created for the hip.

Asbeck et al. [11] developed an exosuit that allows hip extension and contributes up to 30% of the nominal biological moment for walking. It installs facily and does not restrict hip movement with rigid joints, and relies on the user's bone structure. However, it is limited by being unidirectional and only triggers extension, not flexion.

Ding et al. [78] developed an exosuit for the hip and investigated the mechanical power delivered to the user according to different actuation times. Figure 8 shows the components and structure of the exosuit for the hip. This work focuses on establishing optimal efficiency parameters according to different times of assistance in the hip, which is essential to improve future control strategies.

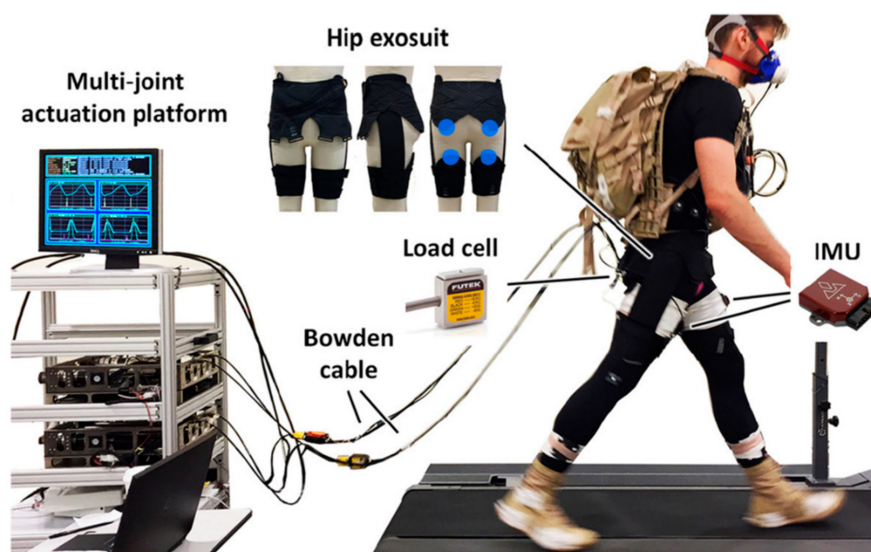


Figure 8. Soft exosuit system for hip movement [78] (Open access).

Poliero et al. [79] developed an exoskeleton that aids gait by moving the hip. It is a soft structure that includes a quasi-passive element that is activated and deactivated according to the subject's gait patterns. It is focused on helping a user with a disability in the right leg. It is a modular device that improves the range of torque and mobility of the affected hip joint.

Most hip exoskeletons focus on assisting gait rather than stability. Zhang et al. [80] developed an exoskeleton driven by series elastic actuators. It assists the movement of the hip and maintains balance both in the sagittal and frontal planes. Further, it allows flexion/extension and abduction/adduction movements. This device does not override human control and involves it in movement. Additionally, it avoids conflicts between the user-exoskeleton interface. The weight of the device, excluding the battery, is 9.2 kg. It has an adjustable mechanism that accommodates a wide range of body sizes and a continuous torque of 40 Nm.

Kim et al. [81] present an exosuit designed for the hip to increase human gait and run. Perform the hip extension movement allowing maximum forces of 300 N. This exosuit can distinguish between walking and running. The detection algorithm is based on the biomechanical definition that the potential energy during the stance phase of walking is out of phase with that of running. This device reduced the metabolic cost of running and walking.

4.2.2. Knee

Quadriceps act as shock absorbers that stabilize the knee joint and produce the extension movement of the leg when walking. Some works on soft exoskeletons focused on the knee are presented in Table 6.

Table 5. Development of soft exoskeletons for the hip.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensors
2015 [11]	Electric	1	Assistance for daily living	-	-	Gear, spool, timing belt	Extension/flexion	7.52 kg	Force sensor, encoder
2016 [78]	-	1	Enhancer	-	198.5 ± 0.1 N	Bowden cable, woven fabric, neoprene, ball screw	Flexion/extension	≈700 g	Inertial measurement unit, load cell
2018 [79]	Electric	1	Assistance for daily living	-	-	Bowden cable, elastic band	-	4.1 kg (all), 0.7 kg (hip actuation)	Pressure sensor
2018 [80]	Electric	4	Assistance for daily living	Adaptive admittance and control scheme based on a conventional finite state machine	40 Nm	-	-	9.2 kg (excluding battery)	Encoder, inertial measurement units, resistive sensor, torque sensor
2018 [81]	Electric	2	Enhancer	Force-based position controller	300 N	Bowden cable, gear, pulley	Extension/flexion	4.7 kg (complete system)	Inertial measuring unit, load cells, incremental encoder

Table 6. Development of soft exoskeletons for the knee.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensors
2014 [82]	Pneumatic	1	Rehabilitation	-	3.5 N extension, 7 N flexion	Air chamber, Kevlar fibers, silicone rubber, elastomer, cloth sleeve	Extension/flexion	-	-
2017 [13]	Pneumatic	1	Rehabilitation	Binary controller	4.4 Nm	Elastic fiber (neoprene), strap, inflatable actuator, pneumatic valve	Extension	160 g (not including electro-pneumatic elements)	Force-sensitive resistance, fluid pressure sensor
2019 [83]	Electric	2	Assistance for daily living	Hierarchical control system	-	Bowden cable, gear, pulley	Extension/flexion and unilateral rotation	1.3 kg (mechanical structure)	Load cell, inertial measuring unit, encoder, force sensor
2019 [84]	Electric	2	Assistance for daily living			Bowden cable, elastic band	Quasi-passive, hip and knee	4.9 kg (complete)	Force sensor
2020 [85]	Pneumatic	1	Enhancer	-	-	Air chamber, personalized garment with fibers and weaving techniques	Extension/flexion	-	-
2020 [14]	Pneumatic	1	Enhancer	Gait estimation model and knee torque model	17 N	Positive and negative pressure valves, air pump, air tubes, vacuum-actuated rotary actuator	Flexion/extension	2.8 kg	Pressure sensors, inertial measurement unit

Park et al. [82] present a soft device that integrates actuators composed of elastomers and fabric sleeves for knee support. The device generates maximum extension and flexion forces of 3.5 N and 7 N, respectively. A key feature in this exoskeleton is its pneumatic elastomer actuators, which allow it to be compact and lightweight.

Sridar et al. [13] present an exosuit for knee rehabilitation. They used soft inflatable actuators made of heat-sealable thermoplastic polyurethane. The exoskeleton provides torque assistance for knee extension during the gait cycle, and its preliminary tests showed a 7% reduction in muscle activity.

Zhou et al. [83] present a soft knee exoskeleton with two degrees of freedom capable of extension/flexion and unilateral rotation movements. Hierarchical control was used to evaluate various system parameters, such as force, current, torque trajectory generation, sensory data, and feedforward compensation. A high-power cable-actuated actuator was developed, and the results show a natural and flexible gait movement.

Natali et al. [84] developed a soft lower limb device to assist people with slight mobility problems. It allows movement of the hip and knee, and the resulting assistance obtained, in terms of power, was $10.9\% \pm 2.2\%$ and $9.3\% \pm 3.5\%$, respectively. The 4.9 kg device has quasi-passive elements that transfer energy between different phases of gait. Further, it reduces the energy needed to do the walk by 10% to 20%. A front and rear view of the exoskeleton is shown in Figure 9.



Figure 9. Soft assistive lower limb exoskeleton, (a) front and (b) rear view [84] (Open access).

Porter et al. [85] designed a soft exoskeleton with adjustable stiffness for the knee joint. Its function is to minimize metabolic expenditure during locomotion in reduced gravity, maximize mobility, and improve astronaut performance. In addition, this device does not require continuous power to maintain inflation, which reduces energy costs.

Zhang et al. [14] made a soft exoskeleton for the knee that helps with walking. It is mainly driven by vacuum-actuated rotary actuators. The results showed that when using the exoskeleton, the metabolic cost was reduced on average by 6.85%. The soft exoskeleton is shown in Figure 10.

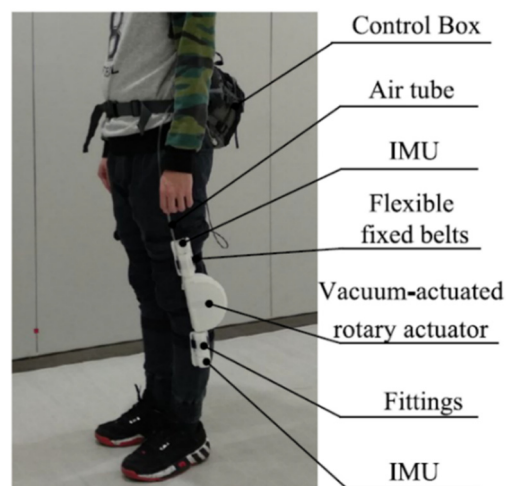


Figure 10. Components of the soft knee device [14] (Open access).

4.2.3. Ankle

Control of foot placement in the mediolateral and anteroposterior directions is essential for gait stability. Further, the ankle is responsible for approximately 40% of the gait [86]. Table 7 shows various works on soft exoskeletons related to the ankle.

Mooney et al. [87] developed an autonomous lightweight exoskeleton capable of providing mechanical power to the wearer's ankle during the plantar flexion phase of gait. The device uses lithium polymer batteries and motors and showed a reduction in the metabolic cost of walking by 36 ± 2 W. Figure 11 shows the functionality and components of the exoskeleton.

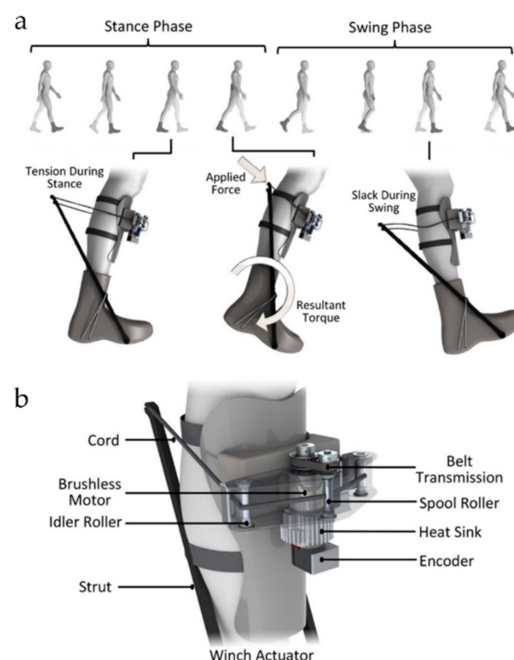


Figure 11. Autonomous powered leg exoskeleton. (a) Force applied during different phases of gait. (b) Device components [87] (Open access).

Table 7. Development of soft exoskeletons for the ankle.

Year	Actuator	DOF	Function	Control Strategy	Power	Power Transmission	Movement	Weight	Sensors
2014 [87]	Electric	1	Enhancer	Position control	-	Belt, polyethylene cord, spool, fiberglass strut, winch actuator	Plantar flex	4 Kg (1.7 kg at waist and 2.3 kg on the legs)	Encoder, gyroscope
2016 [15]	Electric	1	Enhancer and assistance for daily living	Low and high-level control	-	Bowden cable, gear, pulley	Flexion	-	Gyros, load cell
2016 [88]	Pneumatic	1	Rehabilitation	-	-	Elastomer, fabric	Dorsiflexion and plantar flexion	-	Pressure sensor, force sensor
2018 [89]	Pneumatic	1	Assistance for daily living	Open loop pressure controller	39 Nm	Pneumatic tubes, textile-based inflatable actuator, solenoid valve	Plantar flexion	-	Inertial measurement unit, pressure sensor
2020 [90]	Electric	2	Rehabilitation	Current-based torque control	7.9 Nm	Bidirectional cable, rack and pinion, soft thermoplastic polyurethane, PLA filament, polylactic acid	Inversión/eversión and dorsiflexión/plantar flexión	0.98 kg	Inertial measurement unit, force sensor
2021 [91]	pneumatic	1	Rehabilitation	-	-	Bowden tube, Bowden cable, webbing, solenoid valve, cylinder	Dorsiflexion/plantar flexion	-	Flexiforce force-sensing resistors, inertial measurement unit

Many are the factors that hinder the construction of exoskeletons for metabolic reduction. For example, exoskeletons increase the mass of users, have limited mechanical power and scarce power sources. A larger mass requires additional metabolic power. Further, the power required increases as the mass is positioned distal to the joint. For this reason, to reduce energy expenditure, it is necessary to include passive and quasi-passive elements, which absorb power and release it at a determined time. Lee et al. [15] present a soft exosuit that assists in plantar flexion of the ankle. Tests were carried out in healthy subjects to evaluate the proposed control system and its effect on metabolic expenditure. Dioxygen consumption and carbon dioxide production were measured to define metabolic rate. The results showed significant metabolic reductions of up to 14.9% during walking.

Low et al. [88] presents a soft robotic device developed to assist in dorsiflexion and plantar flexion of the ankle. This device is focused on stroke patients at high risk of deep vein thrombosis. It provides rehabilitative therapy that increases blood flow to the lower limb. This device is really helpful when the patient cannot take anticoagulant medications, for example, when there is a risk of uncontrollable bleeding, especially in patients with hemorrhagic stroke. In Chung et al. [89], an inflatable robotic boot was developed that assists plantar flexion of the ankle during gait. It reaches a maximum torque of 39 Nm. Further, the activation is carried out using a pressure controller based on the angular velocity of the ankle. It is composed of high flow solenoid valves and inertial units. It has a soft textile-based actuator, which provides lightness while reducing energy costs.

A stroke can lead to a motor disability, such as hemiplegia, which considerably affects gait locomotion. Xia et al. [90] proposed a multifunctional ankle exoskeleton. It prevents foot drop (difficulty lifting the forefoot), aids propulsion, and stabilizes inversion/eversion during gait in rehabilitation therapy. The device was manufactured with a soft/rigid hybrid structure by 3D printing and a bidirectional movement by wire. Schubert et al. [91] present an exosuit that supports ankle dorsiflexion through an autonomous mechanism that recognizes the phases and conditions of the gait. The components of the device and their location are shown in Figure 12.

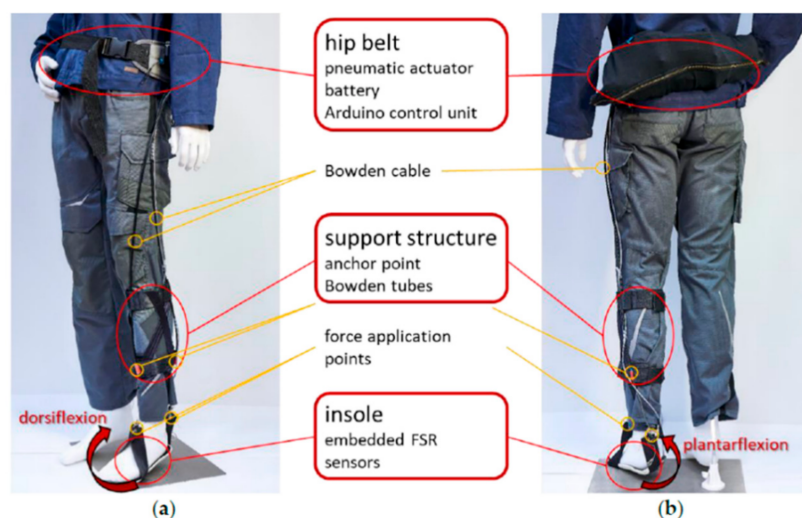


Figure 12. (a) Front and (b) rear view of the soft ankle exosuit [91] (Open access).

5. Discussion and Conclusions

In this article, various research results on soft exoskeletons were summarized, and their qualities and shortcomings were highlighted. Additionally, the technological trend of the last decade was analyzed. Investigations on the upper and lower joints were included, specifically on the shoulder, elbow, wrist, hand, hip, knee, and ankle. Moreover, the main requirements and challenges for the design of these devices were mentioned.

Aspects such as weight, safety, control, portability, softness, comfort, durability, accessibility, bidirectionality, transmission, maneuverability, and actuators were explained in detail.

Undoubtedly, in recent years, the development trend of soft exoskeletons has increased due to their characteristics that overcome the limitations of rigid and heavy structures. Although soft exoskeletons are a viable and feasible option, there are still several limitations in most current devices. For example, most are not efficient for continuous daily use, and weight is still a high user's burden. They have difficulty donning and doffing, plus most are not yet fully portable. Additionally, misalignments in the rotation's axis are common, and the device's cost is still high. Currently, many research groups are focused on creating devices for rehabilitation processes and assistance in daily life. It is known that rehabilitation does not ensure full recovery of sensory-motor functions. Therefore, some patients, despite therapy, must live with permanent disabilities. Causing a reduced quality of life for patients who regularly need help with activities of daily living. For this reason, it is essential to develop devices that minimize the user's disability. Further, soft exoskeletons are a viable option for providing continuous assistance in the future. However, developing an optimal soft exoskeleton remains a challenging task.

A pneumatic drive is a recurring option for soft exoskeletons. Its main drawback is its power supply since the compressor is usually of considerable weight, complicating its portability. In rehabilitation, the lack of portability is not considered a big problem since the therapies are commonly carried out in controlled conditions and delimited places. However, for assistive devices, the lack of portability does not allow users to move comfortably for their activities of daily living. Therefore, the development of exoskeletons activated with pneumatic actuators is more useful in rehabilitative therapies. The energy density of a lithium battery is higher than a compressed air system. A system consisting of an electric battery and a motor is considerably lighter, precise, smaller, and more suitable for portable assistance than a pneumatic system with the equivalent specifications.

Daily care requires exoskeletons for long periods or permanently. Current devices do not yet have all the necessary features for continuous use. Therefore, further research is needed to allow longer use of these devices. The control based on the intention of the movement allows anticipating actions to improve the system. However, the precise identification of the intention of the human movement is still under investigation.

An enhancer exoskeleton helps reduce many injuries in occupations that require constant and excessive effort. Its development is challenging because it must increase the natural capacity of the user and decrease physical effort. Another significant issue to consider is the loss of energy generated by the retention forces applied to the joints to maintain the desired position. For example, a continuous holding force must be applied to the hand when grasping an object. Therefore, it is recommended in robotic devices to include restrictive elements that fix the desired position to avoid retention forces and save energy. Another highly feasible option is the exosuit, which transmits forces on the user's body through trajectories determined by the textile architecture. It has low distal inertia and creates intrinsically aligned torques with biological joints. Exosuits have diverse applicability, such as assisting lifeguards and soldiers by improving their mobility and decreasing the energy required in their work.

In summary, the development of exoskeletons still requires significant advances to minimize limitations and build a highly efficient device that provides comfort and portability to the user. Exoskeletons must be tailored for each user to minimize the risk of injury and increase mechanical efficiency. Actuation power should be increased and weight reduced. Additionally, robust and effective control systems must be adapted. This article will help future research to understand the current trend in the development of soft exoskeletons. Further, it provides an overview of the requirements and challenges that must be considered for its design and construction.

Author Contributions: A.F.P.V. described in detail several recent works on soft exoskeletons in section four. He defined their main characteristics, requirements, and challenges. He also wrote part of the discussion and conclusions. J.Y.R.M. described various exoskeletons related to the lower extremities. He also wrote part of the introduction and organized the document. G.O.T. focused on the exoskeletons of the upper extremities and described their main characteristics, control strategies, and components. He also wrote part of the general applications. F.d.J.S.V. extensively investigated the different applications in soft exoskeletons and wrote part of sections two and four. A.C.R. researched the essential requirements in soft exoskeletons and made a description of the most common actuators and power transmissions used. J.A.B.M. investigated the most recurrent challenges in soft exoskeletons and mentioned their solutions. J.C.R.C. researched the antecedents of exoskeletons and wrote on the introduction, general applications, and discussion. All authors have read and agreed to the published version of the manuscript.

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