Advancements in Soft Wearable Robots: A Systematic Review of Actuation Mechanisms and Physical Interfaces

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***Abstract*—Soft actuators and robotic devices designed for rehabilitation and assistance are a rapidly growing field of research. Their inherent flexibility enhances comfort and usability without restricting the user's natural range of motion. However, despite these advantages, there are still several challenges that need to be addressed before these systems can be commercialized. This paper presents a comprehensive review of the latest developments in soft wearable robots, also known as exosuits. Soft exosuits are composed of two main components: actuation mechanisms (how forces/torques are generated) and physical interfaces (how and where the robot is anchored to the body). This paper reviews the advances in these two areas, while categorizing exosuits based on the intended assisted joint, assisted degrees of freedom (DOF), and device type. The systematic literature review follows the PRISMA guidelines to summarize the relevant studies and investigate their related physical interface, actuation mechanism and its design. Several limitations were identified in these areas, and insights into potential future research directions are presented. In the future, the goal should be to develop an untethered assistive device that can provide assistance to multiple joints while having a low form factor, an intuitive and natural interface, and being comfortable for the user.**

***Index Terms*—Exosuit, rehabilitation and assistive robots, physical interface, anchoring.**

I. INTRODUCTION

EVERY year, a staggering 15 million people suffer from stroke [1], with a significant 75-80% of survivors grappling with movement-related disabilities [2]. Notably, mobility related disabilities extend beyond stroke survivors. In the USA, an estimated 40.4 million adults are living with disabilities and struggling with issues such as severe walking impairments [3]. As our population ages, these impairments are expected to surge, impacting the very essence of independence and quality of life. It is crucial to provide support and assistance to individuals with mobility impairments to help them regain independence and actively participate in society.

Movement-related disabilities can be improved through intensive rehabilitation training [4], typically led by a physiotherapist. Despite its efficacy, this method is time-consuming and labor-intensive. To address these challenges, there is a growing interest in the use of robotic devices for rehabilitation. Advantages include consistent and extended training, objective performance analysis, reduced labor intensity, cost effectiveness, and improved efficiency [5], [6]. Robotic devices for rehabilitation come in many different forms, including exoskeletons, end-effectors, and soft wearable robots and are briefly explained as follows.

Exoskeletons have rigid structures with links and joints that parallel the human body, see Fig. 1-A, to provide support or resistance to movement. For instance, the Apex Alpha [7] is pneumatic actuated exoskeleton that assist the elbow joints. Other assistive robots like HAL [8], Vanderbilt [9], REX [10], HES Hand [11], ReWalk [12], HandeXos-Beta [13], HandSOME [14], and HexoSYS [15] utilize motors and tendons to aid activities of daily life (ADLs) such as climbing stair, balancing, grasping, pouring liquids, and buttoning. These robots have been proven to be effective in augmenting human strength, and aids in stroke rehabilitation [12]. Nonetheless, exoskeletons can be complex, heavy, and bulky thus potentially increasing metabolic costs, limiting them to research laboratories or expensive clinical settings.

End-effectors are devices that are attached to the end of a limb to provide controlled movement, see Fig. 1-B. Unlike exoskeletons, they don't require joint alignment, making them more compact and user-friendly. Some of the commercially available end-effectors are: BWS [18], Inmotion2 [19], EMU back drivable end-effector [16], REAplan [20], and GEO system for gait rehabilitation [21]. For simplicity, end-effector devices usually have fewer degrees of freedom and apply the assistive forces at the point of attachment. This simplicity poses challenges for achieving isolated movements of the individual joints of the user [22]. The resultant impact on other joints makes precise and independent joint control difficult. Additionally, the operation of these devices in a single plane hinders the generation of accurate joint trajectories, thus exhibiting reduced versatility and dexterity in scenarios demanding intricate and varied movements [22], [23]. To address these issues, soft exoskeletons have gained attention as a concept for rehabilitation.

Soft exoskeletons also known as "exosuits" or "exomuscles" have been developed to address the limitations of rigid

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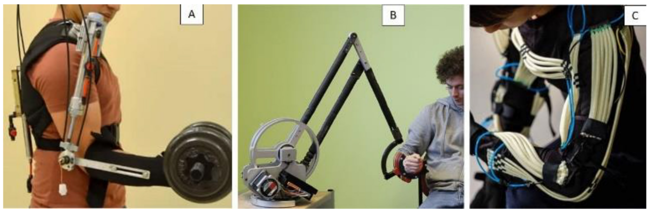


Fig. 1. Example assistive robots: A) APEX-Alpha exoskeleton [7], B) EMU back drivable end-effector [16], C) McKibben actuated soft elbow exosuit [17].

systems. These wearable robotic devices are designed to resemble clothing, wrapped around the user's body [24] as depicted in Fig. 1-C. Unlike their rigid counterparts, exosuits operate in synergy with the user's muscles, relying on the integrity of the human body to transfer forces between different body segments. Essentially, they act as an external layer of muscles [24].

Various exosuit models, classified as either passive or active, have been developed and subject to thorough evaluation. Passive exosuits operate without the need for any active energy source to generate torques or forces; instead, they utilize stored energy, akin to a spring-loaded system, to assist in motion. Some notable examples of passive exosuits are reported in [25] and [26]. On the other hand, active exosuits, which is the focus of this review, relies on active energy sources to generate forces and torques, supporting the movement of the limbs. With a focus on enhancing comfort and mobility, active exosuits, henceforth referred to simply as exosuits, typically employ unobtrusive and compact actuation mechanisms like cable/tendon-driven systems, series elastic actuators, shape memory alloys, pneumatic actuation, and dielectric elastomers. This design approach provides exosuits with the advantage of being lightweight and flexible, facilitating improved alignment with the user's skeletal system and delivering a more natural and intuitive user experience. Due to these inherent advantages, there is a growing interest from research groups in both academic and industrial sectors dedicated to designing exosuits that leverage textiles and elastomers, while moving away from traditional rigid links.

The goal of this paper is to holistically discuss the two main aspects: actuation and physical interface of soft wearable robots for both the upper and lower limb. Despite the availability of several reviews on assistive devices, many of them are subject to certain limitations. For example, review [27] exclusively focuses on soft wearable devices for hand, while [28], [29] centers on assistive devices designed specifically for upper limb rehabilitation. Likewise, [30] considers rehabilitation robots for the lower limb only. Although [24] provides an excellent review of purely soft assistive devices by broadly classifying them into upper and lower limb exosuits with sub-classification of each category into expansive or tensile robotics suits. However, these reviews are overlooking the mechanical details which plays an important role in the design of these devices. Furthermore, recently a new approach which combines soft actuator with rigid components to design hybrid (rigid-soft) devices has been introduced. These devices show promising results in both rehabilitation and assistance but have not been covered previously. So, this review aims to complement the existing body of literature by exploring and discussing the technical details such as actuation mechanisms detailing the generation of the assistive force, and how the forces are transferred to the body by discussing the physical interface of the exosuit with the body which plays a crucial rule in the improving the performance and comfort. We also discuss if the addition of the rigid components will help improve the performance and what should be considered while adding such components. Compared to the previous studies, we classified these devices into soft and semi rigid devices and categorized them based on their actuation mechanism, actuated degrees of freedom and supported joint. We have also reported the assistance level of these devices provided to the intended joints. Furthermore, we have extensively covered the exosuits for both the upper and lower limb both for single and multi-joint case. Fig. 2 shows the exosuits that are considered in this review.

The paper is structured as follows: Section II presents the search methodology, while Section III provides a brief explanation of core actuation technologies. Following this, Section IV details the design and actuation mechanism of soft assistive/rehabilitation robots for both upper and lower limbs. In Section V, we explore hybrid (semi-rigid exosuits), followed by Section VI, which addresses research limitations, outlines future directions, and presents our conclusions.

II. MATERIALS AND METHOD

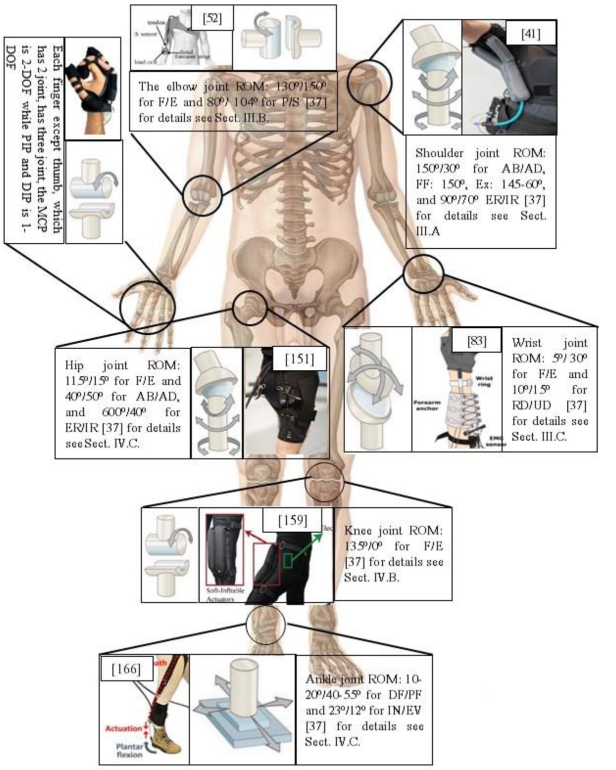
To identify relevant studies for this review, we followed the PRISMA guidelines [31].

Search method: A thorough search was conducted in electronic databases such as Google Scholar, IEEE Xplore, Scopus, and PubMed. Only peer-reviewed articles published between 2013 and 2023 were considered. Various search terms were utilized, including "rehabilitation robots", "assistive robots", "soft exosuits", "soft wearable robots," "lower and upper limb exosuits", and "hand assistive robots" among others. The key words were combined using "or" and "and" operators. We also conducted forward and backward reference searches to identify and include as many related articles as possible. Fig. 3. shows the search matrix for the keywords.

Selection: The following criteria were applied to determine the eligibility of papers for inclusion in this study:

i. The device should be intended for rehabilitation or assistance in ADLs or for power augmentation of healthy individuals.
ii. The device incorporates active actuators and a power source to offer assistance.
iii. The device incorporates either completely soft components or a combination of soft and rigid components.
iv. The paper should be published in a peer-reviewed journal or conference.

The PRISMA criteria we followed is shown in Fig. 4. Initially we had 4,822 studies, out of these 4676 were excluded due to the reasons stated above and shown in Fig. 4. Additionally, 18 references were added to the list by using the



Note: F/E: Flexion/extension, AB/AD: Abduction/adduction, P/S: pronation/supination, RD/UD: Radial/ulnar diviation, ER/IR: External/Internal rotation, In/EV; inversion/Eversion.

Fig. 2. The exosuits considered in this article categorized according to the intended assisted joint.

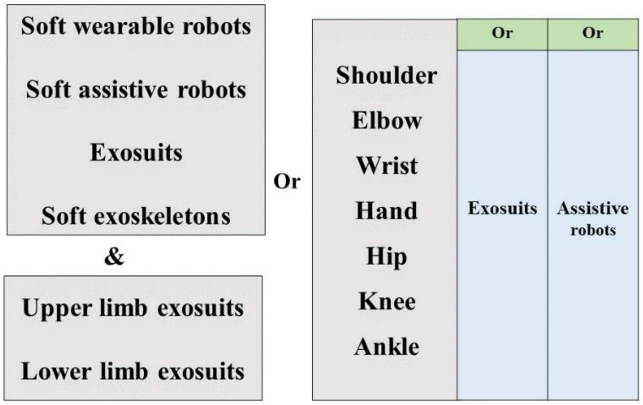


Fig. 3. Search Matrix: List of the key words used in this review.

backward reference check, resulting in a total of 164 relevant studies that are included in this review. We classified the outcomes of these studies based on several criteria, including whether the exosuit was soft or semi-rigid, the assisted limb (upper or lower), and whether the exosuit was intended for a single joint (e.g., shoulder, elbow, or knee) or multiple joints (e.g., shoulder and elbow). It is pertinent to note that currently, there is no clear distinction between hybrid and soft exosuits. However, based on the definition of soft exosuits given in [24], we define a hybrid exosuit as a device that uses a flexible (semi-rigid) joint less structure over the intended joint of assistance.

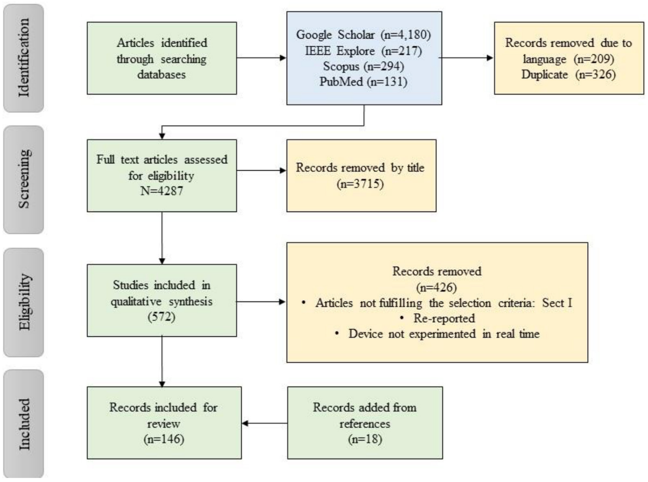


Fig. 4. Flow diagram summarizing the PRISMA guidelines followed in this paper.

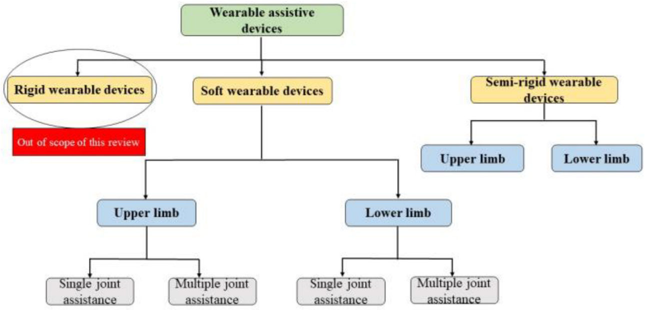


Fig. 5. Flow diagram of the exosuits classification criteria.

The classification criteria for categorizing the exosuits is shown in Fig. 5.

III. CORE ACTUATION TECHNOLOGIES

Assistive and rehabilitation robots employ a variety of actuation technologies to generate motion. The most common actuation technologies include: fluidic actuators, cable driven mechanisms, shape memory alloys and electroactive polymers based actuators. In this section, we will provide a brief introduction to each of these actuation mechanisms, including their working principles as well as pros and cons for their use in soft assistive robots. For more detailed explanations, please refer to [32], [33].

A. Fluidic Actuators

Fluidic soft actuators are among the earliest actuation mechanisms used in soft wearable robots. These actuators consist of inflatable chambers enclosed within a fabric or elastomeric pouch. By utilizing pressurized fluid, they can generate motion and forces through inflation or deflation of the chambers, as depicted in Fig. 6.A [32]. Fluidic soft actuators can be broadly categorized into two main types: hydraulic and pneumatic.

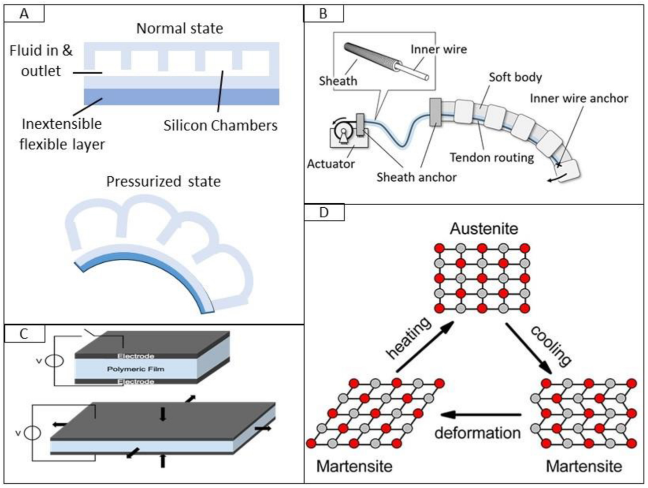


Fig. 6. Core actuation technologies for soft wearable robots: A) Fluid driven actuators [34], B) Motor cable driven actuators [36], C) Dielectric elastomer actuator [37] D) Actuation mechanism of SMA [38].

Hydraulic actuators utilize water or mineral oil to produce motion and forces. They are known for their high output force and power in a compact volume, but they tend to be more complex and expensive compared to pneumatic actuators [32]. On the other hand, pneumatic actuators use compressed air to generate motion and forces. While they are less powerful than hydraulic actuators, they offer the advantages of being lighter and more cost-effective. Due to these favorable characteristics, pneumatic actuators have become the most commonly adopted actuation mechanism in soft wearable robots [34], [35], finding extensive applications in various assistive and rehabilitation devices.

Fluidic soft actuators have the advantage of easy fabrication using molding or 3D printing while allowing for the introduction of physical intelligence that enable these robots to achieve different kind of movements such as bending, twisting, expansion and contraction all these characteristics are favorable for soft exosuits. However, these actuators have some inherent limitations such as slow response, requirements for compressors, pumps and power sources. Furthermore, they are often tethered limiting their portability.

B. *Motor Cable Driven*

This type of actuation mechanism relies on the use of electric motors to generate motion and is the second most commonly used actuation mechanism in soft robots [32], [33]. It consists of an electric motor, gear head, pulleys/spools and cable, see Fig. 6.B. The cable is routed along the body, and one end is connected to the motor and the other end is anchored to the body. To generate force and movement, the electric motor retracts the cable, winding it on a spool or pulley. This type of actuation mechanism has the advantage of precise control and high bandwidth while allowing for remote actuation [33]. However, during actuation, the cables can rub against each other and the human body, leading to friction and potential skin damage. To mitigate this, the cables are usually placed in a Bowden sheath. Nevertheless, this type of transmission may introduce additional friction and backlash issues that need to be addressed in the design of the suit and control architecture [39]. Moreover, the cable-driven actuation mechanism offers the flexibility to slacken the cable, transforming the exosuit into a passive device. This feature is particularly beneficial for reducing discomfort during prolonged use and avoiding restrictions on user movement, especially when the device isn’t required to provide assistance, such as during walking. However, it’s essential to note that this flexibility comes at the expense of lower bandwidth and delayed response, as the slack in the cable needs to be recovered.

To improve compliance and impedance of the motor cable driven system, an elastic element can be added in series with the actuator. The resulting actuator is known as series elastic actuators and solves the problem of cable slacking. These actuators not only offer high compliance and low mechanical impedance but also provide safety, shock absorbance, and precise torque control: a desirable characteristic for wearable robots and prosthesis [40]. However the main disadvantage of the SEAs is the low operating bandwidth, which limits the system rate to respond to the command signals. Though the low band width ($\leq 5Hz$) of the SEAs is not an important issue for exosuit design, they are not popularly used in exosuit because the designers mainly rely on the compliance of the suit and that of the body tissues itself.

Another interesting type of motor cable actuator is the twisted string actuator (TSAs). TSA comprises of a motor and two or more strings that connects motor to the load. Upon actuation the motor twists the string, co-axially along the shaft, thus shortening their length and linearly displacing the attached load. These actuators have the advantages of quite operation, low weight, and can produce an output strain of 30-40% [41]. The downside of this kind of actuation mechanism is the lower bandwidth, shorter life cycle due to the wear and tear caused by the twisting which also is responsible for the nonlinear stiffness and transmission ratio [41], [42].

C. *Shape Memory Alloys*

Shape memory alloys (SMA) are metallic alloys that possess the unique ability to memorize and recover their original shape. When an SMA is deformed plastically, it undergoes a phase transformation from its austenite phase to its metastable martensite phase [32]. Upon heating the SMA above its transition temperature, it returns to its austenite phase, reverting to its initial shape, as depicted in Fig. 6.D [38]. SMAs offer advantages such as high energy density, cost effectiveness, and quiet operation. However, they do have some limitations, including limited stroke and bandwidth. Additionally, SMA actuators exhibit stress-induced phase transitions and the associated pseudo-elasticity, rate dependent hysteresis and temperature dependent responses, making their control challenging and thus restrict its use in the wearable robots [43].

D. *Electroactive Polymer Actuators*

The dielectric elastomer actuators (DEAs) is an emerging type of electroactive polymer actuator that comprises of a dielectric layer sandwiched between two complaint electrodes as is shown in Fig. 6.C [33]. When a voltage is applied across the electrodes, an electric field is generated, causing the elastomer to deform due to the electrostatic forces between the charges. This deformation results in a change in shape and volume of the DEA, leading to its actuation [37]. In addition to being silent, they are light weight, soft, have a very high output strain of up to 300% and large bandwidth [44] these characteristics make them ideal for soft robotic applications. However, there are several challenges that needs to be overcome before embedding them into wearable assistive robots, such as their high operating voltage which can be a safety issue, based on their working principle they can only provide expansion, while the contraction is dependent on the material restoring force [37], limiting its application in wearable robots.

Other than the above mentioned several other soft actuation mechanisms are available such as, liquid crystal actuators (LCEs), magneto active elastomers, piezo electric and shape memory polymers [33] however due to their complex actuation mechanism and low output forces, they are not widely used in the assistive/rehabilitation robots.

IV. SOFT EXOSUIT FOR UPPER LIMB: DESIGN AND ACTUATION

The upper limb is a complex and remarkable structure that enables a wide range of movements and activities. Along with the hand, the upper limb includes other crucial joints such as the shoulder complex, elbow, and wrist joint. In this section we will briefly present the design of exosuit for each of the joints mentioned above.

A. Shoulder Exosuits

The shoulder complex is the connection between the upper limb and the axial skeleton. As is shown in Fig. 7.A, it is composed of the humerus, clavicle, and scapula bone. The main joint, known as the glenohumeral joint, or shoulder joint, allows for a wide range of motion, including flexion, extension, abduction, adduction, rotation, and circumduction [45].

Several soft wearable robots have been introduced to assist shoulder movements. For instance, [51], [52] presents a soft exosuit that utilizes an inflatable beam-type pneumatic actuator to counter gravity and aid with shoulder abduction movement. In [51] the inflatable pneumatic actuator is positioned directly above the shoulder and brachium through a two tired sleeve that acts as a prismatic joint, enabling relative motion between the brachium and actuator. However, the small moment arm results in a large reaction load that needs to be supported. In contrast in [52] the actuator is sewn onto a shoulder mount locating it next to the user's torso and under the arm. However, under low pressure the actuator suffers from buckling which impedes the device effectiveness. In their reiterated design [46] they introduced a pneumatic-reel type actuator with a fiber reinforced plastic bladder wrapped around an axle located at the base. The actuator is located between the torso and the upper arm and grows longitudinally. This effectively decouples the actuator inflation from the shoulder. abduction angle thus avoiding the buckling issue observed in [52]. However, these exosuits are 1-DOF and support the shoulder abduction/adduction (ABA) movement only.

Fig. 7. Shoulder exosuits. A) Shoulder anatomy: Joints and bones, B) Exomuscle: Reel type pneumatic actuator [46], C) Pneumatically actuated soft exosuit to assist the shoulder movement [47], D) An inflatable pneumatic exosuit to support the shoulder against the gravity [48], E) A cable driven exosuit for shoulder movement in 3D space [49], E) A hybrid pneumatic and SMA based exosuit for shoulder [50].

For complete shoulder mobility, [53], [54] designed a 2DOF soft exosuit with four pneumatic actuators arranged in antagonistic pairs, with each pair responsible for 1-DOF movement. Similarly, in [47], a segmented pneumatic actuator integrated into a vest is used to support the ABA movement. Additionally, two antagonistic actuators with wedged-shaped chambers, sewn to the ABA's edges, were employed to support shoulder horizontal flexion-extension by causing rotation upon inflation. An improved version of the device presented in [48] features a 2-DOF inflatable pneumatic actuator, with a "Y" shape, anchored to the arm and torso. To improve the actuator reliability, [55] conducted a series of experiments to find the best sealing method, fabric material and shape of the pneumatic actuator. They designed several different actuators and integrated them in a device that can provide full arm support over at least a range of 120 degree of shoulder abduction. They evaluated the actuators in terms of their breaking strength and maximum angle of abduction and found that rectangular and wing shape actuators are more effective than 'Y' shaped actuators.

Myoshirt [49] is a cable-driven device to support the arm against gravity. It comprises a thorax harness with a bridle mount system to fix the shoulder anchor, an upper arm cuff with two anchors, and a tendon connected to the motor via a spool. The tendon is routed between the shoulder anchor and the upper arm anchor above the medial epicondyle. In addition, they employed a lateral arm anchor with a series spring to support the rotation torque at higher arm elevation. To assist the shoulder movement in 3D, [50] proposed a soft wearable robot for the shoulder assistance using hybrid SMA and pneumatic actuation mechanism. The SMA springs, enclosed in braids were extended from the chest and back to an upper arm cuff acting antagonistically to support the horizontal movement of the arm, while the pneumatic actuator placed in axilla helps in the shoulder abduction.

TABLE I
SHOULDER ASSISTIVE DEVICES

Ref.	Actuation	Supported DOFs/Joints	Assistance level
R.F. Natividad, et al. [51], 2016	Pneumatic	1-DOF/Shoulder AB/AD	AB:30.62°
C.Simpson, et al. [46], 2020	Pneumatic	1-DOF/Shoulder AB/AD	Reduced the muscle effort by up to 74%
R.F. Natividad, et al. [54], 2021	Pneumatic	2-DOF/Shoulder movement	Reduced muscle activation by up to 54%
C. T. O'Neill, et al. [48], 2020	Pneumatic	2-DOF/Shoulder AB/AD and F/E	Reduced the EMG by 65.27±2.48%
C. T. O'Neill, et al. [56], 2022	Pneumatic	1-DOF/Shoulder AB/AD	Moment of 10 N.m at 90°
B. Li , et al. [55], 2021	Pneumatic	1-DOF/Shoulder AB/AD	N/A
A. M. Georgarakis et al. [49], 2022	Cable, Motor	2-DOF/Shoulder AB/AD and F/E	Delayed muscle fatigue by 51.1s
A. Golgouneh, et al. [50], 2021	Pneumatic and SMA spring	2-DOF/Shoulder AB/AD and F/E	N/A

Note: F/E: Flexion/Extension, AB/AD: Abduction/Adduction, N/A: Not available

Fig. 8. Elbow exosuits. A) Elbow anatomy: Joints and bones, B) Cable driven elbow exosuit [57], C) Pneumatically actuated soft exosuit to assist the elbow movement [58], D) A soft exosuit employing thin Mckibben actuator to support the upper limb [17], E) An SMA spring actuated soft exosuit for elbow and forearm [59], F) A DEA actuated soft elbow assistive device [60].

Table I summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

B. Elbow Exosuits

The elbow is a hinge type of joint that allows the forearm to bend and straighten. It is formed by the articulation of three bones: the humerus radius, and ulna, see Fig. 8.A. The ulna pro–vides stability to the joint, while the radius allows for rotational movements of the hand, such as pronation and supination [45].

To assist the elbow joint movement [61] proposed an actuation mechanism comprising of a pair of motors coupled with a multi-stable composite transmission (MCT). The MCT can twist and take any configuration between a coiled and a straight shape, allowing it to have multiple points of local stability. This feature allows the mechanism to hold different static positions and reduces power consumption but is complex and bulky. To simplify the design in [62], the MCT was replaced with electromagnetic clutches, and two cables were coiled in opposite directions around the spool thus allowing a single motor to assist with both elbow flexion and extension. To improve the comfort and usability of the device the subsequent iteration of the exosuit [57] employs a dual-strap design. A proximal strap firmly attaches to the arm and chest, while a distal strap ensures a snug fit around the forearm using a Boa lacing mechanism. Reinforced with in extensible nylon webbing and 3D printed components, that mimic the function of ligaments, the network serves as a path for routing tendons and transferring the reaction load.

In a different approach, [63] proposes an actuation mechanism that considers the human elbow's torque-angle profile, resulting in a device that replicates the natural movement of the human elbow through a variable lever length. This mechanism consists of a motor, elastic bungee, and cam spool system with separate axes of rotation. The elastic bungee serves as a damper, enhancing the interaction by providing smoother movements between the robot and the user, while the cam spool with separate axis provides the variable lever length. Experimental results shows that the device can replicate the torque profile, however, the effect of pre-tension in the elastic bungee needs to be evaluated when the device is used over extended periods of time.

To assist elbow flexion in bimanual tasks, the exosuit introduced in [64] features two twisted string actuators (TSAs): one for each elbow. These TSAs are mounted on a lightweight aluminum frame worn on the back, and the tendons are routed through 3D printed forearm and shoulder supports which are attached to the body using adjustable straps. To provide proper assistance they proposed an sEMG driven control and showed that the device considerably reduces the muscular activity during load lifting. To assist in flexion extension as well as forearm pronation supination, [65] introduced an exosuit using dual motor tendon actuation mechanism. It comprises a vest, upper arm, and wrist strap with 3D printed cable hooks. The device supports elbow flexion extension by simultaneous cable pulling/pushing, while pronation supination utilizes opposing cable movements. To reduce the weight a new actuation mechanism, called one-to-many, proposed in [66] uses a single motor to assist both the elbows independently. The mechanism connects the motor to two separate modules: each having a pinion gear meshed with two bevel gears. A counter shaft coupled to electromagnetic clutches drives a spool, which controls two NiTi cables wrapped in opposite directions for assisting elbow flexion and extension.

A problem with the motor-cable actuated exosuits is the high shear forces and dislocation of the anchors when the motor retracts the cables. To minimize the impact of the cable shear forces at the anchors, LUXBIT [67], uses a 'V' shaped textile clamp to convert cable pulling forces to pushing forces. Additionally, to safeguard the shoulder joint from unwanted forces the exosuit features a pivot piece that rotates around a grooved base attached to a backpack's handler. An improved version of the device presented in [68] uses force-compliant sewing to stack together three different types of breathable fabric to form the anchor. To avoid the shoulder co-opetition, they also incorporated a redesigned 3D printed pivot, placed behind the shoulder articulation. The pivot has a rigid base and deformable central part, allowing for a controlled deformation, thus providing a better fit to the movable surface of the shoulder.

CADEL [69] is a parallel cable-driven elbow assistive device, uses four servo motors positioned on the upper arm cuff which works antagonistically to extend or retract the cable to assist the elbow flexion/extension and lateral orientation. The cuffs are secured to the arm with adjustable straps on the inner sides. To facilitate easy donning and doffing the improved version of the device presented in [70] replaced the adjustable traps with pneumatic chambers below the arm cuffs. Additionally, a flexible elbow guard with a cable passage was incorporated, eliminating the need for an additional structure to prevent collision between the elbow and the cable. To reduce the cable friction, in [71] they used a pulley with a cable passage which also prevents unwrapping of the cable. They also added a removable flexor unit to aid in hand straightening and positioning during exercise.

In addition to motor-based actuation mechanisms, researchers have explored pneumatic actuation as well. For example, the exosuit introduced in [72] utilizes two pairs of antagonistic McKibben actuators to create a 2-DOF exosuit for assisting elbow flexion/extension and forearm pronation/supination. However, these McKibben actuators are usually heavy and require high pressure sources. To tackle this problem and make a light weight exosuit with a compact design, [17] utilized thin McKibben actuators which operate at a lower input pressure. They enhanced the output force of the thin McKibben actuator by weaving the actuator as a fabric using the wrap and weft technique. The weaved actuator was integrated into a suit, connecting the shoulder and elbow support, to a glove to provide support and maintain the desired arm and elbow positions.

Different from the previous ones, the exosuit presented in [73] uses a pneumatic actuator comprising of four wedge shaped segments. The bending movement is achieved by combining materials of different stiffness. However, upon inflation the actuator bulges and was not able to maintain the perpendicularity to the arm. To maintain the actuator perpendicular to the arm, [58] and [74] employed triangular retainers on each side of the actuator and connected it to the elbow using a nylon sleeve secured by adjustable straps against the elbow joint's curvature. To evaluate the effectiveness of the exosuit, [75] conducted a series of experiments under different loading conditions. It was found that with assistance from the exosuit, the muscle activity reduced by 50% with a net metabolic reduction of 61%. To improve the life span and output force, [76] used heat sealable TPU to fabricate pneumatic bellows attached to an inextensible fabric. The actuator has a modular design that allows the actuator to be easily modified to fit any limb size. To reduce the fabrication time, [77] introduced a 3D printed pneumatic actuator, featuring a rectangular shape with 10 interconnect bellows. It also incorporates a solid bottom layer to limit strain and facilitate bending. To assist the elbow flexion the actuator is sewn onto the dorsal side of a free-size fabric elbow sleeve. However, these actuators are 1-DOF and can only assist flexion or extension. Increasing the number of assisted movements requires to increase the number of actuators which not only result in bulkier exosuit but requires for a higher power supply and a more complex control. These issues can be overcome by designing a multi DOF actuator. In this regard [78] proposed a positive negative pressure pneumatic actuator and integrated it in an elbow sleeve. Upon inflation the actuator expands supporting the elbow extension and contracts when deflated thus supporting the elbow flexion.

To assist the forearm pronation/supination the exosuit presented in [79] uses helical pneumatic actuators. The suit features two antagonistic actuators connected to a sleeve that is fastened to the wrist, hand, and forearm. The actuator is fabricated by enclosing a pneumatic chamber in a fabric pouch made of two different materials: an isotropic non stretchable fabric and an anisotropic material extending longitudinally but not orthogonally. In [80], a novel pneumatic actuator utilizing the eversion principle is integrated into the suit. It consists of an airtight fabric-reinforced bladder that is folded inside-out at the tip. Upon applying pressure, the actuator unfolds and generates contraction forces, thereby providing assistance to the elbow.

Different from the above the assistive suit presented in [81] uses a fiber reinforced hydraulic actuator which is fabricated by placing an elastic chamber in radially constrained hollow coil and covering it in a fabric. The suit also features an embedded liquid metal-based piezo resistive sensor for elbow flexion/extension measurement.

To make the suit unobtrusive and reduce the overall weight, in [82], SFM, a fabric-based actuator that incorporates SMA spring bundles in a fabric pouch is integrated with a suit to assist the elbow movement. The suit comprises of a jacket with a shoulder strap sewn to the back garment and an upper arm strap attached to it. The SFM is positioned between the upper arm strap and the forearm band and tightened using a BOA mechanism. However, the SFM suffers from the lower actuation bandwidth usually tens of seconds. To improve the actuation performance, [83] fabricated the SFM by evenly arranging a very fine diameter (0.5mm) SMA spring, inside a breathable fabric. This arrangement increased the surface area to volume ratio, leading to improved heat dissipation and faster response times. To further improve the actuation rate, in their related study [84] they integrated two fans directly on the fabric pouch, this forced air cooling reduced relaxation time by 70.2%. In their subsequent study [85] they further reduced the diameter of the spring to 0.18mm and weaved it in form of a fabric. The SMA woven fabric was then covered in a breathable fabric pouch and was connected to the electrodes

TABLE II
ELBOW ASSISTIVE DEVICES

Ref.	Actuation	Supported DOFs/Joints	Assistance level
L. Cappello, et al. [61], 2015	Motor/MCT	1-DOF/Elbow Flexion	N/A
L. Cappello, et al. [62] , 2016	Motor/Cable	1-DOF/Elbow F/E	N/A
M. Xiloyannis, et al. [86], 2017	Motor/Cable	Elbow F/E and thumb, middle, and forefinger F/E	N/A
D. Chiaradia, et al. [57], 2018	Tendon	1-DOF/Elbow F/E	Reduced EMG up to 64.5%
E. Mobedi, et al. [63], 2021	Motors/Cable/ Elastic Bungee	1-DOF/Elbow F/E	F/E ROM: 108°
M. Hosseini, et al. [64], 2020	TSA	2-DOF/Elbow F/E	Compensated for a muscular activity of up to 220%
R. Ismail, et al. [65], 2019	Motor/Cable	2-DOF/Elbow F/E and P/S	F/E:90°/157°, P/S:19°/18°
M. Canesi et al. [66], 2017	Motor/Cable	2-DOF/Elbow F/E	3.4 N.m torque up to 90° elbow flexion
J. L. S.Escudero et al. [68], 2020	Motor/Cables	1-DOF/Elbow F/E	Reduced Muscle Activation by 26.36%
A. Koziesk et al. [69], 2020	Motor/Cables	2-DOF/Elbow F/E and P/S	N/A
M. Bottin, et al. [70], 2020	Motor/Cables	2-DOF/Elbow F/E and P/S	Flexion Torque: 5N.m
G. Zuccon, et al. [71], 2020	Motor/Cables	2-DOF/Elbow F/E and P/S	N/A
G. Zhang et al [72], 2018	McKibben	2-DOF/Elbow F/E and P/S	N/A
T. Abe, et al. [17], 2019	Thin McKibben	2-DOF/Elbow and Shoulder	Reduced the iEMG by up to 40%
V. Oguntosin, et al. [73], 2015	Pneumatic	1-DOF/Elbow F/E	F/E: 70◦/110◦ @ 50KPa
C. M. Thalman, et al. [58], 2018	Pneumatic	1-DOF/Elbow F/E	Flexion Torque: 27.6 N.m @300 kPa
V. Oguntosin, et al. [78], 2019	Pneumatic	1-DOF/Elbow F/E	N/A
T. T. Hoang, et al. [81], 2021	Hydraulic	1-DOF/Elbow F/E	Reduced the EMG RMS up to 14.5 times
H. W. Cheng, et al. [74], 2023	Pneumatic	1-DOF/Elbow F/E	Reduced the MVC EMG by up to 15%
J. M. D. Vilchis , et al. [76], 2022	Pneumatic	1-DOF/Elbow F/E	N/A
B. W. K. Ang , et al. [77], 2020	Pneumatic	1-DOF/Elbow F/E	Reduced the MVC EMG by 36.9%
J. Realmuto , et al. [79], 2019	Pneumatic	1-DOF/Elbow P/S	Reduced the EMG by 59%/24% for P/S
T. Abrar, et al. [80], 2019	Pneumatic	1-DOF/Elbow F/E	N/A
S. J. Park, et al. [82], 2019	SMA/Fabric	1-DOF/Elbow F/E	N/A
S. J. Park et al [85], 2023	SMA/Fabric	1-DOF/Elbow F/E	Reduced sEMG by 50-70%
J. Jeong , et al. [59], 2022	SMA spring	1-DOF/Elbow F/E and P/S	Reduced the EMG by 13%
M. Duduta , et al. [60], 2019	Stacked DEA	1-DOF/Elbow F/E and P/S	N/A
Note: F/E: Flexion/Extension, AB/AD: Abduction/Adduction, N/A: Not available			

and integrated it in a suit to assist the elbow flexion. With the same goal, [59] proposed an active cooling system where the SMA springs were enclosed in a stretchable elastomeric tub and circulated a coolant, water or cooking oil to dissipate the heat and improve the response time. They proposed SMA based artificial muscle were used in an arm exosuit to support elbow and forearm movements.

Other than the above-mentioned actuation mechanisms some researchers have also used DEAs. For instance [60] used stacked contractile DEA actuator as bicep muscle by anchoring it between the forearm and upper arm, and upon applying the voltage it contracts bringing the forearm close to the upper arm thus assisting the elbow flexion, however they usually require a very high voltage and output force is small and are not durable as compared to the other actuators which limits its application in rehabilitation devices.

Table II summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

C. Wrist Exosuits

The wrist joint, also known as the radiocarpal joint, is formed by the articulation of the radius, ulna, and several carpal bones, see Fig. 9.A. It allows for a wide range of motion in the hand, including flexion/extension, abduction/adduction, and circumduction [45]. The wrist joint is essential for precise hand movements and fine motor skills [87]. However, orthopedic or neurological impairments can damage the nerves and muscles that control the wrist, leading to reduced range of motion, weakness, and pain. This section presents some state-of-the-art devices that aims to restore lost wrist functionalities and assist the wrist in performing ADLs.

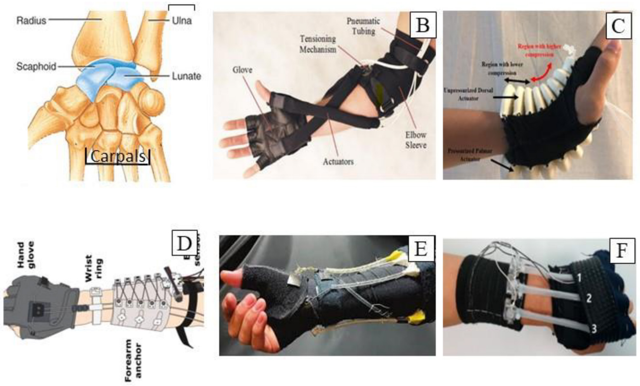


Fig. 9. Wrist exosuits. A) Wrist anatomy: Joints and bones, B) McKibben actuated wrist exosuit [88], C) 3D printed pneumatic actuator-based wrist exosuit [89], D) Exo-wrist: a cable driven wrist assistive device [90], E) Twisted string actuated wrist assistive device [91], E) Soft wrist assist: An SMA spring actuated soft wrist exosuit [92].

TABLE III
Wrist Assistive Robots

Ref.	Actuation	Supported DOFs/Joints	Assistance level
N. W. Bartlett, , et al. [88], 2015	McKibben	3-DOF/wrist movements	F/E: 91°, P/S: 78°,R/U deviation: 32°
S. Das, et al. [97], 2017	McKibben	2-DOF/wrist movements	Reduced the EMG up to 31% for F/E and up to 35% for P/S
S. Liu, et al. [93], 2021	Pneumatic	2-DOF/wrist movements	F/E: 31°/30° and R/U deviation: 33°/22°
B.W.K. Ang, et al. [89], 2019	Pneumatic	2-DOF/wrist movements	F/E: 33.°/34.2°, R/U deviation: 24.6°/17.3°
H. Choi, et al. [90], 2019	Motor/Cables	1-DOF/wrist flexion/extension	0.5 Nm for wrist extension
D. Chiaradia, et al. [94], 2021	Motor/Cables	1-DOF/wrist flexion	Up to 3Nm
N. Li, et al. [95], 2020	Motor/Cables	2-DOF/wrist movements	Reduce EMG by 43.3% and joint force by 35.6%
T. Tsabedze et al. [91], 2021	TSA	3-DOF/Wrist movements	Improve wrist F/E, P/S, AB/AD
J. Jeong, et al. [96], 2019	SMA spring	2-DOF/wrist movements	F/E:33.8°/30.4°, R/U deviation: 21.4°/15.4°
J. Jeong, et al. [92], 2022	SMA Spring	2-DOF/wrist movements	F/E:38°/50°,R/U deviation:34°/35°,
Note: F/E: Flexion/Extension, AB/AD: Abduction/Adduction, N/A: Not available			

To assist the hemiparetic stroke patients with wrist flexion extension as well as pronation/supination, [88] proposed a pneumatically actuated soft orthosis comprising of an elbow sleeve, a fingerless glove and crossing linear McKibben actuators, positioned on both the palmar and dorsal sides of the forearm. The device provide assistance over a range of 32 deg in radial/ulnar deviation, 91 deg in flexion/extension and 78 deg in supination/pronation. To make a more compact device [93] proposed a wrist brace that uses origami inspired modular pneumatic actuators. Each actuator comprises two blow-molded origami sections that expand/contract upon inflation/deflation and a base section for anchoring to the wrist brace. The device has four actuators, two on the dorsal and two on the palmar side, arranged in parallel. This configuration allows the device to assist with wrist flexion/extension and radial/ulnar deviation. Using a different approach [89] proposed a 2-DOF soft robotic wrist sleeve that consists of two 3D printed bending pneumatic actuators sewn onto a fabric wrist sleeve. Each actuator comprises of chambers, each with four quadrants, and a fold-based design with strain limiting at the bottom to facilitate the bending movement. By controlling the pneumatic pressure in specific quadrants, the device assists with flexion/extension and radial/ulnar deviation movements of the wrist.

To aid in constrained movement induced therapy, [90] presents a cable-driven wrist assistive device called Exowrist. The device comprises of a glove, equipped with embedded Teflon tubes to guide the tendons, an oval shape wrist wring, which determines the tendons position on the wrist, and a forearm brace which actively tightens around the forearm when a resistance force is needed. To improve the comfort the wrist assistive device in [94], [95] uses a cable-driven actuation mechanism with an ergonomic design. It includes a reinforced glove with a flexible 3D-printed structure and a forearm strap.

The soft wrist assist (SWA) presented in [96] is a 2-DOF assistive device that supports wrist flexion-extension and ulnar radial deviation. It employs SMA spring actuators to generate the required force, which are transmitted to the wrist through a finger less glove and forearm strap. A revised version of the device presented in [92], improved the actuation performance by integrating an active cooling mechanism with the robot. Additionally, the slippage of the forearm strap observed in the previous design was alleviated by adding an anchor above the elbow joint.

Table III summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

D. Hand Exosuits

Hand is a complex structure with five digits: four fingers and a thumb. Each finger has three joints, while the thumb has two joints, see Fig. 10.A. The joints in the fingers are: metacarpophalangeal (MCP) joints, proximal interphalangeal (PIP) joints, and distal interphalangeal (DIP) joints. While in thumb the carpometacarpal (CMC) joint is the proximal joint, MCP is the middle joint, and the PIP joint is the distal joint [45]. These joints work together to allow the hand to perform a wide range of movements, which are essential for activities of daily living. Hand impairments are common among stroke survivors, hindering their ability to perform activities of daily living (ADLs). Restoring hand function is crucial for independence, but recovery is often slower than other extremities [27]. To overcome these challenges, innovative rehabilitation robotic devices have been developed. In this section, we will explore the design and actuation mechanism of state-of-the-art hand rehabilitation devices.

In 2013, C. J. Walsh's research group [106] developed a soft glove with pneumatic actuators for finger flexion assistance. The glove had an open palm design and the actuators were positioned dorsally on the fingers. However, the actuator suffered from ballooning effect to address this issue and enhance the bending performance, the actuators were redesigned with a corrugated outer layer [98]. In a related study [107], fabric reinforcement was applied to improve the actuator's performance. The design included a fabric layer at the bottom and a corrugated fabric layer on top, preventing unwanted bulging and enabling higher force output at lower pressures. In their subsequent work [108], FBG sensors were integrated to measure kinematics within an MRI environment and implemented a closed-loop PID controller to regulate internal actuator pressure based on sensor readings, ensuring appropriate assistance to users.

Fig. 10. Hand exosuits. A) Hand anatomy: Joints and bones, B, C, D, E) Pneumatically actuated hand assistive device [98]– [101], F, G, H) Cable driven assistive gloves, [102], [103], [104] I) SMA actuated assistive glove for finger flexion/extension [105].

To enhance the compatibility of pneumatic actuators with human fingers, [99] developed an assistive glove that incorporated variable stiffness pneumatic actuators (VSPA). These actuators were designed with higher stiffness at the phalanx and lower stiffness at the joints. In the revised version of the device presented in [109] they replaced the adjacent rectangular channels with a sinusoidal air channel to prevent air channel blockage issues observed in the previous design. Additionally, the bottom layer of the actuator was reinforced with fiber, contributing to improved bending motion. In a similar vein, [100] proposed segmented PneuNets Bending Actuators (SPBA), consisting of a main body with flexible and inflexible segments, along with a highly elastic inner bladder. Inflation of the actuator caused the flexible segment to bend, assisting with finger flexion. Conversely, deflation, combined with the inherent stiffness, facilitated finger extension. It is also pertinent to note that stroke survivors often have difficulty extending their fingers leading to the development of a clenched fist deformity.

To help these patients extended the glove presented in [110], a variable stiffness pneumatic actuator located on the dorsal side. Upon inflation the actuator stiffens, which helps the patients straighten their fingers. A number of other devices, [111], [112], [113], [114], [115] have used fabric based pneumatic actuators, however, these kind of pneumatic actuator often produces low output force and reduced ROM which in most of the cases is insufficient for conducting ADLS.

To increase the output force of a fabric pneumatic actuator, [101] utilized two different materials for the fabric pouch: a non-stretch cotton at bottom, and mono-directional stretchable fabric on top. Additionally, a stretched elastic band is stitched to the excess fabric of the top layer and then to the bottom layer in a relaxed state, creating equally distributed ruffles for bending motion. A distinct approach of utilizing reinforcement pads with pneumatic fabric actuators for wearable applications is presented in [116]. The actuator has asymmetric chambers made of two different fabric layers and a 3D printed interference pad placed on the adjacent pleats surfaces to reinforce the structure. This enable the actuators to have high output force and joint torques. Others [117], [118] have used hybrid structure to improve the positioning stability as well as the ROM and output force.

The devices presented so far can either assist the flexion or extension. To support both the flexion and extension movement of the finger, the assistive glove described in [119], [120] utilizes pneumatic artificial muscles (PAM) located on the forearm brace and connected to the fingers through cables. To support the bidirectional movement, each finger of the glove is equipped with two PAMs. However, this makes the device bulky and heavy. To make a device that is compact and lightweight, [121] proposes a hybrid pneumatic actuator featuring a PneuNet structure, to support the flexion, and a thin strip of flexible steel integrated with the actuator through an embedded pocket, enabling passive assistance for finger extension. Another research [122] introduced a pneumatic actuator with embedded kinked spring. The kinked spring efficiently utilized stored energy from actuator bending to support the finger extension. Using a different approach [123] introduced pneumatic actuators capable of generating assistive forces by applying positive or negative pressure, enabling bending or extension of the actuator thus assisting finger flexion or extension. Additionally, a single bellow actuator placed between the thumb and the side of the palm assists in thumb adduction or abduction through expansion or contraction.

In a different approach, [124] utilized two interconnected bellows to enable bidirectional actuation. When pressurized, one bellow expands while the other contracts, allowing the wearer to flex and extend their fingers. Assistive forces are transferred to the wearer via cables routed through a flexible 3D printed structure. Likewise [125], introduced a 3D printed pneumatic actuator with a folded structure. The actuator tries to unfold when inflated, resulting in asymmetrical bending motion facilitated by a strain-limiting layer at the bottom. When deflated, the actuator returns to its original shape, which helps with finger extension.

The Exo-Glove, introduced in [126], utilizes a bioinspired tendon-driven actuation mechanism with a rigid brace for tendon routing to restore grasp function. However, the use of a fabric glove posed sanitation challenges. To address this, [127] enhanced the design by incorporating a polymer glove and introduced a slack enabling mechanism to alleviate the discomfort caused by cable pretension. In a recent study [102], the device was further improved by replacing the external 3D printed structure with an embedded soft polymer-based mechanism for tendon anchoring. Additionally, a passive mechanism was added for thumb positioning, reducing the number of required actuators. To achieve adaptive grasping, [128] introduced a lightweight design. The device employed one motor for thumb flexion and another motor with a two stage differential mechanism for adaptive finger flexion. The differential mechanism enables individual finger movement based on encountered resistance during adaptive grasping.

BiomHED, [129], [130] takes inspiration from the muscle tendon unit structure of the human hand. The device utilizes a cable driven actuation mechanism with the cables arranged in such a way to replicate the geometry of the major muscle tendon units found in the thumb and fingers. In [131], a revised version of the device, presented in [129], focuses on improving the mechanics of functional tasks for the index and middle fingers. The authors also proposed a subject-specific assistance strategy, where they asked the user to perform a certain task and then determined the assistance level through an iterative approach. Building upon this rationale, [132] introduces a new approach that combines spasticity sensing into the rehabilitation glove. In order to provide tailored assistance, spasticity is estimated by analyzing the relationship between pressure and bending angle in a soft-elastic composite actuator worn on the finger.

References [133], [134], [135] utilizes twisted string actuators (TSA) while [136] utilized linear actuator and tendons that partially replicate flexor tendons to enable finger flexion. Passive control of finger extension is achieved through springs routed along the dorsal side and centered on the fingers. The device also incorporates 3D printed phalanges rings to route extensor tendons parallel to the fingers, reducing discomfort and minimizing the risk of injury. The glove introduced in [135] employed supercoiled polymer strings (SPSs) that passively assist the movement. The SPSs also track finger movement by detecting changes in resistance as the fingers extend. To improve the workspace an 8-DOF assistive device [137] combines cable driven tendons and silicon strips for bidirectional actuation. Palmar tendons, actuated by a servomotor, enable finger and thumb flexion, intrinsic movement, and opposition while the dorsal silicon strips passively assist finger and thumb extension and repositioning.

To improve the efficiency of the cable driven mechanism, the research group led by Biggar and Yao [138], introduced a novel concept of using suction cups which in addition to acting as the tendons route, tightly fits the glove to hand and hold it in place during actuation. Furthermore, they used elastic bands routed on the backside of the hand to passively support finger extension. With the same goal in mind, [103] proposed an assistive device with an actuation mechanism on the dorsal side of the hand and tendons routed along the finger centerline to support flexion and extension movements.

To achieve various intermediate hand configurations between a fully closed and open position the AirExGlove presented in [139] uses a hybrid actuation mechanism. It uses pneumatic actuators on the back of the hand to assist with hand-opening movements, and tendons on the palm to mechanically limit the movement thus providing the necessary shape control for different activities of daily living. Using a similar approach [140] introduced an assistive glove which incorporates six tendons (thumb, middle, and index fingers: 3; thumb abduction/adduction: 2; ring and little fingers: 1). A dorsal laminar jamming structure to maintain finger configuration and aid in finger extension and a soft pneumatic actuators in a “V” shape assist with abduction/adduction, and an additional telescopic pneumatic thumb enhances grasp stability.

Using a different approach [104] introduced a hybrid actuation mechanism called double-acting soft actuator (DASA). It combines a tendon-driven actuator and a fabric-based pneumatic extension actuator, powered by a single motor with it’s shaft connected to a pulley with two cables wound in opposite directions. When the motor rotates, the cables retract the tendons and compress the bellows, which in turn deflates the extension actuators and induces finger flexion. Conversely, when the motor rotates in the opposite direction, it retracts the bellow compression cable, squeezing the air out of the bellow and causing the extension actuators to inflate, which extends the fingers.

To reduce weight of the device, Flexo-glove [142], uses a bidirectional cable driven spooling system to help with flexion and extension movements of the fingers as well as the thumb. Though the cable-driven actuation mechanisms can generate high forces but also apply excessive compression to the wearer. To address this, [147] proposed a compliant force distributing structure (FDC), a flexible frame composed of 3D printed rigid links connected by wire and Kevlar belts connected to servo motors. This modification allows the device to provide assistive forces without imposing harmful loads to the fingers.

Most rehabilitation gloves only help with finger and thumb flexion and extension while overlooking the important thumb opposition, which is essential for daily living activities. To address this, CADEX [143] a soft wearable glove designed to assist stroke patients in their acute stage, utilizes a cable driven actuation mechanism with improved tendon routing, particularly targeting the thumb CMC joint for independent thumb positioning. Similarly, [144] introduced two soft actuators: the fan-ACT and the 3C-ACT. The fan-ACT resembles a fan and can support flexion, abduction, and adduction. The 3C-ACT integrates three chambers to support the same movements. Likewise, [145] presented a cylindrical multi-degree-of-freedom (DOF) pneumatic actuator with granular jamming. It comprises three pneumatic chambers surrounding a granular jamming chamber, all shielded by a reinforcing fiber layer to prevent radial expansion. This multi-DOF design enables the actuator to facilitate finger flexion, extension, abduction, and adduction, while the inclusion of granular jamming enhances system stiffness and output force.

In contrast to the previously mentioned devices, [105] employed antagonistically arranged shape memory alloy wires to assist both flexion and extension. The effectiveness of the device was demonstrated in experiments conducted by [105], which revealed a fingertip force of 10N and a total grasping force exceeding 40N. In another study [146], the assistive device utilized spring roll dielectric elastomer actuators. These actuators consist of multiple layers of the elastomer material wrapped around a compressed elastic spring core. Applying a voltage to the electrodes decreases the elastomer thickness, leading to expansion and causing the spring to uncoil, resulting in an output displacement.

Table VI summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

E. Multi Joint Assistive Exosuits for Upper Limb

In the above studies, the focus is mainly on individual joints, such as the shoulder, elbow, wrist, or hand; however, most of the ADLs requires a coordinated motion of the elbow, shoulder and wrist joint. To address this, a soft wearable suit has been developed to assist polymyositis patients during meals, as discussed in [148]. The suit features, a hybrid actuation mechanism, including Bowden cable systems with two motors for independent elbow flexion and forearm motion, as well as a pneumatic balloon actuator for shoulder abduction support.

Similarly, [149] introduced a 6-DOF bilateral device called CUBE, it utilizes 3D printed shoulder mounts, four arm cuffs, and six motors. The upper arm cuffs have two cables each for shoulder flexion and abduction, while the forearm cuffs have one cable each for elbow flexion. Likewise, Armstrong [150] is a wearable device that uses cable-driven actuation to help people with elbow and shoulder movements. It has six electromechanical actuators worn on the back, and a shoulder saddle with an extended carbon fiber yoke to distribute forces across the chest, back, and abdomen. This helps to avoid compression on the shoulder joint. To reduce weight and complexity, Ausxilio [151] uses two TSAs with a main frame on the back that holds the actuation unit. Cables from the actuation unit are routed to the upper arm and forearm bands via pulleys. The cables transfer assistive forces to the wearer to assist shoulder and elbow flexion. Likewise, Exoflex [152] uses DC motors with gearboxes to generate assistive forces. It uses a fabric jacket reinforced with small nylon 3D printed rigid pieces sewn or velcroed to the cloth to guide the cables.

Inspired from the tensional integrity found in the human body, CRUX, a multi DOF assistive robot for the upper limb is presented in [153]. The exosuit uses a cable driven actuation mechanism with the cables routed along the lines of non extension. To enhance flexibility and compliance, a modified tensegrity design based on lines of minimal extension is used instead of the original design in [154]. This allows to account for the variation between different users.

Using the textile pneumatic actuator as discussed in [48], [155] introduced a soft wearable robot that can assist the shoulder elevation as well as the elbow extension. The suit comprises of two actuation units: an pneumatic actuator with a 'Y' shape, placed in the axilla to support the shoulder abduction, and a pair of beam type inflatable actuators integrated into a sleeve to assist the elbow extension.

Forcearm [156] is a multi-DOF upper limb assistive robot that uses pneumatic gel muscles (PGM). PGMs have a structure similar to McKibben actuators but with a customized pneumatic chamber for higher force production at lower air pressures. The suit includes 14 PGMs attached to commercially available wearables for shoulder, elbow, and hand, supporting shoulder and elbow flexion, wrist flexion/extension, and pronation/supination.

Table IV summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

V. SOFT EXOSUIT FOR LOWER LIMB: DESIGN AND ACTUATION

Bipedal locomotion is a complex biomechanical process that requires the coordinated movement of the skeleton around the joints during each stride [157]. Each gait cycles/stride for a normal walking speed of about 1.3 m/s, as shown in Fig. 11, can be divided into two main phases: the stance phase and the swing phase. The stance phase occurs when the foot is on the ground and includes the heel strike, foot flat, mid-stance, heel off, and pre-swing. It accounts for 60% of the gait cycle and provides stability, support, and propulsion. The swing phase occurs when the foot is off the ground and includes the toe off and leg swinging forward. It accounts for 40% of the gait cycle and facilitates leg and foot advancement [30]. In this section, we will explore soft exosuits designed to support the joints that plays a crucial role in human locomotion.

A. Hip Exosuits

The hip joint, akin to a ball and socket joint, connects the pelvic and thigh bone (Fig. 12.A). It plays a vital role in supporting body weight and facilitating leg movements in different body planes (Fig. 12-B). During walking, it initiates the swing phase by lifting the foot (hip flexion) and propels the body forward during the stance phase (hip extension). Additionally, it contributes to rotational movements for balance and stability [45]. However, individuals with neuromuscular conditions may face challenges with hip flexion and extension due to weakened or paralyzed hip muscles. To address this issue, [158] introduced a hip assistive exosuit consisting of a backpack to carry the motor driven actuation unit. A foot switch detects gait events and activates the motor, which retracts the webbing, pulling the thigh backward to provide support for hip extension. However, the device can only provide unidirectional support for the hip extension on a single leg. Reference [159] introduced a soft exosuit that supports hip flexion while walking. It consists of a waistband, knee brace, and a back-worn actuation mechanism. The actuation unit comprises a motor, a linear slider and a pulley, which transforms the rotational motion of the motor into a linear reciprocating motion of the slider, moving either to the left or right. This movement pulls the knee brace on the corresponding leg through the cables, providing assistive torque for knee flexion during the gait cycle. However due to the requirements of higher assistive forces at the hip joints, the cable driven mechanism can generate high shear forces which can be uncomfortable for the user.

To aid in hip flexion during normal walking, a lightweight and easy-to-wear device was designed by [162] using pneumatic rotary actuators (PRA). The exosuit includes tubular jamming beams (TJB), a set of PRA's, and ergonomic anchors at the torso, hip joint, and thigh. The TJB consists of inflatable tubes within a retaining sleeve that become stiffer upon inflation, thus allowing the PRA's to transmit assistive torque to the user's leg. The PRA's are connected to a central prong, providing effective support during walking. Using the same rational, [163] introduced a soft exosuit that utilizes a low profile vacuum actuator (LPVAc). The LPVAc comprises an air-tight inextensible pouch made of low-density polyethylene and an obround-shaped helical spring enclosed in the pouch. The spring prevents the pouch from collapsing and ensures a rapid return to its initial state. To assist the sit-to-stand movements the actuators are anchored between the waist belt

TABLE IV
HAND ASSISTIVE DEVICES

Ref.	Actuation	Supported DOFs/Joints	Assistance level
P. Polygerinos et al. [106], 2013	Pneumatic	Fingers Flexion	N/A
H.K. Yap et al. [98], 2016	Pneumatic	Finger Flexion	FTP PA/PI grasp: 1.57N/1.24N
H.K.Yap et al. [107], 2015	Pneumatic	Finger Flexion	95% active ROM, FTP of 41 N @ 200kPa
H. K. Yap et al. [108], 2017	VS Pneumatic	Finger F/E	Index FTF wrap/PI grasp: 3.59N/2.72N
H. K. Yap et al. [99], 2015	VS Pneumatic	Finger F/E	Index FTF wrap/PI grasp: 3.59N/2.72N
J. Wang et al. [100], 2019,	SPBA	Finger F/E	FTF of 1.60N @ 150 kPa
C. Suulker et al. [101], 2022	Pneumatic	Finger Flexion	Force 24.8N @ 102 kPa
M. Feng et al. [116], 2021	Pneumatic	Finger Flexion,	Pull up force of 35.5N @ 110 kPa
Y. Jiang et al [117], 2021	Pneumatic	Finger F/E	Increased Finger Flexion up to 42.60%
H. Al-Fahaam et al. [111], 2018	Mckibben	Finger Flexion	N/A
S. Koizumi et al. [112], 2020,	Thin Mckibben	Finger F/E	Finger tip F/E : -49°/106°
Y. Han et al. [113], 2022	Pneumatic	Finger Flexion	FTF of 0.51N @ 0.08 MPa
Y. Chen et al. [118], 2017	Pneumatic	Finger Flexion	N/A
H. K. yap et al, [110], 2016	VS Pneumatic	Finger Extension	Extension torque of 1.0625 Nm @ 100kPa
J Yi et al. [119], 2016	PAM	Finger F/E	FTF of 10N @ 200 kPa
N. Kladovasilakis et al. [120], 2023	Pneumatic	Finger F/E	Palmar grasp force: 19.5 N
C. Rieger et al. [121], 2022	Pneumatic/Spring	Finger F/E	FTF of 12 N @ 120 kPa
B. Wang et al. [122], 2017	Pneumatic/Spring	Finger F/E	Grip force: 4.75N (per finger) @ 0.675 MPa.
D. Hu et al. [123], 2020	Pneumatic	Finger F/E and Thumb AB/AD	AB/AD: 5.7/8.1 N and F/E: 4.6/1.9N @ 90kPa
H. K. Yap et al [114], 2017	Pneumatic	Finger F/E	Grasp force: 11.3±2.5 N
Y. M. Zhou et al. [115], 2019	Pneumatic	Finger F/E	Grasp force improved by 87%.
J Yi et al. [124], 2018	Pneumatic/Cable	Finger F/E	FTF of up to 40N @ 60 kPa
B. W. K. Ang et al. [125], 2017	Pneumatic	Finger F/E	Grip force: up to 41.8 N @ 200 kPa
H. In et al. [126], 2015	Motor/Cable	Thumb, Middle and Index Finger F/E	Pinch/wrap Grasp Force: 20/40 N
B. B. Kang et al. [102], 2019	Motor/cable	Thumb, Middle and Index Finger F/E, Passive Thumb Positioning	Grasp force: 10.3N
S. W. Lee et al. [129], 2014	Motor/Cable	Finger F/E	Workspace of the index finger increased by at least 63%
B. C. Vermillion et al. [131], 2019	Motor/cable	Finger F/E	FTF angular deviation reduced from 16.8° to 3.7°
H. L. Heung et al. [132], 2020	Pneumatic	Finger Flexion	Reduced joint stiffness
S. Biggar et al. [138], 2016	Motor/Cable	Finger F/E	N/A
D. Popov et al. [103], 2017	Motor/Cable, Elastic Bands	Finger F/E Except Little Finger	Pinch force: 16 N
A. Yurkewich et al. [141], 2020	Motor/Cable	Finger F/E	Grip/ Pinch Force:12.7/11.0 N
A Bajaj et al. [128], 2020	Motor/Cable, Elastic Bands	Finger F/E	N/A
H Mohammadi et al. [142], 2018	Motor/Cable	Finger F/E	Pinch/Power grasp force 22/48 N
D. H. Kim et al. [143], 2019	Motor/Cable	Thumb, Middle and Index Finger F/E	Up to 12 N FTF
P. Tran et al. [134], 2020	TSA	Thumb, Index and Middle finger F/E	Pinch force: 5.03N
T. Tsabedze et al. [135], 2021	TSA/SPSs	Finger F/E	FTF: 7 N
D. H. Kim et al. [137], 2022	Motor/Cable, Silicon Strip	Finger F/E	Increased the thumb workspace up to 248% in different directions
A. Stilli st al. [139], 2018	Pneumatic	Finger F/E	Supports hand opening up to 79/51% for 1/5 N of preload.
L Gerez et al et al. [140], 2020	Pneumatic-Motor/cable	Finger F/E and Thumb AB/AD	FTF: 13.8N, Abductoin force: 15.8N, Abduction angle: 30°-73°
H. Liu et al. [104], 2023	Pneumatic-Motor/Cable	Finger F/E	Extension torque of 0.3018 N.m
Y. Wang et al. [144], 2021	Pneumatic	Thumb AB/AD, Thumb and Index finger F/E	Up to 32 N Ab/AD forces
X. Cao et al. [145], 2021	Pneumatic/Tubular jamming	Finger F/E and AB/AD	Force up to 5.7 N @ 200 kPa
A. hadi et al. [105], 2017	SMA wires	Finger F/E	Grasp Force: 40 N
H. Amin et al [146], 2018	Spring Roll DEA	Finger Extension	Actuator axial force: 14.71 N

Note: FTF: Finger tip force, PA: palmar, PI: pincer, F/E: Flexion/Extension, AB/AD: Abduction/Adduction,ROM: Range of motion, VS: Variable stiffness, N/A: Not available

and thigh wrap, parallel to the quadriceps femoris and the gluteus maximus muscles. To provide proper assistance to the user, the authors in [164] integrated an inductive displacement sensing circuit that measures the displacement of the spring as a change in inductance. These values were used to develop a position feedback control using the bang-bang control

TABLE V
MULTI JOINT ASSISTIVE EXOSUITS FOR UPPER LIMB

Ref.	Actuation	Supported DOFs/Joints	Assistance level
I Koo, et al. [148], 2014	Motors/cable and Pneumatic	3-DOF/Shoulder, Elbow and forearm	Reduce the EMG by up to 5 times
J.Fu, et al. [149], 2022	Motor/cables	6-DOF/Shoulder F, AB and Elbow F	Reduced the muscle effort by up to 17.6%
Z. kadivar, et al. [150], 2021	Motor/cable	3-DOF/Shoulder F, AB and Elbow F/E	Can provide up to 50 N.m
I Gaponov, et al. [151], 2017	TSAs	3-DOF/Shoulder F, AB and Elbow F	N/A
S. Lessard, et al. [152], 2019	Motor/cable	4 DOF/Shoulder, Elbow and Wrist	With crux heart rate increased only by 3.3%
T. Proietti, et al. [155], 2021	Pneumatics	3-DOF/ Shoulder and Elbow	Reduced the sEMG by up to 55%
S. Das, et al. [156], 2020	Pneumatic	4 DOF/Shoulder, Elbow and Wrist	Reduced sEMG by up to 15%

Note: F/E: Flexion/Extension, AB/AD: Abduction/Adduction, N/A: Not available

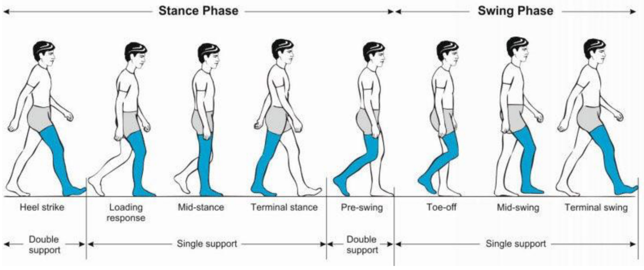


Fig. 11. Gait cycle phases and sub-phases [157].

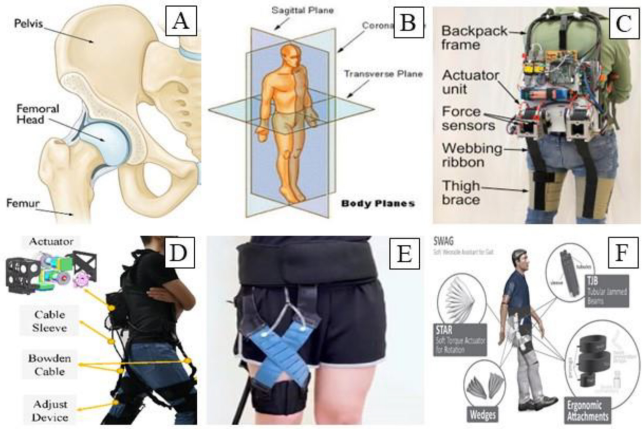


Fig. 12. Hip exosuits: A) Hip anatomy: Joints and Bones, B) Body planes, C, D) Cable driven hip exosuit [158], [160] E, F) Pneumatically actuated hip exosuits [161], [162].

algorithm, which incorporates lower and upper thresholds to regulate the LPVAc.

The exosuits presented previously can only assist with either hip flexion or extension, but not both. To address this, [160] developed a new soft exosuit that can provide assistance with both movements. This exosuit is composed of functional textile apparel and employs two Bowden cables wound in opposite directions on a pulley, extending to the front and back of the body to support hip extension and flexion respectively. The exosuit uses IMUs to detect gait events and regulates the assistive forces through an iterative learning PID. To make a device that is both compact and lightweight, [161] presented SR-HExo, a soft exosuit that uses two sets of flat pneumatic artificial muscles (ff-PAM) for both extension and flexion. The ff-PAMs are arranged in an X orientation and attached to the body through an adjustable waist belt and thigh wraps. When inflated, the actuators contract and provide assistive force in either the flexion or extension direction, based on gait events detected through GRF sensors.

Another problem with the previous designs is that they can either provide assistance in running or walking but not with both. To solve this problem [165] proposed a device that utilizes an online classification algorithm to switch its assistance level between running and walking. The device consists of a waist belt, two thigh wraps, and an actuation unit, which has two electrical motors connected to cables via pulleys, worn at the waist. The motors apply a tensile force between the waist belt and thigh wraps to generate an external flexion/extension moment around the hip joint. The Inertial measurement units affixed to the thigh wraps measure potential energy fluctuations, which are used by the controller to switch between pre-programmed force profiles during both walking and running.

Table V summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

B. *Knee Exosuits*

The knee joint is similar to a hinge joint connecting the femur, tibia, and patella (Fig. 13.A). It enables flexion and extension in the body sagittal plane during walking. In swing phase, it shortens the leg for forward movement, while in stance phase, it absorbs shock and transfers forces to the ground [45]. The knee and ankle joints collaborate for stability, particularly during push-off for propulsion.

To assist the knee joint of patients with neuromuscular condition, [166] introduced a soft knee flexion assistance exosuit. The exosuit uses a curved fabric-based pneumatic actuator made of an inflatable plastic tube covered in nylon fabric. The actuator is attached to the knee by a thigh and shank wrap, and an anti-slippage mechanism consisting of a waist belt and adjustable straps connecting the thigh wrap to the belt. Like wise to assist the knee extension [167] introduced a soft knee extension exosuit utilizing a pneumatic actuator with an I-cross-section configuration. The actuators is enclosed in a fabric pocket and placed below the knee pit through knee sleeve. When the actuator is not inflated, it remains flexible, allowing normal movement without interference. However, upon inflation, the actuator's stiffness increases, providing

TABLE VI
HIP EXOSUITS

Ref.	Actuation	Supported DOFs/Joints	Assistance level
A. T. Asbeck et al. [158], 2013	Motors/cables	Hip extension	N/A
M. H. Hsieh, et al. [159], 2020,	Motor/Cable	Hip Extension	N/A
T. M. M. Jackson et al. [162], 2022	Pneumatic	1 DOF/Hip flexion	Reduced muscle activity by 43.5%
A. L. Kulasekera et al. [164], 2021	LPVAc (Pneumatic)	1 DOF/Hip F/E	Reduced sEMG by 45% in sit-to-stand
Y. liu et al. [160], 2020	Motor/Cables	1 DOF/Hip F/E	Reduced metabolic cost by 15.67%
C. M. Thalman et al. [161], 2021	CFPA (Pneumatic)	1 DOF/Hip F/E	Reduced the sEMG by up to 27%
J. Kim et al. [165], 2019	Motors/cables	1 DOF/ Hip F/E	Reduced metabolic costs by 9.3%
Note: F/E: Flexion/Extension, AB/AD: Abduction/Adduction, N/A: Not available			

Fig. 13. Knee exosuits: A) Knee anatomy: Joints and Bones, B, C) Pneumatically actuated knee exosuit [166], [167], D) Cable driven knee exosuit [168], E) Cable driven knee abduction movement assistance exosuit [169].

supportive torques for knee extension. The performance of the exosuit was tested and evaluated in [170]. The study observed a decrease in hip extension during the swing phase, along with reduced step length and time. To improve the assistive torque, researchers in [169] developed a knee extension exosuit employing a pleated pneumatic interface actuator (PPIA), attached to the leg using velcro and buckles. The PPIA is a modified pneumatic actuator with two valley folds and a mountain fold, creating a buckling effect that enhances its stiffness and output torque.

In [166], [167], [169] bulky positive pressure pneumatic actuators were used in the exosuit design, which resulted in delayed actuation with a large hysteresis. To overcome these issues, [171] introduced an exosuit that utilizes a vacuum actuated rotary pneumatic actuator attached to the body through a thigh and calf brace. The actuator is made of elastic radial and circumferential beams with interconnected sector ring structured cavities, enclosed in a thin silicone membrane. Negative pressure causes the actuator to produce rotational motion and bending torque through the difference in thickness between the radial and circumferential beams, resulting in a large change in circumferential angle. Conversely, positive pressure stretches the beams, generating stretching torque, hereby assisting both knee flexion and extension.

Another soft exosuit that imitates the function of the quadriceps muscle to assist with knee extension during stair climbing is presented in [168]. It consists of a twisted string actuator (TSA), soft straps, and Bowden cables. The TSA use a motor and soft strings to generate assistive forces that are transferred to the knee joint through the Bowden cable. To ensure that the exosuit provides assistance efficiently and accurately, the climbing intention is detected using four IMU sensors that track changes in the lower-limb angle.

To compensate for the knee abduction movement (KAM) caused knee osteoarthritis, [169] developed a soft exosuit that applies torque about the hip joint in the frontal plane during the stance phase. The device includes a waist belt, thigh wraps, actuation units, and a high-tension rope connected to a spool and thigh wrap. The actuators release or pull the rope to provide assistive torques, while a two-level hierarchical closed loop control system regulates the assistive force based on gait events detected through an IMU.

Table VI summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

C. Ankle Exosuits

The ankle joint is a pivotal hinge joint that connects the tibia, fibula, and talus bones, see Fig. 14.A. It allows for dorsiflexion (DF) and plantarflexion (PF), as well as inversion/eversion movement of the foot during walking [45].

After stroke, many survivors experience some residual motor function at ankle, but often exhibit inefficient walking patterns that lead to high metabolic costs. To address this issue, a soft exosuit that uses cable driven actuation mechanism is introduced in [177]. The exosuit consists of two textile modules, one for plantarflexion (PF) to aid in forward propulsion and one for dorsiflexion (DF) to assist with ground clearance. A waist belt supports the downward forces, while a calf wrap tightens the suit around the body and anchors the outer sheet of the cable. A modified shoe provides attachment points for the inner cables. However, the device requires an off-board actuation unit and is not suitable for use outside the lab environment. An improved version of the exosuit presented in [177], which features a mobile actuation unit, is described in [173]. The exosuit has the same structure as the one in [177], with the waist belt serving as an anchor for the actuation system at the back.

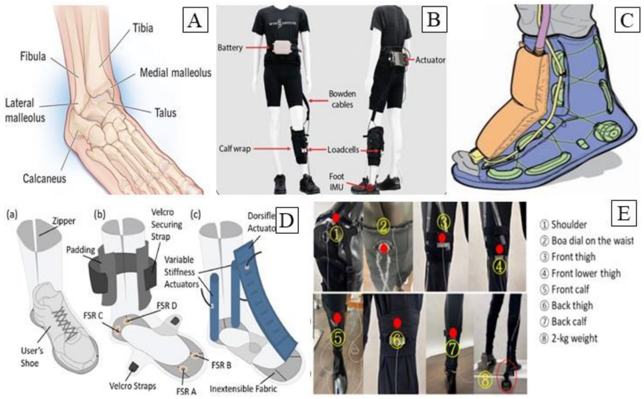


Fig. 14. Ankle exosuits: A) Ankle anatomy: Joints and Bones, B) An ankle assistive device utilizing cable-driven mechanisms to support PF and DF movements [173], C) Exobot a pneumatically actuated exosuit for PF assistance [174], D) Pneumatic ankle exosuit for PF/DF as well as inversion/eversion movement [175], E) An SMA actuated ankle assistive suit [176].

Using the same articulation for the load path as in [178], [179] presents a soft exosuit design that can assist the ankle joint during different phases of walking. The exosuit comprises a spandex base layer, waist belt, calf wrap, and leg straps that distribute the actuation load. The suit is connected to an actuation system using Bowden cables, which run from the pulley cover to the calf wrap connecting it with a metal bracket at the back of the shoe heel.

An alternative design, called Exobot, introduced in [174] features a mechanically transparent soft inflatable boot that incorporates a textile-based pneumatic actuator sewn onto a custom-made boot. At a neutral ankle position of 90 degrees, a wrinkle forms on the inner side of the actuator. Upon inflation the actuator tries to straighten thus applying assistive torques to the foot in the direction of plantarflexion. Similarly, [180] presents a soft ankle foot orthosis in the form of a sock. The orthosis includes a soft textile-based human-robot interface layer and an actuation layer with two sets of pneumatic actuators. One set of actuators provides assistive torques in the dorsiflexion direction using a contractile mechanism, while the other set of variable stiffness pneumatic actuators prevents ankle joint buckling during the heel strike event.

Inspired by the human musculoskeletal system, [175] proposed a biologically inspired soft robotic device for ankle-foot rehabilitation. The device has a three-layer structure: a base layer acting as an interface between the robot and human, an actuation layer, and a sensing layer. The device features four pneumatic artificial muscles that can generate assistive torques for dorsiflexion/plantarflexion and inversion/eversion movement. To reduce the power consumption, [75] proposed the use of a multi layered electrostatic clutch placed in series with a polymer spring. They integrated the clutch with a pneumatic powered ankle exoskeleton where it was used to store energy during stance phase and release it during the swing phase allowing for a free rotation of the ankle. The clutch is lightweight only 11g and delivered a force of 100N at power consumption of 0.6mW and a response time of 30ms. However, it exhibits oscillation in the response when reaching the rest state.

To achieve a lightweight and low-profile design, [181] introduced a soft exosuit that incorporates shape memory alloy (SMA) wires embedded into the exosuit fabric. The exosuit utilizes two SMA wires per leg, extending from the front of the waist, crossing at the top of the knee, and routed to the heel. When the SMA wire is heated, it contracts and pulls the heel strap, generating a driving torque on the ankle joint, resulting in ankle plantar flexion. To prevent the heated SMA wires from contacting the human body, they were enclosed within a Teflon tube. To solve the anchoring problem and reduce garment pressure, [176] designed a soft exosuit that uses different fabrics in different locations. For instance, the thighs, back, and below the knees use stretchy fabric, while mesh-like fabric is used in areas prone to sweat, such as the knee pits. A high-tensile, non-stretchy fabric is used at the waist to provide a strong anchoring point. In addition, webbing bands, boa dials, and 3D printed parts are used to prevent dislocation of the actuator. The actuation forces are generated through SMA wires that run from the waist belt on the front, crosses just above the knee, and extend towards the ankle on the backside of the leg.

The studies presented above are mainly focused on reducing the weight and bulkiness of the device while increasing the magnitude of the assistive forces. To see if the assistive device can reduce the metabolic cost below that of walking without the assistive device, [182] conducted a series of experiments by varying the varying the actuation time of a pneumatic actuated exoskeleton. They found that at 43% of the stride cycle occurs a metabolic cost reduction of 0.64±0.05 W/kg which is the highest and is due to its correspondence with the positive biological ankle power. In their subsequent study [183] they also considered the correlation of the power magnitude and timing on the reduction of the metabolic cost and found metabolic cost reduction of up to 12% can be achieved with an actuation onset at 42% stride and an average power of 0.4 W/kg. However, the exosuit used in these experiments was tethered and the experiments conducted were in a lab setting using a treadmill. Furthermore, it has been proved that the assistance outcome can be maximized by optimizing the assistance profile for the individuals which usually requires lengthy user test. To overcome this issue and optimize the suit performance in real settings, [184] proposed a logistic regression-based data driven model which shows how likely a control law is to reduce the metabolic cost, which is used as a factor to rank and optimize the control laws. With this approach they were able to achieve an optimal control law in a shorter span of time, 4 times less than the conventional human in loop optimization, which resulted in 17±5% less metabolic cost compared to normal walk.

Table VII summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

D. Multi Joint Exosuits for Lower Limb

The exosuits we discussed previously were focused on the hip, knee or ankle joint. However, for locomotion all these three joints needs to work synergistically. In this regard [178]

TABLE VII
KNEE EXOSUITS

Ref.	Actuation	Supported DOFs/Joints	Assistance level
I. M. Hasan, et al. [166], 2022	Pneumatic	1-DOF/ Knee Extension	Reduced sEMG by 32%
S. Sridar et al. [167], 2017	Pneumatic	1-DOF/ Knee extension	Reduced sEMG by 7%
A. J. Veale et al. [169], 2021	PPIA (Pneumatic)	1-DOF/Knee extension	Upto 324 Nm torque @ 320kPa
L. Zhang et al. [171], 2020	VARA (Pneumatic)	1-DOF/Knee F/E	Reduced muscle activity by 6.85%
S. Zhao et al. [168], 2019	Twisted string actuator	1-DOF/Knee extension	N/A
H. D. Yang et al. [172], 2022	Motor/Cable	Assist hip joint in frontal direction	20% of the body weight
Note: F/E: Flexion/Extension, AB/AD: Abduction/Adduction, N/A: Not available			

introduced a bioinspired cable-driven exosuit. The exosuit is designed to provide short, well-timed pulses of assistive forces to the hip and ankle joints while walking on flat surfaces. The exosuit is made up of a waist belt and a thigh wrap and generates assistive forces using Bowden cables that run from an actuation unit on the wearer's back to the ankle joint anchor. The exosuit is secured to the wearer using webbing straps, allowing it to be worn like clothing and minimizes the mechanical impedance due to the absence of rigid components. Similarly, [185] introduced a multi-joint actuation platform that improves the design of the exosuit presented in [178]. This platform features three actuation units per leg, which can assist the hip and ankle joints separately or simultaneously. To assess the effectiveness of the exosuit on human walking, researchers conducted a series of experiments as described in [186]. The study found that when assisting both the hip and ankle joints, the metabolic cost of walking reduced by 14.6%. However, when only the hip extension was assisted, the reduction was only 4.6%. A mobile version of this exosuit presented in [187] uses two actuation units: one for hip extension and the other for combined hip flexion and ankle plantarflexion. Depending on the direction of the motor's rotation, the cables deliver a controlled force to either the left or the right leg of the wearer. In their evaluation of the exosuit's performance [188], a significant metabolic reduction of 7.5±0.6 W/Kg was observed in addition the exosuit also reduced the total joint positive biological work.

In these studies, the focus is on assisting the hip and ankle joint, however the bio-mechanical analysis conducted in [42] shows an explicit coordination between the hip and ankle joint, they showed that these two joints are responsible for generating 60% of the required power during normal walking. Taking inspiration from the bi-articular muscle for the hip and knee joints in human body, [189] and [190] proposed a multi articular exosuit that can simultaneously assist the hip and knee joint during walking. These devices use a simple design with one actuator per leg, providing support to the knee and hip joint in a coupled fashion. They also proposed a neuromechanical control, which uses force control during the stance and position control to lock the motor during swing phase, copying this human walking behavior results in reduction of motor involvement during assistance. The muscle weakness also affects legs functions such as sit to stand and stair climbing. To help in these kinds of movements, [191] presents the design of a bi-articular cable driven exosuit called MyoSuit. Unlike other exosuit presented previously, MyoSuit provides anti-gravity assistance to the user in activities such as standing, walking and sitting transfer.

It is pertinent to note that complete gait rehabilitation requires the exosuit to assist all the three (Knee, Hip and ankle) joints. The exosuit presented in [192], uses custom-made McKibben pneumatic actuators arranged antagonistically to assist the hip, knee, and ankle joints. This exosuit addresses common issues associated with soft suits, such as slippage and skin irritation, by utilizing the virtual anchoring technique to transfer reaction forces to key anchors via in-extensible webbing straps. However, the McKibben actuators offers a limited range of motion and torque. To overcome this, [193] proposed a flexible exoskeleton with six fully steerable degrees of freedom, driven by agonist-antagonist Bowden cables. The exoskeleton consists of a waist belt connected to the shoulders via suspenders, as well as thigh and calf brackets and shoe anchors. A pair of Bowden cables, functioning as agonist and antagonist pairs of muscles, which are retracted by off-board motors, actuate each joint.

Table VIII summarizes the actuation mechanism, nature of the robot, assisted degrees joints, and level of assistance of the robots explained above.

VI. HYBRID: RIGID-SOFT ASSISTIVE DEVICES

The exosuits presented previously are helpful in addressing joint misalignment issues caused by rigid exoskeletons, but they have limited capacity to provide maximum assistance. To address this issue, semi rigid exosuits have been developed for both the upper and lower limbs. Currently, there is no clear distinction between hybrid and soft exosuits. However, based on the definition of soft exosuits given in [24], we define a hybrid exosuit as a device that uses a flexible (semi-rigid) structure over the intended joint of assistance. In this section, we will briefly introduce the hybrid type of device for the upper and lower limbs.

Hybrid exosuits for upper limb: The cable-driven semi-rigid assistive device SPAR presented in [194] used a reinforced curved rigid palm bar to guide the tendons for finger flexion and thumb opposition. This helped to reduce glove deformation and distribute reaction forces. Additionally, a dorsal hyper extension vertebra was used to guide the tendons for finger extension and prevent hyper-extension. To speed up the design process and allow customization, [195] introduced a user-centered approach to fabricate a cable tendon driven flexible exoskeleton for finger rehabilitation. The user's finger

TABLE VIII
ANKLE EXOSUITS

Ref.	Actuation	Supported DOFs/Joints	Assistance level
J. bae et al. [177], 2015	Motors/Cables	DOF/ Ankle PF and DF	N/A
J. Bae et al. [173], 2018	Motors and Bowden cables	DOF/ Ankle PF and DF	25% of the body weight
S. Lee et al. [179], 2016	Motors and Bowden cables	DOF/ Ankle PF and DF	Reduced the metabolic cost by 11-15%
J. Chung et al. [174], 2018	Pneumatic	DOF/Ankle PF	Up to 39 N.m Torque
M. Thalman et al. [180], 2019	Pneumatic	DOF/Ankle DF	N/A
Y. L. Park et al. [175], 2014	Pneumatic	DOF/ Ankle PF/DF and I/E	N/A
Kim et al. [181], 2023	SMA wires	DOF/Ankle PF	N/A
J. Piao et al. [176], 2023	SMA wires	DOF/Ankle PF	N/A

Note: F/E: Flexion/Extension, I/E: Inversion/Eversion, N/A: Not available

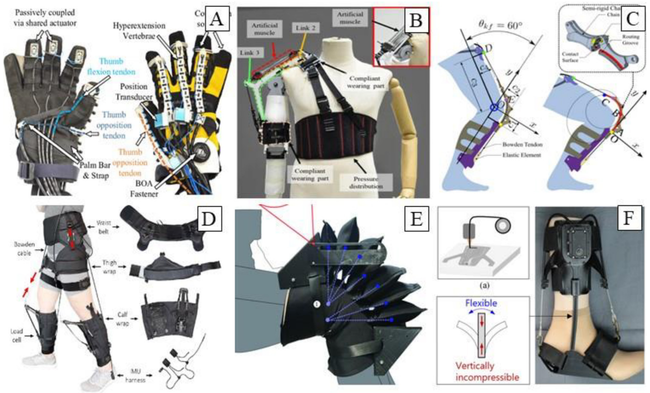


Fig. 15. Semi-rigid exosuits: A) SPAR: a cable driven hand assistive device with 3-D printed vertebra to avoid fingers hyperextension [194], B)SMA actuated flexible mechanism for shoulder support [198], C) A semi rigid chain mechanism for knee extension support [199], D)A hinge free semi rigid exosuit knee extension [200] [59], E)A hybrid rigid exosuit for knee extension assistance [201], F) A 3D printed flexible ankle brace for ankle flexion/extension [202].

is scanned with a 3D scanner and then replicated using a 3D printer, creating a lightweight and flexible exoskeleton. Likewise, the cable driven anthropomorphic hand assistive device presented in [196] all components, except the glove, are 3D printed. It offers users the flexibility to customize the design and integrate additional sensors for enhanced control capabilities. Similarly, [197] used the 3D printing technology to design a wrist assistive flexible exoskeleton. It consists of two parts worn on the hand and forearm, with tendons transmitting force from motors positioned on the forearm brace. The authors also proposed a GUI which allows the user to select any exercise from the available ones. Using the SMA spring-based actuation; [198] proposed a semi rigid assistive device with a four-bar linkage based hinge mechanism to support the shoulder abduction. To allow for the change in the axis of rotation during shoulder abduction, a device is designed to follow the arm movement trajectory modeled using scapulohumeral rhythm.

Hybrid exosuits for lower limb: To provide deterministic assistive torques to the knee joint, [199] introduced a rehabilitation robot that uses a semi rigid chain mechanism. The semi rigid chain, covering the knee, comprises of five rigid components connected serially through a constrained pin joint, allowing the chain to change its structure from ellipse to circle thus allowing for the knee joint translation movement. This chain also offers a grove, which allows routing the tendon to cross the knee joint without any contact. The device is actuated through a Bowden cable mechanism, which extends from thigh wrap to the calf wrap guided by the semi rigid chain. Similarly, to aid in the knee extension [200] introduced a hinge-free semi-rigid exosuit that uses a combination of soft textiles and rigid components. The calf part of the exosuit has a textile wrap with a lightweight rigid frame on the shin. This increases the moment arm and provides clearance for the cable over the knee. The thigh wrap is also reinforced with a rigid structure to limit its structural deformation. To support both knee flexion and extension, [203] introduced a hybrid mechanism comprising of two cuffs worn on the shank and thigh part of the leg. A cable driven linear actuator, comprising of a static cylindrical part and moving piston, connects the two cuffs through hinges located on their backside. To provide support during flexion and extension of the knee joint the cable driven platform uses a bidirectional driving unit to drive the actuator in lengthening and the shortening direction.

Using the pneumatic actuation mechanism, [201] introduced a hybrid rigid-soft robot design to aid in knee extension. The device is composed of several pneumatic cells made of TPU coated nylon fabric situated between two 3D printed retainers. To prevent the pouches from slipping during inflation, a rod is placed on the side of the retainer. The entire structure is then sewn onto a flexible knee brace and secured to the body using straps.

To make a device that is lightweight, easy to use, and inexpensive, [202] introduced an ankle foot orthosis that uses 3D printed flexible ankle brace, consisting of a heel and shank pad connected by a vertical column, and a bidirectional tendon driven actuation mechanism to support the ankle PF and DF movement. The 3D printed brace has the advantage of preventing vertical compression and thus slippage even if the brace is loosely tied to the shank. Reference [204] introduced a device that has an origami inspired wedged shape structure with cable guides. The structure is connected between the thigh and west belt and is actuated using a series elastic actuator. The exosuit uses a single actuator to assist both the hip flexion. The device also features two foot switches along with two IMUs to detect the toe off and heal strike events.

TABLE IX
MULTI JOINT EXOUITS FOR LOWER LIMB

Ref.	Actuation	Supported DOFs/Joints	Assistance level
A. T. Asbeck et al. [178], 2013	Motor/cables	2-DOF/ hip extension, hip flexion+ankle PF	Reduced the metabolic cost by 7.5 W/kg
Y. Ding et al. [186], 2016	Motors/cables	3-DOF/ hip F/E, ankle PF	N/A%-
V Bartenbach et al. [190], 2015	Motor and Bowden cable	Coupled knee and hip extension	N/A
K. Schmidt et al. [191], 2017	Motors and Bowden cable	Hip and knee extension	N/A
M. Wehner et al. [192], 2013	Mckibben	3-DOF/Hip, knee and ankle	Metabolic Cost Reduced by 10.2%
A. Davoodi et al. [189], 2013	SEA	2-DOF/Hip and knee	Metabolic Cost Reduced by 27%
Note: F/E: Flexion/Extension, DF:Dorsiflexion, N/A: Not available			

The IMUs detects the maximum hip angle to differentiate between running and walking while the heal strike and toe off event detected through foot switches are used to accordingly generate an assistive force.

The devices presented so far can be used in the chronic phase, to help stroke survivors in their acute phase [205] proposed a semi-rigid type of ankle rehabilitation robot. It offers three types of exercises: isometric torque generation, passive stretching, and active movement training. The device has a motor, leg brace, and foot holder, and is attached on the lateral side of the leg with adjustable straps that transfer the actuation forces and torque to the ankle joint. The motor has a planetary and bevel gear set to increase torque and support both PF and DF motion. Similarly, a soft, modular lower limb exoskeleton called XoSoft is presented in [206]. This device is intended to assist individuals with low mobility impairments and utilizes a quasi-passive actuation system, that includes an electromagnetic clutch in series with an elastic band and Bowden cable to transfer assistive forces in a unilateral configuration that supports knee and hip flexion. This actuation system is attached to the human body through a waist belt, a thigh wrap, and a calf wrap. XoSoft also includes a flexible tension sensor to measure joint torque and uses an inertial sensor and foot pressure sensor to detect walking intention, ensuring that it provides appropriate assistance to the user.

Table IX summarizes the actuation mechanism, nature of the robot, assisted degrees of freedom (DOF), and level of assistance of the robots explained above.

VII. COMMERCIALLY AVAILABLE EXOSUIT

Exosuits are a relatively new technology and are not yet widely available in the market except a few. In this section, we will briefly summarize some of the commercially available exosuits.

ReWalk Robotics ReStore [207]: ReWalk Robotics' ReStore is a commercially available soft exosuit that assists individuals with lower limb impairments. The exosuit employs a cable driven actuation mechanism, worn on the back, to provide support for both PF and DF movement of the ankle joint. This assistance aids individuals in achieving a more natural and functional gait pattern, enhancing their mobility and overall quality of life.

Carbon Hand [209]: Carbon Hand is a soft wearable exosuit that enhances grip strength and endurance of the SCI or stroke patients by assisting the flexion of the thumb, middle, and ring fingers. It consists of a cable-driven actuation mechanism worn on the back, a fabric glove as an interface, and pressure sensors on the palm and fingers. These sensors detect hand movement and grip and trigger servomotors for force feedback control. Iron hand [211] is another product by the same company. It aims to reduce muscle fatigue and enhance grip strength for workers by assisting the flexion of all five fingers using a cable-driven actuation mechanism and a fabric glove interface.

Neofect smart glove [208]: The Neofect Smart Glove is a wearable biofeedback training tool designed to assist individuals with hand impairments. It utilizes electromechanical actuators for controlled resistance/assistance during finger flexion/extension. The device also includes sensors to track finger and wrist movement to create a virtual reality environment where patients can use their hand to control objects, improving hand functionality.

Neomano [212]: Neomano, a soft wearable glove that assists individuals with limited hand strength. It uses a cable driven mechanism on the dorsal side to flex the middle and index fingers. The device also has an adjustable metal stay for the thumb, allowing for improved grip on objects of different sizes.

NUADA glove [210]: The NUADA Glove is a wearable assistive glove that enables independent movement of all fingers in a natural way. It utilizes a cable-driven actuation mechanism controlled by embedded sensors. When the user grips an object, the artificial tendons lock in place, providing support. The grip is released only when the user attempts to open their hand or manually releases the grip, thus, to use the device the user should be able to move hands.

VIII. DISCUSSION AND FUTURE WORK

The goal of this review was to investigate the actuation mechanism and physical human robot interface for soft exosuit and identify problems in these key areas. Based on the papers reviewed in this section we are going to discuss and answer the following questions.

i- Physical interface, what are the short comings and possible solutions?

ii- Is hybrid (rigid soft) exosuit the best possible solution, if so what should be considered when designing such an exosuit.

TABLE X
HYBRID: RIGID-SOFT ASSISTIVE DEVICES

Ref.	Actuation	Supported DOFs/Joints	Assistance level
C. G. Rose et al. [194], 2019	Motr/cable	Finger F/E	Grasp Force: 83 N
D. Cafolla [195], 2019	Motor/cable	Finger F/E	N/A
G. Rudd et al. [196] 2019	Motor Cable	Finger F/E	N/A
K. Hyeon , et al. [198], 2022	SMA/springs	1-DOF/Shoulder AB/AD	Can provide up to 10.1N.m torque
M. Dragusanu, et al. [197], 2020	Motor/Cable	2-DOF/Wrist F/E, AB/AD	N/A
E. J. Park et al. [200], 2020	Motor/Cable	1-DOF/Knee extension	Reduced positive biological power by 23.2%
P. Kabir et al. [201], 2022	Pneumatic	1-DOF/ Knee Extension	N/A
Y. Zhang et al. [199], 2021	Motor/Cable	1-DOF/Knee extension	N/A
Z. Wang et al. [203], 2023	Cable driven linear actuator	1-DOF/Knee flexion extension	N/A
J. Kwon et al. [202], 2019	Bidirectional tendon driven	1-DOF/ Ankle PF/DF	Improve PF and DF Performance
Y. Ren et al. [205], 2017	Motors and braces	1-DOF/ Ankle PF/DF	Can prfouce upto 7N.m torque
C. D. Natali et al. [42], 2019	Quasi-passive actuation	Bai-articulated knee flexion hip extension	Reduced the gait related power by 10.2%

Note: F/E: Flexion/Extension,AB/AD: Abduction/Adduction, PF/DF:Plantarflexion/Dorsiflexion, N/A: Not available

Fig. 16. Commercially available exosuits: A) ReWalk Robotics ReStore [207], B) Neofect smart glove [208] C) carbon hand [209], D) NUADA glove [210]

iii- Which actuation mechanism should be used and how can be improved further.

v. Are these exosuit usable for older/disabled population what should be done to achieve the goal.

In this review, we summarize the state of the art in exosuits, focusing on their physical interfaces and actuation mechanisms. We detailed how different actuation mechanisms, such as motor cables, fluidic actuators (both positively and negatively actuated), SMA's, and DEA's, are modified and integrated into the suit to enhance performance. While motor cables, fluidic actuators, SMA's, and DEAs are successfully used in rehabilitation and assistive robots, others like liquid crystal-based, shape memory polymer, and magneto responsive polymers are still in the conceptual stage. These mechanisms, along with exosuits, offer several advantages over traditional exoskeletons. Specifically, the inherent softness and light weight nature of these mechanisms allows them to provide a better human robot interface and adaptability to different conditions allowing for a seamless integration with the user's movements. However, the papers presented in this review allowed us to identify significant challenges in these key areas, which are likely a major reason that despite these advantages, many exosuits remain in the prototype stage and yet to be commercialized. Here we will discuss a number of areas that need further attention to make these devices readily available, comfortable and user friendly.

Exosuit Interface: The physical interface of wearable robots is a crucial aspect of their design. It determines how the robot interacts with the user's body and how forces are transferred between them which in turn has a huge impact on improving the user performance both during assistance and rehabilitation. Mostly neoprene sleeves, cuffs and straps are used to attach the actuator and transfer loads to the human body. The inherent flexibility of these kinds of materials allows for better compatibility and conformability to the human body while avoiding the issues of joint misalignment and kinematic incompatibility with the user. In addition, these interfaces also allow for optimizing the actuator locations thus effectively reducing the weight of the wearable part. All these advantages are making these functional fabrics a common choice for physical interface. However, using only fabrics poses several challenges. For instance, in the case of cable driven system when the tendons are retracted it causes the fabric to deform. This deformation causes the exosuit to displace from the original position which might apply unwanted and inaccurate forces to the joints. To avoid this deformation these exosuits (fabrics) needs to be tightened against the body. However, this tightening results in continuous application of pressure on the limb. Which increase further when exosuit apply assistive forces to the limb.

Hybrid Rigid Exosuits: The problem with soft exosuit is the mechanical inefficiency and the inability to properly pressure distribution a characteristic required for the comfortable use of the device. To study the effect pressure distribution and its relation with pain threshold, [213] reported that circumferential limb pressure becomes painful at 10-18 kPa and even unbearable below 25kPa. Though it is very difficult to quantify a safe threshold based only physical interface, as it depends on several things including the nature of underlying tissues, proximity of bones etc. [214], conducted an experimental study and used force mapping to find the effect of using different stiffness interface padding on the pressure distributions. They concluded that rather than the thickness of the interface the pressure distribution is more dependent on its stiffness and surface area of the interface padding. This suggest that the use of rigid components in exosuits can improve the performance. In [200], [203], where they used 3-D printed structures to reinforce the fabric interface, the reinforcement resulted in improved mechanical efficiency. In the completely soft design, due to the deformation caused by the application of assistive forces can cause unpredictable excursion of the tendon which leads to inaccurate control. This problem can be solved with the use of rigid components at optimal locations. However, the addition of the rigid component may compromise the comfort of the exosuit. Attention should be paid to their design w.r.t the anatomical region where they are going to be attached. The stiffness of the wearable soft robots should be appropriately determined to ensure proper pressure distribution, exosuit functionality, safety, and compatibility of the device with humans, i.e., it should not restrict other joints or ROM of the intended joint.

Another important issue is the shear forces applied by the cable driven mechanism. As this not only stretches the skin and tissues but, in some cases, they apply compressive forces on the joints which not only cause pain but can also damage the joint cartilage. The shear force can be reduced by properly optimizing the tendon anchoring. Reference [187] suggests that placing the interface at bony landmarks can reduce the effect of shear deformation, however this is not always possible. Another possible solution for this as discussed in [67] proposed the idea of converting the pulling force to pushing and for this they used 'V' shaped fabric clamps, but it contracts along with the cable putting a limit on the maximum assistance by the exosuit. A substantial amount of research needs to be dedicated to this area to understand the dynamics of assistance and interface. Researchers should focus on optimizing the design of exosuits to minimize deformation and ensure that the forces that are applied are accurate and safe. They should also focus on designing the suit to optimize pressure distribution and joint reaction forces, while making them adaptable to different users according to their physical characteristics. Currently there is no definitive answer on the best way to attach a wearable robot to the human body, however [42] can act as a guide to select the actuation and sensing unit as well as the frame for the design.

Actuation An important aspect of the soft robot is the actuation mechanism. Almost 80-85% of the current soft assistive robots rely on decades old actuation mechanisms like cable/tendons with motors and pneumatics which has a number of limitations. For instance, the pneumatic actuation due to their light weight, flexibility and the ability to generate different movements is the dominant actuation mechanism in soft wearable robotics [32] and is used by 55 devices reported in this review. However, they require pressurized fluid for actuation which in-turn requires pumps and reservoirs. These pumps can be quite heavy and bulky and in some cases are not portable which limits the use of these devices in ADLs. To overcome these problems some researchers are trying to design low pressure pneumatic actuation such as thin McKibben [17], [112] however they often produce low output forces.

A promising direction in this can be the use and investigation of new (single/multi) materials to design actuators that can be actuated with low pressure with the capability to withstand external deforming forces. To fabricate these actuators molding is the most commonly adopted technique which can be quite time consuming. Though recently 3D printing [77], [89], [125] has been used as a one-step approach, however it usually takes hours to fabricate a single airtight bellow for the actuator. Further research needs to be focused on the material as well as on the use of new 3D printing technologies to fabricate complex geometries.

Attention should also be paid to the design of light weight and powerful fluidic soft pumps [215] as this can considerably reduce the weight and improve portability. Though these actuators themselves are quiet, the pumps and values used with them can emit a lot of noise which is usually not desirable. They are also sometime responsible for vibration which can be annoying to the user. Another promising area here will be to reduce the number of pumps, as the number of pumps required depends on the number of DOFs that needs to be independently actuated. Using inexpensive, light fluidic circuits [189] can help us achieve the goal.

In the quest to reduce the form factor some researchers have used negative pressure pneumatic actuators, however this system still suffers from the problems such as leakages and noises [171], and often are very slow to respond. This issue can be tackled with the use of self-healable materials.

The second most commonly adopted method, Cable-driven and twisted string actuation, combinedly used by 59 devices reported in this review, offers a number of advantages over pneumatic actuators. They are more compact, lightweight, and silent, making them well-suited for the development of untethered exosuits. The motors can be located remotely, and the torques and forces can be transmitted through Bowden cables, making the wearable part lightweight and unobtrusive. However, these systems also have some disadvantages. One of the most significant is the challenge of managing cable tension and slack. Ensuring precise and consistent cable tension throughout the range of motion is difficult. Cable slack or excessive tension can lead to imprecise and inaccurate movements, affecting the robot's functionality. The problem can be solved up to certain extent by the use of SEAs which uses an elastic component placed in series with the actuators. In addition to helping in regulating the cable tension they also absorb shocks and vibrations, ensuring a smoother interface. However, SEAs introduce additional nonlinear behavior into the system, which can make control more complex. Another area that needs to be explored further is the optimization of the cable route. This can reduce interference and friction, ensuring smooth and efficient actuation. Also, the pressure often peaks around the anchor points, so anchoring should be optimized to distribute the pressure evenly.

These problems with the pneumatic and cable tendon driven actuation mechanism have led the researchers to look for other possible solution such as using shape memory alloys (SMAs). Though the SMAs has a very high energy density with zero noise or complete silent performance and have a large recovery strain when fabricated in the form of springs. However, to achieve the actuation these systems need to be heated above their transition temperature, which puts a limit on the bandwidth of theses system. To improve their actuation performance some researchers have used active cooling methods [59], [84], however this requires additional setup which makes the system expensive and bulky. In addition, the SMAs suffers from high nonlinearities and hysteresis which makes it difficult to control these type of actuators that needs to be solved.

Some researchers have also tried the dielectric elastomer based actuators, however they require a very high operating voltage usually in kilo volts, which makes them dangerous to be used with humans. In addition the output force of these actuators is very low, some researchers have introduced the multi-layer/stacked structure or the DEAs with a spring rolled structure [146] however this makes the system bulky and heavy which puts a limit on its use in the assistive robots, and still there are safety issues that need to be resolved on priority bases to enable these systems to be used with humans.

Applications: The biggest driving force behind the design of these soft actuators and exosuits is the growing population and the continuous increase in the number of patients with movement related disabilities. These assistive robots have the potential to solve some of the problems for these peoples. For instance, these robots can help them in conducting ADLs such as eating food, walking etc. Unlike traditional mobility supports such as wheelchair etc. which can only take them from place to place, these robots can help them in sitting, standing and other such transitions by augmenting their muscle strength. Reference [216] conducting a study to see the effectiveness of soft robots in home-based rehabilitation and found that participants who were using these assistive devices performed better than the others. However, most of the current exosuit are focusing on a single joint furthermore they are employing simple control strategies and are lacking haptic feedback which is limiting their widespread acceptance. Advanced sensing and control strategies that take into consideration the robot and user dynamics and the user intention as well as the surrounding environment needs to be investigated.

To conclude, we have reviewed the recent trends in the field of soft wearable robots, focusing on the physical interface, actuation mechanism, and design. Soft actuators and robotic devices for rehabilitation and assistance are a rapidly emerging field of research. These devices have the potential to improve the lives of people with disabilities by providing them with greater mobility and independence. However, the field is still in its infancy, and there are several challenges that need to be addressed. For example, new materials and actuators need to be developed that are soft, compliant, and yet strong enough to provide the necessary assistance. Despite these challenges, the potential benefits of these devices are significant. With continued research and development, soft actuators and robotic devices for rehabilitation and assistance could have a major impact on the lives of people with disabilities and healthy individuals alike.

REFERENCES

[1] (WHO, Geneva, Switzerland). *Stroke, Cerebrovascular Accident*. (2023). [Online]. Available: https://www. emro.who.int/health-topics/stroke-cerebrovascular-accident/index.html

[2] L. Dongen, T. Hafsteinsdottir, E. Parker, I. Bjartmarz, I. Hjaltadóttir, and H. Jonsdóttir, "Stroke survivors' experiences with rebuilding life in the community and exercising at home: A qualitative study," *Nurs. Open*, vol. 8, no. 5, pp. 2567–2577, 2021.

[3] (CDC, Atlanta, GA, USA). *Web*. (2023). [Online]. Available: https://www.cdc.gov/ncbddd/disabilityandhealth/infographic-disability-impacts-all.html

[4] J. Hidler and R. Sainburg, "Role of robotics in neurorehabilitation," *Topical Spinal Cord Inj. Rehabil.*, vol. 17, no. 1, pp. 42–49, 2011.

[5] B. French et al., "Repetitive task training for improving functional ability after stroke," *Cochrane Database Syst Rev.*, vol. 14, no. 1, 2016, Art. no. CD006073.

[6] W. E. Clark, M. Sivan, and R. J. O'Connor, "Evaluating the use of robotic and virtual reality rehabilitation technologies to improve function in stroke survivors: A narrative review," *J. Rehabil. Assist. Technol. Eng.*, vol. 6, Nov. 2019, Art. no. 2055668319863557.

[7] R. P. Matthew, E. J. Mica, W. Meinhold, J. A. Loeza, M. Tomizuka, and R. Bajcsy, "Introduction and initial exploration of an active/passive exoskeleton framework for portable assistance," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2015, pp. 5351–5356.

[8] Y. Sankai, "HAL: Hybrid assistive limb based on cybernics," in *Robotics Research* (Springer Tracts in Advanced Robotics), vol. 66. Berlin, Germany: Springer, 2010, pp. 25–34.

[9] R. J. Farris, H. A. Quintero, and M. Goldfarb, "Preliminary evaluation of a powered lower limb orthosis to aid walking in paraplegic individuals," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 6, pp. 652–659, Dec. 2011.

[10] N. Birch et al., "Results of the first interim analysis of the *RAPPERII* trial in patients with spinal cord injury: Ambulation and functional exercise programs in the REX powered walking aid," *J. NeuroEng. Rehabil.*, vol. 14, p. 60, Jun. 2017.

[11] M. Bianchi et al., "Design of a series elastic transmission for hand exoskeletons," *Mechatronics*, vol. 51, pp. 8–18, May 2018.

[12] A. Esquenazi, M. Talaty, A. Packel, and M. Saulino, "The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury," *Am. J. Phys. Med. Rehabil.*, vol. 9, no. 11, pp. 911–921, 2012.

[13] D. Marconi, A. Baldoni, Z. McKinney, M. Cempini, S. Crea, and N. Vitiello, "A novel hand exoskeleton with series elastic actuation for modulated torque transfer," *Mechatronics*, vol. 61, pp. 69–82, Aug. 2019.

[14] E. B. Brokaw, I. Black, R. J. Holley, and P. S. Lum, "Hand spring operated movement enhancer (handsome): A portable, passive hand exoskeleton for stroke rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 4, pp. 391–399, Aug. 2011.

[15] J. Iqbal, H. Khan, N. G. Tsagarakis, and D. G. Caldwell, "A novel exoskeleton robotic system for hand rehabilitation—Conceptualization to prototyping," *Biocybern. Biomed. Eng.*, vol. 34, no. 2, pp. 79–89, 2014.

[16] V. Crocher, J. Fong, T. J. Bosch, Y. Tan, I. Mareels, and D. Oetomo, "Upper limb deweighting using underactuated end-effector-based backdrivable manipulanda," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2116–2122, Jul. 2018.

[17] T. Abe et al., "Fabrication of "18 weave" muscles and their application to soft power support suit for upper limbs using thin McKibben muscle," *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2532–2538, Jul. 2019.

[18] F. Molteni, G. Gasperini, G. Cannaviello, and E. Guanziroli, "Exoskeleton and end-effector robots for upper and lower limbs rehabilitation: Narrative review," *PMR*, vol. 10, no. 9S2, pp. S174–S188, 2018.

[19] N. Nordin, S. Q. Xie, and B. Wunsche, "Assessment of movement quality in robot-assisted upper limb rehabilitation after stroke: A review," *J. Neuroeng. Rehabil.*, vol. 11, pp. 1–23, Sep. 2014.

[20] M. Gilliaux et al., "Using the robotic device REAplan as a valid, reliable, and sensitive tool to quantify upper limb impairments in stroke patients," *J. Rehabil. Med.*, vol. 46, no. 2, pp. 117–125, 2014.

[21] I. Aprile et al., “Efficacy of robotic-assisted gait training in chronic stroke patients: Preliminary results of an Italian bi-centre study,” *NeuroRehabilitation*, vol. 41, no. 4, pp. 775–782, 2017.

[22] S. Bhujel and S. Hasan, “A comparative study of end-effector and exoskeleton type rehabilitation robots in human upper extremity rehabilitation,” *Hum.-Intell. Syst. Integr.*, vol. 5, no. 1, pp. 11–42, 2023.

[23] S. H. Lee et al., “Comparisons between end-effector and exoskeleton rehabilitation robots regarding upper extremity function among chronic stroke patients with moderate-to-severe upper limb impairment,” *Sci. Rep.*, vol. 10, no. 1, p. 1806, 2020.

[24] M. Xiloyannis et al., “Soft robotic suits: State of the art, core technologies, and open challenges,” *IEEE Trans. Robot.*, vol. 38, no. 3, pp. 1343–1362, Jun. 2022.

[25] R. Nasiri, A. Ahmadi, and M. N. Ahmadabadi, “Reducing the energy cost of human running using an unpowered exoskeleton,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 10, pp. 2026–2032, Oct. 2018.

[26] H. Barazesh and M. A. Sharbafi, “A biarticular passive exosuit to support balance control can reduce metabolic cost of walking,” *Bioinspir. Biomimet.*, vol. 15, no. 3, 2020, Art. no. 036009.

[27] C.-Y. Chu and R. M. Patterson, “Soft robotic devices for hand rehabilitation and assistance: A narrative review,” *J. NeuroEng. Rehabil.*, vol. 15, p. 9, Feb. 2018.

[28] E. Bardi, M. Gandolla, F. Braghin, F. Resta, A. L. Pedrocchi, and E. Ambrosini, “Upper limb soft robotic wearable devices: A systematic review,” *J. NeuroEng. Rehabil.*, vol. 19, no. 1, p. 87, 2022.

[29] T. Proietti, E. Ambrosini, A. Pedrocchi, and S. Micera, “Wearable robotics for impaired upper-limb assistance and rehabilitation: State of the art and future perspectives,” *IEEE Access*, vol. 10, pp. 106117–106134, 2022.

[30] A. M. Khomami and F. Najafi, “A survey on soft lower limb cable-driven wearable robots without rigid links and joints,” *Robot. Auton. Syst.*, vol. 114, no. 1, Oct. 2021, Art. no. 103846.

[31] M. J. Page et al., “Updating guidance for reporting systematic reviews: Development of the PRISMA 2020 statement,” *J. Clin. Epidemiol.*, vol. 134, pp. 103–112, Jun. 2021.

[32] N. El-Atab et al., “Soft actuators for soft robotic applications: A review,” *Adv. Intell. Syst.*, vol. 2, no. 10, Oct. 2020, Art. no. 2000128.

[33] M. Li, A. Pal, A. Aghakhani, A. Pena-Francesch, and M. Sitt, “Soft actuators for real-world applications,” *Nat. Rev. Mater.*, vol. 7, pp. 235–249, Nov. 2022.

[34] M. S. Xavier et al., “Soft pneumatic actuators: A review of design, fabrication, modeling, sensing, control and applications,” *IEEE Access*, vol. 10, pp. 59442–59485, 2022.

[35] M. Pan et al., “Soft actuators and robotic devices for rehabilitation and assistance,” *Adv. Intell. Syst.*, vol. 4, no. 4, 2022, Art. no. 2100140.

[36] U. Jeong, K. Kim, S.-H. Kim, H. Choi, B. D. Youn, and K.-J. Cho, “Reliability analysis of a tendon-driven actuation for soft robots,” *Int. J. Robot. Res.*, vol. 40, no. 1, pp. 494–511, 2021.

[37] J.-H. Youn et al., “Dielectric elastomer actuator for soft robotics applications and challenges,” *Appl. Sci.*, vol. 10, no. 2, p. 640, 2020.

[38] W.-S. Chu et al., “Review of biomimetic underwater robots using smart actuators,” *Int. J. Precis. Eng. Manuf.*, vol. 13, pp. 1281–1292, Jul. 2012.

[39] C. Lee et al., “Soft robot review,” *Int. J. Control, Autom. Syst.*, vol. 15, pp. 3–15, Jan. 2017.

[40] H. Liu, P. Ferrentino, S. Pirozzi, B. Siciliano, and F. Ficuciello, “The PRISMA hand II: A sensorized robust hand for adaptive grasp and in-hand manipulation,” in *Proc. Int. Symp. Robot. Res.*, 2019, pp. 971–986.

[41] D. Bombara, R. Coulter, R. Konda, and J. Zhang, “A twisted string actuator-driven soft robotic manipulator,” *IFAC-PapersOnLine*, vol. 54, no. 20, pp. 141–146, 2021.

[42] M. Grimmer, M. Eslamy, and A. Seyfarth, “Energetic and peak power advantages of series elastic actuators in an actuated prosthetic leg for walking and running,” *Actuators*, vol. 3, pp. 1–19, Feb. 2014.

[43] Q. Hamid, W. W. Hasan, M. A. Hanim, A. Nuraini, M. Hamidon, and H. Ramli, “Shape memory alloys actuated upper limb devices: A review,” *Sens. Actuators Rep.*, vol. 5, Jun. 2023, Art. no. 100160.

[44] A. O’Halloran, F. O’Malley, and P. McHugh, “A review on dielectric elastomer actuators, technology, applications, and challenges,” *J. Appl. Phys.*, vol. 104, no. 7, 2008, Art. no. 071101.

[45] C. C. Norkin and D. J. White, *Measurement of Joint Motion: A Guide to Goniometry*, 5 ed. Philadelphia, PA, USA: F.A. Davis Company, 2016.

[46] C. Simpson, B. Huerta, S. Sketch, M. Lansberg, E. Hawkes, and A. Okamura, “Upper extremity exomuscle for shoulder abduction support,” *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 3, pp. 474–484, Aug. 2020.

[47] C. T. O’Neill, N. S. Phipps, L. Cappello, S. Paganoni, and C. J. Walsh, “A soft wearable robot for the shoulder: Design, characterization, and preliminary testing,” in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, 2017, pp. 1672–1678.

[48] C. O’Neill et al., “Inflatable soft wearable robot for reducing therapist fatigue during upper extremity rehabilitation in severe stroke,” *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 3899–3906, Jul. 2020.

[49] A.-M. Georgarakis, M. Xiloyannis, P. Wolf, and R. Riener, “A textile exomuscle that assists the shoulder during functional movements for everyday life,” *Nat. Mach. Intell.*, vol. 4, pp. 574–582, Jun. 2022.

[50] A. Golgouneh et al., “Design of a hybrid SMA-pneumatic based wearable upper limb exoskeleton,” in *Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 179–183.

[51] R. Natividad and C. Yeow, “Development of a soft robotic shoulder assistive device for shoulder abduction,” in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatron. (BioRob)*, 2016, pp. 989–993.

[52] C. S. Simpson, A. M. Okamura, and E. W. Hawkes, “Exomuscle: An inflatable device for shoulder abduction support,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2017, pp. 6651–6657.

[53] 2019 R. Natividad and R. Y. Chen-Hua, “Parallel, modular fabric actuators for a 2-DOF pneumatic sleeve,” 2019, *arXiv:1911.04068*.

[54] R. F. Natividad, T. Miller-Jackson, and R. Y. Chen-Hua, “A 2-DOF shoulder exosuit driven by modular, pneumatic, fabric actuators,” *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 1, pp. 166–178, Feb. 2021.

[55] B. Li, H. Cao, B. Greenspan, and M. A. Lobo, “Development and evaluation of pneumatic actuators for pediatric upper extremity rehabilitation devices,” *J. Text. Inst.*, vol. 113, no. 7, pp. 1372–13797, 2021.

[56] C. T. O’Neill, C. M. McCann, C. J. Hohimer, K. Bertoldi, and C. J. Walsh, “Unfolding textile-based pneumatic actuators for wearable applications,” *Soft Robot.*, vol. 9, no. 1, pp. 163–172, 2022.

[57] D. Chiaradia, M. Xiloyannis, C. W. Antuvan, A. Frisoli, and L. Masia, “Design and embedded control of a soft elbow exosuit,” in *Proc. IEEE Int. Conf. Soft Robot. (RoboSoft)*, 2018, pp. 565–571.

[58] C. M. Thalman, Q. P. Lam, P. H. Nguyen, S. Sridar, and P. Polygerinos, “A novel soft elbow exosuit to supplement BICEP lifting capacity,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2018, pp. 6965–6971.

[59] J. Jeong et al., “Soft wearable robot with shape memory alloy (SMA)-based artificial muscle for assisting with elbow flexion and forearm supination/pronation,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 3, pp. 6028–6035, Jul. 2022.

[60] M. Duduta, E. Hajiesmaili, H. Zhao, and D. R. Clarke, “Realizing the potential of dielectric elastomer artificial muscles,” *IEEE Robot. Autom. Lett.*, vol. 116, no. 7, pp. 2476–2481, Jan. 2019.

[61] L. Cappello, A. Pirrera, P. Weaver, and L. Masia, “A series elastic composite actuator for soft arm exosuits,” in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, 2015, pp. 61–66.

[62] L. Cappello, D. K. Binh, S.-C. Yen, and L. Masia, “Design and preliminary characterization of a soft wearable exoskeleton for upper limb,” in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatron. (BioRob)*, 2016, pp. 623–630.

[63] E. Mobedi, W. Kim, E. D. Momi, N. G. Tsagarakis, and A. Ajoudani, “A soft assistive device for elbow effort-compensation,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2021, pp. 9540–9547.

[64] M. Hosseini, R. Meattini, A. San-Millan, G. Palli, C. Melchiorri, and J. Paik, “A sEMG-driven soft ExoSuit based on twisted string actuators for elbow assistive applications,” *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 4094–4101, Jul. 2020.

[65] R. Ismail et al., “Soft elbow exoskeleton for upper limb assistance incorporating dual motor-tendon actuator,” *Electronics*, vol. 8, no. 10, p. 1184, 2019.

[66] M. Canesi, M. Xiloyannis, A. Ajoudani, A. Bicchi, and L. Masia, “Modular one-to-many clutchable actuator for a soft elbow exosuit,” in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, 2017, pp. 1679–1685.

[67] J. L. Samper-Escudero, S. Coloma, M. A. Olivares-Mendez, M. A. Sanchez-Uran, and M. Ferre, “Assessment of a textile portable’ exoskeleton for the upper limbs’ flexion,” in *Proc. IEEE 2nd Int. Conf. Hum.-Mach. Syst. (ICHMS)*, 2021, pp. 1–6.

[68] J. L. Samper-Escudero, A. Gimenez-Fernandez, M. A. Sanchez-Uran, and M. Ferre, “A cable-driven exosuit for upper limb flexion based on fibres compliance,” *IEEE Access*, vol. 8, pp. 153297–153310, 2020.

[69] M. Ceccarelli, A. Kozisek, A. Laribi, and L. Ferrara, “Experimental characterization of a cable-driven device for elbow motion assistance,” in *Proc. IFToMM Conf. MESROB, Med. Robot., Basel*, 2020, pp. 71–78.

[70] M. Bottin, M. Ceccarelli, C. Morales-Cruz, and G. Rosati, “Design and operation improvements for CADEL cable-driven elbow assisting device,” in *Proc. Int. Conf. IFToMM*, 2020, pp. 503–511.

[71] G. Zuccon, M. Bottin, M. Ceccarelli, and G. Rosati, “Design and performance of an elbow assisting mechanism,” *Machines*, vol. 8, no. 4, p. 68, Oct. 2020.

[72] G. Zhang and M. Lin, “Design of a soft robot using pneumatic muscles for elbow rehabilitation,” in *Proc. 3rd Int. Conf. Robot. Autom. Eng. (ICRAE)*, 2018, pp. 14–18.

[73] V. Oguntosin, W. S. Harwin, S. Kawamura, S. J. Nasuto, and Y. Hayashi, “Development of a wearable assistive soft robotic device for elbow rehabilitation,” in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, 2015, pp. 747–752.

[74] W. Huang, M. Feng, D. Yang, and G. Gu, “Low-resistance, highforce, and large-rom fabric-based soft elbow exosuits with adaptive mechanism and composite bellows,” *Sci. China Technol. Sci.*, vol. 66, no. 1, pp. 24–32, 2023.

[75] J. Nassour, G. Zhao, and M. Grimmer, “Soft pneumatic elbow exoskeleton reduces the muscle activity, metabolic cost and fatigue during holding and carrying of loads,” *Sci. Rep.*, vol. 11, no. 1, 2021, Art. no. 12556.

[76] J.-M. Davila-Vilchis, J. C.’ Avila-Vilchis, A. H. Vilchis-Gonz’ alez,’ L. A. Zu’niga-Avilẽs, and J. M. Jacinto-Villegas, “Fabric inflatable soft’ actuators for soft wearable devices: The MOSAR case,” *Machines*, vol. 10, no. 10, p. 871, 2022.

[77] B. W. K. Ang and C.-H. Yeow, “Design and modeling of a high force soft actuator for assisted elbow flexion,” *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 3731–3736, Apr. 2020.

[78] V. Oguntosin and A. Akindele, “Design and characterization of artificial muscles from wedge-like pneumatic soft modules,” *Sens. Actuators A, Phys.*, vol. 297, Oct. 2019, Art. no. 111523.

[79] J. Realmuto and T. Sanger, “A robotic forearm orthosis using soft fabric-based helical actuators,” in *Proc. 2nd IEEE Int. Conf. Soft Robot. (RoboSoft)*, 2019, pp. 591–596.

[80] T. Abrar, F. Putzu, J. Konstantinova, and K. Althoefer, “EPAM: Eversive pneumatic artificial muscle,” in *Proc. 2nd IEEE Int. Conf. Soft Robot. (RoboSoft)*, 2019, pp. 19–24.

[81] T. T. Hoang et al., “A wearable soft fabric sleeve for upper limb augmentation,” *Sensors*, vol. 21, no. 22, p. 7638, 2021.

[82] S. J. Park and C. H. Park, “Suit-type wearable robot powered by shapememory-alloy-based fabric muscle,” *Sci. Rep.*, vol. 9, no. 1, p. 9157, 2019.

[83] S. J. Park, U. Kim, and C. H. Park, “A novel fabric muscle based on shape memory alloy springs,” *Soft Robot.*, vol. 7, no. 3, pp. 321–331, 2020.

[84] S. J. Park, K. Choi, H. Rodrigue, and C. H. Park, “Fabric muscle with a cooling acceleration structure for upper limb assistance soft exosuits,” *Sci. Rep.*, vol. 12, no. 1, 2022, Art. no. 11398.

[85] S. J. Park, K. Choi, H. Rodrigue, and C. H. Park, “Soft exosuit based on fabric muscle for upper limb assistance,” *IEEE/ASME Trans. Mechatron.*, vol. 28, no. 1, pp. 26–37, Feb. 2023.

[86] M. Xiloyannis, L. Cappello, K. D. Binh, C. W. Antuvan, and L. Masia, “Preliminary design and control of a soft exosuit for assisting elbow movements and hand grasping in activities of daily living,” vol. 4, pp. 1–15, Jan. 2017.

[87] C. Ockenfeld, R. K. Y. Tong, E. A. Susanto, S.-K. Ho, and X.-L. Hu, “Fine finger motor skill training with exoskeleton robotic hand in chronic stroke: Stroke rehabilitation,” in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, 2013, pp. 1–4.

[88] N. W. Bartlett et al., “A soft robotic orthosis for wrist rehabilitation,” *J. Med. Devices*, vol. 9, no. 3, 2015, Art. no. 030918.

[89] B. W. Ang and C.-H. Yeow, “Design and characterization of a 3d printed soft robotic wrist sleeve with 2 dof for stroke rehabilitation,” in *Proc. 2nd IEEE Int. Conf. Soft Robot. (RoboSoft)*, 2019, pp. 577–582.

[90] H. Choi, B. B. Kang, B.-K. Jung, and K.-J. Cho, “Exo-wrist: A soft tendon-driven wrist-wearable robot with active anchor for dart-throwing motion in hemiplegic patients,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 4499–4506, Oct. 2019.

[91] T. Tsabedze, E. Hartman, C. Brennan, and J. Zhang, “A compliant robotic wrist orthosis driven by twisted string actuators,” in *Proc. Int. Symp. Med. Robot. (ISMR)*, 2021, pp. 1–7.

[92] J. Jeong et al., “Wrist assisting soft wearable robot with stretchable coolant vessel integrated SMA muscle,” *IEEE/ASME Trans. Mechatron.*, vol. 27, no. 2, pp. 1046–1058, Apr. 2022.

[93] S. Liu et al., “A compact soft robotic wrist brace with origami actuators,” *Front. Robot. AI*, vol. 8, Mar. 2021, Art. no. 614623.

[94] D. Chiaradia, L. Tiseni, M. Xiloyannis, M. Solazzi, L. Masia, and A. Frisoli, “An assistive soft wrist exosuit for flexion movements with an ergonomic reinforced glove,” *Front. AI Robot.*, vol. 7, Jan. 2021, Art. no. 595862.

[95] N. Li et al., “An assistive soft wrist exosuit for flexion movements with an ergonomic reinforced glove,” *J. Bionic Eng.*, vol. 17, pp. 1163–1174, Jan. 2021.

[96] J. Jeong, I. B. Yasir, J. Han, C. H. Park, S.-K. Bok, and K.-U. Kyung, “Design of shape memory alloy-based soft wearable robot for assisting wrist motion,” *Appl. Sci.*, vol. 9, no. 19, p. 4025, 2019.

[97] S. Das, Y. Kurita, and T. Tsuji, “Design and development of a PAM-enabled wrist assist glove,” in *Proc. ICRA Workshop Adv. Chall. Develop., Test. Assess. Assist. Rehabil. Robots*, 2017, pp. 16–17.

[98] H. K. Yap, B. W. K. Ang, J. H. Lim, J. C. H. Goh, and C.-H. Yeow, “A fabric-regulated soft robotic glove with user intent detection using EMG and RFID for hand assistive application,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2016, pp. 3537–3542.

[99] H. K. Yap, J. H. Lim, F. Nasrallah, J. C. H. Goh, and R. C. H. Yeow, “A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2015, pp. 4967–4972.

[100] J. Wang, Y. Fei, and W. Pang, “Design, modeling, and testing of a soft pneumatic glove with segmented PneuNets bending actuators,” *IEEE/ASME Trans. Mechatron.*, vol. 24, no. 3, pp. 990–1001, Jun. 2019.

[101] C. Suulker, S. Skach, and K. Althoefer, “Soft robotic fabric actuator with elastic bands for high force and bending performance in hand exoskeletons,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 4, pp. 10621–10627, Oct. 2022.

[102] B. B. Kang, H. Choi, H. Lee, and K.-J. Cho, “Exo-glove poly II: A polymer-based soft wearable robot for the hand with a tendon-driven actuation system,” *Soft Robot.*, vol. 6, no. 2, pp. 214–227, 2019.

[103] D. Popov, I. Gaponov, and J.-H. Ryu, “Portable exoskeleton glove with soft structure for hand assistance in activities of daily living,” *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 2, pp. 865–875, Apr. 2017.

[104] H. Liu et al., “Finger flexion and extension driven by a single motor in robotic glove design,” *Adv. Intell. Syst.*, vol. 5, no. 5, 2023, Art. no. 2200274.

[105] A. Hadi, K. Alipour, S. Kazeminasab, A. Amerinatanzi, and M. Elahinia, “Design and prototyping of a wearable assistive tool for hand rehabilitation using shape memory alloys,” in *Proc. Smart Mater., Adapt. Struct. Intell. Syst.*, 2016, Art. no. V001T04A009.

[106] P. Polygerinos et al., “Towards a soft pneumatic glove for hand rehabilitation,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2013, pp. 1512–1517.

[107] H. K. Yap, J. H. Lim, F. Nasrallah, F.-Z. Low, J. C. H. Goh, and R. C. H. Yeow, “MRC-glove: A fMRI compatible soft robotic glove for hand rehabilitation application,” in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, 2015, pp. 735–740.

[108] H. K. Yap, N. Kamaldin, J. H. Lim, F. A. Nasrallah, J. C. H. Goh, and C.-H. Yeow, “A magnetic resonance compatible soft wearable robotic glove for hand rehabilitation and brain imaging,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 6, pp. 782–793, Jun. 2017.

[109] H. K. Yap, J. H. Lim, F. Nasrallah, J. C. H. Goh, and C.-H. Yeow, “Characterisation and evaluation of soft elastomeric actuators for hand assistive and rehabilitation applications,” *J. Med. Eng. Technol.*, vol. 40, no. 4, pp. 199–209, 2016.

[110] H. K. Yap, J. H. Lim, J. C. H. Goh, and C.-H. Yeow, “Design of a soft robotic glove for hand rehabilitation of stroke patients with clenched fist deformity using inflatable plastic actuators,” *J. Med. Devices*, vol. 10, no. 4, 2016, Art. no. 044504.

[111] H. Al-Fahaam, S. Davis, S. Nefti-Meziani, and T. Theodoridis, “Novel soft bending actuator-based power augmentation hand exoskeleton controlled by human intention,” *Intell. Service Robot.*, vol. 11, pp. 247–268, Apr. 2018.

[112] S. Koizumi et al., “Soft robotic gloves with thin McKibben muscles for hand assist and rehabilitation,” in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, 2020, pp. 93–98.

[113] Y. Han, Q. Xu, and F. Wu, “Design of wearable hand rehabilitation glove with bionic fiber-reinforced actuator,” *IEEE J. Transl. Eng. Health Med.*, vol. 10, pp. 1–10, 2022.

[114] H. K. Yap et al., "A fully fabric-based bidirectional soft robotic glove for assistance and rehabilitation of hand impaired patients," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1383–1390, Jul. 2017.

[115] Y. M. Zhou et al., "Soft robotic glove with integrated sensing for intuitive grasping assistance post spinal cord injury," in *Proc. Int. Conf. Robot. Autom. (ICRA)*, 2019, pp. 9059–9065.

[116] M. Feng, D. Yang, and G. Gu, "High-force fabric-based pneumatic actuators with asymmetric chambers and interference-reinforced structure for soft wearable assistive gloves," *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 3105–3111, Apr. 2021.

[117] Y. Jiang et al., "Multifunctional robotic glove with active-passive training modes for hand rehabilitation and assistance," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2021, pp. 4969–4974.

[118] Y. Chen, S. Le, Q. C. Tan, O. Lau, F. Wan, and C. Song, "A lobsterinspired robotic glove for hand rehabilitation," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2017, pp. 4782–4787.

[119] J. Yi, Z. Shen, C. Song, and Z. Wang, "A soft robotic glove for hand motion assistance," in *Proc. IEEE Int. Conf. Realtime Comput. Robot. (RCAR)*, 2016, pp. 111–116.

[120] N. Kladovasilakis et al., "A novel soft robotic exoskeleton system for hand rehabilitation and assistance purposes," *Appl. Sci.*, vol. 13, no. 1, p. 553, 2022.

[121] C. Rieger and J. Desai, "A preliminary study to design and evaluate pneumatically controlled soft robotic actuators for a repetitive hand rehabilitation task," *Biomimetics*, vol. 7, no. 4, p. 139, 2022.

[122] B. Wang, A. McDaid, M. Biglari-Abhari, and K. C. Aw, "Design and development of a glove for post-stroke hand rehabilitation," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, 2017, pp. 1047–1051.

[123] D. Hu, J. Zhang, Y. Yang, Q. Li, D. Li, and J. Hong, "A novel soft robotic glove with positive-negative pneumatic actuator for hand rehabilitation," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, 2020, pp. 1840–1847.

[124] J. Yi, X. Chen, and Z. Wang, "A three-dimensional-printed soft robotic glove with enhanced ergonomics and force capability," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 242–248, Jan. 2018.

[125] B. W. K. Ang and C.-H. Yeow, "Print-it-yourself (PIY) glove: A fully 3D printed soft robotic hand rehabilitative and assistive exoskeleton for stroke patients," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2017, pp. 1219–1223.

[126] H. In, B. B. Kang, M. Sin, and K.-J. Cho, "Exo-Glove: A wearable robot for the hand with a soft tendon routing system," *IEEE Robot. Autom. Mag.*, vol. 22, no. 1, pp. 97–105, Mar. 2015.

[127] B. B. Kang, H. Lee, H. In, U. Jeong, J. Chung, and K.-J. Cho, "Development of a polymer-based tendon-driven wearable robotic hand," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2016, pp. 3750–3755.

[128] A. Bajaj, V. Jain, P. Kumar, A. Unal, and A. Saxena, "Soft hand exoskeleton for adaptive grasping using a compact differential mechanism," in *Proc. Mech. Mach. Sci. Sel. Asian (MMS)*, 2020, pp. 733–746.

[129] S. W. Lee, K. A. Landers, and H.-S. Park, "Development of a biomimetic hand exotendon device (BiomHED) for restoration of functional hand movement post-stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 4, pp. 886–898, Jul. 2014.

[130] D. H. Kim, S. W. Lee, and H. S. Park, "Development of a biomimetic extensor mechanism for restoring normal kinematics of finger movements post-stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 10, pp. 2107–2117, Oct. 2019.

[131] B. C. Vermillion, A. W. Dromerick, and S. W. Lee, "Toward restoration of normal mechanics of functional hand tasks post-stroke: Subjectspecific approach to reinforce impaired muscle function," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 8, pp. 1606–1616, Aug. 2019.

[132] H. L. Heung, Z. Q. Tang, X. Q. Shi, K. Y. Tong, and Z. Li, "Soft rehabilitation actuator with integrated post-stroke finger spasticity evaluation," *Front. Bioeng. Biotechnol.*, vol. 8, p. 111, Feb. 2020.

[133] P. Tran, S. Jeong, and J. P. Desai, "Voice-controlled flexible exotendon (FLEXotendon) glove for hand rehabilitation," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2019, pp. 4834–4839.

[134] P. Tran, S. Jeong, S. L. Wolf, and J. P. Desai, "Patient-specific, voicecontrolled, robotic FLEXotendon glove-ii system for spinal cord injury," *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 898–905, Apr. 2020.

[135] T. Tsabedze, E. Hartman, and J. Zhang, "A compact, compliant, and biomimetic robotic assistive glove driven by twisted string actuators," *Int. J. Intell. Robot. Appl.*, vol. 5, pp. 381–394, Aug. 2021.

[136] G. S. Patterson, T. D. Zell, D. E. Parker, J. Grieve, S. C. Watson, and V. Vikas, "Flexion and extension capable motor tendon actuated exosuit glove with open palm," in *Proc. Int. Design Eng. Techn. Conf. Comput. Inf. Eng. Conf.*, 2019, Art. no. V05AT07A042.

[137] D. H. Kim, Y. Lee, and H.-S. Park, "Bioinspired high-degrees of freedom soft robotic glove for restoring versatile and comfortable manipulation," *Soft Robot.*, vol. 9, no. 4, pp. 734–744, 2022.

[138] S. Biggar and W. Yao, "Design and evaluation of a soft and wearable robotic glove for hand rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 10, pp. 1071–1080, Oct. 2016.

[139] A. Stilli et al., "AirExGlove—A novel pneumatic exoskeleton glove for adaptive hand rehabilitation in post-stroke patients," in *Proc. IEEE Int. Conf. Soft Robot. (RoboSoft)*, 2018, pp. 579–584.

[140] L. Gerez, G. Gao, A. Dwivedi, and M. Liarokapis, "A hybrid, wearable exoskeleton glove equipped with variable stiffness joints, abduction capabilities, and a telescopic thumb," *IEEE Access*, vol. 8, pp. 173345–173358, 2020.

[141] A. Yurkewich, I. J. Kozak, D. Hebert, R. H. Wang, and A. Mihailidis, "Hand extension robot orthosis (HERO) grip glove: Enabling independence amongst persons with severe hand impairments after stroke," *J. Neuroeng. Rehabil.*, vol. 17, pp. 1–17, Feb. 2020.

[142] A. Mohammadi, J. Lavranos, P. Choong, and D. Oetomo, "Flexo-glove: A 3D printed soft exoskeleton robotic glove for impaired hand rehabilitation and assistance," in *Proc. 40th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, 2018, pp. 2120–2123.

[143] D. H. Kim and H.-S. Park, "Cable actuated dexterous (CADEX) glove for effective rehabilitation of the hand for patients with neurological diseases," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2018, pp. 2305–2310.

[144] Y. Wang, S. Kokubu, Z. Zhou, X. Guo, Y.-H. Hsueh, and W. Yu, "Designing soft pneumatic actuators for thumb movements," *IEEE Robot. Autom. Lett.*, vol. 6, no. 4, pp. 8450–8457, Oct. 2021.

[145] X. Cao, K. Ma, Z. Jiang, and F. Xu, "A soft robotic glove for hand rehabilitation using pneumatic actuators with jamming structure," in *Proc. 40th Chin. Control Conf. (CCC)*, 2021, pp. 4120–4125.

[146] H. Amin and S. F. M. Assal, "Design methodology of a spring roll dielectric elastomer-based actuator for a hand rehabilitation system," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, 2018, pp. 997–1002.

[147] Y.-J. Kim, Y.-J. Jeong, H.-S. Jeon, D.-W. Lee, and J.-I. Kim, "Development of a soft robotic glove with high gripping force using force distributing compliant structures," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2017, pp. 3883–3890.

[148] I. Koo et al., "Development of a meal assistive exoskeleton made of soft materials for polymyositis patients," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2014, pp. 542–547.

[149] J. Fu, S. M. Hosseini, R. Simpson, A. Brooks, R. Huff, and J.-H. Park, "A bilateral six degree of freedom cable-driven upper body Exosuit," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, 2022, pp. 617–623.

[150] Z. Kadivar, C. E. Beck, R. N. Rovekamp, and M. K. O'Malley, "Single limb cable driven wearable robotic device for upper extremity movement support after traumatic brain injury," *J. Rehabil. Assist. Technol. Eng.*, vol. 8, pp. 1–15, Apr. 2021.

[151] I. Gaponov, D. Popov, S. J. Lee, and J.-H. Ryu, "A portable cabledriven exosuit for upper extremity assistance," *Int. J. Control, Autom. Syst.*, vol. 15, pp. 73–84, Jan. 2017.

[152] D. Pont et al., "A bilateral six degree of freedom cable-driven upper body exosuit," in *Proc. 4th Iberian Robot. Conf.*, 2019, pp. 617–623.

[153] S. Lessard et al., "CRUX: A compliant robotic upper-extremity exosuit for lightweight, portable, multi-joint muscular augmentation," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, 2017, pp. 1633–1638.

[154] S. Lessard, P. Pansodtee, A. Robbins, J. M. Trombadore, S. Kurniawan, and M. Teodorescu, "A soft exosuit for flexible upper-extremity rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 8, pp. 1604–1617, Aug. 2018.

[155] T. Proietti et al., "Sensing and control of a multi-joint soft wearable robot for upper-limb assistance and rehabilitation," *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 2381–2388, Apr. 2021.

[156] S. Das and Y. Kurita, "ForceArm: A wearable pneumatic gel muscle (PGM)-based assistive suit for the upper limb," *IEEE Trans. Med. Robot. Bion.*, vol. 2, no. 2, pp. 269–281, May 2020.

[157] C. L. Vaughan, "Theories of bipedal walking: An odyssey," *J. Biomech.*, vol. 36, no. 4, pp. 513–523, 2003.

[158] A. T. Asbeck, K. Schmidt, and C. J. Walsh, "Soft exosuit for hip assistance," *Robot. Auton. Syst.*, vol. 73, pp. 102–110, Nov. 2015.

[159] M.-H. Hsieh, Y. H. Huang, C.-L. Chao, C.-H. Liu, W.-L. Hsu, and W.-P. Shih, “Single-actuator-based lower-limb soft exoskeleton for preswing gait assistance,” *Appl. Bion. Biomech.*, vol. 2020, no. 1, 2020, Art. no. 5927657.

[160] Y. Liu, C. Chen, J. Lu, Y. Liu, Y. Zhang, and Z. Wang, “A novel soft exosuit based on biomechanical analysis for assisting lower extremity,” in *Proc. IEEE Int. Conf. E-Health Netw., Appl. Services (HEALTHCOM)*, 2021, pp. 1–6.

[161] C. M. Thalman, L. Baye-Wallace, and H. Lee, “A soft robotic hip exosuit (sr-hexo) to assist hip flexion and extension during human locomotion,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2021, pp. 5060–5066.

[162] T. M. Miller-Jackson, R. F. Natividad, D. Y. L. Lim, L. HernandezBarraza, J. W. Ambrose, and R. C.-H. Yeow, “A wearable soft robotic exoskeleton for hip flexion rehabilitation,” *Front. Robot. AI*, vol. 9, Apr. 2022, Art. no. 835237.

[163] A. L. Kulasekera, R. B. Arumathanthri, D. S. Chathuranga, T. D. Lalitharatne, and R. C. Gopura, “A low-profile vacuum actuator: Towards a sit-to-stand assist exosuit,” in *Proc. 3rd IEEE Int. Conf. Soft Robot. (RoboSoft)*, 2020, pp. 110–115.

[164] A. L. Kulasekera, R. B. Arumathanthri, D. S. Chathuranga, R. A. R. C. Gopura, and T. D. Lalitharatne, “A low-profile vacuum actuator (LPVAc) with integrated inductive displacement sensing for a novel sit-to-stand assist exosuit,” *IEEE Access*, vol. 9, pp. 117067–117079, 2021.

[165] J. Kim et al., “Reducing the metabolic rate of walking and running with a versatile, portable exosuit,” *Science*, vol. 365, no. 6454, pp. 668–672, 2019.

[166] I. M. Hasan, E. Q. Yumbla, and W. Zhang, “Development of a soft inflatable exosuit for knee flexion assistance,” in *Proc. 9th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, 2022, pp. 1–6.

[167] S. Sridar, P. H. Nguyen, M. Zhu, Q. P. Lam, and P. Polygerinos, “Development of a soft-inflatable exosuit for knee rehabilitation,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2017, pp. 3722–3727.

[168] S. Zhao, Y. Yang, Y. Gao, Z. Zhang, T. Zheng, and Y. Zhu, “Development of a soft knee exosuit with twisted string actuators for stair climbing assistance,” in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, 2019, pp. 2541–2546.

[169] A. J. Veale, K. Staman, and H. Van Der Kooij, “Soft, wearable, and pleated pneumatic interference actuator provides knee extension torque for sit-to-stand,” *Soft Robot.*, vol. 8, no. 1, pp. 28–43, 2021.

[170] S. Sridar et al., “Evaluating immediate benefits of assisting knee extension with a soft inflatable exosuit,” *IEEE Trans. Medical Robot. Bion.*, vol. 2, no. 2, pp. 216–225, May 2020.

[171] L. Zhang, Q. Huang, K. Cai, Z. Wang, W. Wang, and J. Liu, “A wearable soft knee exoskeleton using vacuum-actuated rotary actuator,” *IEEE Access*, vol. 8, pp. 61311–61326, 2020.

[172] H. D. Yang, M. Cooper, A. Eckert-Erdheim, D. Orzel, and C. J. Walsh, “A soft exosuit assisting hip abduction for knee adduction moment reduction during walking,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 3, pp. 7439–7446, Jul. 2022.

[173] J. Bae et al., “A lightweight and efficient portable soft exosuit for paretic ankle assistance in walking after stroke,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2018, pp. 2820–2827.

[174] J. Chung, R. Heimgartner, C. T. O’Neill, N. S. Phipps, and C. J. Walsh, “Exoboot, a soft inflatable robotic boot to assist ankle during walking: Design, characterization and preliminary tests,” in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, 2018, pp. 509–516.

[175] Y.-L. Park et al., “Design and control of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation,” *Bioinspiration Biomimetics*, vol. 9, no. 1, 2014, Art. no. 016007.

[176] J. Piao et al., “Development of a comfort suit-type soft-wearable robot with flexible artificial muscles for walking assistance,” *Sci. Rep.*, vol. 13, no. 1, p. 4869, 2023.

[177] J. Bae et al., “A soft exosuit for patients with stroke: Feasibility study with a mobile off-board actuation unit,” in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, 2015, pp. 131–138.

[178] A. T. Asbeck, R. J. Dyer, A. F. Larusson, and C. J. Walsh, “Biologically-inspired soft exosuit,” in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, 2013, pp. 1–8.

[179] S. Lee, S. Crea, P. Malcolm, I. Galiana, A. Asbeck, and C. Walsh, “Controlling negative and positive power at the ankle with a soft exosuit,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2016, pp. 3509–3515.

[180] C. M. Thalman, J. Hsu, L. Snyder, and P. Polygerinos, “Design of a soft ankle-foot orthosis exosuit for foot drop assistance,” in *Proc. Int. Conf. Robot. Autom. (ICRA)*, 2019, pp. 8436–8442.

[181] C. Kim et al., “Shape memory alloy actuator-embedded smart clothes for ankle assistance,” *Smart Mater. Struct.*, vol. 29, no. 5, 2020, Art. no. 055003.

[182] P. Malcolm, W. Derave, S. Galle, and D. De Clercq, “A simple exoskeleton that assists plantarflexion can reduce the metabolic cost of human walking,” *PloS One*, vol. 8, no. 2, 2013, Art. no. e56137.

[183] S. Galle, P. Malcolm, S. H. Collins, and D. De Clercq, “Reducing the metabolic cost of walking with an ankle exoskeleton: Interaction between actuation timing and power,” *J. Neuroeng. Rehabil.*, vol. 14, no. 1, pp. 1–16, 2017.

[184] P. Slade, M. J. Kochenderfer, S. L. Delp, and S. H. Collins, “Personalizing exoskeleton assistance while walking in the real world,” *Nature*, vol. 610, no. 7931, pp. 277–282, 2022.

[185] Y. Ding, I. Galiana, A. Asbeck, B. Quinlivan, S. M. M. De Rossi, and C. Walsh, “Multi-joint actuation platform for lower extremity soft exosuits,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2014, pp. 1327–1334.

[186] Y. Ding et al., “Biomechanical and physiological evaluation of multi-joint assistance with soft exosuits,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 2, pp. 119–130, Feb. 2017.

[187] A. T. Asbeck, K. Schmidt, I. Galiana, D. Wagner, and C. J. Walsh, “Multi-joint soft exosuit for gait assistance,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2015, pp. 6197–6204.

[188] F. A. Panizzolo et al., “A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking,” *J. Neuroeng. Rehabil.*, vol. 13, no. 1, pp. 1–14, 2016.

[189] A. Davoodi, M. Iranikhah, A. Ahmadi, A. Seyfarth, and M. A. Sharbafi, “Bioinspired design and control of BATEX, an exosuit with biarticular compliant actuators,” *IEEE/ASME Trans. Mechatronics*, vol. 29, no. 2, pp. 1352–1362, Apr. 2024.

[190] V. Bartenbach, K. Schmidt, M. Naef, D. Wyss, and R. Riener, “Concept of a soft exosuit for the support of leg function in rehabilitation,” in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, 2015, pp. 125–130.

[191] K. Schmidt et al., “The Myosuit: Bi-articular anti-gravity exosuit that reduces hip extensor activity in sitting transfers,” *Front. Neurorobot.*, vol. 11, p. 57, Oct. 2017.

[192] M. Wehner et al., “A lightweight soft exosuit for gait assistance,” in *Proc. IEEE Int. Conf. Robot. Autom.*, 2013, pp. 3362–3369.

[193] L. Biao, L. Youwei, X. Xiaoming, W. Haoyi, and X. Longhan, “Design and control of a flexible exoskeleton to generate a natural full gait for lower-limb rehabilitation,” *J. Mechan. Robot.*, vol. 15, no. 1, 2023, Art. no. 011005.

[194] C. G. Rose and M. K. O’Malley, “Hybrid rigid-soft hand exoskeleton to assist functional dexterity,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 73–80, Jan. 2019.

[195] D. Cafolla, “A personalized flexible exoskeleton for finger rehabilitation: A conceptual design,” in *Proc. 15th IFToMM World Congr. Mech. Mach. Sci.*, 2019, pp. 73–82.

[196] G. Rudd, L. Daly, V. Jovanovic, and F. Cuckov, “A low-cost soft robotic hand exoskeleton for use in therapy of limited hand–motor function,” *Appl. Sci.*, vol. 9, no. 18, p. 3751, 2019.

[197] M. Dragusanu, T. L. Baldi, Z. Iqbal, D. Prattichizzo, and M. Malvezzi, “Design, development, and control of a tendon-actuated exoskeleton for wrist rehabilitation and training,” in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, 2020, pp. 1749–1754.

[198] K. Hyeon, J. Jeong, C. Chung, M. Cho, S. Hussain, and K.-U. Kyung, “Design of a wearable mechanism with shape memory alloy (sma)based artificial muscle for assisting with shoulder abduction,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 4, pp. 10635–10642, Oct. 2022.

[199] Y. Zhang, A. Ajoudani, and N. G. Tsagarakis, “Exo-muscle: A semirigid assistive device for the knee,” *IEEE Robot. Autom. Lett.*, vol. 6, no. 4, pp. 8514–8521, Oct. 2021.

[200] E. J. Park et al., “A hinge-free, non-restrictive, lightweight tethered exosuit for knee extension assistance during walking,” *IEEE Trans. Med.Robot. Bion.*, vol. 2, no. 2, pp. 165–175, May 2020.

[201] P. Kabir, M. Zareinejad, H. A. Talebi, M. Soleimanifar, M. Mavajian, and M. Ashoori, “Development and evaluation of a soft wearable knee rehabilitation apparatus,” in *Proc. 10th RSI Int. Conf. Robot. Mechatronics (ICRoM)*, 2022, pp. 159–164.

[202] J. Kwon, J.-H. Park, S. Ku, Y. Jeong, N.-J. Paik, and Y.-L. Park, “A soft wearable robotic ankle-foot-orthosis for post-stroke patients,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2547–2552, Jul. 2019.

[203] Z. Wang, Z. Zhou, L. Ruan, X. Duan, and Q. Wang, “Mechatronic design and control of a rigid-soft hybrid knee exoskeleton for gait intervention,” *IEEE/ASME Trans. Mechatronics*, vol. 28, no. 5, pp. 2553–2564, Oct. 2023.

[204] T. Zhang, K. Feng, B. Zeng, and Z. Gong, “Design and validation of a lightweight soft hip exosuit with series-wedge-structures for assistive walking and running,” *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 5, pp. 2863–2874, Oct. 2022.

[205] Y. Ren, Y.-N. Wu, C.-Y. Yang, T. Xu, R. L. Harvey, and L.-Q. Zhang, “Developing a wearable ankle rehabilitation robotic device for in-bed acute stroke rehabilitation,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 6, pp. 589–596, Jun. 2017.

[206] C. Di Natali et al., “Design and evaluation of a soft assistive lower limb exoskeleton,” *Robotica*, vol. 37, no. 12, pp. 2014–2034, 2019.

[207] L. N. Awad, A. Esquenazi, G. E. Francisco, K. J. Nolan, and A. Jayaraman, “The rewalk restore$^{\mathrm{TM}}$ soft robotic exosuit: A multisite clinical trial of the safety, reliability, and feasibility of exosuitaugmented post-stroke gait rehabilitation,” *J. Neuroeng. Rehabil.*, vol. 17, pp. 1–11, Jun. 2020.

[208] (NEOFECT Co., South Korea, Germany). *Neofect Smart Glove*. (2023). [Online]. Available: https://www.neofect.com/us/smart-glove

[209] “Carbon hand.” 2023. [Online]. Available: https://www.bioservo.com/products/carbonhand?

[210] “Nuda glove.” 2023. [Online]. Available: https://bionicsforeveryone.com/nuada-glove/

[211] “Ironhand.” 2023. [Online]. Available: https://www.bioservo.com/products/ironhand?

[212] “Robotic grasp assist.” 2023. [Online]. Available: https://www.neofect.com/us/neomano

[213] K. K. Petersen, T. Graven-Nielsen, O. Simonsen, M. B. Laursen, and L. Arendt-Nielsen, “Preoperative pain mechanisms assessed by cuff algometry are associated with chronic postoperative pain relief after total knee replacement,” *Pain*, vol. 157, no. 7, pp. 1400–1406, 2016.

[214] L. Levesque, S. Pardoel, Z. Lovrenovic, and M. Doumit, “Experimental comfort assessment of an active exoskeleton interface,” in *Proc. IEEE Int. Symp. Robot. Intell. Sensors (IRIS)*, 2017, pp. 38–43.

[215] Q. He and S. Cai, “Soft pumps for soft robots,” *Sci. Robot.*, vol. 6, Feb. 2021, Art. no. eabg6640.

[216] B. A. Osuagwu et al., “Home-based rehabilitation using a soft robotic hand glove device leads to improvement in hand function in people with chronic spinal cord injury: A pilot study,” *J. Neuroeng. Rehabil.*, vol. 17, pp. 1–15, Mar. 2020.

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