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Original Paper

Exploring Challenges and Opportunities of Wearable Robots: A Comprehensive Review of Design, Human-Robot Interaction and Control Strategy

Lufeng Chen[1], Hongqin Xie[1], Zicheng Liu[2*], Bin Li[1] and Hong Cheng[1*]

[1]*School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China*
[2]*Microsoft Research, Redmond, WA, USA*

ABSTRACT

The aging population and increased number of individuals with motor dysfunction pose significant challenges to the workforce. This situation is further exacerbated by a declining working-age population, which has resulted in labor shortages. A potential remedy to these issues lies in the employment of wearable robots. As a form of human-robot collaboration, these devices can augment motor capabilities and offer assistance with various motor functions. To this end, this paper presents a systematic review of the current research status of wearable robots, focusing on the applications of Supernumerary Robotic Limbs (SRL) and exoskeletons for task assistance and motor function restoration in the field of industrial and rehabilitation, respectively. The paper also deliberates on the research trends, challenges, and prospective directions of human-robot interaction and control strategies regarding wearable robots.

*Corresponding authors: Zicheng Liu, zliu@microsoft.com and Hong Cheng, hcheng@uestc.edu.cn.

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1 Introduction

The working-age population is experiencing a significant decline in size and proportion, leading to a severe labor shortage in recent years. Compounded by an increase in the aging and empty nesting population, and a rise in people with lower limb motor dysfunction, the care and nursing needs for these individuals have become increasingly critical [110]. The combination of labor shortages and an aging population necessitate substantial enhancements in human work and mobility assistance. The progressive maturity of robotics technology offers a solution to these issues. Industrial robots are gradually being deployed on factory front lines to alleviate some labor constraints, while nursing robots are emerging to enhance the quality of life for the elderly and alleviate some of the stress associated with caregiving.

In an effort to fully harness the unique strengths of both humans and robots, a Human-Robot Collaboration (HRC) mode has been initiated. This technique encourages humans and robots to work together to accomplish shared tasks within the same space. The tasks that can be undertaken within this collaboration are generally categorized into two broad areas: enhancing motor capabilities and assisting with motor functions. Wearable robots, which have been extensively researched, are a primary example of a human-robot collaborative devices. These robots can be broadly divided into two categories, namely Supernumerary Robotic Limbs (SRL) and exoskeletons, based on their degree of motor coupling. An SRL is a wearable robot designed to augment, repair or extend human operational capabilities by acting as an additional limb [74]. It can replace, compensate for, or work in conjunction with a non-functioning limb. On the other hand, an exoskeleton is a type of wearable robot chiefly used to offer lower limb mobility assistance or to facilitate upper limb rehabilitation training. A key distinction between an SRL and an exoskeleton lies in their interaction with human joints. While an SRL does not need to be closely linked with human joints to maintain movement consistency and enhance limb strength, it can operate independently of human joints and move freely to complete tasks. The exoskeleton, a typical example of a human-in-the-loop complex human-robot hybrid system, provides support and protection to the wearer while also assisting with medical rehabilitation and daily life activities, thereby enhancing the wearer's motor function.

In this paper, we present an overview of the current research trends in the field of wearable robotics, focusing on the applications of SRL and exoskeletons for assistance in mobility and rehabilitation. In Section 2, we delve into the system design of these two representative types of wearable robots, categorizing them based on their wear locations or target extremities. Section 3 explores the human-robot interaction and control strategies implemented in these wearable robots with comparative analysis. Section 5 outlines several primary research directions and challenges in wearable robots. A conclusion is given in Section 6.

The contributions of the paper are summarized as follows:

- This paper reviews the advances in the system design, human-robot interaction and control strategy pertaining to the two representative wearable robots utilized for assistance and rehabilitation purposes.
- The paper discusses some open research challenges concerning the system design and human-robot collaboration in the context wearable robots.
- This review can serve as a preliminary reference for researchers, propelling further development and investigation of diverse control methods for different applications of wearable robots.

2 System Design

2.1 Supernumerary Robotic Limbs

The exploration of augmenting and improving the human body's motor functions has been a focal point in both academic and industrial research. While the application of robotics can undeniably alleviate the load of human tasks, it remains a distinct entity from the human body, failing to truly enhance our physical capabilities. The rubber hand illusion experiment revealed a phenomenon of self-attribution, leading researchers to theorize that if a robotic limb was designed to closely mimic a human one, the human body might "mistakenly" perceive it as its own [105]. This convergence of human-robot interaction and control strategies could potentially extend the human body in a conventional sense, achieving the integration and unification of mechanical limbs with the human body. To validate this hypothesis, several countries and research institutions have initiated related studies. Asada *et al.*, since 2012, have been focusing on the development of Supernumerary Robotic Arms (SRA) [74], Supernumerary Robotic Legs (SRLG) [75], and Supernumerary Robotic Fingers (SRF) [55], with their systematic studies yielding numerous valuable insights. Other institutions, such as the University of Siena [82], Keio University [95], Cornell University [106], the University of Montpellier [23] and Harbin Institute of Technology [117], have also embarked on novel research into additional limbs, propelling the continuous advancement of external limb robots within the realm of intelligent manufacturing and human-robot interaction.

2.1.1 Supernumerary Robotic Arms (SRA)

The SRA is bionically engineered, taking inspiration from the human upper limb, to achieve limb coordination. It is designed to replicate as many motor functions as possible, such as flexion, extension, retraction, rotation, and circular rotation of shoulder, elbow, and wrist joints. In a simplified model of the human upper limb, its kinematic characteristics are summarized as having seven degrees-of-freedom (DoF) [66]. This allows it to reach the target position through multiple trajectories. To closely mimic the kinematics of the human upper limb, the ideal SRA should also possess seven DoF in movement. However, such high DoF not only suggest more complex control strategies but also increase the design complexity and weight of the overall mechanism.

Parietti and his colleagues [7, 25, 74, 76] innovated a series of SRLs for industrial and daily support purposes. These robots, equipped with two robotic arms offering three (or five) DoF and anchored at the waist, are capable of performing tasks such as object manipulation, workpiece fixation, tool gripping, assembly work, and door opening. The SRL can alternate between various modes to adapt to different upper limb tasks. Besides, it can function as an extra leg, providing support and stability in various postures. Moreover, it can also serve in a hybrid mode with both arm and leg, facilitating upper limb work while simultaneously assisting in worker support. Vatsal and Hoffman [106] developed a lightweight SRL robot with five DoF, attached via strapping on the forearm to extend the work space. In comparison, Sasaki and his colleagues [23, 94, 95] designed an SRL robot with dual arms, each of which possessed six DoF, allowing for dynamic movement in space. This SRL system incorporates a variety of user interfaces to enable three distinct operational modes: passive assist, power assist, and playback modes. Zhang *et al.* [116] engineered a reconfigurable SRL with differentially actuated joints, endowing the system with an expansive workspace, enhanced support performance, and the capacity to handle a wide range of tasks in conjunction with wearers.

Other scholars and research institutions have also explored the SRA technology, examining various aspects such as structural design, wearing position, motion flexibility and applications. Table 1 presents a comprehensive review of the common SRA used in industry and daily life. These are predominantly worn on the shoulder, back, and waist that offer greater freedom of movement, thus enhancing the operational range and the ability to reach objects. The drive system is typically categorized into three types: motor-driven, hydraulic-driven, and pneumatic-driven, with the majority employing a motor-driven design to ensure precise object manipulation. Through component optimization and task simplification, contemporary SRA generally offer four to five DoF. Aside from the popular multi-DoF articulated mechanism design achieved through rigid linkage with articulated motors, there is a growing interest in SRA featuring flexible fabric designs. This innovation aims to increase the

Table 1: Summary of SRA.

Authors	**Wear Location**	**Driving Mode**	**Structure**	**Features**
[62, 63, 74]	Back	Electric motors	Dual 3-DoF limbs	Assist with tasks such as body mounting, etc.
[72, 76]	Back	Electric motors	Dual 4-DoF limbs	Assist with guided assembly in aircraft manufacturing.
[23, 94, 95]	Back	Electric motors	Dual 7-DoF limbs	Assist with daily activities, auxiliary welding and other tasks
[106]	Forearm	Electric motors	Single 5-DoF limb	Assist with tasks such as grabing and stabilizing objects
[7]	Shoulder	Electric motors	Dual 5-DoF limbs	Assist worker in overhead tasks
[25]	Wrist	Electric motors	3-DoF limb with soft hand gripper	Helps open doors when both hands are occupied
[116]	Back	Electric motors with cable-driven	Dual 3- or 5-DoF limb	Reconfiguable configuration for object support and delicate manipulation
[47, 48]	Wrist	Electric motors with passive joints	Single 4-DoF limb	Panel fixing during ceiling or light fixture installation tasks
[42]	Shoulder	Electric motors	Single 4-DoF limb	Assist drummer with instrument manipulation
[8]	Shoulder	Electric motors	3-DoF limb with grapper	Assist with overhead assembly tasks
[88, 89]	Portable	Electric motors	Single 25-DoF limb	3D printed snake-like waist-worn robots with multiple types of feedback
[107]	Wrist	MR-Hydrostatic actuators	Single 2-DoF	Stabilize object with force tracking
[113]	Back	Electric motors	Dual 5-DoF limb	Assisting with holding, weight bearing, etc.
[67]	Back	Electric motors	Dual 3-DoF limbs	Assist with motor skill acquisition
[77, 78]	Not attached	Electric motors	Single 5-DoF limb	Multitasks with BMI control
[60]	Not attached	Pneumatic	Fabric-based soft limb	Assist in grasping objects
[71]	Back	Pneumatic	Fabric-based soft limb	Assist in grasping objects

wearable robot's safety and enhance task execution flexibility. Figure 1 shows some typical SRA robots.

2.1.2 Supernumerary Robotic Legs (SRLG)

The SRLG is a bionic design inspired by the human lower limb, enabling it to mimic the flexion, extension, retraction, rotation and circular rotation of the human hip, knee, and ankle joints. This is to replicate the movement functionality of the lower limb. In terms of the human lower limb kinematic description, the model comprises three DoF for the hip joint, one for the knee joint, and one for the ankle joint [2]. However, contemporary SRLG robots simplify the joint DoF so that each joint retains a maximum of just one DoF. This simplification reduces the complexity of high-level control but may also limit the ability to perform complex tasks. Currently, there isn't much variation in the structural design of SRLG. The primary research focus is on further optimization in the underlying key areas: scenario adaptability, wearing position, and the driving method, as well as the type and DoF arrangement. Figure 2 shows some typical SRLG robots.

Table 2 presents a selection of commonly studied SRLG. Similar to human physiology, these legs are robust and sturdy, designed for supporting and

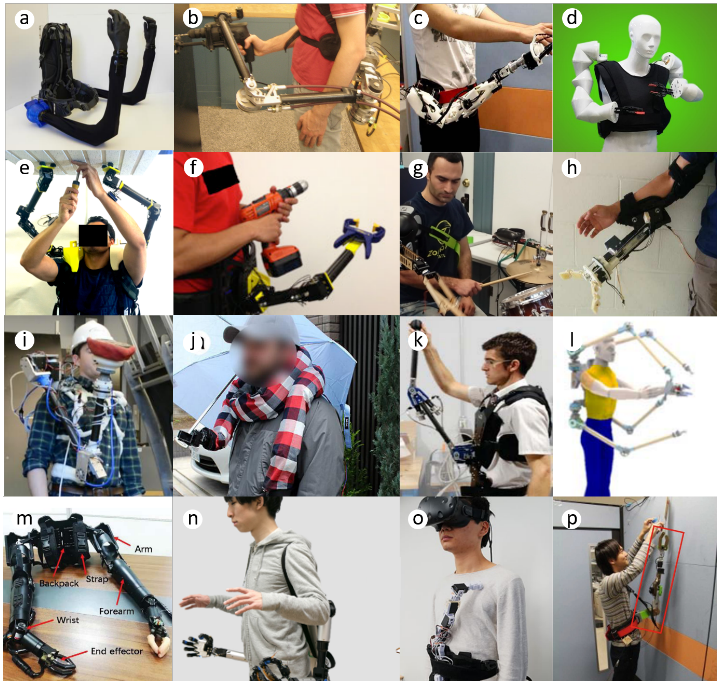

Figure 1: Different kinds of SRA. (a) A dual arm SRL for holding objects, lifting weights and streamlining the execution of a task [63]; (b)A SRL with "bracing" technique to suppress the human-induced disturbances [74]; (c) A wearable robot arm named Assist Oriented Arm (AOA) for accurate fingertip manipulation [47]; (d) A reconfigurable robot arm named AstroLimbs for extravehicular activities assistance [117]; (e) SRL prototype worn on the shoulders aiding the human worker in overhead tasks [7]; (f) SRL with wearable sensors monitoring workers actions [62]; (g) A 3rd arm platform built for the evaluation of the user satisfactory under the vibration-control method [42]; (h) A lightweight SRL as a collaborative tool for various applications [106]; (i) A new type of Granular Jamming Gripper (GJG) that can grasp diverse objects from an arbitrary direction is installed on the SRL [8]; (j) A multipurpose SRL called Orochi for daily assistance [88]; (k) A lightweight and force-controllable SRL using magnetorheological (MR) clutches [107]; (l) A reconfigurable, lightweight, and compact SRL for the wearers in industrial fields [116]; (m) A wearable SRL with dual arm for various tasks [113]; (n) A dual arm SRL (MetaLimbs) using artificial limbs substitution metamorphosis to acheive better human-robot interactions [95]; (o) A 3rd arm equipped with VR for haptic feedback [89]; (p) A lightweight SRL with passive actuators for various assistance scenarios [48].

maintaining an upright posture, bearing weight, and assisting in walking. As listed in the table, most SRLGs can provide additional support positions due to their extensive range of motion, thereby enhancing the stability of the user's posture. Equipped with two rotational joints and one linear joint, they can counterbalance the forces exerted on the human body during standing or

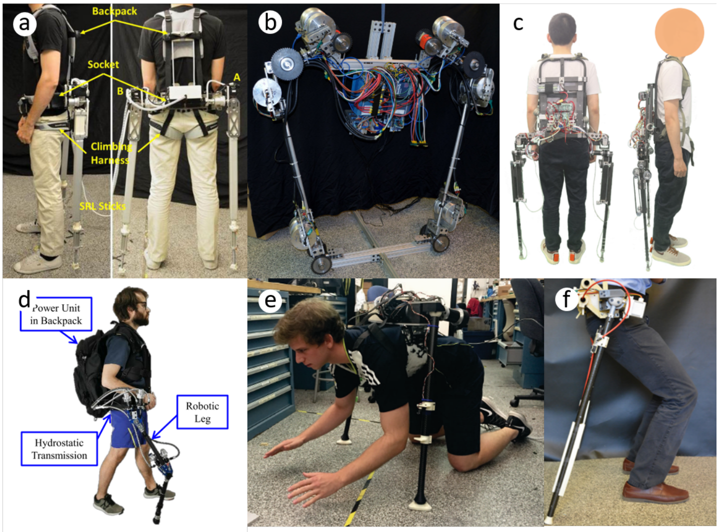

Figure 2: Different kinds of SRLG. (a) An SRL wearing around the waist used for body support [73]; (b) An extra robotic legs (XRL) system consisting of two articulated robotic legs is built to assist the operator in carrying a heavy payload [21]; (c) An XRL system assists the human in a natural walking with low self-weight [28]; (d) A supernumerary leg powered by delocalized magnetorheological clutches to assist walking with three different gaits [41]; (e) SRL with two legs to support the wearer while performing bi-manual tasks in the near-ground position [50]; (f) A lightweight SRL with the assistive control strategy to support the wearer during sitting and standing motions [103].

Table 2: Summary of SRLG.

Authors	Wear Location	Driving Mode	Structure	Features
[73, 75]	Back	Electric motors	Dual 3-DoF limbs	Support and stabilize the body while performing tasks
[21]	Back	Electric motors	Dual 3-DoF limbs	Provide support of various positions in hazardous environments
[28]	Back	Electric motors	Dual 3-DoF limb	Reconfigurable configuration for object support and manipulation
[41]	Wrist	MR-Hydrostatic actuators	Single 2-DoF limb	Assist with walking with less effort
[50]	Back	Electric motors	Dual 3-DoF limbs	Support wearer in a crawling-like position for near-ground tasks
[103]	Back	Electric motors and pneumatic cylinders	Dual 3-DoF limbs	Provide assistive torque for sit-to-stand movements

walking. In terms of task execution, these legs can be utilized for both static and dynamic tasks. For static tasks such as fixed position operations, the SRLG help bear a portion of the user's weight, reducing the physical strain on the user. For dynamic tasks they offer steady cyclical support during walking, thereby enhancing the mobility and reducing fatigue.

2.2 Exoskeleton

The wearable exoskeleton robot represents a novel field in robotics, which has gained significant attention in recent years. Rehabilitation exoskeletons are a prime example, showcasing the potential for collaborative interaction between the robot and the patient. These robots are designed to assist in the rehabilitation assessment and training of patients with various sensorimotor or cognitive impairments, partially or fully substituting traditional rehabilitation therapy. The goal of this robotic therapy is to promote patients' functional recovery through motor rehabilitation. Given that the rehabilitation training primarily targets the upper and lower extremities [9, 84], rehabilitation exoskeletons have become a focal point of research and application recently.

The human body is a remarkably complex structural system. Misalignment between the joint movements of exoskeletons and the kinematic characteristics of human joints could compromise the effectiveness of rehabilitative training, potentially leading to patient harm. Therefore, the design of these robots must fulfill not only mechanical design requirements but also the specifications for medical devices, including safety, motion functionality, structure, rehabilitation effect, and comfort. As a complex human-machine system, current wearable exoskeletons struggle with issues like limited freedom of movement, excessive weight, and poor human-machine interaction. However, with the ongoing advancement in robotics, an increasing number of institutions are researching into wearable robots that offer multi-DoF, multi-drive mode, lightweight, and intelligent designs with superior ergonomics [90].

2.2.1 Upper Limb Exoskeleton

The upper limb rehabilitation system is a form of medical robot that assists patients in exercising their upper limbs, such as the shoulder, elbow, and hand. By facilitating certain training strategies, the system is capable of enhancing the strength of the patient's muscle movements and increasing the flexibility of upper limb joints [6]. Numerous rehabilitation robots have been developed to facilitate upper limb rehabilitation in recent years. Mechanically, these robotic devices can be divided into two categories: end-effector type robots (e.g., MIT Manus, GENTLE/s, ACRE, NeReBot, CRAMER, MACARM, ReoGo) and exoskeleton-based robots (e.g., ARMin, CADEN-7, Pneu-WREX) [84]. Some representative upper limb exoskeleton for rehabilitation training is shown in Figure 3.

End-effector type robots use their end effectors, usually a handle, to guide the movement of one or multiple joints in the patient's upper limbs. The simplicity of this configuration makes the robot easy to control. However, due to its limited rotational movement, it cannot fully replicate the versatility of the human arm [52]. On the other hand, exoskeleton-based robots allow the

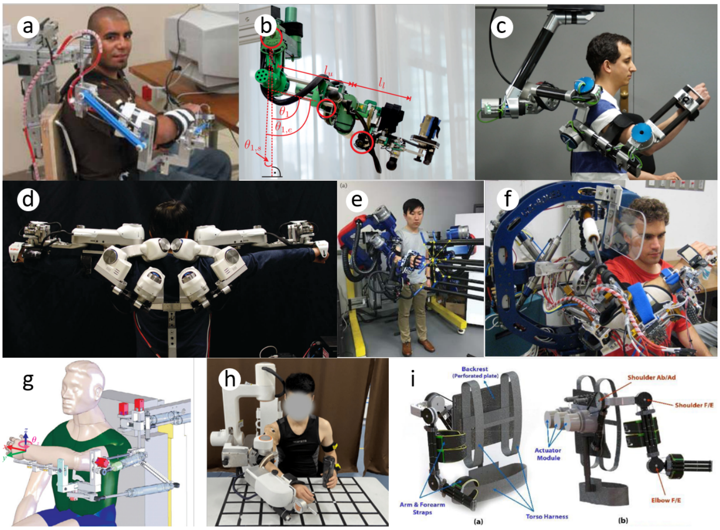

Figure 3: Different kinds of upper limb rehabilitation exoskeleton. (a) An upper limb training exoskeleton called T-WREX with passive training mode to provide support against gravity [33]; (b) An actuated upper limb rehabilitation robot called ARMin V with seven DoF to compensate the arm length difference and adapt to patient's anthropometry [38]; (c) A versatile upper limb rehabilitation exsokeleton called ANYexo with low-impedance torque controller for robust interaction force control [120]; (d) An upper limb exoskeleton for rehabilitation called Harmony with force and impedance controllability [44]; (e) A dual-arm rehabilitation exoskeleton named EXO-UL8 with passive and AAN modes [96]; (f) A 3-DoF lightweight upper limb rehabilitation exoskeleton named BONES [46]; (g) A pneumatically actuated upper limb rehabilitation exoskeleton called Pneu-WREX with force control [109]; (h) A 6-DoF upper limb exoskelton with a collaboration strategy that integrats affected and healthy limbs [12]; (i) A bamboo-inspired upper limb exoskelton named BiEXO with cable-driven mechanisms [114].

patient to wear them. The alignment of the robot axes with the anatomical axes of the wearer passively controls the patient's joint movement, and these robots have been successfully applied to upper extremity rehabilitation [12]. A selection of highlight studies on upper limb rehabilitation exoskeletons are listed in Table 3.

2.2.2 Lower Limb Exoskeleton

Lower limb rehabilitation exoskeleton robots, a prominent type of rehabilitation robots, are designed to be worn and can regulate the motion of all joints during rehabilitation sessions. The study of these lower limb rehabilitation exoskeleton robots dates back to the 1960s. However, early models did not meet expectations due to technological limitations, but they paved the way for future research. In the past few decades, following the clinical application

Table 3: Summary of upper limb rehabilitation exoskeletons.

Authors	Driving Mode	Structure	Features
[38]	Electric motors	7-DoF	An actuated exoskeleton to adapt to anthropometry in passive, impedance and teach modes
[120]	Electric motors	6-DoF	A versatile exsokeleton called with low-impedance torque controller in active mode
[44]	Electric motors	Dual 6-DoF	A compliant exoskeleton with natural coordinated motion on shoulder in active mode
[31]	Pneumatic muscles	5-DoF	Rotation and the length for each segment are adjustable with passive and assistive modes
[49, 91]	Electric motors	1-DoF	Single-joint wearable robot with well-synchronized active elbow motion detection and enhancement
[79]	Electric motors	6-DoF	Equip with compliant cable trasmission to guide the patient's limb following in passive, assistive and AAN modes
[51]	Electric motors	3-DoF	A portable cable-driven motion device that provides symmetric bilateral movements in mirror-image mode
[56]	Electric motors	Multi-DoF	A compliant, lightweight soft exoskeleton that conforms to the body with mirror-image mode
[104]	Pneumatic muscles	5-DoF	Assist patients to do daily activities by motion replication function in passive mode
[100]	Pneumatic muscles	1-DoF	A power-assist exoskeleton controlled by motion intention with neurological signal in active mode
[53]	Hydraulic	10-DoF	A light wearable robotic hand/arm system driven by hydraulic system in passive mode
[16]	Electric motors	1-DoF	A soft exoskeleton with bowden cable-driven system in active mode
[87]	Electric motors	7-DoF	A powered exoskeleton with single- or multi-joints assistive strategy in passive mode

of Lokomat [15], the focus on lower limb rehabilitation exoskeleton robots has noticeably increased, transforming them into a significant area of research. In recent years, numerous businesses and research institutions have made significant advancements in the theory and application of these robots.

The exoskeletons can be roughly classified into two categories: commercial exoskeletons and research exoskeletons. Examples of the commercial rehabilitation robots include eLEGS (Exoskeleton Lower limb Gait System) [1], HAL (Hybrid Assistive Limb) [91], ReWalk [18], MINDWALKER [108], Indego [101], and AIDER [121]. Most of the commercial ones have recognizable clearances, like FDA, CE or CFDA. These robots are designed to support real-world mobility and can be used in a variety of environments [98]. The rest of the research exoskeletons in universities or research centers with sophisticated technology are developed for the validation of various advanced methods, like gait planning, human-machine interaction methods. While advances have been made in designing the lower limb exoskeleton robots for walking assistance with anthropomorphic rigid structures, several challenges remain. The individual elements of design-specific mechanism, DoF configuration, drive mode, and controller integration—all contribute to the overall parameters of the exoskeleton system such as weight, size, drive capability, and motion function. Balancing these parameters to ensure the exoskeleton robot meets

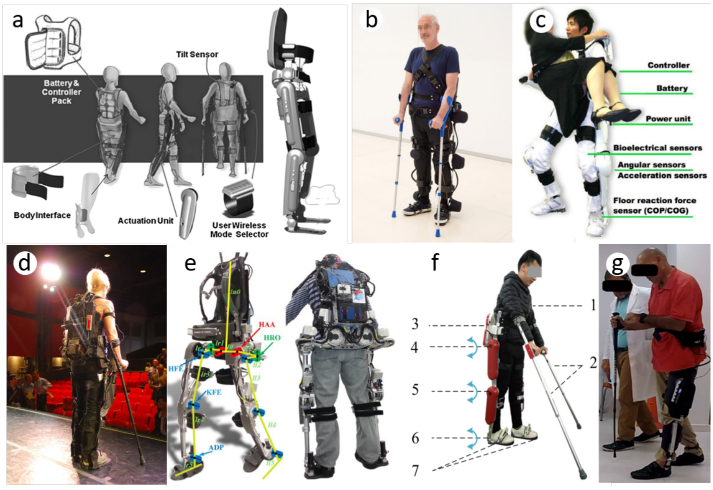

Figure 4: Different kinds of lower limb rehabilitation exoskeleton. (a) A lower limb powered exoskeleton named ReWalk with independently controlled bilaterial hip and knee joint motors [18]; (b) The HANK exoskeleton with compact ankle, knee and hip actuators for motor restoration of stroke patient [20]; (c) The Hybrid Assistive Lims (HAL) to enhance and upgrade the human capabilities [91]; (d) An efficient walking-assist lower limb exsokeleton called eLEGS for spinal injury patients [1]; (e) A powered lower limb wearable exoskeleton called MINDWALKER with active control for assisted walking [108]; (f) A walking assistance lower limb exsokeleton called AIDER with adaptive gait planning for paraplegic patients [121]; (g) A new portable exoskeleton called Marsi Active Knee (MAK) for gait rehabilitation in patients with neurological disorders [83].

user's functional requirements while also achieving high system integration, lightness, and reliability is a delicate task. For instance, a highly integrated system might increase the weight of the exoskeleton, which in turn might compromise its lightness or the user's comfort. Similarly, prioritizing reliability might limit the system's drive capability or motion function. Thus, various researchers dedicate to developing prototypes that are user-friendly and efficient but also lightweight, reliable, and highly integrated remains a significant challenge. This necessitates an innovative approach in the mechanical design and optimization that balances between these competing requirements [80]. Figure 4 provides some representative lower limb exoskeletons. A selection of highlight studied on lower limb rehabilitation exoskeletons are listed in Table 4.

2.3 System Design Comparison

Both SRL and exoskeleton are two distinct types of wearable robots that have some similarities but also have different characteristics and are designed for different scenarios. One common feature of both SRL and exoskeleton is that

Table 4: Summary of lower limb rehabilitation exoskeletons.

Authors	Driving Mode	Structure	Features
[91]	Electric motors	3-DoF	A powered exsokeleton with EMG-based feedback in active mode
[1]	Electric motors	3-DoF	A powered exoskeleton with finite state machine to determine movement in passive mode
[18]	Electric motors	2-DoF	Assist with walking by actuating hip and knee joints in passive mode
[108]	SEA	5-DoF	An assist walking exoskeleton with finite state machine in active control
[121]	Electric motors	2-DoF	A walking assistance exsokeleton with adaptive gait planning in passive mode
[20]	Electric motors	3-DoF	Adjustable guidance force for stroke patient in active mode
[83]	Electric motors	1-DoF	A portable lower limb device with one active degree of freedom for knee joint assistance in gait rehabilitation

they are wearable, meaning they can be attached or integrated onto the human body to seamlessly interact between the robot and the user, enhancing human capabilities or aid in rehabilitation.

However, they differ in terms of their kinematics with respect to the human body. SRLs are independent of the kinematics of the human body. Unlike exoskeletons that rely on mimicking the movements of the human body, SRLs have the ability to compensate for motion defects that may not naturally exist in the human body. This independence enables SRLs to adapt to a wide range of situations and assist users in performing tasks that would otherwise be difficult or impossible. On the other hand, exoskeletons often adopt an isomorphic design to resemble all DoF of the extremities so that all motions can be trained during rehabilitation. In summary, SRLs are typically compact and lightweight, making them ideal for the industry. Exoskeletons, on the other hand, are more robust and substantial, designed to support or restore physical functions in people with disabilities or hemiplegia.

In terms of applications, wearable robots can be broadly classified into two main categories based on the support they provide to the extremities of the body. Specifically, SRLs can be subdivided into SRA, which is designed for versatile upper limb grasping or holding, and SRLG, which primarily provides unique body support for the wearer. Meanwhile, exoskeletons can be categorized into upper limb and lower limb ones, contingent upon the targeted rehabilitation joints.

The design process of the wearable system can be segmented into four primary stages: task allocation, ontological design coupled with DoF assignment, determination of wear location and driving mode, and sensor selection. Figure 5 illustrates the flowchart of the system design for the two previously mentioned wearable robots, i.e., SRLs and exoskeletons.

The system design commences with task allocation. SRLs are predominantly employed to augment the capabilities of human wearers, whereas

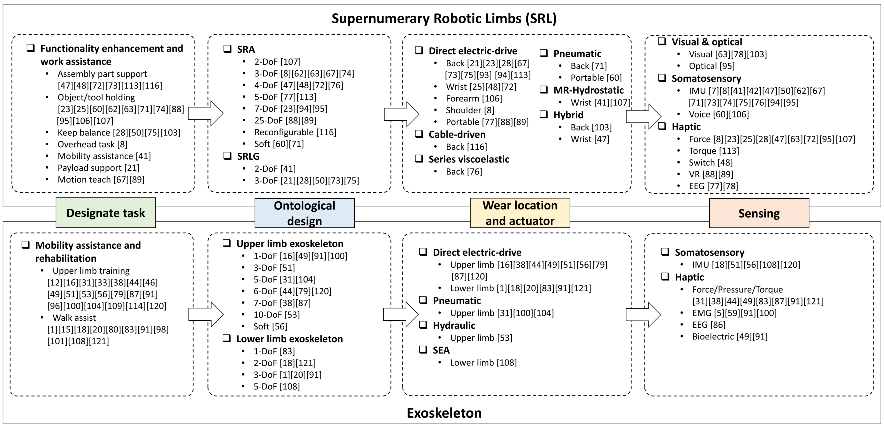

Figure 5: Flowchart of system design of SRLs and exoskeletons.

exoskeletons are primarily utilized to facilitate walking for individuals with disabilities or to restore motor functions for hemiplegia patients. The subsequent stage involves ontological design and DoF assignment. The system's DoF should be carefully determined according to the assigned task by examining the necessary DoF, while maintaining the system's lightweight nature through the selection of active and passive joints. Given that the upper limb offers more versatility than the lower limb, both robots have a wider range of options when it comes to the assignment of DoF for upper limb activities. The next stage involves identifying the wear location and the driving mode. Direct electric motors, favored for their high power density ratio, are frequently used in wearable robots. Nonetheless, some alternative drive systems like pneumatic and hydraulic are also seen in some designs of both types. In the final stage, the appropriate sensors are selected to record data that will be integrated into the control loop as feedback. As devices that enhance functionality, SRLs typically utilize IMUs and force sensors. These sensors allow the determination of the current posture of human wearers and the reaction force between the wearer and the environment. Similarly, these two types of sensors are commonly used in exoskeletons for rehabilitation purposes, enabling the tracking of human motion and interactions with the environment. Additionally, physiological feedback signals like electromyography (EMG) and electroencephalography (EEG) are also employed as non-invasive and convenient methods for machine interface applications.

In conclusion, the design process of wearable systems such as SRLs and exoskeletons is a complex and multifaceted procedure involving three main stages. This process highlights the importance of careful planning and design of effective and efficient wearable robotic systems.

3 Human-Machine Interaction

In order to achieve harmonious cooperation between humans and wearable robots, effective control methods and strategies are crucial. The perceptual interaction capability between humans and these robots lays the foundation for the implementation of control strategies during collaboration. In this section, the human-machine interaction of two representative wearable robots will be examined in detail.

3.1 Supernumerary Robotic Limbs

Through the interaction between humans and robots, we can improve the strengths of both to enhance task allocation and coordination, resulting in increased productivity and reduced human stress and workload. The pliability, wearability, human-like attributes, and close contact with humans that SRLs offer, open up new needs and possibilities for human-robot interaction. Human-machine interaction includes the entire communication channel between humans and machines, encompassing the information sender, receiver, and carrier. The SRL robot, as an auxiliary limb of the human body, is typically the receiver. However, in practice, information interaction is often acted in a two-way fashion. As human-machine interaction technology continues to evolve, SRL robots are finding more and more applications. Presently, research primarily focuses on somatosensory interaction and the emerging field of virtual reality interaction.

Somatosensory interaction translates physical body movements into signals that SRLs can interpret. The process primarily depends on a variety of sensors to collect physical parameters of limb movements, visual images, and sounds. These data are then used to create a model to facilitate somatosensory interaction. Vatsal *et al.* [106] and Liang *et al.* [60] have employed voice commands to directly control external limbs. While this method is convenient and precise, it increases the cognitive load on the human body. It's also less effective in noisy industrial environments. Other works, such as Treeres *et al.* [103] and Penaloza *et al.* [78], have used visual data to measure human joint angles for interpretation. However, this method has environmental limitations and requires human cooperation, making it less user-friendly. Some researchers, like Parietti *et al.* [75], Khodambashi *et al.* [42], Bright and Asada [8], Kojima *et al.* [47] and Khazoom *et al.* [41], have used somatosensory interaction to obtain data on movement parameters like acceleration, bend angle, and posture. Others, like Penaloza and Nishio [77], Nguyen *et al.* [71] and Guggenheim *et al.* [25], have used bioelectrical signals to discern a person's current intention via pattern features for interaction. Besides, Al-Sada *et al.* [88, 89] incorporated haptic feedback into augmented virtual reality, providing a more immersive environment to study and verify users' impressions of external limb interaction feedback.

3.2 Exoskeleton

Human-robot interaction technology forms the crux of rehabilitation robots. Its primary aim is to equip the robot with the ability to interact with patients, thereby perceiving, understanding, learning, and responding to environmental information during the interaction. This technology paves the way for machine transparency and intelligent human-robot interaction [111]. A significant challenge in stroke rehabilitation is enabling mutual understanding between the rehabilitation robot and the patient's intentions under uncertain conditions and facilitating reciprocal feedback.

The interaction can be bifurcated into two categories: physical and cognitive human-robot interaction. Physical Human-Robot Interaction (pHRI) involves a human and a robot exchanging energy through direct physical contact to jointly accomplish tasks in a rehabilitation robot application. This interaction primarily utilizes sensors to gather the current motion state of the patient's limb joints and feeds it back to the control unit to establish a corresponding closed-loop control system. The primary detectable physical interaction signals include position angle signals and tactile signals [13, 37, 68]. Cognitive Human-Robot Interaction (cHRI) focuses on the study of representations and actions that allow robots to participate in joint human activities. It aims to understand human expectations and cognitive responses to robot actions more deeply and establish joint activity models and task assignments for human-robot interaction. In cHRI, the rehabilitation robot captures physiological electrical signals from the patient and performs feature extraction and classification of the signals to identify the patient's movement intention [14]. This movement intention then forms the basis for designing the controller to propel the patient's limbs for rehabilitation training. The main physiological feedback signals used in rehabilitation robots are EMG [5, 59] and EEG [86].

Human-machine collaboration is a newly emerged control scheme that aims to enhance the transparency and trust between humans and machines. This is achieved through the establishment of mutual understanding models, which allow for efficient, precise, and safe collaborative decision-making and task collaboration in complex tasks [36]. It acknowledges the unique characteristics of both human and machine intelligence.

In the context of a rehabilitation exoskeleton robot, the machine needs to control its movements based on the patient's intent. Similar to the SRL, there are two main modes of human-robot collaboration: master-slave mode and co-learning mode. In the master-slave mode, the patient plans the movement and assigns the task, while the exoskeleton executes the movement task. The exoskeleton serves as a compensatory or augmentative device for the patient's movements. In the co-learning mode, both human and machine work together in executing the motor task. The exoskeleton compensates for any control errors caused by the patient's movement while encouraging maximum participation from the patient. As the patient's motor ability improves, the exoskeleton reduces its intervention, allowing the patient to independently complete rehabilitation training tasks. This way, the patient progresses towards achieving motor learning and functional rehabilitation goals. Apart from these, various human-machine control collaboration approaches are employed for rehabilitation robots including impedance control [118], admittance control [69, 97], force-position hybrid control [4], and Assist-As-Needed (AAN) collaborative control [22, 58, 115].

4 Control Strategy

4.1 Supernumerary Robotic Limbs

Diverse interaction methods allow for continual optimization of the control of SRL robots. The conventional control schemes, like position control, speed control and torque control are still applicable. However, considering user comfort, admittance control and impedance control are developed to balance the position and force. Leigh *et al.* [54] have categorized the upper layer control methods based on the varying degrees of autonomy in SRL control into direct control, pseudo-mapping control, auxiliary control, and shared control. In a different approach, Tong and Liu [102] classified these methods into mapping control, myoelectric signal control, and brain-computer interface control, based on the complexity of external limb control. Based on the relationship between humans and SRL robots, the control methodology can be categorized into demonstration control, master-slave control, and collaborative control.

4.1.1 Demonstration Control

Demonstration control in robotics involves a teaching phase, where the robot is set to move freely without resisting any external forces. During this phase, the robot records the movements made by a human operator, storing them for future reproduction. Once complete, the robot can mimic the recorded movements independently, without the need for human intervention. For multi-joint SRL, Al-Sada *et al.* [88] proposed a method where the joint was physically moved to a predetermined position and the action was saved to form action frames. These frames are then combined sequentially to create a desired action. In effect, this creates an action library that can be used in a range of application scenarios. Maekawa *et al.* [67] took yet another approach with a navigation arm that recorded and saved the arm movement trajectories of skilled operators. These saved movements can then be shared with beginners, allowing them to replicate the movements in terms of timing, pattern, and sequence. This can be particularly useful for sequential skill training tasks.

However, demonstration control has limitations. Capturing the desired movements of a human body accurately can be challenging. Achieving the desired level of precision following the complex path can be difficult. Furthermore, the more diverse the range of movements to be recorded, the greater the learning curve, potentially leading to increased complexity and reduced efficiency.

4.1.2 Master-Slave Control

Master-slave control is another specific method in robotics and automation, which involves creating a relationship between two or more machines where one dominates (master) and the others follow (slaves). This control scheme is primarily used in mapping control, bioelectric control, teleoperation, and other areas that require an input-response mechanism. The master provides the input, and the slave responds accordingly. The slave can also provide feedback to the master, allowing it to adjust its input and meet the desired control requirements. This feedback loop is crucial for achieving precision and accuracy in control systems. Several researchers have utilized master-slave control to achieve various outcomes. For instance, Guggenheim *et al.* [25] developed a control system by interpreting different signal patterns formed by fingertip contact forces. Penaloza [78] implemented a non-invasive EEG-based control system that activates the SRL to achieve the gripping action. Kieliba *et al.* [43] utilized a pseudo-mapping control scheme, enabling the flexion and inward retraction of external fingers through the activation of the right and left big toes.

However, while master-slave control offers numerous advantages, it also has limitations. One significant challenge is the inevitable time lag in control due to the sequential nature of the input and output. This time lag can result in SRLs appearing less intelligent during operation, impacting the system's efficiency and performance.

4.1.3 Collaborative Control

Collaborative control is a dual-principal, cooperative control strategy that brings significant benefits of collaboration in a setting where humans and SRL share a common workspace. This strategy simplifies complex tasks by pre-assigning specific roles and responsibilities. Notably, the SRL doesn't require human intervention to make decisions regarding its assigned task, effectively reducing the physical strain on the human body. In the experiments conducted by Bonilla and Asada [7], the SRL lessened the human workload by lifting panels or collaborating with humans to carry out basic tasks such as panel fixation, thereby completing overhead work tasks. Parietti *et al.* [72], used the robot to hold objects, thereby providing bodily support during operations.

This was achieved by guiding human hands to a drilling tool fixture placed on the drilling spot, assisting the operator in the drilling task. This not only reduced the physical strain on the human body but also improved the task's stability and precision.

While collaborative control is currently a favored control scheme, it still requires addressing certain issues. These include task distribution and fostering efficient collaboration between humans and robotic limbs, especially when dealing with complex tasks.

4.2 Exoskeleton

The human-in-control loop is a critical component of exoskeleton robots, with the system's control strategy playing a pivotal role in shaping the performance of these robots in assisting human movement. The objective of rehabilitation exoskeleton robots is to enhance limb motor function and stimulate the nervous system's self-repair and reorganization. This is achieved by guiding patients to actively engage in the personalized rehabilitation training, which in turn, helps restore their motor cognitive ability.

Rehabilitation training strategies and human-machine collaborative control methods form the crux of exoskeleton robot research. Rehabilitation training strategies can be broadly categorized into passive and active types [27, 70, 98], with training modes primarily including passive training, active training, and impedance training. These strategies and modes are designed to address the unique needs and capabilities of each individual, ensuring a more personalized and effective approach to rehabilitation.

4.2.1 Passive Control Strategy

The passive rehabilitation training strategy, often employed during the initial stages of rehabilitation, makes use of a position control that is based on limb motion trajectory to build a connection between the patient and the exoskeleton robot [97, 112]. In this approach, a predetermined limb motion trajectory acts as the desired trajectory while the real-time state of the exoskeleton robot provides the feedback information. The control target is either the error in position or velocity.

The study of human-robot cooperative control methods primarily concentrates on two aspects: the acquisition of limb motion trajectories and the design of motion cooperative control strategies. There are three main methods of acquiring limb motion trajectories:

- Pre-defined trajectory method: This approach uses a human clinical limb motion analysis database as the reference motion trajectory [11, 57, 81] or the limb motion trajectory of a healthy person as a trajectory playback [10, 12].

- Mathematical model-based limb motion trajectory generation method: This method utilizes the inverted pendulum model [92, 93], the linear inverted pendulum model [24, 39], ZMP models [119], and so on.
- Gait planning methods: These are based on industrial robotic arm trajectory planning theories like dynamic-manipulability ellipsoid [45] and dynamic motion primitive theory [40, 64].

In the motion cooperative control strategy, the limb motion velocity adaptive approach and the triggered cooperative strategy are commonly used. The limb motion velocity adaptive approach seeks to harmonize the body motion of the exoskeleton robot and the wearer by adjusting the motion running speed. This approach is suitable for an exoskeleton robot that operates with a continuous motion trajectory [35]. However, it requires the wearer to be proficient in using the exoskeleton robot to avoid potential falls due to uncoordinated human-robot movement. Triggered cooperative strategies, on the other hand, rely on the perception and cognition of the human-machine system state to trigger individual or discrete motions. This could be achieved either by keystroke triggering or a finite state machine (FSM) based on the state perception of the human-machine system [81, 85, 99]. Some finite state machine approaches utilize neural interfaces, such as EEG signals [32, 45].

4.2.2 Active Control Strategy

In passive rehabilitation training, the exoskeleton robot required to supplement assistance to guide the individual following a pre-determined training trajectory. In contrast, active rehabilitation training is a more complex process, driven by the patients themselves. This method, facilitated by an exoskeleton robot, is more challenging to accomplish than its passive counterpart. The primary difficulty lies in accurately capturing the person's active movement intent and providing suitable assistance [34].

Similar to the control of the SRL, determining human motion intent plays a crucial role which chiefly relies on biosignal-based recognition methods [30, 61], human-machine interaction signals [19, 65], and device parameters [29]. As the patient progresses through the rehabilitation process, the rehabilitation robot transitions from offering passive training to active training. Thereby, the associated control strategies are adjusted accordingly. For instance, position control is employed in the early phases of rehabilitation, followed by on-demand interaction control in the middle stages, and impedance control in the latter stages. This process ensures efficient, precise, and safe dynamic collaborative decision-making and behavioural task coordination throughout the entire rehabilitation cycle.

5 Future Trends

Wearable robotic systems offer exciting opportunities for innovation and impact. They can provide assistance for individuals with physical disabilities, enhance human capabilities in industrial settings. It also presents many challenges. By summarizing the existing work of two representative wearable robots, four main research directions and research difficulties are listed in this paper.

5.1 Design of Lightweight and Compliant Wearable Robot

In order to fit different body size, the inherent individual differences among wearers poses a significant challenge in accurately estimating the dynamics model of a robot. This, consequently, hinders the complete elimination of the impact of the wearable device's weight on the wearer. In fact, it might even add an extra burden, threatening the stability of the wearer's center of gravity and requiring excessive energy to keep balance. Furthermore, the current capabilities of wearable robots are restricted by the rigid designs, motors, materials, and manufacturing technologies in use. It becomes a struggle to strike a balance between high operational adaptability and lightweight structures. Some wearable robots leverage flexible materials and rope drives to reconfigure the structural layout and weight distribution, offering a certain level of relief [3]. However, this is often at the expense of performance, resulting in reduced output torque, diminished precision, and complex control.

Therefore, one of the future directions for wearable robot research is to incorporate a rigid-flexible compliant structure and drive design, which can be achieved by integrating soft materials, flexible structures, and effective drive technologies. These innovations will not only reduce safety risks but also enhance wearing comfort, all the while ensuring satisfactory performance.

5.2 Cooperative Compliance Control Strategy for Human-Machine Interaction

Whether it's an engineer using an exoskeleton for assistance or a patient undergoing rehabilitation training with an exoskeleton robot, the active involvement of the wearer is essential for enhancing the assistive and rehabilitative effects. This necessitates a two-way understanding within the human-robot interaction. In other words, the robot must comprehend the wearer's current state of motion and anticipate next steps, while the wearer needs to perceive the sensory stimulation and movement process facilitated by the exoskeleton to effectively plan their tasks.

However, the current EMG and EEG technologies have their limitations. They are primarily utilized as trigger signals for specific movements rather than for extracting comprehensive movement patterns [32]. Consequently, a promising research direction for rehabilitation robots lies in harnessing multimodal biosignal extraction to discern human movement intent which helps to form human-machine interaction data, leading to a more adaptable human-machine cooperative and compliance control strategies. Such advancements will ultimately enhance the efficiency and effectiveness of human-machine collaboration in assistive tasks and rehabilitation training.

5.3 Integration of Robot Execution and Realtime Assessment

The efficacy of assistance and rehabilitation training should ideally be quantified using objective indices. These indices could then be utilized to optimize subsequent decisions based on the property of tasks. For instance, in the case of exoskeleton robots used for rehabilitation, current assessment methods only provide a superficial evaluation based on the degree of task completion by using the rating scale. These assessments fail to quantify the changes occurring in the muscle and nervous system during the rehabilitation process, which results in evaluations that do not accurately reflect the specific rehabilitation effects for each patient, leading to suboptimal personalized rehabilitation plans. Moreover, most existing rehabilitation exoskeleton robots only analyze the results of motor rehabilitation training, rather than directly measuring the biological data of the human body during training. This issue also affects SRLs, which, due to the lack of objective evaluation, cannot adjust their task decisions based on the wearer's physiological state, such as fatigue. This also reduces the effectiveness of the assistive device.

One potential solution to these issues is the integration of advanced sensors and big data analytics into wearable robots. These sensors could collect data from human muscles, bones, and nervous systems, enabling dynamic evaluation and analysis during the assistance and rehabilitation training process. As a consequence, more accurate, intuitive, and quantitative evaluation indicators can be established, which will provide a data foundation for personalized assistance and rehabilitation training plans.

5.4 Evolution Towards Embodied Intelligence

Embodied intelligence is a concept that centers around the interaction between machines and the physical world, creating an intelligent entity that integrates both hardware and software [26]. This entity is capable of learning and evolving independently. Contrasting traditional robotic systems, which achieve task decision-making based on rules and artificial intelligence through the fusion of multiple sensory data, embodied intelligence emphasizes direct interaction between robots and the environment through perception and action. Robots gain knowledge and experience from these interactions and evolve in practice to gradually enhance their ability to adapt and resolve complex tasks more naturally and efficiently.

The emergence of Large Multimodal Models (LMMs) has recently brought about a new phase in the development of wearable robots [17]. As an extension of the Large Language Model (LLM), LMMs can integrate additional modalities beyond vision and language. The application of LMMs in wearable robots holds significant promise. As these models continue to evolve and improve, they have the potential to revolutionize various fields. Whether it's SRL assisting a worker in performing tasks, or an exoskeleton aiding a stroke or paraplegic patient in rehabilitation or walking assistance, the incorporation of information about the wearer's physiology, user habits, body function deviation, and the surrounding environment into the decision-making model can enhance the understanding of the wearer's intent. The introduction of LMMs into wearable robots can, on one hand, customize the functionality of these robots to meet the individual needs of users, resulting in a more personalized and effective performance in fulfill tasks. On the other hand, it can enhance the predictive capabilities of the robots by processing and interpreting data from various sensors embedded within the wearable robots, which facilitates a more natural and intuitive interaction between the wearer and the robot. However, there are also challenges to consider. The development and implementation of LMMs in wearable robots require significant expertise and resources. Additionally, privacy and security concerns regarding the handling of sensitive user data arise. Moreover, it is critical to ensure the reliable and safe operation of these systems under all circumstances.

6 Conclusion

The working-age population is declining, leading to a labor shortage, especially in the context of an aging population and an increase in people with extremity motor dysfunction or extra assistance. To address these challenges, wearable robots have been developed as a form of human-robot collaboration to enhance motor capabilities and assist with motor functions. The paper provides a comprehensive review on the current status of wearable robot research, with a particular focus on the application of SRL and exoskeletons for assistance, mobility, and rehabilitation purposes. The paper also highlights the challenges and opportunities of wearable robots, including the need for effective control methods and strategies to achieve more effective and natural cooperation between humans and wearable robots.

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References

[1] E. Ackerman, "Berkeley Bionics Introduces eLEGS Robotic Exoskeleton", *IEEE Spectrum*, 10, 2010.
[2] E. M. Arnold, S. R. Ward, R. L. Lieber, and S. L. Delp, "A model of the lower limb for analysis of human movement", *Annals of Biomedical Engineering*, 38(2), 2010, 269–79.
[3] T. A. Asbeck, S. M. M. D. Rossi, G. Ignacio, D. Ye, and W. Conor, "Stronger, Smarter, Softer: Next Generation Wearable Robots", *IEEE Robotics and Automation Magazine*, 21(4), 2011, 22–33.
[4] S. K. Banala, S. H. Kim, S. K. Agrawal, and J. P. Scholz, "Robot assisted gait training with active leg exoskeleton (ALEX)", *IEEE Transactions on Neural and Rehabilitation Systems Engineering*, 17(1), 2009, 2–8.
[5] G. Bao, K. Li, S. Xu, P. Huang, L. Wu, and Q. Yang, "Motion identification based on sEMG for flexible pneumatic hand rehabilitator", *Industrial Robot*, 42(1), 2015, 25–35.
[6] A. A. Blank, J. A. French, A. U. Pehlivan, and M. K. O'Malley, "Current trends in robot-assisted upper-limb stroke rehabilitation: promoting patient engagement in therapy", *Current Physical Medicine and Rehabilitation Reports*, 2(3), 2014, 184–95.
[7] B. L. Bonilla and H. H. Asada, "A robot on the shoulder: Coordinated human-wearable robot control using Coloured Petri Nets and Partial Least Squares predictions", in *IEEE International Conference on Robotics and Automation*, 2014, 119–25.
[8] Z. Bright and H. H. Asada, "Supernumerary Robotic Limbs for Human Augmentation in Overhead Assembly Tasks", in *Robotics: Science and Systems*, 2017.
[9] W. H. Chang and Y.-H. Kim, "Robot-assisted therapy in stroke rehabilitation", *Journal of Stroke*, 15(3), 2013, 174–81.
[10] B. Chen, C. H. Zhong, H. Ma, X. Guan, L. Y. Qin, K. M. Chan, S. W. Law, L. Qin, and W. H. Liao, "Sit-to-stand and stand-to-sit assistance for paraplegic patients with CUHK-EXO exoskeleton", *Robotica*, 36(4), 2018, 535–51.
[11] L. Chen, J. Qiu, L. Zhou, H. Wang, F. Jiang, and H. Cheng, "Design and Control of a Bimanual Rehabilitation System for Trunk Impairment Patients", in *International Conference on Intelligent Robotics and Applications*, 2022, 3–11.

[12] L. Chen, J. Qiu, X. Zou, and H. Cheng, "A Dual-Arm Participated Human-Robot Collaboration Method for Upper Limb Rehabilitation of Hemiplegic Patients", in *IEEE International Conference on Robotics and Automation*, 2023, 12617–23.

[13] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M. C. Carrozza, "Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation", *IEEE/ASME Transactions on Mechatronics*, 17(5), 2012, 884–94.

[14] J. U. Chu, I. Moon, Y. J. Lee, S. K. Kim, and M. S. Mun, "A supervised feature-projection-based real-time EMG pattern recognition for multifunction myoelectric hand control", *IEEE/ASME Transactions on Mechatronics*, 12(3), 2007, 282–90.

[15] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, "Treadmill training of paraplegic patients using a robotic orthosis.", *Journal of rehabilitation research and development*, 37(6), 2000, 693–700.

[16] B. K. Dinh, M. Xiloyannis, L. Cappello, C. W. Antuvan, S. C. Yen, and L. Masia, "Adaptive backlash compensation in upper limb soft wearable exoskeletons", *Robotics and Autonomous Systems*, 92, 2017, 173–86.

[17] D. Driess, F. Xia, M. S. M. Sajjadi, C. Lynch, A. Chowdhery, B. Ichter, A. Wahid, J. Tompson, Q. Vuong, T. Yu, W. Huang, Y. Chebotar, P. Sermanet, D. Duckworth, S. Levine, V. Vanhoucke, K. Hausman, M. Toussaint, K. Greff, A. Zeng, I. Mordatch, and P. Florence, "PaLM-E: An Embodied Multimodal Language Model", 2023.

[18] 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", *American Journal of Physical Medicine and Rehabilitation*, 91(11), 2012, 911–21.

[19] D. B. Fineberg, P. Asselin, N. Y. Harel, I. Agranova-Breyter, S. D. Kornfeld, W. A. Bauman, and A. M. Spungen, "Vertical ground reaction force-based analysis of powered exoskeleton-assisted walking in persons with motor-complete paraplegia", *Journal of Spinal Cord Medicine*, 36(4), 2013, 313–21.

[20] Á. Gil-Agudo, Á. Megía-García, J. L. Pons, I. Sinovas-Alonso, N. Comino-Suárez, V. Lozano-Berrio, and A. J. Del-Ama, "Exoskeleton-based training improves walking independence in incomplete spinal cord injury patients: results from a randomized controlled trial", *Journal of NeuroEngineering and Rehabilitation*, 20(1), 2023, 1–11.

[21] D. J. Gonzalez and H. H. Asada, "Design of Extra Robotic Legs for Augmenting Human Payload Capabilities by Exploiting Singularity and Torque Redistribution", in *IEEE International Conference on Intelligent Robots and Systems*, 2018, 4348–54.

[22] D. Gopinath, S. Jain, and B. D. Argall, "Human-in-the-loop optimization of shared autonomy in assistive robotics", *IEEE Robotics and Automation Letters*, 2(1), 2017, 247–54.

[23] G. Gourmelen, A. Verhulst, T. Sasaki, B. Navarro, G. Ganesh, and M. Inami, "Co-Limbs : An Intuitive Collaborative Control for Wearable Robotic Arms", in *SIGGRAPH Asia 2019 Emerging Technologies*, 2019.

[24] R. Griffin, T. Cobb, T. Craig, M. Daniel, N. Van Dijk, J. Gines, K. Krämer, S. Shah, O. Siebinga, J. Smith, and P. Neuhaus, "Stepping Forward with Exoskeletons", *IEEE Robotics and Automation Magazine*, 24(4), 2017, 66–74.

[25] J. Guggenheim, R. Hoffman, H. Song, and H. H. Asada, "Leveraging the Human Operator in the Design and Control of Supernumerary Robotic Limbs", *IEEE Robotics and Automation Letters*, 5(2), 2020, 2177–84.

[26] A. Gupta, S. Savarese, S. Ganguli, and L. Fei-Fei, "Embodied intelligence via learning and evolution", *Nature Communications*, 12(1), 2021.

[27] M. F. Hamza, R. A. R. Ghazilla, B. B. Muhammad, and H. J. Yap, "Balance and stability issues in lower extremity exoskeletons: A systematic review", *Biocybernetics and Biomedical Engineering*, 40(4), 2020, 1666–79.

[28] M. Hao, J. Zhang, K. Chen, and C. Fu, "Design and Basic Control of Extra Robotic Legs for Dynamic Walking Assistance", in *Proceedings of IEEE Workshop on Advanced Robotics and its Social Impacts*, 2019, 246–50.

[29] O. Harib, A. Hereid, A. Agrawal, T. Gurriet, S. Finet, G. Boéris, A. Duburcq, M. E. Mungai, M. Masselin, A. D. Ames, K. Sreenath, and J. W. Grizzle, "Feedback Control of an Exoskeleton for Paraplegics: Toward Robustly Stable, Hands-Free Dynamic Walking", *IEEE Control Systems*, 38(6), 2018, 61–87.

[30] H. He and K. Kiguchi, "A study on EMG-based control of exoskeleton robots for human lower-limb motion assist", in *International Conference on Information Technology Applications in Biomedicine*, 2007, 292–5.

[31] J. He, E. J. Koeneman, R. S. Schultz, H. Huang, J. Wanberg, D. E. Herring, T. Sugar, R. Herman, and J. B. Koeneman, "Design of a robotic upper extremity repetitive therapy device", in *IEEE 9th International Conference on Rehabilitation Robotics*, 2005, 95–8.

[32] E. Hortal, D. Planelles, F. Resquin, J. M. Climent, J. M. Azorín, and J. L. Pons, "Using a brain-machine interface to control a hybrid upper limb exoskeleton during rehabilitation of patients with neurological conditions", *Journal of NeuroEngineering and Rehabilitation*, 12(1), 2015, 1–16.

[33] S. J. Housman, V. Le, T. Rahman, R. J. Sanchez, and D. J. Remkensrneyer, “Arm-training with T-WREX after chronic stroke: Preliminary results of a randomized controlled trial”, in *International Conference on Rehabilitation Robotics*, 2007, 562–8.

[34] J. Hu, Y. Zhuang, Q. Meng, and H. Yu, “Active Training Control Method for Rehabilitation Robot Based on Fuzzy Adaptive Impedance Adjustment”, *Machines*, 11(5), 2023.

[35] A. I. A. Ahmed, H. Cheng, Z. Liangwei, M. Omer, and X. Lin, “On-line Walking Speed Control in Human-Powered Exoskeleton Systems Based on Dual Reaction Force Sensors”, *Journal of Intelligent and Robotic Systems*, 87(1), 2017, 59–80.

[36] F. Ishowo-Oloko, J.-F. Bonnefon, Z. Soroye, J. Crandall, I. Rahwan, and T. Rahwan, “Behavioural evidence for a transparency–efficiency tradeoff in human–machine cooperation”, *Nature Machine Intelligence*, 1(11), 2019, 517–21.

[37] S. H. Jeong, K. S. Kim, and S. Kim, “Development of a robotic finger with an active dual-mode twisting actuation and a miniature tendon tension sensor”, in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2016, 1–6.

[38] F. Just, K. Baur, R. Riener, V. Klamroth-Marganska, and G. Rauter, “Online adaptive compensation of the ARMin Rehabilitation Robot”, in *IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, IEEE, 2016, 747–52.

[39] T. Kagawa, H. Ishikawa, T. Kato, C. Sung, and Y. Uno, “Optimization-Based Motion Planning in Joint Space for Walking Assistance with Wearable Robot”, *IEEE Transactions on Robotics*, 31(2), 2015, 415–24.

[40] K. Kamali, A. A. Akbari, and A. Akbarzadeh, “Trajectory generation and control of a knee exoskeleton based on dynamic movement primitives for sit-to-stand assistance”, *Advanced Robotics*, 30(13), 2016, 846–60.

[41] C. Khazoom, P. Caillouette, A. Girard, and J. S. Plante, “A Supernumerary Robotic Leg Powered by Magnetorheological Actuators to Assist Human Locomotion”, *IEEE Robotics and Automation Letters*, 5(4), 2020, 5143–50.

[42] R. Khodambashi, G. Weinberg, W. Singhose, S. Rishmawi, V. Murali, and E. Kim, “User oriented assessment of vibration suppression by command shaping in a supernumerary wearable robotic arm”, in *IEEE-RAS International Conference on Humanoid Robots*, 2016, 1067–72.

[43] P. Kieliba, D. Clode, R. O. Maimon-Mor, and T. R. Makin, “Robotic hand augmentation drives changes in neural body representation”, *Science Robotics*, 6(54), 2021.

[44] B. Kim and A. D. Deshpande, "An upper-body rehabilitation exoskeleton Harmony with an anatomical shoulder mechanism: Design, modeling, control, and performance evaluation", *International Journal of Robotics Research*, 36(4), 2017, 414–35.

[45] W. Kim, S. Lee, M. Kang, J. Han, and C. Han, "Energy-efficient gait pattern generation of the powered robotic exoskeleton using DME", in *International Conference on Intelligent Robots and Systems*, 2010, 2475–80.

[46] J. Klein, S. Spencer, J. Allington, J. E. Bobrow, and D. J. Reinkensmeyer, "Optimization of a parallel shoulder mechanism to achieve a high-force, low-mass, robotic-arm exoskeleton", *IEEE Transactions on Robotics*, 26(4), 2010, 710–5.

[47] A. Kojima, H. Yamazoe, M. G. Chung, and J. H. Lee, "Control of wearable robot arm with hybrid actuation system", in *IEEE/SICE International Symposium on System Integration*, 2017, 1022–7.

[48] A. Kojima, H. Yamazoe, and J. H. Lee, "Practical-use oriented design for wearable robot arm", in *International Conference on Intelligent Robotics and Applications*, 2016, 125–34.

[49] S. Kubota, Y. Hara, Y. Shimizu, H. Kadone, T. Kubo, A. Marushima, T. Ueno, H. Kawamoto, M. Koda, A. Matsumura, Y. Hada, Y. Sankai, and M. Yamazaki, "A newly developed upper limb single-joint HAL in a patient with elbow flexion reconstruction after traumatic brachial plexus injury: A case report", *Interdisciplinary Neurosurgery: Advanced Techniques and Case Management*, 10, 2017, 66–8.

[50] D. A. Kurek and H. H. Asada, "The MantisBot: Design and impedance control of supernumerary robotic limbs for near-ground work", in *IEEE International Conference on Robotics and Automation*, 2017, 5942–7.

[51] S. Kyeong, Y. Na, and J. Kim, "A Mechatronic Mirror-Image Motion Device for Symmetric Upper-Limb Rehabilitation", *International Journal of Precision Engineering and Manufacturing*, 21(5), 2020, 947–56.

[52] S. H. Lee, G. Park, D. Y. Cho, H. Y. Kim, J. Y. Lee, S. Kim, S. B. Park, and J. H. Shin, "Comparisons between end-effector and exoskeleton rehabilitation robots regarding upper extremity function among chronic stroke patients with moderate-to-severe upper limb impairment", *Scientific Reports*, 10(1), 2020, 1–8.

[53] Y. K. Lee, "Design of exoskeleton robotic hand/arm system for upper limbs rehabilitation considering mobility and portability", in *International Conference on Ubiquitous Robots and Ambient Intelligence*, IEEE, 2014, 540–4.

[54] S. W. Leigh, H. Agrawal, and P. Maes, "Robotic Symbionts: Interweaving Human and Machine Actions", *IEEE Pervasive Computing*, 17(2), 2018, 34–43.

[55] S. W. Leigh, T. Denton, K. Parekh, W. S. Peebles, M. H. Johnson, and P. Maes, "Morphology extension kit: A modular robotic platform for customizable and physically capable wearables", in *International Conference on Tangible, Embedded, and Embodied Interaction*, 2018, 11–8.

[56] S. Lessard, P. Pansodtee, A. Robbins, J. M. Trombadore, S. Kurniawan, and M. Teodorescu, "A Soft Exosuit for Flexible Upper-Extremity Rehabilitation", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(8), 2018, 1604–17.

[57] H. Li, H. Yu, Y. Chen, X. Tang, D. Wang, Q. Meng, and Q. Du, "Design of a Minimally Actuated Lower Limb Exoskeleton with Mechanical Joint Coupling", *Journal of Bionic Engineering*, 19(2), 2022, 370–89.

[58] M. Li, J. Zhang, G. Zuo, G. Feng, and X. Zhang, "Assist-As-Needed Control Strategy of Bilateral Upper Limb Rehabilitation Robot Based on GMM", *Machines*, 10(2), 2022, 1–16.

[59] Q. L. Li, Y. Song, and Z. G. Hou, "Estimation of Lower Limb Periodic Motions from sEMG Using Least Squares Support Vector Regression", *Neural Processing Letters*, 41(3), 2015, 371–88.

[60] X. Liang, H. K. Yap, J. Guo, R. C. H. Yeow, Y. Sun, and C. K. Chui, "Design and characterization of a novel fabric-based robotic arm for future wearable robot application", in *IEEE International Conference on Robotics and Biomimetics*, 2018, 367–72.

[61] D. Liu, W. Chen, Z. Pei, and J. Wang, "A brain-controlled lower-limb exoskeleton for human gait training", *Review of Scientific Instruments*, 88(10), 2017.

[62] B. Llorens-Bonilla and H. H. Asada, "Control and Coordination of Supernumerary Robotic Limbs Based on Human Motion Detection and Task Petri Net Model", in *Proceedings of the ASME 2013 Dynamic Systems and Control Conference*, 2013, 1–7.

[63] B. Llorens-Bonilla, F. Parietti, and H. H. Asada, "Demonstration-based control of supernumerary robotic limbs", in *IEEE International Conference on Intelligent Robots and Systems*, 2012, 3936–42.

[64] L. Luo, M. J. Foo, M. Ramanathan, J. K. Er, C. H. Chiam, L. Li, W. Y. Yau, and W. T. Ang, "Trajectory Generation and Control of a Lower Limb Exoskeleton for Gait Assistance", *Journal of Intelligent and Robotic Systems*, 106(3), 2022.

[65] S. Luo, G. Androwis, S. Adamovich, E. Nunez, H. Su, and X. Zhou, "Robust walking control of a lower limb rehabilitation exoskeleton coupled with a musculoskeletal model via deep reinforcement learning", *Journal of neuroengineering and rehabilitation*, 20(1), 2023, 34.

[66] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation", *Journal of NeuroEngineering and Rehabilitation*, 11, 2014, 3.

[67] A. Maekawa, S. Takahashi, M. H. Saraiji, S. Wakisaka, H. Iwata, and M. Inami, "Naviarm: Augmenting the learning of motor skills using a backpack-type robotic arm system", in *ACM International Conference Proceeding Series*, 2019, 1–8.

[68] A. Malik, M. Ali, Z. M. Yusof, A. K. Kushairy, F. H. Zaharah, and A. Ismail, "Development of Smart Glove system for therapy treatment", in *International Conference on BioSignal Analysis, Processing and Systems*, 2015, 67–71.

[69] J. Meuleman, E. Van Asseldonk, G. Van Oort, H. Rietman, and H. Van Der Kooij, "LOPES II - Design and Evaluation of an Admittance Controlled Gait Training Robot with Shadow-Leg Approach", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 24(3), 2016, 352–63.

[70] F. Molteni, G. Gasperini, G. Cannaviello, and E. Guanziroli, "Exoskeleton and End-Effector Robots for Upper and Lower Limbs Rehabilitation: Narrative Review", *PM and R*, 10(9), 2018, 174–88.

[71] P. H. Nguyen, C. Sparks, S. G. Nuthi, N. M. Vale, and P. Polygerinos, "Soft Poly-Limbs: Toward a New Paradigm of Mobile Manipulation for Daily Living Tasks", *Soft Robotics*, 6(1), 2019, 38–53.

[72] F. Parietti and H. H. Asada, "Supernumerary Robotic Limbs for aircraft fuselage assembly: Body stabilization and guidance by bracing", in *IEEE International Conference on Robotics and Automation*, 2014, 1176–83.

[73] F. Parietti and H. Asada, "Supernumerary Robotic Limbs for Human Body Support", *IEEE Transactions on Robotics*, 32(2), 2016, 301–11.

[74] F. Parietti and H. H. Asada, "Dynamic analysis and state estimation for wearable robotic limbs subject to human-induced disturbances", in *IEEE International Conference on Robotics and Automation*, 2013, 3880–7.

[75] F. Parietti, K. C. Chan, B. Hunter, and H. H. Asada, "Design and control of Supernumerary Robotic Limbs for balance augmentation", in *IEEE International Conference on Robotics and Automation*, 2015, 5010–7.

[76] F. Parietti, K. Chan, and H. H. Asada, "Bracing the human body with supernumerary Robotic Limbs for physical assistance and load reduction", in *IEEE International Conference on Robotics and Automation*, 2014, 141–8.

[77] C. I. Penaloza and S. Nishio, "BMI control of a third arm for multitasking", *Science Robotics*, 3(20), 2018.

[78] C. Penaloza, D. Hernandez-Carmona, and S. Nishio, "Towards Intelligent Brain-Controlled Body Augmentation Robotic Limbs", in *EEE International Conference on Systems, Man, and Cybernetics*, IEEE, 2018, 1011–5.

[79] E. Pirondini, M. Coscia, S. Marcheschi, G. Roas, F. Salsedo, A. Frisoli, M. Bergamasco, and S. Micera, “Evaluation of the effects of the Arm Light Exoskeleton on movement execution and muscle activities: A pilot study on healthy subjects”, *Journal of NeuroEngineering and Rehabilitation*, 13(1), 2016, 1–21.

[80] A. Plaza, M. Hernandez, G. Puyuelo, E. Garces, and E. Garcia, “Lower-Limb Medical and Rehabilitation Exoskeletons: A Review of the Current Designs”, *IEEE Reviews in Biomedical Engineering*, 16, 2023, 278–91.

[81] J. Poonsiri, M. Rachagorngij, and W. Charoensuk, “Biomechanical based design of an active knee ankle foot orthosis to augment the knee motions”, in *Biomedical Engineering International Conference*, 2014.

[82] D. Prattichizzo, G. Salvietti, F. Chinello, and M. Malvezzi, “An object-based mapping algorithm to control wearable robotic extra-fingers”, in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2014, 1563–8.

[83] G. Puyuelo-Quintana, R. Cano-De-La-Cuerda, A. Plaza-Flores, E. Garces-Castellote, D. Sanz-Merodio, A. Goñi-Arana, J. Marín-Ojea, and E. García-Armada, “A new lower limb portable exoskeleton for gait assistance in neurological patients: A proof of concept study”, *Journal of NeuroEngineering and Rehabilitation*, 17(1), 2020, 1–16.

[84] H. M. Qassim and W. Z. Wan Hasan, “A review on upper limb rehabilitation robots”, *Applied Sciences (Switzerland)*, 10(19), 2020, 1–18.

[85] Z. Qi, Q. Song, Y. Liu, and C. Guo, “FSM-HSVM-Based Locomotion Mode Recognition for Exoskeleton Robot”, *Applied Sciences (Switzerland)*, 12(11), 2022.

[86] M. S. Al-Quraishi, I. Elamvazuthi, S. A. Daud, S. Parasuraman, and A. Borboni, “Eeg-based control for upper and lower limb exoskeletons and prostheses: A systematic review”, *Sensors (Switzerland)*, 18(10), 2018, 1–27.

[87] M. H. Rahman, M. J. Rahman, O. L. Cristobal, M. Saad, J. P. Kenné, and P. S. Archambault, “Development of a whole arm wearable robotic exoskeleton for rehabilitation and to assist upper limb movements”, *Robotica*, 33(1), 2015, 19–39.

[88] M. Al-Sada, T. Höglund, M. Khamis, J. Urbani, and T. Nakajima, “Orochi: investigating requirements and expectations for multipurpose daily used supernumerary robotic limbs”, in *Proceedings of the 10th Augmented Human International Conference*, 2019, 1–9.

[89] M. Al-Sada, K. Jiang, S. Ranade, M. Kalkattawi, and T. Nakajima, “HapticSnakes: multi-haptic feedback wearable robots for immersive virtual reality”, *Virtual Reality*, 24(2), 2020, 191–209.

[90] M. d. C. Sanchez-Villamañan, J. Gonzalez-Vargas, D. Torricelli, J. C. Moreno, and J. L. Pons, "Compliant lower limb exoskeletons: a comprehensive review on mechanical design principles", *Journal of NeuroEngineering and Rehabilitation*, 16(1), 2019, 55.

[91] Y. Sankai, "HAL: Hybrid assistive limb based on cybernics", in *Robotics Research*, Vol. 66, 2010, 25–34.

[92] D. Sanz-Merodio, M. Cestari, J. C. Arevalo, X. A. Carrillo, and E. Garcia, "Generation and control of adaptive gaits in lower-limb exoskeletons for motion assistance", *Advanced Robotics*, 28(5), 2014, 329–38.

[93] D. Sanz-Merodio, M. Cestari, J. C. Arevalo, and E. Garcia, "A lower-limb exoskeleton for gait assistance in quadriplegia", in *IEEE International Conference on Robotics and Biomimetics*, 2012, 122–7.

[94] M. Y. Saraiji, T. Sasaki, K. Kunze, K. Minamizawa, and M. Inami, "MetaArms: Body Remapping Using Feet-Controlled Artificial Arms", in *Annual ACM Symposium on User Interface Software and Technology*, 2018, 65–74.

[95] T. Sasaki, M. Y. Saraiji, C. L. Fernando, K. Minamizawa, and M. Inami, "MetaLimbs: Multiple arms interaction metamorphism", in *ACM SIGGRAPH 2017 Emerging Technologies*, 2017.

[96] Y. Shen, J. Sun, J. Ma, and J. Rosen, "Admittance control scheme comparison of EXO-UL8: A dual-arm exoskeleton robotic system", in *IEEE International Conference on Rehabilitation Robotics*, 2019, 611–7.

[97] Z. Shen, Y. Zhuang, J. Zhou, J. Gao, and R. Song, "Design and Test of Admittance Control with Inner Adaptive Robust Position Control for a Lower Limb Rehabilitation Robot", *International Journal of Control, Automation and Systems*, 18(1), 2020, 134–42.

[98] D. Shi, W. Zhang, W. Zhang, and X. Ding, "A Review on Lower Limb Rehabilitation Exoskeleton Robots", *Chinese Journal of Mechanical Engineering*, 32(1), 2019.

[99] K. A. Strausser and H. Kazerooni, "The development and testing of a human machine interface for a mobile medical exoskeleton", in *IEEE International Conference on Intelligent Robots and Systems*, 2011, 4911–6.

[100] Z. Tang, K. Zhang, S. Sun, Z. Gao, L. Zhang, and Z. Yang, "An upper-limb power-assist exoskeleton using proportional myoelectric control", *Sensors (Switzerland)*, 14(4), 2014, 6677–94.

[101] C. Tefertiller, K. Hays, J. Jones, A. Jayaraman, C. Hartigan, T. Bushnik, and G. F. Forrest, "Initial Outcomes from a Multicenter Study Utilizing the Indego Powered Exoskeleton in Spinal Cord Injury", *Topics in Spinal Cord Injury Rehabilitation*, 24(1), 2018, 78–85.

[102] Y. Tong and J. Liu, "Review of Research and Development of Supernumerary Robotic Limbs", *IEEE/CAA Journal of Automatica Sinica*, 8(5), 2021, 929–52.

[103] L. Treers, R. Lo, M. Cheung, A. Guy, J. Guggenheim, F. Parietti, and H. Asada, "Design and Control of Lightweight Supernumerary Robotic Limbs for Sitting/Standing Assistance", in *International Symposium on Experimental Robotics*, 2016, 299–308.
[104] T. Y. Tsai, C. Y. Chang, M. T. Chung, K. C. Lu, J. F. Huang, and W. P. Shih, "A portable exoskeleton driven by pneumatic artificial muscles for upper limb motion replication", in *ACM International Conference Proceeding Series*, 2018, 133–8.
[105] M. Tsakiris and P. Haggard, "The rubber hand illusion revisited: Visuotactile integration and self-attribution", *Journal of Experimental Psychology: Human Perception and Performance*, 31(1), 2005, 80–91.
[106] V. Vatsal and G. Hoffman, "Design and analysis of a wearable robotic forearm", in *IEEE International Conference on Robotics and Automation*, 2018, 5489–96.
[107] C. Véronneau, J. Denis, L. P. Lebel, M. Denninger, J. S. Plante, and A. Girard, "A lightweight force-controllable wearable arm based on magnetorheological-hydrostatic actuators", in *IEEE International Conference on Robotics and Automation*, 2019, 4018–24.
[108] L. Wang, S. Wang, E. H. Van Asseldonk, and H. Van Der Kooij, "Actively controlled lateral gait assistance in a lower limb exoskeleton", in *IEEE International Conference on Intelligent Robots and Systems*, 2013, 965–70.
[109] E. T. Wolbrecht, D. J. Reinkensmeyer, and J. E. Bobrow, "Pneumatic control of robots for rehabilitation", *International Journal of Robotics Research*, 29(1), 2010, 23–38.
[110] World Health Organization, "International perspectives on spinal cord injury", *tech. rep.*, World Health Organization, 2013.
[111] H. Wu, Y. Wang, J. Qiu, J. Liu, and X. (Luke). Zhang, "User-defined gesture interaction for immersive VR shopping applications", *Behaviour and Information Technology*, 38(7), 2019, 726–41.
[112] Q. Wu, X. Wang, F. Du, and R. Xi, "Modeling and position control of a therapeutic exoskeleton targeting upper extremity rehabilitation", *Journal of Mechanical Engineering Science*, 231(23), 2017, 4360–73.
[113] C. Xu, Y. Liu, and Z. Li, "Biomechtronic design of a supernumerary robotic limbs for industrial assembly", in *IEEE International Conference on Advanced Robotics and Mechatronics*, 2019, 553–8.
[114] A. Zahedi, Y. Wang, N. Lau, W. T. Ang, and D. Zhang, "A Bamboo-inspired Exoskeleton (BiEXO) Based on Carbon Fiber for Shoulder and Elbow Joints", *IEEE Transactions on Medical Robotics and Bionics*, 5(2), 2023, 375–86.

[115] J. Zhang, P. Fiers, K. A. Witte, R. W. Jackson, K. L. Poggensee, C. G. Atkeson, and S. H. Collins, "Human-in-the-loop optimization of exoskeleton assistance during walking", *Science*, 356(6344), 2017, 1280–4.

[116] Q. Zhang, Y. Zhu, X. Zhao, Y. Yang, H. Jing, G. Zhang, and J. Zhao, "Design of Reconfigurable Supernumerary Robotic Limb Based on Differential Actuated Joints", *International Journal of Computer and Information Engineering*, 14(4), 2020, 115–22.

[117] S. Zhao, J. Zhao, D. Sui, T. Wang, T. Zheng, C. Zhao, and Y. Zhu, "Modular robotic limbs for astronaut activities assistance", *Sensors*, 21(18), 2021, 1–18.

[118] Y. Zhou, J. She, Z. T. Liu, C. Xu, and Z. Yang, "Implementation of impedance control for lower-limb rehabilitation robots", *Proceedings - 2021 4th IEEE International Conference on Industrial Cyber-Physical Systems, ICPS 2021*, 2021, 700–4.

[119] Z. Zhu, "ZMP Preview Control of Lower Limb Exoskeleton Robot Based on 3D Linear Inverted Pendulum", in *International Conference on CYBER Technology in Automation, Control, and Intelligent Systems*, IEEE, 2022, 554–7.

[120] Y. Zimmermann, A. Forino, R. Riener, and M. Hutter, "ANYexo: A Versatile and Dynamic Upper-Limb Rehabilitation Robot", *IEEE Robotics and Automation Letters*, 4(4), 2019, 3649–56.

[121] C. Zou, R. Huang, H. Cheng, Q. Chen, and J. Qiu, "Adaptive gait planning for walking assistance lower limb exoskeletons in slope scenarios", in *2019 International Conference on Robotics and Automation (ICRA)*, 2019, 5083–9.