



Review Article

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Wearable Robots for Rehabilitation and Assistance of Gait: A Narrative Review

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Wearable robotic exoskeletons have emerged as promising technologies for enhancing gait rehabilitation and providing mobility assistance in individuals with neurological and musculoskeletal disorders. This narrative review summarizes recent advances in wearable robots—including both rigid exoskeletons and soft exosuits—and evaluates their clinical application across diverse conditions such as stroke, spinal cord injury, cerebral palsy, and Parkinson's disease. For rehabilitation purposes, these devices enable repetitive, task-specific gait training that promotes motor learning, reduces therapist burden, and facilitates improvements in walking speed, balance, and endurance. Rigid exoskeletons provide substantial joint support and are particularly effective for patients with severe gait impairments, whereas soft exosuits offer lightweight assistance suited to individuals with milder deficits or fatigue, albeit with limited capacity to deliver high-torque support. Beyond rehabilitation, wearable robots are increasingly used as assistive devices to compensate for permanent gait limitations and restore mobility in daily life. However, widespread clinical adoption remains constrained by several challenges, including a lack of standardized protocols; limited evidence from large-scale, multicenter studies; and practical issues such as device weight, comfort, and ease of use in community settings. Recent developments—such as adaptive control algorithms, volition-adaptive assistance, and artificial intelligence integration—are addressing these barriers by enabling more personalized and responsive support. With continued research investment, user-centered design, and supportive policies, wearable exoskeletons hold considerable potential to improve independence, participation, and quality of life for individuals across a broad spectrum of mobility impairments.

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INTRODUCTION

Gait impairments affect millions worldwide, particularly those suffering from not only neurological and musculoskeletal disorders, but also aging and associated frailty. With the global rise in the aging population and the incidence of stroke and spinal cord

injuries, there is an increasing demand for effective interventions to restore walking ability because freedom of movement is one of the most fundamental elements for leading a healthy and fulfilling life.

The advancement of robotics is precipitating revolutionary changes across diverse medical fields, notably in rehabilitative

medicine, and presenting new opportunities for incumbent service providers. For individuals with disabilities and the elderly, whose activities are often restricted and societal participation limited, robotic technologies present promising avenues to foster greater autonomy, minimize dependence on caregivers, and enhance overall well-being. Over the past several decades, rehabilitation robotics has progressed rapidly in both scale and sophistication, signaling a paradigm shift in the way rehabilitative care is delivered and managed.

Robot-assisted gait training (RAGT) is increasingly recognized as an effective approach for improving gait and balance, as it enables task-specific and intensive rehabilitation sessions [1]. This is a new global physiotherapy modality that applies robotics technology along with high-intensity repetitive exercises to improve mobility of patients with neuromuscular disorders. RAGT offers a controlled setting that facilitates the delivery of higher therapy intensity and greater training volume. In a study involving children with cerebral palsy (CP), RAGT enabled participants to take nearly 1,000 steps during a 30-minute session, representing approximately 4.7 times the training intensity of conventional therapy [2]. It can also provide the individually tailored therapy settings and reduce the physical burden on the therapist. Therefore, robotics for rehabilitation holds considerable promise, as it delivers at least similar effectiveness with improved efficiency. The development of rehabilitation robots for the lower extremity began in 1994 with the design of the Lokomat® (Hocoma AG), which combined body-weight-supported treadmill training with robotic gait orthosis assistance [3].

Robot-assisted rehabilitation techniques are generally categorized into three types: tethered exoskeletons, end-effector devices, and wearable exoskeletons. Tethered exoskeletal systems, such as the Walkbot® (P&S Mechanics) [4] deliver movement assistance through a rigid, jointed frame that synchronizes with a bodyweight support mechanism to guide the patient's leg motions. End-effector devices, such as the Morning Walk® (Curexo) [5], operate by constraining the distal part of the leg, thereby defining its path while exerting less robotic influence on the proximal joints. Wearable exoskeletons, such as the ReWalk® (Lifeward Ltd.) [6] and Angel Legs® (Angel Robotics Co., Ltd.) [2], are powered suits with articulated joints and onboard control systems, enabling a more natural walking experience [7]. RAGT especially with the tethered devices allows early mobilization and verticalization especially for the patients with acute and severe disabilities. Although most research has not demonstrated a clear advantage of RAGT over traditional reha-

bilitation approaches, there is evidence to suggest that individuals who are non-ambulatory may gain more from RAGT than those who can already walk. As recovery of locomotor ability progresses—especially in proximal joints—patients may transition from tethered exoskeletal support to end-effector devices. This can then be followed by gait training on level ground using wearable robotic exoskeletons with minimal assistance [8].

Wearable powered exoskeletons offer the benefits of fixed robotic systems while enabling gait training in real-life settings, thereby promoting greater user engagement and presenting increased physical challenges [9]. Their use is rapidly expanding across various fields, including healthcare, rehabilitation, assistive technology, military, and industrial applications [10]. Early designs of wearable powered exoskeletons primarily targeted individuals with near-complete paralysis due to spinal cord injury (SCI), a population for whom gait training imposes significant physical demands on therapists [6]. As clinical adoption of wearable locomotor training devices grows, their use has extended to individuals with diverse conditions—such as incomplete SCI and stroke—who often benefit from either reduced support or tailored asymmetrical assistance [8]. Moreover, wearable devices have recently been developed using various materials, such as rigid or soft components, and have been designed to support different body parts and assistive strategies. These innovations support ongoing rehabilitation beyond the hospital setting and assist in addressing remaining functional impairments during everyday activities. Given the recent rapid advancements and growing interests, this review explores the technologies underpinning wearable robots focusing on their application and clinical efficacy across various conditions in the context of gait rehabilitation and mobility assistance, then also discuss the challenges and future directions.

OVERVIEW OF WEARABLE ROBOTIC GAIT SYSTEMS

Wearable robotic gait systems can be classified into two major types: rigid exoskeletons and soft exosuits. Rigid exoskeletons consist of powered actuators that provide joint movement through a rigid structure. They are often heavy and bulky due to the rigid structure, actuators, and batteries. For instance, the average weight of hip-knee exoskeletons for adults is about 15 kg. This weight, which is more than half the weight of an average adult human leg, can add to the metabolic cost. However, this rigid structure can support user body weight and facilitate

a more efficient transfer of high assistive torque to severely weakened limbs. In contrast, soft exosuits are made of flexible materials and typically used to augment gait in individuals with mild impairments or fatigue. Most soft exosuits are based on wire-driven actuation mechanisms, which offer lighter weight and less restriction but limit assistance for individuals with severe motor impairments [11].

In addition to this distinction between rigid and soft designs, these wearable robotic gait systems can also be categorized by the joints they actuate, with various commercially available devices targeting the hip, knee, and ankle in different combinations (Fig. 1).

Furthermore, their application can be broadly divided into two main purposes: rehabilitation and assistance. The first application is aimed at replacing traditional, therapist-assisted gait training with RAGT. Numerous neuroscience studies have demonstrated that damaged brain and spinal cord functions can be partially recovered through repetitive rehabilitation therapy. Such rehabilitation therapy promotes functional recovery through repetitive training based on appropriate assistance provided by a therapist. This reliance on human skill and expe-

rience poses challenges for standardizing treatment quality and limits the duration of therapy. Robotic rehabilitation equipment can deliver prolonged, repetitive training in a more precise, objective, and standardized manner, thereby maximizing functional recovery.

The second application involves assisting individuals with permanent or progressive physical impairments. Even with advanced rehabilitation, some degree of residual disability often remains, particularly in conditions such as lower limb paralysis or age-related muscle weakness. Mobility impairments are a major barrier to social participation and quality of life. Traditional assistive tools such as lower limb orthoses, canes and walkers offer limited compensation due to their passive mechanics and fixed structural properties. As a result, they are not suitable for all users and often provide suboptimal functional improvement. To address these limitations, wearable robotic technologies that actively assist movement by detecting user intent and applying power at key joints have emerged as promising solutions—especially for conditions such as sarcopenia and neuromuscular disorders [9].

As described above, wearable robotic gait systems can be

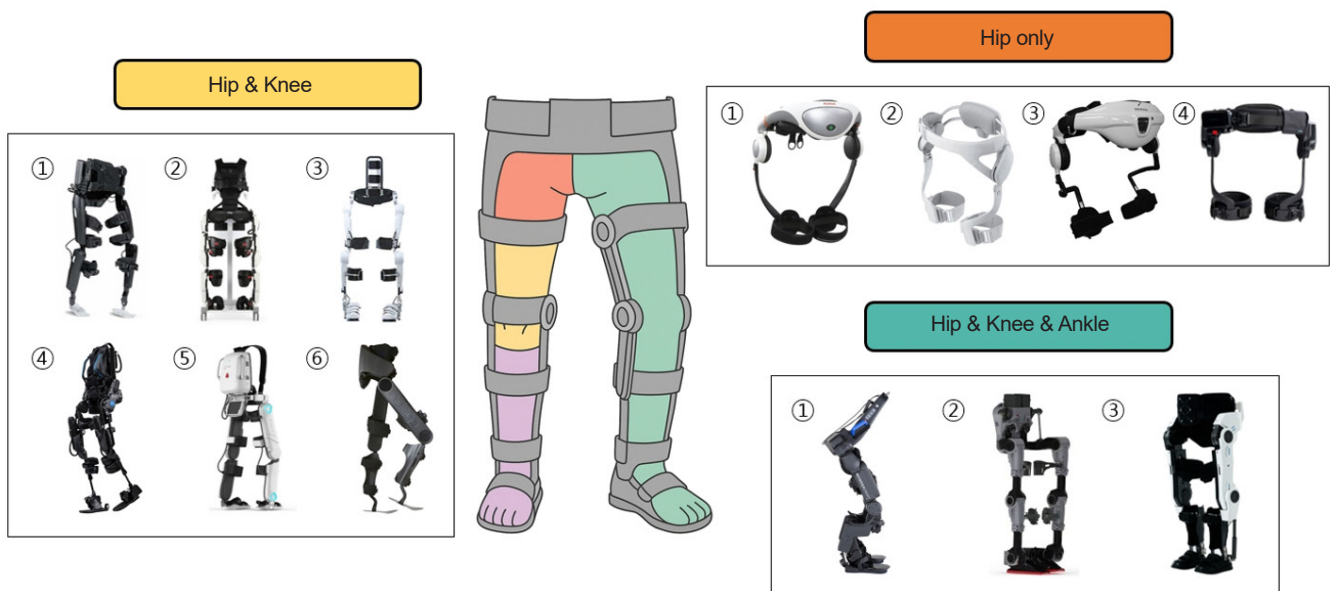


Fig. 1. Classification of lower-limb wearable robotic exoskeletons by joint actuation level. Wearable robotic exoskeletons can be categorized based on the joints they assist—hip only, hip and knee, or hip, knee, and ankle. Representative devices for each category are illustrated. Hip & Knee: ① ReWalk® (Lifeward Ltd.), ② Angel Legs M20® (Angel Robotics Co., Ltd.), ③ HAL® (CYBERDYNE Inc.), ④ Ekso GT® (Ekso Bionics), ⑤ BEAR-H1® (Milebot Robotics), ⑥ Indego® (Parker Hannifin Corporation). Hip only: ① SMA® (Honda R&D Co., Ltd.), ② GEMS® (Samsung Electronics Co., Ltd.), ③ HWA-01® (Honda R&D Co., Ltd.), ④ Angel Legs H10® (Angel Robotics Co., Ltd.). Hip & Knee & Ankle: ① Atalante X® (Wandercraft), ② XoMotion® (Human In Motion Robotics), ③ WalkOn Suit® (Angel Robotics Co., Ltd.).

broadly classified by structural design, targeted joints, and clinical application [12]. Among these, the following sections will elaborate on two major applications—rehabilitative and assistive use—in more detail.

CLINICAL EVIDENCE OF RAGT USING WEARABLE ROBOT-ASSISTED GAIT TRAINING

Stroke

Wearable robot-assisted gait training (w-RAGT) clinically applied in stroke rehabilitation can be categorized into rigid and soft devices. Rigid devices include HAL® (CYBERDYNE Inc.), Ekso GT® (Ekso Bionics), BEAR-H1® (Milebot Robotics), and Angel Legs M20® (Angel Robotics Co., Ltd.) which support the hip and knee joints, as well as devices such as SMA® (Honda R&D Co., Ltd.) and GEMS® (Samsung Electronics Co., Ltd.), which primarily assist the hip joint [13–19]. In contrast, soft exosuits have not yet been widely commercialized, although active research and development are ongoing in this area [20]. These systems are used under therapist supervision to facilitate overground gait training and promote active trunk and limb movement.

A systematic review and meta-analysis demonstrated w-RAGT significantly improves walking speed and balance compared to dose-matched conventional gait training (CGT). Most studies suggest that effective interventions typically consist of sessions lasting 45–60 minutes, performed three to five times per week for at least four weeks [21]. In particular, w-RAGT in individuals with chronic stroke (more than six months post-onset) showed superior improvements in walking speed, balance, and endurance compared to the CGT group [13,22], whereas no greater benefits have been observed over CGT in the earlier stages of recovery [16,19].

Among recent studies, an interim analysis involving 93 subacute stroke patients reported that overground gait training with a torque-assisted exoskeleton showed gait function improvement comparable to conventional rehabilitation, with additional gains in lower extremity strength [23].

Moreover, w-RAGT is actively exploring new strategies for correcting gait asymmetry, such as adjusting hip joint stiffness, with promising initial results. Studies on unimpaired individuals have shown neural adaptation for symmetric gait retraining using bilateral asymmetric hip stiffness [24,25], and research with healthy subjects mimicking hemiplegic gait through ar-

tificial impairment has demonstrated effective gait symmetry restoration with adaptive torque control [26]. However, their therapeutic effectiveness for correcting gait asymmetry in actual stroke populations remains to be fully validated.

SCI

For w-RAGT of SCI patients, several clinical studies have reported improvements in key gait parameters such as walking speed, step length, cadence, and lower limb motor scores following robot-assisted interventions, particularly in individuals with incomplete SCI. For example, HAL® has been applied during the early and subacute phases of rehabilitation after spinal decompression, with significant gains in locomotor outcomes and no adverse events [27]. Similarly, short-term application of the hip-focused robotic device HWA-01® (Honda R&D Co., Ltd.) in individuals with chronic SCI resulted in improvements in walking speed and step length [28].

Moreover, a recent network meta-analysis further highlighted the superior effectiveness of overground wearable exoskeletons in improving walking speed compared to treadmill-based robotic systems, as evidenced by greater gains in the 10-Meter Walk Test [29]. Collectively, these findings support the therapeutic value of wearable robotic exoskeletons as rehabilitation devices for enhancing locomotor outcomes in individuals with SCI.

Meanwhile, unlike brain injury populations who often present with cognitive dysfunction, the presence of cognitively intact individuals in certain groups has enabled a broader range of experimental applications and innovative approaches using wearable exoskeletons. For example, systems incorporating volition-adaptive control—which use neural signals to trigger and modulate exoskeleton assistance in real time—have enabled user-intent-driven gait training, leading to personalized movement trajectories and progressive improvements in joint kinematics [30].

CP

Distinct from other adult-onset neurological disorders, CP children present with unique gait characteristics shaped by early-onset spasticity and developmental motor impairments, prompting the exploration of w-RAGT as a targeted intervention to improve walking efficiency and motor control. Notably, w-RAGT offers advantages in promoting active engagement—a key factor for successful pediatric RAGT—[31] and recent randomized controlled trials have demonstrated its effectiveness in

improving gross motor function, gait symmetry, balance, and endurance [2,32].

Moreover, resistance-based training protocols have been proposed based on motor learning principles to target selective muscle recruitment during the propulsive phase of gait. For example, short-term interventions with ankle exoskeletons providing adaptive resistance have resulted in significant gains in plantar flexor activity, reduced co-contraction with antagonist muscles, and improved biomechanical gait parameters such as increased ankle push-off power and reduced metabolic cost of transport [33].

Parkinson's disease

In patients with Parkinson's disease (PD), wearable robotic exoskeletons are used not only to compensate for muscle weakness and provide experience of normative gait patterns—the traditional goal of RAGT, but also to specifically target and correct characteristic pathological gait features such as reduced stride length, hypokinesia, and freezing of gait. Several recent clinical studies demonstrate the feasibility and efficacy of RAGT in this population [34,35]. For example, w-RAGT using hip exoskeletons with adaptive oscillators, which assist hip motion based on real-time joint angles rather than fixed patterns, has been shown to improve natural gait variability and key gait outcomes [36,37]. Additionally, another study has proposed RAGT protocols that integrate functional magnetic resonance imaging and electroencephalography data synchronized with rigid exoskeletal robots, enabling the design of rehabilitation strategies that simultaneously address both neuromuscular and biomechanical features [38].

Other conditions

In addition to aforementioned major neurological conditions, wearable robotic exoskeletons have been applied to a wide range of pathological neurologic disorders, including multiple sclerosis [39], cerebellar ataxia (such as spinocerebellar ataxia and multiple system atrophy) [40,41], essential tremor, Huntington's disease [42], myelomeningocele or spina bifida [43], peripheral nerve injuries, and chronic inflammatory demyelinating polyneuropathy [44], as well as in patients with gait impairments after brain tumor surgery and poliomyelitis [45].

Beyond neurologic disorders, these systems have also been used in musculoskeletal conditions—particularly for gait rehabilitation following total knee arthroplasty in osteoarthritis and rheumatoid arthritis, and post-operative recovery after anterior

cruciate ligament reconstruction [46], as well as for patients with spinal stenosis and ossification of the posterior longitudinal ligament [47,48]. Furthermore, wearable robots have shown promise in critically ill patients, such as improving mobility and exercise tolerance in patients with chronic lung disease and advanced heart failure [49,50]. They are also increasingly utilized in aging-related conditions, including elderly individuals with reduced mobility and transfemoral amputees, and even in those recovering from lower extremity burn injuries [51-53]. While these expanding applications highlight the versatility of wearable exoskeletons, further robust, disease-specific clinical studies are necessary to establish their efficacy across these diverse populations.

ASSISTIVE USE OF ROBOTIC GAIT ORTHOSES

Many wearable robots are designed not only for therapy but also for day-to-day use. These assistive orthoses are valuable tools for restoring independence in individuals with permanent mobility loss. Wearable devices exhibit considerable diversity depending on the specific joints they assist and the intended purpose of assistance. The initial development of wearable robots for assistive use of gait impairment group originated in lower limb paralysis, such as those with complete SCI, who rely on wheelchairs for mobility. The first pilot study evaluating the ReWalk® exoskeleton suit for ambulation in individuals with complete SCI was published in 2012 [6]. Since then, assistive robotic devices such as HAL®, Indego® (Ekso Bionics), and WalkON Suit (Angel Robotics Co.) [54], have been developed to address the limitations of earlier-generation exoskeletons. However, the practical implementation of these early versions of assisted wearable robots was often limited. Key challenges included the overall weight of the robot, the need for batteries capable of sustaining high power demands, and pre-programmed movement trajectories that made it difficult to adapt to various walking environments. Additionally, real-world adoption remains restricted by safety concerns, difficulties in navigating uneven terrain, and the inability to perform hands-free tasks, which continue to pose barriers to widespread use in home and community settings [55].

With advancements in actuator technology and controller precision, which allow more refined and adaptive motion control, efforts have been made to overcome these limitations. One notable direction has been the development of robots that assist

only selective joints rather than the entire lower limb. For instance, hip-assist robots have been applied to aging populations. A soft robotic hip exosuit has been shown to instantly eliminate freezing of gait in medication-refractory PD and improve stride length and walking speed, although the study was limited to a single subject [56]. In addition to the hip-assist robots, robotic devices targeting other joints such as the knee and ankle joints have also been developed and applied to populations with neurologic impairments, such as stroke, and CP.

Beyond patient applications, the scope of exoskeleton technology is evolving towards alleviating locomotion burden for able-bodied individuals and potentially extending to those with diverse gait impairments. Supporting this broader applicability, recent research reports a custom hip exoskeleton achieving a notable reduction in walking metabolic rate by an average of 24.3% in non-disabled healthy persons [57].

However, despite numerous attempts to explore their clinical potential, most reports remain at the level of case studies involving a very limited number of patients or have shown effectiveness only under constrained walking environments [58-60]. Accordingly, large-scale investigations across diverse populations are essential to validate the clinical efficacy of these devices beyond constrained experimental settings.

CURRENT CHALLENGES AND FUTURE DIRECTIONS

As discussed above, a variety of wearable robotic exoskeletons have been developed and utilized for diverse purposes, including both rehabilitation and assistive applications. However, several challenges remain before these technologies can achieve widespread and effective integration into routine clinical and daily life settings as below.

First, the clinical integration of wearable robotic devices remains challenging due to a lack of sufficient evidence guiding their use across diverse patient populations and device types. Establishing clinical validity is essential but time-consuming and expensive, leaving key parameters—such as indications, timing, frequency, and intensity—undefined. With numerous devices and varied clinical presentations, clearer guidance on selection and settings is still needed [8].

Second, human-robot interaction is crucial but underexplored compared to technical performance. Wearable robots exchange mechanical and physiological signals with the user, and misalignment from poor fitting can cause discomfort, higher

metabolic cost, or injury. The weight and bulk of many current devices also reduce usability [11]. Improving interaction quality is essential for safety and efficiency. Further research and developments are needed, such as advanced sensing for better user intent detection or the development of more compliant and adaptive control strategies.

Third, although personalization plays a key role in enhancing the effectiveness of wearable robots, related research remains insufficient. Adaptive approaches, such as assist-as-needed control using torque-assisted wearable robots, can adjust joint-level force based on the user's effort [2,8,11,61]. These systems are essential for maximizing motor learning by promoting active participation and dynamic gait pattern adaptation. Artificial intelligence (AI) integration further enables real-time responsiveness to movement and environmental demands [62]. Given the diversity of user needs, wearable robots must be designed with user-specific adaptability rather than relying on a one-size-fits-all solution.

Fourth, wearable robots should be developed to meet the specific size, weight, and fit requirements of children, who differ significantly from adults in anthropometry [2]. To address this, lightweight designs and mechanisms that allow continuous adjustment for growth are essential, as the wide variability in body size presents unique challenges in achieving effective and adaptable pediatric applications.

Fifth, expanding wearable robot use into home and low-resource environments requires innovations that improve affordability, accessibility, and ease of use [8]. High device costs, lengthy donning/doffing processes, and fitting challenges are major barriers [11,63]. Despite these issues, opportunities remain for innovation to make wearable robotic solutions more practical and widely available.

CONCLUSION

Wearable exoskeletons have shown significant potential to enhance mobility and independence in individuals with neurological and musculoskeletal conditions, including stroke, SCI, CP, and PD [64]. While clinical evidence is expanding, challenges remain in translating research into real-world practice. To maximize their impact, continued research, technological innovation, and supportive policy frameworks are essential. Successful adoption depends on user-device co-adaptation and designs that reflect the practical needs and lived experiences of end-users. As rehabilitation enters a new era driven by ad-

vanced technologies—such as robotics, AI, sensor systems and augmented reality—these tools are reshaping clinical practice. This transformation underscores the growing importance of interdisciplinary collaboration, particularly the role of engineers as key contributors within rehabilitation teams to ensure the effective development and implementation of wearable robotic systems [8].

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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