

Review

Overview: A Comprehensive Review of Soft Wearable Rehabilitation and Assistive Devices, with a Focus on the Function, Design and Control of Lower-Limb Exoskeletons

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Abstract

With the global ageing population and the increasing prevalence of mobility impairments, the demand for effective and comfortable rehabilitation and assistive solutions has grown rapidly. Soft exoskeletons have emerged as a key direction in the development of wearable rehabilitation devices. This review examines how these systems are designed and controlled, as well as how they differ from the rigid exoskeletons that preceded them. Made from flexible fabrics and lightweight components, soft exoskeletons use pneumatic or cable mechanisms to support movement while keeping close contact with the body. Their compliant structure helps to reduce joint stress and makes them more comfortable for long periods of use. The discussion in this paper covers recent work on lower-limb designs, focusing on actuation, power transmission, and human–robot coordination. It also considers the main technical barriers that remain, such as power supply limits, the wear and fatigue of soft materials, and the challenge of achieving accurate tracking performance, low latency, and resilience to external disturbances. Studies reviewed here show that these systems help users regain functionality and improve rehabilitation, while also easing caregivers' workload. The paper ends by outlining several priorities for future development: lighter mechanical layouts, better energy systems, and adaptive control methods that make soft exoskeletons more practical for everyday use as well as clinical therapy.

Keywords: lower-limb exoskeleton; design and control; soft wearable robotics; rehabilitation; assistive devices



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1. Introduction

In recent years, numerous researchers have shown a strong interest in wearable exoskeletons, which are robots designed to support and protect human body parts, and this field is experiencing an unprecedented era [1–3]. In the UK alone, 6.8 million people suffer from disabilities related to free movement, primarily due to stroke and other musculoskeletal diseases. With advancements in medical technology, the survival time of these patients is continuously increasing [4,5]. Additionally, the overall population is gradually ageing. According to predictions, the number of people aged 85 and over will rise from 1.8 million in 2018 to 3 million by 2043 [4]. As people age, their muscles and bones become weaker, and the ageing population means that this group needs assistance for a longer period [4]. Therefore, developing an effective tool that can assist them in leading a normal life is urgently needed.

Rehabilitation exoskeletons, particularly lower-extremity rehabilitative exoskeletons, are highly important for patients unable to move freely, such as the elderly and those disabled due to illness, because of their potential applications in assisting movement and rehabilitation therapy. Approximately 12.5% of the world's population, or about 1 billion people, are facing disabilities such as muscle weakness and stroke, a number expected to increase with the ageing population. As shown in Figure 1, from 2002 to 2017, among all stroke patients, young people accounted for only 5.7%, middle-aged people accounted for 27.7%, and older people accounted for 66.6%. This indicates that most stroke patients are elderly [6–8]. Rehabilitative exoskeletons help these patients by supporting weak muscles, particularly when muscle weakness results from impaired neural pathways. Research suggests that repetitive motion can stimulate neural pathways, assisting patients to regain movement abilities [9,10].

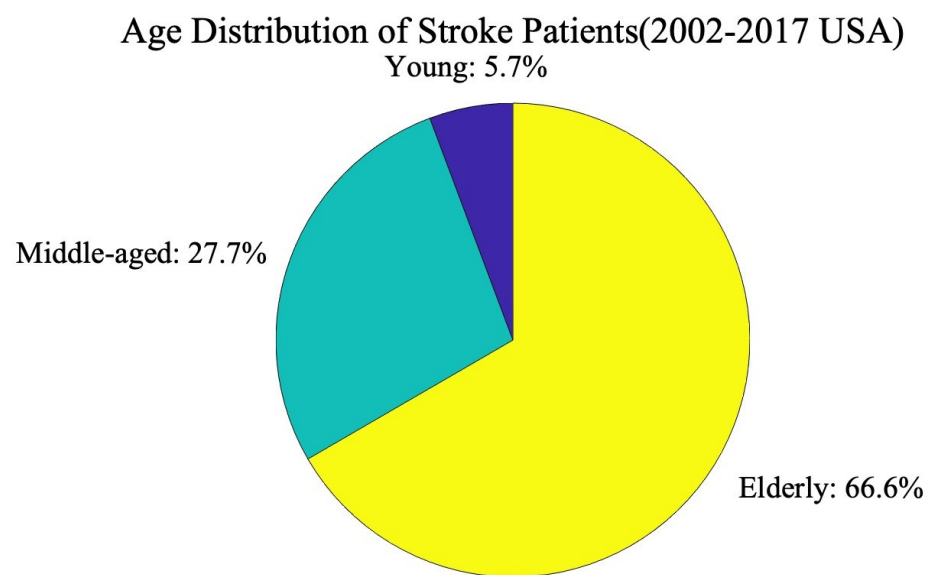


Figure 1. Age distribution of stroke-affected patients for the period of 2002–2017 in the USA, with the data available in 2021 [6].

Lower-limb rehabilitative exoskeletons are wearable robotic systems that can substitute some functions of human muscles to facilitate movement. Despite ongoing research since the 1960s, technological advancements have been slow, and many exoskeletons remain in the experimental phase without achieving commercialisation [11]. Currently, most commercialised exoskeletons are of rigid structures. These structures typically utilise a series of parallel links and pivots that connect to the human body at specific points [2]. However, a significant drawback of these rigid exoskeletons is that misalignment can occur between the traditional rigid exoskeleton and human joints during movement due to the complexity of human joint structures. Determining the exact position of the joints is challenging without the use of imaging technology [2,12,13].

Compared to rigid exoskeletons, soft exoskeletons can be lighter in weight and more comfortable. These exoskeletons use flexible structures to replace traditional rigid structures [14,15], such as pneumatic systems [16,17] and cable-driven systems [18]. The main difference between these two driving methods lies in the amount of force they provide. Rigid structures offer greater force and can support the human body, making them suitable for the initial stages of patient rehabilitation or healthy individuals engaging in heavy and intense activities. In contrast, soft exoskeletons are suitable for scenarios that do not require much force, such as reducing effort for healthy users or later stages of patient rehabilitation training [2].

Given the increasing societal need for rehabilitative exoskeletons, this article aims to review various exoskeleton designs, providing a comprehensive overview of the development of lower-limb exoskeletons. It is divided into the following sections:

Section 2, Search Strategy, introduces the literature screening strategies, including time limitations, keywords, and types of literature. Then, the number and types of selected literature will be analysed. In Section 3, we analyse the skeletal structure, joints, and muscle composition of the lower limbs, along with the gait analysis. In Section 4, we classify and compare different exoskeletons based on their attributes, design approach, functionalities, actuators, sensors, and control strategies. Then, we discuss future development directions in terms of weight reduction, flexibility, universality, cost, energy, and control aspects. Lastly, we conclude this review and provide final remarks on the outlook for lower-limb exoskeleton technologies.

2. Search Strategy

In this review, searches and filters were performed using keywords such as human lower-limb biomechanics, human lower-extremity joints, human lower-limb muscles, lower extremities exoskeletons, and soft exoskeletons in databases like Google Scholar, IEEE: Piscataway, NJ, USA, ScienceDirect, and Scopus.

In ScienceDirect, the keywords “LOWER LIMB EXOSKELETON” and “LOWER LIMB SOFT EXOSKELETON” were used for the search, and with filters to focus on Exoskeleton, 3262 articles were identified. A year-wise distribution from 2015 to 2024 was observed and is shown in Figure 2. Publication numbers have generally been increasing over the years. Moreover, as a new exoskeleton type, the number of soft exoskeletons can increase yearly. However, a significant gap remains compared to the existing literature on exoskeletons.

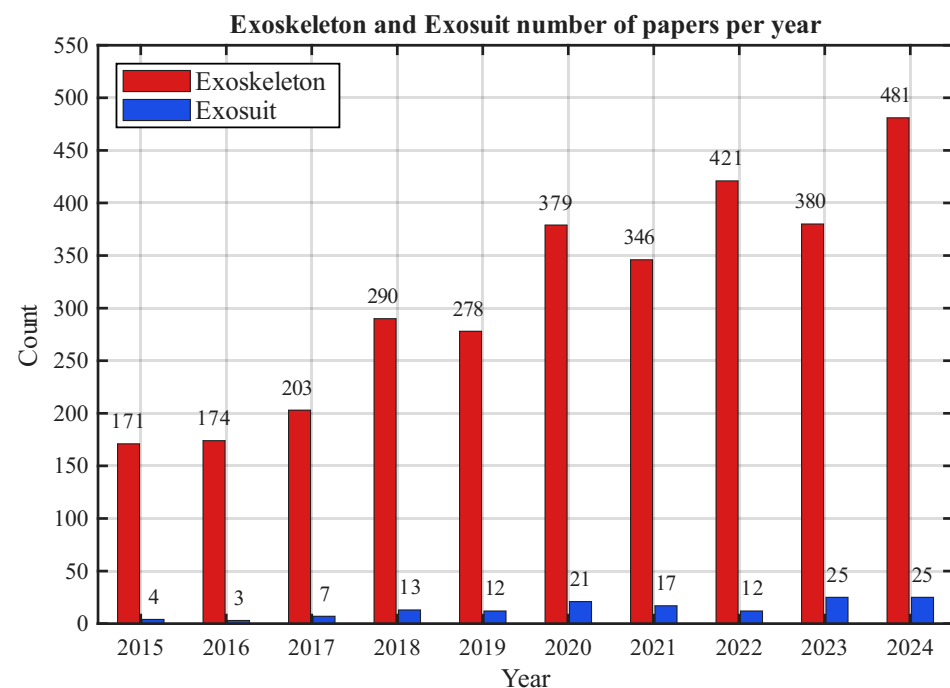


Figure 2. The year-wise breakdown of the number of papers published on lower-limb rigid and soft exoskeletons (available on 20 October 2024).

Tables 1–3 show the bibliometric results from the Scopus database (dated 27 October 2025) with the keyword words “lower-limb exoskeleton” and “lower-limb soft exoskeleton.” The statistics show that China and the United States released the majority of the papers in this field, followed by India, the United Kingdom, Italy, and Germany. The citation

analysis reveals that the top five papers on lower-limb exoskeletons are all review articles. In comparison, among the top five papers on soft lower-limb exoskeletons, three are reviews and two are research papers on control strategies and novel exoskeleton designs. In general, the research focus has increasingly shifted from rigid mechanical systems to soft wearable robots that prioritise comfort, flexibility, and practical application in rehabilitation.

Table 1. Top five countries publishing papers on lower-limb exoskeletons and soft exoskeletons (Scopus database, accessed on 27 October 2025).

Country	Lower-Limb Soft Exoskeleton	Lower-Limb Exoskeleton
China	55	1283
Italy	18	200
United States	17	471
Germany	15	118
United Kingdom	13	119
India	2	149
Spain	4	146

Table 2. Top-cited publications on lower-limb exoskeletons (Scopus database, 2015–2024).

No.	Title	Authors	Citations	Reference
1	State of the Art and Future Directions for Lower Limb Robotic Exoskeletons	Kapsalyamov, A.; Jamwal, P.K.; Hussain, S.; et al.	761	[7]
2	Control Strategies for Active Lower Extremity Prosthetics and Orthotics: A Review	Tucker, M.R.; Olivier, J.; Vallery, H.; et al.	719	[19]
3	Review of Assistive Strategies in Powered Lower-Limb Orthoses and Exoskeletons	Yan, T.; Cempini, M.; Oddo, C.M.; Vitiello, N.	635	[20]
4	Recent Developments and Challenges of Lower Extremity Exoskeletons	Chen, B.; Ma, H.; Qin, L.; Liao, W.	434	[21]
5	A Review on Lower Limb Rehabilitation Exoskeleton Robots	Shi, D.; Zhang, W.; Ding, X.	432	[22]

Table 3. Top-cited publications on soft lower-limb exoskeletons (Scopus database, 2015–2024).

No.	Title	Authors	Citations	Reference
1	A Review on Lower Limb Rehabilitation Exoskeleton Robots	Shi, D.; Zhang, W.; Ding, X.	432	[22]
2	A Biologically-Inspired Multi-Joint Soft Exosuit That Can Reduce the Energy Cost of Loaded Walking	Panizzolo, F.A.; Galiana, I.; Asbeck, A.T.; Walsh, C.J.	269	[23]
3	Human-in-the-Loop Control of Soft Exosuits Using Impedance Learning on Different Terrains	Li, Z.; Li, X.; Kan, Z.; He, W.	126	[24]

Table 3. Cont.

No.	Title	Authors	Citations	Reference
4	Design and Evaluation of a Soft Assistive Lower-Limb Exoskeleton	Di Natali, C.; Poliero, T.; Sposito, M.; Ortiz, J.; Caldwell, D.G.	103	[25]
5	Soft Smart Garments for Lower-Limb Joint Position Analysis	Totaro, M.; Poliero, T.; Beccai, L.; Ortiz, J.L.; et al.	90	[26]

3. Lower-Limb Bio-Mechanics

Human biomechanics studies how the body moves through the coordinated action of muscles, bones, tendons, and ligaments [27]. Since performing direct measurements on the human body is often difficult, mathematical models are widely used to predict joint loads and dynamics [28].

3.1. Lower-Limb Joint Movements

The primary joints involved in the functioning of the lower limbs during walking are the hip joint, knee joint, and ankle joint, as shown in Figure 3.

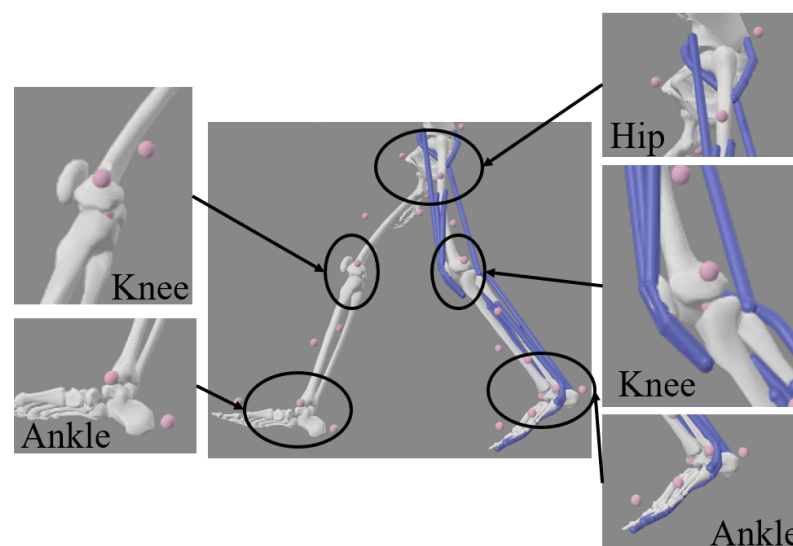


Figure 3. Musculoskeletal model in OpenSim with focus on hip, knee and ankle joints along with muscle markers [29].

As shown in Figure 3 and Table 4, the degrees of freedom (DoFs) of each lower-limb joint provide essential biomechanical guidance for the design of exoskeletons. The human hip exhibits approximately three DoFs—flexion–extension (-30° to 120°), abduction–adduction (-50° to 30°), and internal–external rotation (-40° to 40°). The knee joint primarily provides two DoFs, while the ankle joint allows about three DoFs with compound rotations. When configuring an exoskeleton, these motion ranges should be used as quantitative boundaries to enable the artificial joints to reproduce natural movement while preventing hyperextension. Designers usually set the exoskeleton joint limits slightly smaller than the physiological ranges listed in Table 4 to ensure safety and comfortable motion coordination between the device and the user [30–32].

Table 4. Degrees of freedom (DoFs) of each joint in the lower limb [30–32].

Joints	DoFs	Movement	Degree (°)
Hips	3	Flexion–extension	–30 to 120
		Abduction–adduction	–50 to 30
		Internal–external rotation	–40 to 40
Knees	2	Flexion–extension	0 to 120
		Rotation	–45 to 25
Ankles	3	Plantar flexion–dorsiflexion	40 to 50, –10 to 20
		Abduction–adduction	–40 to 30
		Eversion–inversion	–12 to 23

3.1.1. Hip Joint

The hip is central to balance and locomotion. Unlike birds, which have a centre of gravity below the hip, humans require muscular activity to stabilise the trunk above the joint, leading to higher energy expenditure [33]. Structurally, the hip joint comprises the acetabulum, femur, capsule, and muscles. Its trabecular bone and deformable cartilage distribute stress effectively, allowing the joint to bear heavy loads [33,34].

3.1.2. Knee Joint

The knee enables complex movements through the interaction of ligaments, menisci, and muscles [27]. It can be modelled as two rigid bodies with nearly frictionless contact surfaces [35]. Knee pathologies, such as osteoarthritis, alter gait by changing muscle activity and joint rotation, often reducing pain at the cost of potentially harming long-term stability [36–38].

3.1.3. Ankle Joint

The leg connects to the foot through the ankle region, a complex that includes the main ankle joint (talocrural joint) and several other joints. In contrast, the entire foot contains a total of 33 joints [39], providing stability against compressive and shear forces [32]. Its main motions include dorsiflexion, plantarflexion, inversion, and eversion, with daily ranges of 10°–30° and up to 56° when climbing stairs [40,41]. During activity, the ankle sustains loads up to 13 times body weight [42], making it highly vulnerable to trauma in ageing populations.

3.2. Lower-Limb Muscles

The lower-limb muscles can be divided into gluteal, thigh, knee, calf, and ankle groups (Figure 4).

Gluteal muscles: The gluteus maximus, unique to humans, stabilises the trunk and powers high-intensity actions like sprinting and stair climbing [43,44].

Thigh muscles: Include quadriceps, hamstrings, adductors, sartorius, and others, which support weight bearing and enable hip/knee movement [39].

Knee muscles and ligaments: Stability depends on cruciate and collateral ligaments, while muscles like the gastrocnemius and gluteals generate and stabilise motion [45,46].

Calf muscles: The gastrocnemius and soleus drive walking and running via the Achilles tendon; the former is prone to strain during intense activity [39].

Ankle muscles: Ligament groups (deltoid, lateral, syndesmotric) and muscles coordinate dorsiflexion and plantarflexion, ensuring gait control [39].

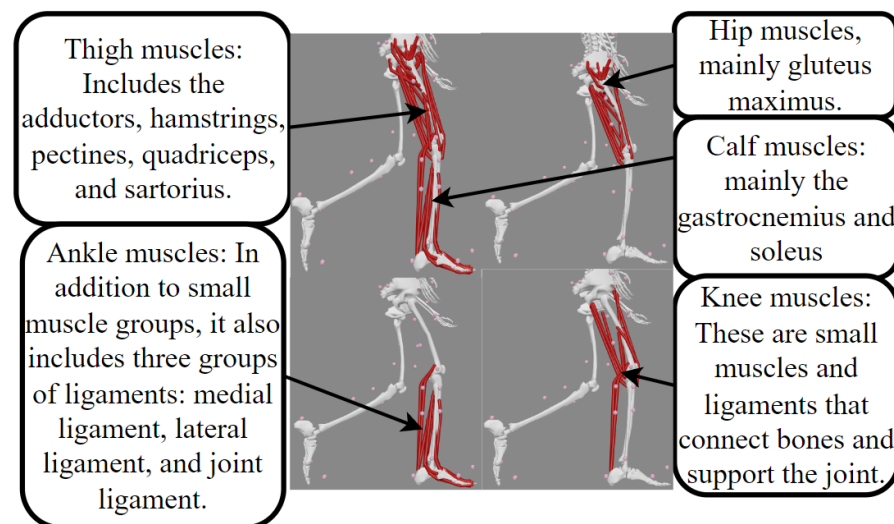


Figure 4. The lower-limb muscle distribution for the human lower extremity. Here, the muscles are shown for three joints: hip, knee & ankle, and thigh & calf links [29].

3.3. Gait Analysis

Throughout history, people have consistently been fascinated by the act of walking. In the early 19th century, the Weber brothers in Germany conducted the first formal studies on biomechanics, marking the beginning of the field. Since then, the development of gait analysis has been greatly influenced by four disciplines: namely, kinematics, dynamics, electromyography, and engineering mathematics [47]. Human movement involves a complex series of actions by the head, trunk, lower extremities, and arms, with the primary goal of safely moving from one point to another [48,49]. Three measurement methods can provide a rough understanding of people's walking conditions: cycle time, stride length, and speed [47]. The movement of the lower extremities during human walking can be considered the chain of motion of three joint configurations (hip joint, knee joint, ankle joint) [50]. As shown in Figure 5.

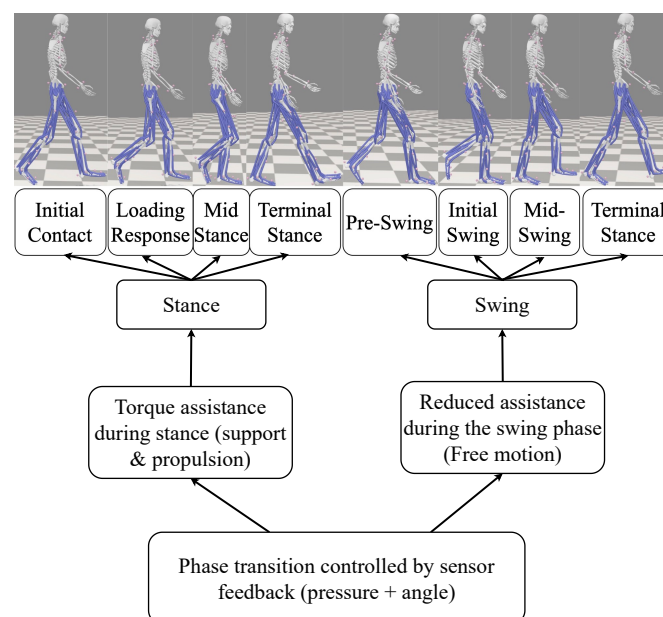


Figure 5. Step-by-step analysis of the human gait cycle and corresponding assistance strategies of lower-limb exoskeletons. During the stance phase, torque assistance is applied for support and propulsion, while during the swing phase, the assistance is minimised to allow free motion. Phase transitions between stance and swing are controlled by sensor feedback from pressure and joint-angle measurements [29,51].

When designing control algorithms for exoskeletons, it is important to determine the range of rotation for each joint of the user to ensure safety. Moreover, the exoskeleton's joint range of rotation should be slightly less than that of the user's own joints. In rehabilitation, the strength of the exoskeleton's artificial muscles should be adjusted. This adjustment enables patients to freely adjust their muscle strength during exoskeleton rehabilitation training, thereby improving efficiency.

4. Rigid and Soft Exoskeletons

In recent years, research on lower-limb exoskeletons has undergone rapid diversification, with numerous prototypes and commercial systems developed to address different levels of assistance, target users, and actuation technologies. Table 5 provides an overview of representative exoskeletons developed during the past five years, summarising their joint configurations, actuation principles, drive modes, and intended purposes. This overview helps to contextualise the subsequent discussion on rigid and soft architectures.

Table 5. Overview of recently developed exoskeletons and some widely popular exoskeletons in the past five years.

Year	Name	Body Joints	Actuator	Drive Mode	Soft and Rigid	DOFs (Left + Right)	Purpose	Subject Population
2025	AES-SEA lower-limb exoskeleton [52]	Knee Hip (active drive), Ankle (passive drive)	Electric motor	Electric (cable-driven)	Rigid	3 (2 active + 1 passive)	Gait rehabilitation and motion assistance	Healthy adults
2024	Parallel Compliant Leg (PCL) [53]	Hip knee ankle	Electric motor	Spring	Soft and rigid	3 + 3	Rehabilitation of paraplegic patients	Healthy subject and simulations
2024	J-Exo [54]	Hip, knee, ankle	Electric motor	Telescopic pole	Rigid	3 + 3	Help older people climb stairs and squat	6 healthy subjects
2023	BATE [55]	Ankle	N/A	Bowden cable	Soft and rigid	3 + 3	Helps support the ankle joint	Experimental platform to simulate the BATE loading process.
2023	Single-leg exoskeleton (SLE) for children with CP [56]	Hip knee ankle	Electric motor	Gear	Rigid	3	Help children with CP	Prototype
2022	Adaptive lower-limb rehabilitation exoskeleton [57]	Hip knee ankle	servo motor	Hydraulic connecting rod	Rigid	3 + 3	Patients with lower-extremity injuries	Prototype
2022	N/A [58]	Hip knee ankle	Electric motor	cable drive	Soft	N/A	Going up and down stairs	Healthy subject
2021	unpowered exoskeleton [59]	Hip knee ankle	N/A	Spring	Rigid	3 + 3	The load is transferred to the ground	Prototype
2020	PALExo [60]	Hip knee ankle	Electric motor	Hydraulic pressure	Rigid	6 + 6	Carry high loads	Healthy subject
2020	N/A [61]	Hip Knee	Electric motor	Gear and link	Rigid	2 + 2	Gravity compensation	Healthy subject and simulations
2019	Honda walking assist (HWA) [62]	Hip	Electric motor	trochanter	Rigid	1 + 1	Stroke	5 paralytic

Table 5. Cont.

Year	Name	Body Joints	Actuator	Drive Mode	Soft and Rigid	DOFs (Left + Right)	Purpose	Subject Population
2019	SEU-EXO [63]	Hip, knee, ankle	Electric motor	Tendon-sheath artificial muscle	Rigid and soft	3 + 3	Assist the elderly and patients with lower-limb diseases	Healthy subject
2016	XoSoft [64]	Hip knee ankle	Electric motor	Cord	Soft	N/A	Assist the elderly and patients to walk	More than 20 patients (including elderly, stroke patients, etc.).
2015	Indego [65]	Hip knee	Electric motor	Gear and link	Rigid	2 + 2	Assisting patients with spinal cord injury	16 SCI subjects
2006	HAL [66]	Hip knee ankle elbows shoulders	Electric motor	Gear and link	Rigid	5 + 5	Medical, rescue, load	Healthy subject
2004	BLEEX [49]	Hip knee	Electric motor	Gear and link	Rigid	2 + 2	Enhance the load capacity of the user	Healthy subject

Currently, the types of exoskeleton mechanisms are mainly divided into two categories based on the degree of rigidity: Rigid and Soft Exoskeletons [67].

Rigid exoskeletons are constructed from hard materials (such as metals, plastics, fibres, etc.) to enhance load-carrying capacity [67]. For instance, the Berkeley Lower Extremity Exoskeleton (BLEEX) includes four hydraulic actuators. It is designed anthropomorphically, with each leg having seven degrees of freedom: three in the hip joint, one in the knee joint (rotation in one direction only) and three in the ankle joint. BLEEX has been demonstrated to support up to 75 kg (exoskeleton weight + payload) while walking at speeds of up to 1.3 m/s [68].

Soft exoskeletons are made primarily from flexible materials such as textiles and silicone, suitable for rehabilitation and similar applications [67]. XoSoft is a tendon-driven lower-limb exoskeleton designed for stroke patient rehabilitation, comprising custom-fit apparel, belts connected to electromagnetic clutches and tension bands controlled by actuators, along with a backpack equipped with a control system acting as a microcomputer for motion control, communication, and power management. In a study, a 68-year-old male participant who had suffered a stroke eight years earlier showed an improvement of 8 degrees in knee flexion angle after using XoSoft, reducing the risk of tripping and demonstrating the significant role of soft exoskeletons in human rehabilitation [69].

In this section, we describe and summarise the design, functions, actuators, sensors, and control strategies of existing exoskeletons. As shown in the Figure 6.

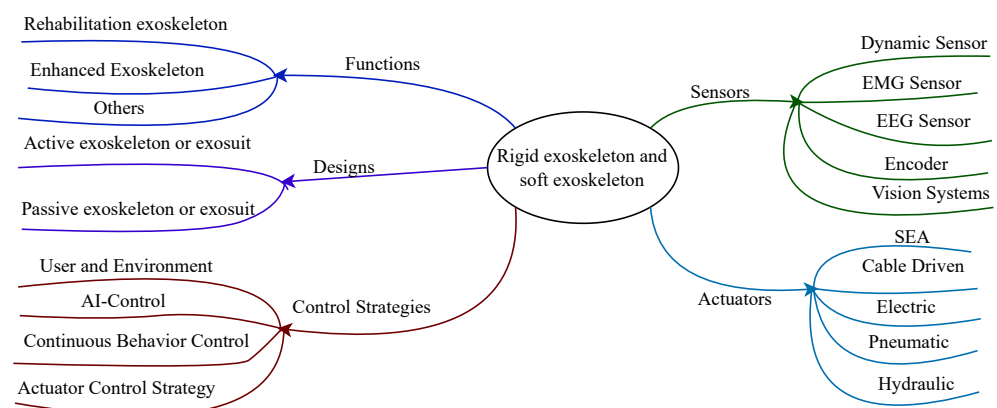


Figure 6. Classification of rigid exoskeletons and soft exoskeletons based on their design, function, actuation, sensing, and control strategies.

4.1. Active and Passive Exoskeletons

Active exoskeletons, as a primary design approach in exoskeleton technology, primarily use electric power for operation [70]. These designs involve integrating numerous sensors and controllers within the exoskeleton to manage their motion. In addition to fixed rehabilitation devices used in hospitals or homes, many portable assistive devices are available. However, the battery life of these portable exoskeletons is relatively short, usually not exceeding three hours [71]. As shown in the Table 6, these three exoskeletons are among the most common exoskeletons available on the market.

Table 6. The weight, price, and battery life of some exoskeletons [72–76].

Name	Weight (kg)	Cost (dollar)	Battery Life (h)
Rewalk	23.3	77,000	2
Indego	12	80,000	1.5
Ekso	23	100,000	4

Due to the need for muscles to perform work for braking [77], a wearable knee-mounted energy harvester has been developed. This harvester assists muscles during braking by driving a gear set with the knee's extension movements as the user walks. The harvester features a one-way roller clutch during knee flexion, where muscles must work to pull the lower leg. This clutch selectively engages the gear system only during knee extension and disengages during knee flexion [78]. This design can be integrated into exoskeletons, allowing the exoskeleton to convert its mechanical energy into the gravitational potential energy of the leg. As the leg descends, the gravitational potential energy is converted back into mechanical energy, which drives a generator and produces electrical energy. Although this cycle incurs energy losses, it still enhances the battery life of the exoskeleton.

Additionally, exoskeletons' significant weight makes them difficult to carry, especially for individuals with mobility issues and the elderly. References [15,79] have developed a hydraulic system powered by a two-stroke internal combustion engine, a high-power-to-weight-ratio engine easily integrated into exoskeleton systems. This engine can drive a piston pump at high speeds, with a rated power of 2.4 kW at 13,000 rpm and a weight of 16.6 kg. Despite the weight, the internal combustion engine offers advantages in rapid recharging capability and high energy density. Another type of exoskeleton, which does not rely on electrical or chemical energy but instead uses gravity compensation during human walking to aid movement.

The exoskeleton designed in Reference [80] utilises springs for gravity compensation. It consists of gears, compressed and extended springs, adjustment mechanisms, and output links to store and return the gravitational force generated when humans walk, returning it to the user. This protects not only human joints but also reduces physical exertion.

4.2. Lower-Limb Exoskeleton Based on Functions

Exoskeletons can be classified into two types based on the function humans want to achieve by using them: enhancement exoskeletons and rehabilitation exoskeletons.

4.2.1. Rehabilitation Exoskeleton

Rehabilitative exoskeletons can be categorised into two distinct types. The first type is therapeutic exoskeletons. These exoskeletons help patients regain muscle strength and control over their bodies by providing assistance or resistance during physical therapy or training. This enables patients to eventually wean off the exoskeleton and regain the ability to move independently [81]. An example is the LOPES-II developed in [82]. As a stationary exoskeleton, this type can be placed on the floor or suspended, so the patient does not need to bear the weight of the exoskeleton itself. These exoskeletons are typically very large and heavy, making them almost impossible to use on a daily basis, and are commonly found in rehabilitation centres or hospitals.

The second type is disability-assistance exoskeletons. These are usually used for patients with permanent injuries. This exoskeleton type, including powered prosthetics, can improve mobility and freedom of movement [81]. For those who do not have limb loss but are unable to move like usual due to spinal cord injuries, stroke, cerebral palsy, and other conditions, this type of disability-assistance exoskeleton can be used. For example, the Ekso-GT was designed in [83]. The characteristic of this kind of exoskeleton is high rigidity, as muscle damage in these patients may make it difficult for them to support their own bodies. This exoskeleton aims to restore the patient's original physiological functions while allowing them to move short distances independently at home or outdoors, preventing physiological and psychological disorders caused by long periods of sitting or lying down.

Additionally, patients require systematic and comprehensive scientific treatment. Through the assistance of exoskeleton training, guidance, and treatment from doctors, they can gradually recover their physiological functions. Patients with less severe symptoms can also use single-joint exoskeletons for assistance and rehabilitation training to facilitate a faster recovery.

4.2.2. Enhanced Exoskeleton

Enhanced exoskeletons can be divided into two types. The first type is the load-enhancing exoskeleton, which wearers can use to lift heavier objects, carry heavy items over longer distances, or use heavy-duty tools [81]. For example, the BLEEX exoskeleton can transfer the load that would normally be borne by the human body to the ground, assisting in walking with the lower limbs. As previously mentioned, the BLEEX exoskeleton enables the wearer to walk at a speed of 1.3 m/s. A descriptive meta-analysis consolidating data from 23,111 healthy subjects found that gait speed significantly declines with age. The mean usual walking speed for the oldest group (women aged 80 to 99 years) was 0.94 m/s, while it was highest for men aged 40 to 49 years at 1.43 m/s. This established trend of age-related decline underscores the need for assistive devices to accommodate reduced walking capacity. [84]. This demonstrates that the BLEEX exoskeleton offers substantial support to its users.

Another type is the endurance-enhancing exoskeleton. This exoskeleton can be used to enhance the stamina of physically able individuals or help those with mobility issues to walk further distances [81]. The weight of the exoskeleton is reduced, and it assists by providing additional torque to save energy during movement, allowing the user to maintain activity longer. It also enhances the independence of elderly people in walking, enabling them to perform daily activities such as standing up and walking without external assistance. This exoskeleton provides power through actuators in the backpack that pull Bowden cables, and the backpack is equipped with a battery, allowing the user to move freely [85]. However, such large backpacks are usually heavy and unsuitable for elderly people to carry for extended periods. Therefore, efforts are made to reduce the weight of the batteries and actuators, or to transfer some of this weight to the ground through rigid supports, without hindering the user's ability to walk due to the rigidity of the supports.

4.2.3. Others

Apart from the commonly used exoskeletons in daily life, exoskeletons with special functions also play a significant role in many fields. For example, spacesuits used by astronauts in space are a type of exoskeleton, and protective exoskeletons are also used in military or exploration fields [81].

With respect to space exoskeletons, these are mainly used to alleviate lower-extremity fatigue in astronauts during space operations or to enable movement in a weightless environment by adjusting the joints. This helps prevent conditions like osteoporosis [81].

Protective exoskeletons can be divided into two categories. One is the military tactical exoskeleton, which is equipped with numerous sensors. These sensors can monitor the user's physical condition and improve strength, protection, and other functions. The other type is the radiation-proof exoskeleton. The primary function of this exoskeleton is to carry the weight of heavy, radiation-proof suits, thereby reducing the physical burden on the user and allowing for extended periods of work, which offers more options for developing high-performance protective suits [81].

4.3. Actuator Types of Lower-Limb Exoskeleton

The current exoskeleton actuators can be roughly divided into the following categories: electric motor-driven [66,86–89], pneumatic/artificial muscle-driven [89,90], hydraulic-

driven [49,91], cable-driven [23,92,93], and series elastic actuated [50,94]. Among the actuator types mentioned above, direct motor drives account for 73%, pneumatic systems account for 13%, hydraulic systems account for 9%, and other drive methods (including cable-driven and shape memory alloy actuators) make up 5% (as shown in Figure 7) [95].

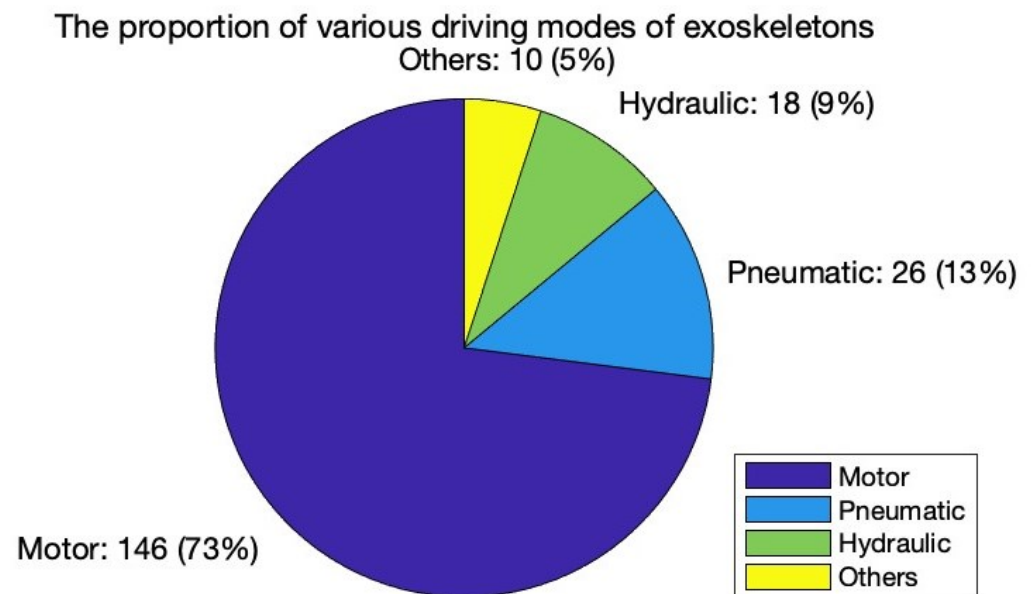


Figure 7. The proportion of various driving modes of exoskeletons from a set of 200 [95].

4.3.1. Electric

The electric motor actuator is a more prevalent drive type in rigid lower-limb exoskeletons. This actuator exhibits a high degree of standardisation, ease of manufacture and a well-developed control system. The utilisation of mature manufacturing technology has resulted in a simpler structure when compared with other actuator types. Furthermore, the electric drive has been demonstrated to have no detrimental effect on the environment. However, electric motors have a low power density. To drive human extremities movement, larger motors are often required, thereby making it difficult to reduce the size of the exoskeleton. In addition, electric motors generate significant inertia when rotating, making it difficult to stop and reverse directions immediately, delaying the user's movement [81].

There are three representative electric motor-driven exoskeletons known today: HAL [66], Indego [86,87], and Rewalk [88,89].

HAL (Hybrid Assistive Limb) is a robotic suit that integrates cybernetics, mechatronics, and informatics, helping people who are unable to perform daily activities independently, such as the disabled and elderly, with tasks like walking, climbing stairs, standing, and sitting. HAL consists of a body support frame (supporting the entire system, not burdening the user), power units (including motor actuators), bioelectrical signal sensors, angle sensors, posture sensors, ground reaction force sensors, and an integrated computer controlling the entire system, powered by a battery. It can be applied in medical care, heavy work support, rescue support, and other fields [66].

Indego comprises five components: left and right thighs, left and right calves, and the hip section. It contains four motors, with two on either side of the hip joints and the other beside the knee joints. A rechargeable lithium battery is installed on the hip joint component to power the entire system. No motors are at the ankle joints; instead, carbon fibre foot orthotics are installed. The entire exoskeleton weighs 26 pounds, but the system's weight can be directly transferred to the ground through the ankle joints without burdening the user's body. The exoskeleton operates by receiving sensor signals and analysing

them through a microprocessor, which controls the entire system. In addition, it supports Bluetooth connectivity for use with mobile devices [87].

The Rewalk exoskeleton features an internal battery unit with a computer controller, a wireless mode selector, and sensors for measuring upper body tilt angle, joint angles, and ground contact, all housed within a backpack. The location of the built-in motors is similar to that of Indego, being placed at the hip and knee joints for movement. Rewalk utilises closed-loop algorithm software for control. The activation of movements is triggered by sensors detecting the user's actions, making the motion safety of Rewalk relatively higher compared to other exoskeletons that rely purely on robotic drive control. Furthermore, built-in software can prevent rapid bending of the hip and knee joints due to falls [89].

In addition to normal walking functions, Rewalk also includes four additional modes: sitting, standing, ascending stairs, and descending stairs [89]. These additional modes have a positive impact on the user's daily life.

4.3.2. Pneumatic

Pneumatic actuators are quite common in soft exoskeletons, offering several advantages. They have a minimal impact on the user and provide good flexibility. Due to their inherent softness, they are unlikely to harm the user, ensuring high safety. The structure of pneumatic pumps is mature, cost-effective, and easy to manufacture. Furthermore, the energy generated by compressed air does not cause pollution.

However, pneumatic actuators have significant drawbacks. For example, the power generated by compressed air is relatively low with a short travel distance, which may not provide sufficient force to the user. The response time of compressed gas is also slow, making it difficult to control the system's travel precisely. When the temperature changes, water vapour in the air may form droplets on the walls of the airbag [81]. The most critical issue is the high requirement for air-tightness in the airbags. Non-uniform airbag walls or leaks can lead to fluctuations in force and speed, potentially causing damage and failure of the exoskeleton.

In Reference [96], a high-power pneumatic muscle was used to drive the operation of a lower-limb exoskeleton. This muscle can deform by 30–35% of its length during contraction, comparable to natural muscles. Moreover, this pneumatic muscle can generate ten times the force of natural muscles with the same cross-sectional area and possesses high displacement accuracy.

In Reference [90], the Pleated Pneumatic Artificial Muscle (PPAM) features a folding membrane. Compared to traditional pneumatic muscles, PPAMs exhibit virtually no threshold pressure when expanded, resulting in almost no elastic deformation on the exterior of the airbag. This design significantly reduces energy loss, enabling the generation of greater force to assist the user. Furthermore, after deflation, the muscle length can extend by 40%.

Since PPAM is an inflating contraction device when applied to exoskeletons, two separate PPAMs must work against each other to allow for the free rotation of human joints, thereby achieving bidirectional joint rotation. PPAMs also include a control system, pressure sensors, force sensors, and encoders to ensure smooth operation of the entire system. This new type of pneumatic muscle can simulate the contraction and relaxation of human muscles, thus facilitating assistance [90].

An exoskeleton, primarily used to enhance the physical capabilities of healthy users, is introduced in Reference [97]. The exoskeleton itself weighs 3.5 kg, and with other equipment (not including the air pump), it weighs 7.144 kg. This type of exoskeleton is lightweight compared to other exoskeletons. Since its target audience is healthy people, the system has no hard supports, resulting in low mechanical impedance and inertia. When

users simply wear the exoskeleton without activating it, they feel no significant resistance due to the mechanical compliance of the soft exoskeleton. Although the researchers did not ultimately prove that the exoskeleton made walking easier, it introduced a new design paradigm to the exoskeleton field [97].

This design mode enables elderly individuals or patients who can walk independently on a daily basis to walk more effortlessly. It does not impose significant resistance on the user's body when not in use. Additionally, the system is lightweight and compact, making it easily concealable under clothing, which in turn makes the user less conspicuous.

As shown in Table 7. For cable-driven (tendon-sheath or Bowden) soft exoskeletons, the achievable response speed and output force mainly depend on the characteristics of the proximal electric motor (torque constant, gear ratio, and motor bandwidth). However, due to friction, backlash, and compliance within the flexible cable transmission, both the effective output force and the dynamic response are inevitably lower than those of direct motor-driven systems. Despite this limitation, cable-driven systems offer high adaptability to different body shapes, excellent transparency and backdrivability, and significantly greater comfort and wearability, as the heavy actuation unit can be placed away from the limbs, with only lightweight cables routed along the body.

Table 7. Comparison of three actuation methods used in lower-limb exoskeletons (Note: Limited quantitative data are available for cable-driven systems, as they rely on electric motors. Their torque and response characteristics are expected to be similar to those of motor-driven actuators but are reduced due to cable friction and compliance).

	Advantage	Disadvantage	Torque Output	Response Time
Cable-driven	Lighter in mass	Limited power output		800 mm/s (Max Speed) [98]
	Flexible	Less durable		
	Lower cost	High friction		
Pneumatic driven	Provide strong power support	Requires an air pump, which adds weight.	4.39 Nm on 21 PSI [99]	0.22 s [99]
	Good dynamic response	The complexity and air tightness requirements are high.	9.1 Nm on 100 Kpa [100]	0.5 s [100]
	Soft and comfortable	Efficient gas management systems are required.		<0.2 s from 0 to 100 Kpa [101]
Motor-driven	Precise control	Higher cost	120 Nm [102]	0.001 s [102]
	Technology is mature	Heavier	17.5 Nm [103]	0.016 s [103]
	Support larger payloads	Hard exoskeletons may not be wearable around the clock.	100 Nm [50]	

For pneumatic exoskeletons, the response speed and output force are significantly lower than those in electrically actuated systems due to the compressibility of air, valve dynamics, and airflow delay in the tubes. Nevertheless, pneumatic actuation provides several distinct advantages: it ensures inherently safe and compliant interaction with the human body, allows smooth, continuous motion with natural joint trajectories, maintains low distal mass for easier walking, and can deliver high power-to-weight ratios when operated at moderate pressures. These features make pneumatic systems particularly attractive for rehabilitation and daily assist applications, where comfort, safety, and long-term wearability are more important than maximum torque bandwidth.

4.3.3. Hydraulic

Hydraulic actuators are commonly used in rigid exoskeletons. The advantages of hydraulic structures include their simplicity in cases of overloading, due to the incompressibility of liquids, which leads to stable and reliable operation with a strong load-bearing

capacity. Furthermore, the pressure of the hydraulic rod allows for variable speed control, making the user experience more comfortable [81].

However, the drawbacks of hydraulic systems are significant. Some precision parts in hydraulic structures are challenging to manufacture. Similar to pneumatic artificial muscles, hydraulic systems require high water tightness. Due to the incompressibility of liquids, hydraulic oil tends to leak and is sensitive to temperature changes when pressurised. In high or extremely low temperatures, hydraulic oil can be adverse in cases of overload; the hydraulic rod is prone to damage [81].

Two common exoskeletons that use hydraulic actuators as their driving mechanism are BLEEX [49] and HULC [91].

As mentioned earlier, BLEEX is an exoskeleton capable of carrying loads up to 34 kg. It has applications in the military, disaster relief, firefighting, and heavy lifting. The fundamental principle of BLEEX's control is the need for the exoskeleton to rapidly and seamlessly track the user's voluntary and involuntary movements. This requirement enables BLEEX to have high sensitivity in detecting forces applied to the exoskeleton, particularly those exerted by the user. However, excessive sensitivity can reduce the universality of the exoskeleton. For example, if the exoskeleton encounters an external force, its high sensitivity can cause it to transmit this force to the user, who then reacts with a counterforce. When the exoskeleton detects and responds to this counterforce, it can inadvertently harm the user [49].

The HULC exoskeleton is a model based on the design of BLEEX, primarily intended for use by the U.S. military. Lockheed Martin developed it in February 2009. This exoskeleton is designed to improve the endurance of soldiers and reduce the physical strain of carrying heavy loads. As HULC specifically aims to assist soldiers in movement, its structure has been simplified, yet it retains a comprehensive set of basic functionalities. Powered by a lithium battery, the HULC can operate for about one hour under normal conditions. It assists soldiers in walking with a maximum speed of up to 16 km/h [104].

4.3.4. Cable Driven

Cable-driven systems are commonly used in soft exoskeletons. This type of actuation is characterised by its small size and lightweight, which offers flexibility when worn. It eliminates the need to install drive motors or actuators at the knee and ankle joints. Instead, the entire actuator, the power source, and other components can be integrated at the waist, with only traction cables placed on the legs [81].

However, cable-driven systems have certain drawbacks due to friction between the cables and fabric or between the cables and the human body, resulting in low transmission efficiency. Additionally, the stretch of the cable and the movement of the user's legs cannot be precisely matched, resulting in an inability to accurately control the pulling force of the actuators [81]. When the pulling force is transmitted to the body through the cables, a delay can occur, and the entire system may collapse due to the wear and tear on the cables. Despite these challenges, cable Drive systems offer a unique approach to exoskeleton design, particularly for applications where flexibility and lightness are critical.

The Soft Exoskeletons mentioned in [23] consist of a soft fabric that extends from the waist to the feet, including a waist belt, thigh components, calf straps, and a backpack. This backpack houses two sets of actuators connected through Bowden cables. These actuators pull on the suit by retracting the cables, transferring force to the wearer. The suit's design directs force to the legs, driving the knee and hip joints through two pathways. One pathway extends from the waist, over the knee, to the shinbone, assisting knee bending, while the other runs from the waist, over the buttocks, to the thigh, assisting

hip bending. This Soft Exoskeleton design aims to assist the user's movements effectively while maintaining a lightweight and flexible structure.

XoSoft is a highly precise passive modular soft exoskeleton for the lower extremities. It adopts a user-centred design (UCD) and primarily features a quasi-passive drive principle. This means XoSoft does not use any actuators for movement but instead uses components capable of storing and releasing mechanical energy regulated by active elements [64,105].

The prototype underwent two iterations. The first generation, Beta 1, was designed to assist unilateral hip and knee joints, facilitate knee and hip bending, and improve functional walking parameters. An electromagnetic clutch was used. To ensure the soft structure, designers opted for rubber bands instead of springs for the elastic components. This clutch translates the rotational motion at the joints into linear motion and incorporates an adjustable strap and pulley system. This helps in the recovery of the system and prevents slack, although this elastic structure introduces some resistance [64].

Beta 2 is significantly improved compared to Beta 1. This iteration can assist both sides of the hip, knee, and ankle joints. It employs soft pneumatic clutches, which combine the principle of particle and fabric jamming with the functionality of electromagnetic clutches [64].

The main difference between XoSoft Gamma and Beta 2 is the clothing used. Beta 2 utilises tight-fitting garments to ensure a fit between the components and the user. At the same time, Gamma employs loose clothing, allowing for easy and quick donning and doffing by the user. This flexibility in clothing choice can improve the usability and comfort of the XoSoft system [64].

4.3.5. Series Elastic Actuation (SEA)

As a passive drive method, series elastic actuation is relatively uncommon in exoskeletons. This type of actuation is primarily used in rigid exoskeletons and typically involves utilising springs to store and release energy, thereby enhancing movement efficiency. In addition, it offers shock-absorbing properties, providing further protection to the user's joints [81].

However, series elastic actuation is as complex and unreliable as other drive methods. It requires intricate motion control, and the installation of complex springs in the exoskeleton can increase its weight. Furthermore, this added complexity increases costs, making it less economically viable [81]. Despite these drawbacks, series elastic actuation offers distinct benefits, particularly in applications where energy efficiency and joint protection are paramount.

To summarise, the advantages and disadvantages of the three most common drive methods are shown in Table 7.

4.4. Sensors Used in Exoskeleton

Sensors are core components of exoskeleton systems, primarily used to monitor user interactions and environmental information, which is critical to the control system. Various sensors are utilised in different exoskeletons based on their sensor type, application scenario, and control mode. The control system makes decisions based on sensor data, such as monitoring joint angles and muscle activity in rehabilitation exoskeletons and detecting load and posture in industrial exoskeletons. Designers select and deploy sensors tailored to the specific needs of the exoskeleton to ensure optimal performance and safety [95]. These sensors are primarily categorised into dynamic sensors, EMG sensors, EEG sensors, encoders, and visual system sensors. As shown in Figure 8.

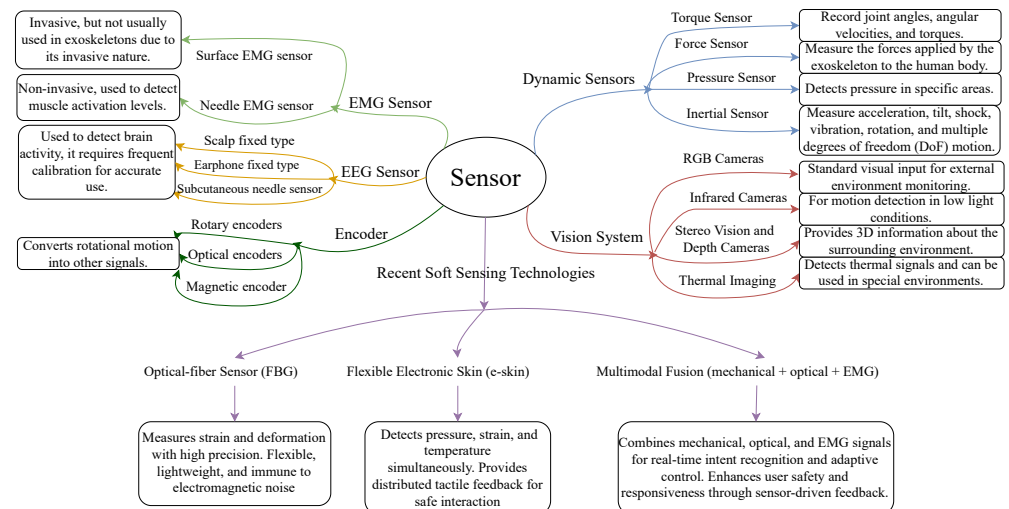


Figure 8. Classification and functions of sensors in lower-limb exoskeletons, including recent developments in soft and flexible sensing technologies such as optical-fibre sensors, flexible electronic skin (e-skin), and multimodal fusion strategies [64,95,106–114].

4.4.1. Dynamic Sensor

Pressure, force, torque, and inertial sensors are essential for controlling and providing feedback to exoskeletons, supporting effective operation and gait analysis.

Pressure Sensors: These measure pressure to analyse movement, such as foot–floor contact points. XoSoft integrates force-sensing resistors into silicone insoles, adaptable to any shoe type. To address inaccuracies in force measurement, a binary detection method is used [64,95].

Force Sensors: Often replaced by load cells, these measure forces applied by and on exoskeletons for motion control and performance assessment. A compact system with two force-sensitive resistors has been developed for force and power monitoring [95,106].

Torque Sensors: Mainly used in lower-limb exoskeletons, they record joint angles, angular velocities, and torque. XoSoft employs a capacitive soft sensor that mimics torque sensors by detecting changes in capacitance caused by knee bending [64,95].

Inertial Sensors: Common in lower-limb exoskeletons, these sensors are often paired with others for gait analysis and motion tracking. For example, they measure knee joint pitch angles to aid in movement tracking [95,107].

4.4.2. Electromyography (EMG) Sensor

In Reference [108], electromyography (EMG) detects and records skeletal muscle electrical activity, aiding in assessing muscle disorders and activation levels. Types of EMG include invasive needle EMG (with electrodes inserted into muscles) and surface EMG (with electrodes placed on the skin near muscles). Needle EMG requires professional handling and is not suitable for detachable exoskeletons, which typically use surface EMG. Although surface EMG may be less accurate due to skin movement and environmental factors, needle EMG’s invasiveness can cause bodily harm [95].

4.4.3. Electroencephalography (EEG) Sensors

Electroencephalography (EEG) detects spontaneous oscillations of membrane potentials at the synaptic level, capturing signals generated by neurons on the surface of the cerebral cortex [109]. EEG electrodes are available in various forms, including scalp-fixed, headset-fixed, and subcutaneous needle-fixed types. Readings vary significantly between individuals, influenced by medical conditions. Consequently, EEG systems require highly

customised setups and adaptive learning to interpret brain waves accurately. For rapidly progressing conditions, regular recalibration of EEG wave characteristics is essential to ensure accuracy [95].

4.4.4. Encoders

Encoders include rotary, optical, and magnetic types. Rotary encoders are commonly used in rigid exoskeletons. These convert the angular position of a shaft into digital or analogue signals for the control system, which converts them into information such as position, speed, or distance. Rotary encoders come in absolute and incremental types: Absolute encoders provide the shaft's current position based on angle sensing, while incremental encoders output shaft movement information, converted into proper forms by the signal control system [95].

4.4.5. Vision Systems

To evaluate external conditions, installing vision systems in exoskeletons is essential. Common types include RGB cameras, infrared cameras, wide-angle cameras, stereovision cameras, depth cameras, and thermal imagers. Vision systems are used not only for assessing the external environment. For example, in [110], monochrome CCD cameras and high-resolution cameras are used to monitor the motion angles of exoskeletons, and their data are compared with those of rotary encoders to improve accuracy. In [111], a six-camera infrared motion capture system is also employed to track the movements of healthy subjects and patients, providing motion data of healthy subjects for rehabilitation therapy.

4.4.6. Recent Advances in Soft and Flexible Sensing Technologies

The sensing landscape in wearable exoskeletons has evolved rapidly in the past few years, moving from conventional force or EMG sensors toward soft and highly compliant sensing systems that better match the mechanical behaviour of the human body. Flexible electronic-skin (e-skin) devices are among the most significant of these developments. Recent studies report e-skin structures that combine stretchable conductive materials with multilayer elastomers to capture pressure, strain, and temperature simultaneously [112]. These thin and conformable films can be laminated directly onto the human body or the surface of soft actuators, offering spatially distributed feedback that improves comfort and motion perception during long-term use. Compared with discrete force sensors, e-skin arrays provide a continuous map of contact forces and body posture, supporting safer and more adaptive interaction between the wearer and the device.

Parallel progress has been made in wearable optical-fibre sensing, particularly through the use of fibre Bragg gratings (FBGs). Optical-fibre sensors exhibit excellent flexibility, immunity to electromagnetic interference, and high sensitivity to strain, making them suitable for integration into textile or pneumatic structures [113]. Peng et al. reviewed their use in rehabilitation systems, where embedded fibres measure joint angles and muscle deformation without adding noticeable stiffness. This approach enables precise biomechanical feedback in soft exoskeletons and improves motion estimation accuracy compared with conventional electromechanical sensors.

At the same time, multimodal and sensor-driven control strategies are emerging as a key step toward intelligent exoskeletons. Karasheva et al. summarised recent frameworks that fuse mechanical, optical, and electromyographic signals to estimate user intent and adjust actuator torque in real time. Such fusion reduces control latency and enhances user safety by allowing the device to react to subtle changes in muscular activation. Together, these innovations demonstrate a clear shift from rigid, single-mode sensing toward integrated soft sensing networks that provide richer, safer, and more intuitive human–robot interaction [114].

4.5. Control Strategies of Lower-Limb Exoskeleton

4.5.1. User and Environment Controls

The interaction between the user and the environment is key to exoskeleton behaviour, enabling mode transitions like walking, stair climbing, standing, and sitting. These transitions are typically infrequent and may take a few seconds to complete [115].

Common control methods include:

Manual User Input (MUI): Users control the exoskeleton via buttons or voice commands, offering ease of operation and accurate signals but requiring a user-friendly interface, especially for patients with complete spinal cord injuries (SCIs) [115].

Brain–Computer Interface (BCI): This approach uses electroencephalography to measure brain activity but demands prolonged user focus. Current technical limitations cause delays, making it unsuitable for exoskeletons [116].

Motion Recognition: Exoskeletons adapt to the user’s intended movements, offering natural interaction without manual input. However, patients with complete lower-limb immobility typically rely on upper limb movements for control [117].

Terrain Recognition: Sensors like cameras and 3D depth sensors detect terrain and obstacles. While promising, this method involves high computational costs and hardware requirements [118,119].

4.5.2. AI-Driven Control Strategies

AI control can be categorised into four types: reinforcement learning [120,121], neural networks [122], support vector machines [123], and decision trees [124–126]. The principle of AI-controlled exoskeletons driving the user’s limbs is illustrated in Figure 9. The AI focuses on the user, detecting the user’s movements and commands via the exoskeleton. The AI then classifies the current movement and detects the user’s intent, using this data to predict the next joint movements and positions. These predictions are sent to the exoskeleton, which reacts accordingly, moving the user’s limbs. This process forms a continuous feedback loop [126].

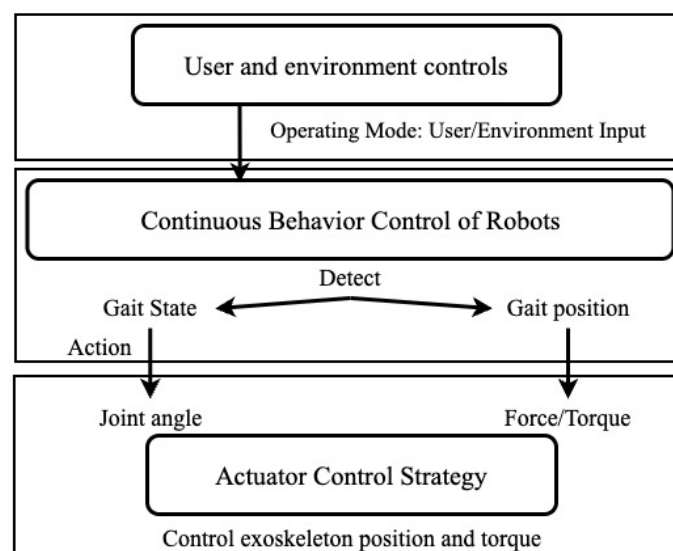


Figure 9. Exoskeleton control process [127].

4.5.3. Continuous Behaviour Control of Robots

Robotic continuous behaviour control primarily involves adjusting the torque and position of exoskeleton robot joints per unit time through a controller, which is crucial for the interaction between the device and the user. Research on exoskeleton control primarily

focuses on this area. The control of users and the environment affects the behavioural parameters but does not alter the mode of interaction. The control strategy is divided into detection/synchronisation and action layers: the first estimates the gait phase and state, while the latter determines the physical output [115].

Different control schemes are used for different joints of this controller. For example, in [127], springs are used in the ankle joint, torque control in the hip joint, and active dampers in the knee joint. This indicates that the control system of the exoskeleton is very complex and diverse. Robots' continuous behaviour control strategy plays a pivotal role in this context (As shown in Figure 9).

In soft exoskeletons, effective coordination between the user and the device is crucial so that the mechanical assistance follows rather than interferes with the wearer's natural motion. In practice, this coordination depends on how well the system aligns its actuation with the user's gait rhythm and movement intention. For example, feedback from joint torque or pressure sensors can help the controller recognise when the leg moves from stance to swing, adjusting the support level accordingly. In some systems, electromyography (EMG) signals are fused with data from inertial measurement units (IMUs) to catch the first signs of muscle activity, giving the controller a short time window to react before motion actually begins. During stance, impedance or torque regulation usually provides stability and supports body weight, while in swing, assistance is reduced to allow free movement. More recent adaptive methods try to learn each user's timing and joint patterns, which helps to lower physical effort and make the interaction feel smoother over time [128,129]. Overall, human-robot coordination in wearable robots is achieved through a mix of multi-modal sensing, prediction, and compliant actuation that together enable safer and more natural assistance.

4.5.4. Actuator Control Strategy

All exoskeleton control strategies focus on actuator control, with applications extending to other robotics fields.

Rigid Position Control: Typically using PID regulators, this method ensures high precision but may not suit unpredictable user movements. A "proxy-based sliding mode controller" offers smoother control for exoskeletons [130,131].

Torque Control: Essential for soft exoskeletons, this strategy addresses their nonlinear actuation by integrating stiffness, actuator dynamics, and leg movement models to generate accurate control signals [115].

Fully Passive Systems: These rely on mechanical components like springs and dampers, utilising user-generated energy (e.g., gravity) and stored mechanical energy to assist without actuators [132].

The choice of control strategy affects exoskeleton performance: rigid position control excels in high-precision tasks, torque control suits complex motions in soft exoskeletons, and passive systems offer innovative, energy-efficient solutions with limited applications.

Comparative Analysis of Control Algorithms: Various control algorithms have been implemented in lower-limb exoskeletons depending on the sensing modality and assistance objective. PID and impedance control remain the most widely adopted to date due to their simplicity and reliable performance in torque tracking [133]. Adaptive control and model predictive control (MPC) have been introduced to handle nonlinear actuator dynamics and user-specific variability, resulting in smoother torque responses and improved gait synchronisation [134]. In comparison, EMG-based control has shown great potential in improving user intent detection and reducing control delay, particularly for soft exosuits that rely on physiological feedback [135]. More recent hybrid approaches combine mechanical and bio-signal control, offering better adaptability during rehabilitation sessions.

In general, studies indicate that adaptive and EMG-based approaches offer more responsive and natural support compared with conventional PID control, albeit at the cost of higher computational complexity. The selection of a control strategy, therefore, involves a trade-off between accuracy, responsiveness, and computational complexity, a challenge that remains central to future soft exoskeleton design.

5. Discussion

As shown in Table 7, a comparison between rigid and flexible systems, rigid frames offer higher joint torque and lower drive delay, while flexible systems, although improving wearing comfort, are limited by transmission friction/compression and the logistical support of the power source. Therefore, their applicability differs: rigid systems are better suited for early rehabilitation and heavy-duty tasks, while flexible systems are better suited for daily assistance and extended use.

5.1. Clinical Trial Status and Details

Walking impairments are a significant healthcare issue, and exoskeletons offer the potential to help users regain independent mobility. While exoskeletons show promise for rehabilitation and health benefits [136], risk analysis is limited by inconsistent study criteria and insufficient reporting of adverse events. This section examines three notable exoskeletons: ReWalk, Indego, and Ekso.

ReWalk: The first FDA-approved personal-use rehabilitation exoskeleton in the U.S., ReWalk has demonstrated safety and efficacy in clinical trials. However, it lacks fall prevention features, posing risks of severe injury or death, necessitating post-market monitoring [137].

Indego: Sharing risks and mitigation strategies with ReWalk, Indego adds fall detection and knee joint locking during power failures, enhancing safety and reducing fall risks [137].

Ekso: Clinical studies have shown improvements in gait speed and duration for SCI patients after 20 training sessions [138–140]. Simulated falls during tests caused no harm, but results are limited as the falls were performed using a suspension system [137].

5.2. Challenges and Future Works

As discussed above, lower-limb exoskeletons have been applied in various fields (military, industrial, rescue, medical, etc.). In the future, lower-limb exoskeletons face the following challenges and areas for improvement:

5.2.1. Weight Reduction

Although rigid exoskeletons can partially transfer weight to the ground through mechanical structures to alleviate the user's burden, their weight may still affect user activity and battery life. For soft exoskeletons, because the weight is borne directly by the user, it is important to choose lightweight materials. However, limiting the weight can affect the power source's size and battery life. Therefore, balancing battery life, user load, and driving power is crucial.

5.2.2. Flexibility

Flexibility in lower-limb exoskeletons not only refers to weight reduction but also encompasses the adaptability of exoskeletons beyond rehabilitation centres and hospitals. Patients cannot always live indoors; many need to work and return to normal life outdoors. This requires the exoskeleton to be easy to wear, lightweight, and have at least a full day's battery life, similar to portable electronic devices used today.

5.2.3. Universality

To help patients return to normal life, exoskeletons need to support a variety of human motion patterns. Each patient's condition and required functionality differ, and most exoskeletons, like prosthetics, need to be custom-made, increasing production costs and preventing mass production. For example, patients vary in muscle strength and body size, so it's important to include adjustable features in the exoskeleton design based on patient needs.

5.2.4. Cost

As mentioned above, the need for customisation makes exoskeletons very expensive, making them out of reach for many low-income users and even budget-constrained hospitals and rehabilitation centres. Developing a fully-featured, adjustable exoskeleton, or creating single-joint exoskeletons that patients can freely combine based on their needs, could reduce costs. Once exoskeletons can be mass-produced, their cost decreases significantly.

5.2.5. Energy

As previously stated, the endurance of the power source or other energy devices in the exoskeletons is greatly affected by weight. The energy density of the power source itself is also crucial for endurance. Using a material with high energy density as the power source could reduce the size of the energy device and improve endurance, which would be highly beneficial for the development of exoskeletons.

5.2.6. Control

Since each patient has different body types and conditions, a single control method cannot be suitable for every patient. In the future, machine learning could be used for control, allowing patients to interact directly with built-in artificial intelligence in the exoskeleton. The AI would control the exoskeleton's operation, enabling users to customise their exoskeletons.

5.2.7. Durability Evaluation of Soft Exoskeletons

The durability of soft exoskeletons is a practical concern that often receives less attention than actuation or control. During prolonged use, flexible materials can age or deform—fabrics may stretch, seals may begin to leak, and friction in cable transmissions can gradually increase. Even sensing components that rely on strain or pressure feedback may drift after repeated operation. At present, there is no unified method for testing durability: pneumatic systems are typically evaluated through repeated pressurisation cycles, while cable mechanisms undergo long-term motion endurance tests. Because these evaluation approaches differ, it remains difficult to compare reported lifetimes across designs. Improving wear resistance, sealing integrity, and transmission smoothness could help extend service life, while the integration of local pressure or strain monitoring would allow early detection of degradation and ensure consistent assistance over extended use.

In addition to material fatigue and structural durability, other practical user issues also affect the long-term use of soft exoskeletons. Hygiene is an important consideration, as soft wearable components often come into direct contact with the skin and may absorb sweat or moisture during extended use. Therefore, the use of antibacterial or washable textile layers is recommended to enhance user comfort and prevent odour accumulation. Maintenance is another critical factor, particularly for pneumatic or cable-driven systems, where tubing, seals, and connectors require periodic inspection and replacement to ensure reliable operation. Addressing these issues through modular design and easy disassembly

can significantly enhance the usability and long-term acceptance of soft exoskeletons in daily rehabilitation and mobility assistance.

5.2.8. Future Research Directions

Future research on lower-limb soft exoskeletons should move beyond improving individual components to achieving fully integrated, intelligent systems. First, adaptive control frameworks that combine physiological signals (EMG, EEG) with kinematic and dynamic feedback could provide more personalised and intuitive assistance. Second, the development of lightweight, fatigue-resistant, and washable materials will be critical for ensuring long-term wearability and user comfort. Third, advances in soft sensors—particularly stretchable pressure and fibre-optic sensors—should focus on improving durability, calibration stability, and real-time data fusion with control algorithms. In addition, miniaturised and energy-efficient pneumatic or hydraulic power sources are required to enable true mobility in daily life settings. Finally, large-scale clinical trials and standardised testing protocols are necessary to evaluate long-term safety, adaptability, and rehabilitation outcomes across diverse user populations. These directions collectively indicate a shift toward more autonomous, adaptive, and user-centred soft exoskeleton systems in the future.

6. Conclusions

This review first analyses the structure and biomechanics of the human lower limbs, including muscles, bones, and joints, before examining the current state of exoskeleton development in terms of functionality, actuators, sensors, and control strategies. Particular attention has been paid to soft exoskeletons, which employ flexible materials and pneumatic or cable-driven actuators to achieve natural, compliant interaction with the human body. Compared to rigid exoskeletons, soft exoskeletons offer higher comfort, lighter weight, and improved adaptability to different users, making them especially suitable for rehabilitation and daily assistance.

Despite these advantages, the development of exoskeletons—including soft systems—still faces four key challenges: energy efficiency, cost, versatility, and safety. Among these, energy remains the most critical. The limited energy density and heavy weight of current power sources restrict the portability and endurance of soft wearable systems. The development of lightweight, high-energy-density batteries or alternative pneumatic/hydraulic energy storage systems will be vital to overcoming this barrier.

Versatility and cost are closely related. Soft exoskeletons, by virtue of their flexible structure and textile-based construction, already demonstrate potential for scalable, size-adaptive manufacturing. If modular designs allow users to select devices based on body size and intended use, mass production could further reduce costs and promote wider adoption.

In terms of safety, soft exoskeletons have inherent advantages due to their compliant materials, but reliable sensor integration is still essential. Embedding distributed sensors to monitor pressure, muscle activity, and motion can enable real-time feedback and ensure user comfort and protection.

Addressing these challenges will facilitate the broader application of soft exoskeletons—not only in rehabilitation and elderly assistance, but also in industrial and daily-use scenarios—helping patients regain motor function while reducing fatigue and injury risk for healthy users. Future development should therefore prioritise lightweight, energy-efficient, and intelligent soft exoskeletons that integrate flexible actuation, adaptive sensing, and advanced control strategies to achieve safe, comfortable, and universal human–robot interaction.

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