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A review on robotic exoskeletons for the assistance of musculoskeletal rehabilitation

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Abstract. Musculoskeletal health refers to the performance of the locomotive system, which comprises of muscles, bones, joints, and adjacent connective tissues. Globally, musculoskeletal disorders are the primary cause of disabilities. Mechatronic devices called robotic exoskeletons are made to help people to improve performance of locomotive system. Robotic exoskeletons devices can assist to restore joint mobility, increase muscle strength and enable highly precise and consistent repetitive motion training. In traditional physiotherapy, frequently finds difficult to deliver such things. In addition to providing a thorough analysis of robotic exoskeleton systems, including their framework, sensors, actuators, and control architectures, as well as their functional role in rehabilitation, this paper introduces the general concept of exoskeletons. The application of exoskeletons in musculoskeletal rehabilitation, their performance benefits, limitations of currently developed exoskeletons, and the future scope and emerging trends in this field are also discussed.

1 Introduction

Musculoskeletal conditions are characterized by limitations in mobility and reducing people's ability to walk and work. A study of the Global Burden of Diseases, conducted by the Institute for Health Metrics and Evaluation (IHME) in 2021, states that approximately 1.71 billion people are affected by musculoskeletal disorders, making them the largest contributor to disabilities in the world [1]. Although the occurrence of these conditions varies with age, people of all age groups are being affected by them.

Rehabilitation plays a pivotal role in restoring the mobility, strength, and functional independence in patients affected by musculoskeletal disorders. The World Health Organization's (WHO) 'Rehabilitation Need Estimator' states that around 2.5 billion people experienced conditions that could be satisfied through rehabilitation [2]. This data also states that 340 million years have been lived with disability, out of which musculoskeletal disorders have been a leading cause as seen in Fig. 1. Conventional rehabilitation is performed through physiotherapy, in which the results and outcomes heavily depend on the expertise of the therapist. In many countries, rehabilitation is not considered as a priority even though a lot of people are affected by it. Due to this, the rehabilitation needs are not

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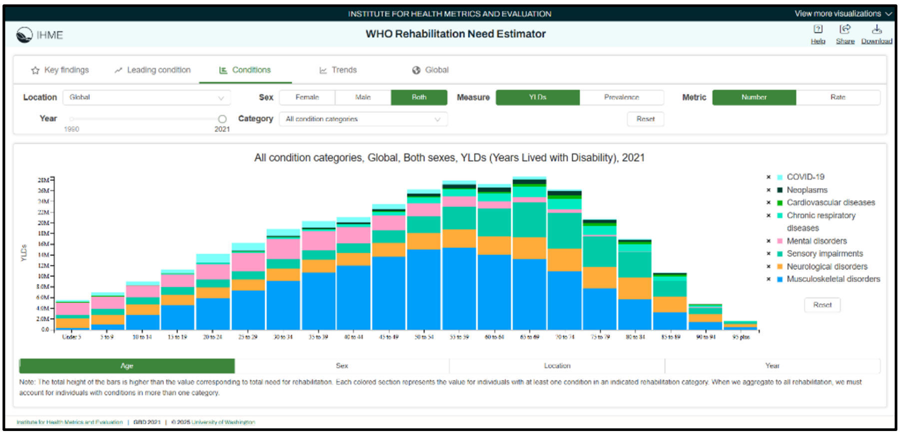
satisfied and lifelong consequences are faced by the people. The quality and intensity of therapy sessions can also vary widely because delivering repetitive therapy manually is physically demanding for physiotherapists, limiting the duration and frequency of the sessions. This leads to inconsistent patient outcomes.



Note: The total height of the bars is higher than the value corresponding to total need for rehabilitation. Each colored section represents the value for individuals with at least one condition in an indicated rehabilitation category. When we aggregate to all rehabilitation, we must account for individuals with conditions in more than one category.

Fig. 1. Years Lived with Disability [2]

To overcome these limitations, technologically sophisticated solutions like robotic exoskeletons are developed. Robotic exoskeletons help to satisfy the requirements for consistency, adaptability, and successful therapy, such attributes are absent in traditional rehabilitation techniques. Robotic exoskeletons are biomechatronic devices intended to improve human strength, gait, and motor function [3]. It works with the embedded software systems that monitor biomechanics in real time, detect user intent (using sensors or external commands), and assist or resist motion. Exoskeletons are sophisticated therapeutic tools in musculoskeletal rehabilitation. Exoskeletons allows for guided, repetitive, and task-specific movement to support neuromuscular rehabilitation, facilitate gait training, and improve muscle engagement. It is beneficial in patients affected by stroke, spinal cord injury, orthopedic trauma, or age-related degeneration.

In musculoskeletal rehabilitation domain, the development of robotic exoskeletons is an interdisciplinary process that combines advances in material science, biomechanics, robotics, and rehabilitation medicine. Development started out as a military-industrial project in the early 1960s [3] and has matured now as a life-changing medical technology used at rehabilitation centers, hospitals, and even homes.

The review is intended to present a thorough analysis of robotic exoskeleton systems as a cutting-edge approach to musculoskeletal rehabilitation. This paper presents the current state of exoskeleton technology, includes key components and control strategies, and critically analyzes the current challenges, research gaps, and future trends, including the integration of artificial intelligence.

2 Classification of exoskeletons

Robotic exoskeletons can be classified using several criteria, with respect to design, clinical use, and therapeutic objectives. The most common classification is based on the body part being assisted (limb coverage). Modern exoskeletons differ significantly in actuation, control logic, materials, and functionality. Based on limb coverage, exoskeletons are classified into three categories. Lower limb exoskeletons assist in walking, standing, and sit-to-stand transitions. They are clinically used for gait rehabilitation in stroke, spinal cord injury, multiple sclerosis, and orthopaedic recovery. Some examples of lower limb exoskeletons are

Lokomat [4], ReWalk [5], EksoGT [6], and Honda Walking Assist [7]. Upper limb exoskeletons support shoulder, elbow, wrist, and hand movement. They are clinically used for Hemiplegia after stroke, muscle atrophy, and cerebral palsy. Armeo Spring [8], Myomo e100 [9], ReGrasp [10] are some examples of upper limb exoskeletons. The third category is full-body exoskeletons, which support both upper and lower limbs, sometimes including trunk support. They are clinically used for patients with complete spinal cord injury or extensive neuromuscular degeneration. Some popular full-body exoskeletons are HAL (Hybrid Assistive Limb) [11], ExoAtlet II [12], Phoenix [13]. Some of the examples can be seen in Fig. 2.

(1) (2) (3)

Fig. 2. Exoskeletons categorized based on limb coverage 1. ReWalk (lower-limb) [5], 2. MyoPro Hand Brace (upper-limb) [14] 3. EksoGT (lower-limb) [6]

Based on actuation methods, they can be classified into active, passive and hybrid exoskeletons. Active exoskeletons are equipped with powered actuators (motors, hydraulics, or pneumatics) to generate movement. They actively assist or resist user motion based on intent or preprogrammed patterns. Examples of active exoskeletons are EksoGT [6], HAL [11], and ReWalk [5]. Passive exoskeletons use springs, dampers, or elastic bands to store and release energy, instead of powered actuators. They provide support and resistance, not movement and are often used for fatigue reduction or joint offloading in workplace settings. Example of a passive exoskeleton is the Auxivo – Liftsuit [15]. Dynamic alteration of passive and active modes according to task and fatigue level, hybrid exoskeletons maximizes energy efficiency and user comfort. Table 1 shows a comparative analysis of representative exoskeletons, describing their design, control, and main clinical applications, to give a better picture of the current situation.

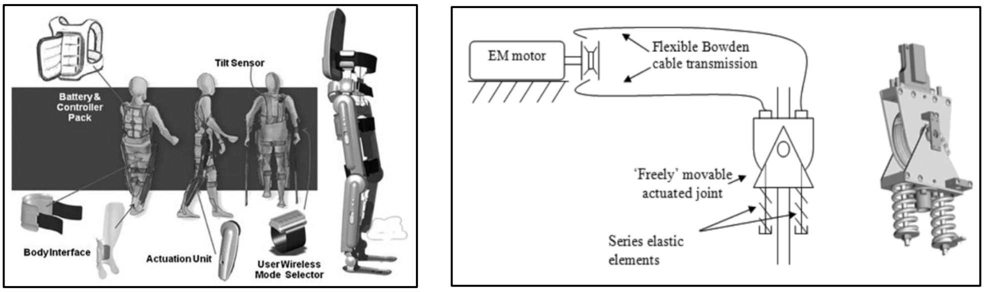
Table 1. Comparative Analysis of Representative Robotic Exoskeletons

Sr. No.	Exoskeleton	Body Part	Actuation	Control Strategy	Primary Application	Reference
1	ReWalk	Lower-limb	Active (Electric Motors)	User-initiated (tilt sensor)	Spinal Cord Injury (SCI)	[5]
2	EksoGT	Lower-limb	Active (Electric Motors)	Assist-as-Needed	Stroke, SCI	[6]
3	Lokomat	Lower-limb	Active (Electric Motors)	Preprogrammed Trajectory	Stroke, SCI, Gait Training	[4]
4	HAL	Full-body	Hybrid (Active)	EMG-driven (bio-adaptive)	Stroke, SCI	[11]

5	MyoPro	Upper-limb	Active (Electric Motors)	EMG-driven	Stroke, Hemiplegia	[9]
6	Myosuit	Lower-limb	Active (Textile-based)	Adaptive	Elderly, Frailty, Post-surgery	
7	Harvard Wyss Exosuit	Lower-limb	Active (Cable-driven)	Gait-event-based	Post-stroke, Gait assist	[16]

3 Components of exoskeletons

Real-time support and rehabilitation to the patients is possible due to an exoskeleton's intricate and multidisciplinary structure integrating mechatronics, control theory, biomedical sensors and computational intelligence. Fig. 3(1) shows an example of a schematic of the ReWalk exoskeleton. The mechanical frame is usually made from lightweight yet durable materials such as aluminium alloys, carbon fibre, or titanium. The design must align accurately with biomechanical joints to ensure natural motion and avoid discomfort or injury. The frame acts as the exoskeleton's "skeleton." Actuators generate assistive force for joint movement, control joint speed, torque, and position, and enable adaptive resistance in training modes. They are the "muscles" of the exoskeleton, producing motion at joints. Most used type of actuators are DC/brushless electric motors due to their precision, compactness, and efficiency [17]. Hydraulic actuators offer high torque, but are bulky. Pneumatic actuators are lightweight and compliant, and are often used in soft robotics, whereas series elastic actuators incorporate springs to improve compliance and safety. The schematic representation of actuators used in the LOPES exoskeleton [18] can be seen in Fig. 3(2).



(1) (2)

Fig. 3. Exoskeleton Structures 1. Schematic of the ReWalk exoskeleton system [5] 2. Schematic representation of the actuators used in LOPES exoskeleton [18]

Sensors provide the real-time data required for feedback control, safety, user monitoring, assist-as-needed algorithms, movement correction and calibration, and patient progress tracking and diagnostics. Some common sensors used are [17] inertial measurement units, force and pressure sensors, electromyography sensors, encoder sensors, and torque sensors. They are used for the detection of joint angles, orientation, and acceleration, measurement of ground reaction forces, foot placement, and load distribution, capture muscle activation signals for intent detection, track joint rotation and positioning, and monitor joint load to modulate actuator output respectively.

The control system acts as the “brain” of the exoskeleton, coordinating actuators and sensors in real-time to produce smooth, safe, and responsive motion. Exoskeleton software includes embedded firmware and user interfaces, often integrated with cloud platforms for remote updates and monitoring. The key components include motion control modules, sensor integration layers, user interface software (for therapists/patients), and data logging and analysis modules [19,20]. In order to guarantee accurate and timely responses, the interfaces frequently operate on real-time operating systems. Depending on the function, degree of support, and user input capability of the exoskeleton, different kinds of control algorithms [19, 20] are employed. EMG-driven control [11,9] uses electromyographic signals from the user's muscles to detect movement intent; machine learning/AI-based control [21] predicts user needs and adapts the assistance based on patterns in motion and recovery history, enabling personalized therapy plans and long-term monitoring; position control moves joints through predetermined trajectories; impedance control regulates interaction forces between the exoskeleton and the user, allowing for more natural movement by adapting to user effort. Advanced control systems detect faults via software. These systems monitor joint temperature, battery voltage, sensor connectivity, and actuator load. Errors in these parameters automatically trigger shutdown, safe mode transitions, or alerts to users and clinicians. Such fall detection system can be seen in the Smart Walking Assistant for elderly care [22]. The proposed architecture of this can be seen in Fig. 4. Feedback channels include visual, auditory, and haptic channels, used for corrective feedback, motivation, and performance tracking.

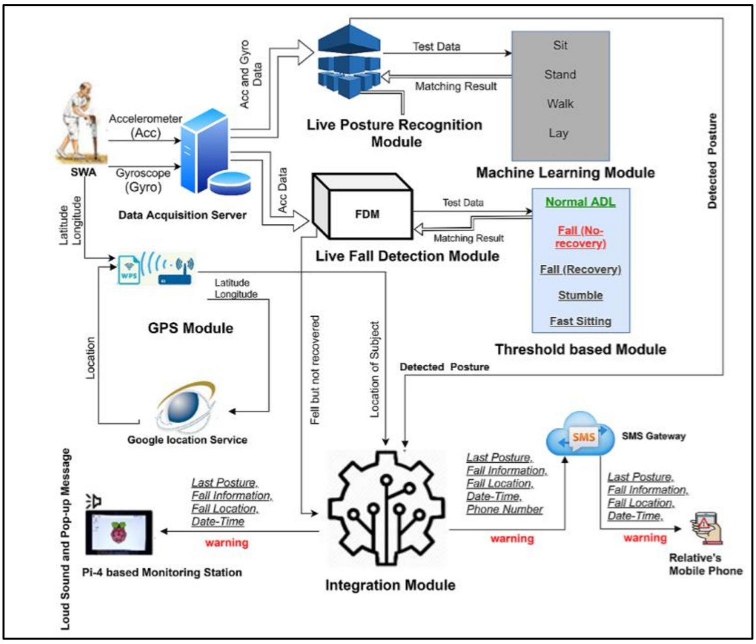


Fig. 4. System architecture of the Smart Walking Assistant for elderly care [22]

4 Applications in musculoskeletal rehabilitation

Stroke remains one of the leading causes of adult disability, often resulting in hemiplegia or motor impairment affecting gait and upper-limb function [23]. Robotic exoskeletons play an important role in delivering repetitive, symmetric, and guided gait training that promotes motor relearning, stimulating neuroplasticity by enabling thousands of consistent step cycles or arm movements per session, supporting early mobilization in sub-acute phases, where recovery potential is highest. Exoskeletons like Lokomat [4] – for treadmill-based gait therapy, EksoGT [6] – for overground walking practice, and Myomo [9] – for upper-limb rehabilitation with gravity support and biofeedback, all work for post-stroke gait and muscle rehabilitation. The clinical benefits of exoskeletons are also proven for improved balance, stride length, and walking speed and restoration of hand coordination and reach in patients, by physiotherapists [24].

Patients with partial or complete lower limb paralysis due to spinal cord injury benefit significantly from exoskeletons that enable re-learning of walking skills through assisted, weight-bearing steps and reduction in muscle atrophy and spasticity due to improved circulation and controlled motion. Psychological benefits from standing and walking, including increased self-esteem and social reintegration. Exoskeletons like ReWalk [5] and HAL [11] show significant improvements in patient results and therapy sessions [25,26]. These systems have EMG or joystick-triggered motion and adjustable support levels for patients with varying degrees of residual function. Both these systems are FDA-cleared for both clinical and home environments.

Exoskeletons enable early mobilization following procedures such as hip arthroplasty, knee replacement, or ligament reconstruction to avoid complications like muscle atrophy and joint stiffness. The use of exoskeletons for such applications facilitates quicker recovery, shorter hospital stays, and lessens the effort required of therapists to support and direct early ambulation. Exoskeletons like Honda Walking Assist [7] and ExoAtlet [12] are used in these applications. Aging populations often face sarcopenia (loss of muscle mass, strength, and function), reduced balance, and fall risk due to musculoskeletal degeneration. Exoskeletons are designed to help in such cases by supporting safe walking and daily activities with partial limb assistance, enhancing confidence, independence, and physical activity levels, and reducing caregiver dependence and improving quality of life [27]. The exoskeletons used for this application are soft, lightweight, have textile-based support, and are designed for community and home-based rehabilitation. In addition to this, exoskeletons are increasingly being used for targeted rehabilitation and performance optimization in athletes recovering from ligament injuries, tendon ruptures, stress fractures, or post-operative corrections. This shortens time to return-to-play, and reduces reinjury risk through sensor-driven feedback and gait retraining. Other emerging applications [27] include use of exoskeletons support fatigue management and gait symmetry in progressive multiple sclerosis patients, also improving endurance and walking confidence and in children with cerebral palsy [28] to assist with early gait training and motor learning, and helps in building neuromuscular coordination.

5 Performance benefits

The clinical effectiveness of robotic exoskeletons is validated by a growing body of evidence demonstrating measurable improvements in functional recovery. Efficacy is typically quantified using standardized clinical metrics, which provide objective data on patient progress. Table 2 summarizes the most common metrics used in clinical trials [29].

Table 2. Gait Performance Metrics [29]

Outcome Measure	Purpose	Typical Robotic Therapy Results

10-Meter Walk Test (10MWT)	Measures gait speed (m/s) over 10 meters	10–50% increase in walking speed post-intervention
6-Minute Walk Test (6MWT)	Assesses endurance by distance walked in 6 minutes	Up to 30–60% increase in stroke and SCI patients
Timed Up and Go (TUG)	Evaluates basic mobility and fall risk	Reduction in time by 10–25%
Functional Ambulation Category (FAC)	Measures level of independence during walking	Patients often improve by 1–2 FAC levels

5.1 Gait and locomotor recovery (stroke and SCI)

The most extensive research has focused on post-stroke hemiparesis and spinal cord injury (SCI). For stroke patients, electromechanical-assisted gait training, when combined with physiotherapy, significantly improves the chances of regaining independent walking [30]. Scoping reviews confirm that powered exoskeletons increase gait speed, endurance, and patient motivation compared to conventional therapy alone [31,32]. Significant functional improvements were observed in a male stroke patient aged sixty two. The patient was put on EksoGT [31] exoskeleton for eighteen sessions. The patient's FAC score improved from Level 2 (needing constant manual assistance) to Level 4 (capable of walking independently on level surfaces) and 10MWT speed increased by 60.5%.

Powered exoskeletons add an innovative approach to overground, weight-bearing ambulation for people with SCI. Use of ReWalk exoskeleton has demonstrated that people with thoracic-level SCI can walk functionally, with additional advantages like better bowel or bladder function and less spasticity. A thirty four year-old wheelchair-bound woman has a T11 complete SCI and received training on ReWalk Personal 6.0 system [5]. She reported a 42.8% decrease in pain, demonstrated a 53.8% improvement in depression scores. She was able to finish the 6MWT with 312 meters after six weeks, demonstrating both functional and significant psychological benefits.

5.2 Upper-limb and hand rehabilitation

Upper-limb exoskeletons are showing promise in task-specific training, despite their rarity. The domain of upper-limb exoskeletons has been greatly expanded by recent soft robotics research [33]. Researchers have demonstrated that fabric-based soft robotic (SR) gloves are a practical and useful tool for patients with chronic stroke [34]. A soft robotics tool gives repetitive, task-specific hand opening and closing motion. These attributes aids in quantifiable gains in hand strength and function. The performance benefit of these new devices lies in their advanced EMG-based adaptive control [35]. An adaptive learning strategy can actively work to minimize the user's own muscle effort, ensuring the exoskeleton provides assistance that is complementary to the patient's intent and residual strength.

5.3 Orthopaedic, geriatric, and pain-related benefits

The application of exoskeletons is expanding to new patient populations including geriatric care and orthopedic recovery. Lightweight, soft exosuits are particularly effective for older adults or those recovering from joint replacement surgery. A seventy six year-old female with frailty syndrome recovering from a total knee replacement used the Myosuit [36] (a soft, textile-based device). After twelve sessions, her TUG time decreased by 37.1%, her

6MWT distance increased by 60.6%, and her "fear of falling" score (FES-I) decreased by 32.1%.

A 2022 systematic review highlighted the emerging use of exoskeletons for non-specific low back pain (NSLBP) [37]. Studies found that exoskeletons can significantly reduce pain (measured by the Visual Analog Scale) and improve functional disability, suggesting a promising new application for orthopedic rehabilitation [37].

5.4 Qualitative benefits (patient and therapist perspectives)

Qualitative feedback goes beyond quantitative data to show how robotic exoskeletons technology improves performance in the real world. Exoskeletons reduces the considerable physical strain that comes with manually assisted gait training for therapists, particularly when working with patients who have severe SCI [24]. Better clinical decisions and programmable, progressive treatment plans are made possible by the integrated data-logging. It gives a real-time feedback on patient performance. SCI users describes the emotional boost of being able to stand and walk again, report feeling more independent and hopeful [5]. The safe, regulated setting increases trust and motivation to participate in more intense therapy by lowering the fear of falling.

5.5 Critical analysis of current clinical evidence

Robotic exoskeletons have shown therapeutic potential in a number of studies and case reports. In this domain, still significant clinical research methodology issues that need to be resolved for the technology to be widely used and covered by insurance. The statistical power and generalizability of the results are limited by the small sample sizes (10–50 participants) used in the majority of trials to date. It is challenging to assess long-term results, sustainability of improvements, or relapse risk, particularly for chronic conditions, because studies are frequently brief (2–8 weeks).

Another challenge is to get an ideal patient profiles for particular devices. Trials frequently group patients with wide variability in injury type, recovery phase (acute vs. chronic), and age. Cross-study comparisons are difficult due to the lack of standardization in assessment instruments and procedures. A significant research gap exists in high-quality studies for pediatric (e.g., cerebral palsy) and geriatric (e.g., frailty reversal) applications.

6 Limitations and challenges

6.1 Technical and design hurdles

The implementation of important mechatronic systems is the main source of technical limitations rather than the concept itself. Accurately determining user intent is a significant challenge in the human-robot interface (HRI) [38]. In case of EMG-based systems like HAL, many exoskeletons still have trouble in achieving a smooth, user-friendly control that can adjust to non-rhythmic movements or user fatigue [39]. Patients may become frustrated, if the device feels sluggish or counterintuitive due to this weak "intent detection" [40].

Robotic exoskeletons systems in use are large, heavy, and stiff. From patient perspective, can be uncomfortable for prolonged use, in case of elderly or frail users. Actuator power is frequently directly traded off for this bulk. Many systems last for two to four hours between charges, it limits exoskeletons usefulness in hectic clinical schedules. Mechanical function frequently takes precedence over ergonomics and long-term usability.

Robotic exoskeletons systems adoption is hampered due to frequent user complaints about device weight, pressure points after extended sessions, and discomfort from tight-fitting straps.

6.2 Clinical and Usability Challenges

Along with the hardware implementation, there are additional difficulties in implementing these devices for a therapeutic workflow. Patients may become overly dependent on the exoskeletons, decreasing intent of using own muscular effort and engagement. This passivity or "learned helplessness," can happen if the exoskeleton takes the place of natural effort instead of enhancing it. Next-generation control systems are actively addressing mitigation. Patients must actively participate because contemporary "assist-as-needed" (AAN) algorithms are made to only offer the bare minimum of assistance [35]. In order to guarantee that the user is constantly challenged, more sophisticated "Human-in-the-Loop" (HITL) controllers can even optimize assistance based on real-time metabolic or muscular feedback [35].

User acceptance of Robotic exoskeletons varies greatly. Some patients may experience anxiety, social stigma, or a fear of malfunctioning, but many report feeling more confident [5]. The psychological component of HRI is a crucial, frequently disregarded obstacle to compliance. Therapists must receive specialized technical training because initial setup, calibration, and fitting can be time-consuming. For clinics without specialized technical staff, this poses a challenge.

6.3. Socioeconomic and Implementation Barriers

The biggest obstacles are accessibility and high cost. Exoskeletons for commercial use can cost anywhere from $40,000 to more than $100,000. High cost and limited adaptability are the main obstacles to be overcome, according to a 2025 review [41]. Due to high cost constraint; limits Robotic exoskeletons access to upscale urban hospitals and wealthy nations. Robotic rehabilitation is still categorized as "experimental" in many healthcare systems. Regardless of demonstrated clinical benefits, adoption is stalled because clinics are unable to pay the high acquisition costs due to the lack of widely accepted insurance and public health reimbursement codes.

7 Future scope

Robotic rehabilitation is changing from inflexible, pre-programmed devices to lightweight, intelligent and co-adaptive systems. The major constraints of cost, weight, usability, and over-reliance mentioned in the preceding section are directly addressed by the main research frontiers. Soft exosuits, in comparision to rigid exoskeletons, are composed of textile fabrics and compliant actuators (such as cables or pneumatic artificial muscles). They become much lighter, more comfortable, and possibly less costly to produce as a result. Exosuits devices are perfect for patients who require help but not complete support, like those receiving long-term stroke care or elder care. The creation of fabric-based soft robotic (SR) gloves, which aid in hand opening and other daily tasks and demonstrate quantifiable functional improvements, is a prime example [33, 34].The Harvard Wyss Soft Exosuit [16] is another prominent example targeting gait assistance.

Research is concentrated on intelligent control systems to address the serious issues of inadequate intent detection and patient over-reliance. According to a 2025 review [41], artificial intelligence is the primary enabler for overcoming the main obstacles of cost and adaptability. Adaptive AAN (assist-as-needed) technology is the way of the future for control. The patient must actively participate because the system only applies the minimal amount of force required, as opposed to pre-programmed motion [35]. To develop truly personalized therapy, deep learning and reinforcement learning models are being developed [42]. To maintain the therapy's difficulty and efficacy, these systems are able to evaluate a patient's performance in real time and automatically modify the assistance parameters. "Human-in-the-Loop" (HITL) Control strategy optimizes assistance based on real-time physiological feedback, such as the user's metabolic cost or muscular effort. It assures, the device is always operating in accordance with the user's biological state and representing a truly symbiotic human-robot interface. Future systems will incorporate advanced interfaces and multisensory feedback to enhance patient engagement and make the devices more user-friendly. Exoskeletons and immersive virtual reality (VR) environments can be combined to gamify therapy and increase motivation and engagement [43]. AR (augmented reality) can provide intuitive, real-time feedback by superimposing visual cues for posture correction or step timing over real-world tasks.

For patients with severe paralysis, BCIs (brain computer interfaces) offer a way to control an exoskeleton directly through thought [44]. Bypassing the damaged nervous system, a BCI can convert the intention to move directly into a motor command for the device by decoding EEG (electroencephalogram) signals. These developments seek to produce exoskeletons that are intelligent rehabilitation partners: lightweight, reasonably priced, user-intent-adaptive, and enjoyable to use.

8 Conclusion

By bridging the gap between traditional physiotherapy and cutting-edge assistive technologies, robotic exoskeletons represent a revolution in musculoskeletal rehabilitation. Their clinical efficacy in offering reliable, high-intensity, and quantifiable therapy for orthopedic recovery, SCI, and post-stroke has been presented in this review. Widespread adoption is not assured and faces significant obstacles. The key research gaps are not just technical but also socioeconomic as well. To avoid a rehabilitation gap, future efforts must shift from demonstrating efficacy to addressing the fundamental issues of high cost, lack of insurance reimbursement, and accessibility. Human-centered innovation that prioritizes affordability, user-friendly design, and the creation of intelligent, adaptable systems that can be distributed fairly in homes and clinics will be the key to success.

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